Fourteenth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS

Calisolar: contactless traceability from feedstock to cell

Silver lining: Linx Consulting presents progress in silver past cost reduction

Laser edge isolation: Laser Zentrum Hannover shares results of its ablation study

Fraunhofer IKTS: why PECVD of ZnO is preferable to sputtering techniques

TÜV Rheinland: type approval testing of junction boxes

Fourth Quarter, November 2011

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Photovoltaics International

Fourteenth Edition

2011


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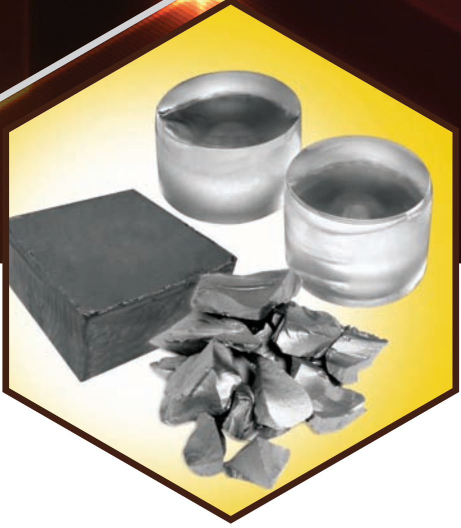

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Cover image shows TÜV Rheinland's new combined sun simulator in the PV-testing lab in Cologne. PSE AG's simulator allows combined measurement of both PV modules and thermal solar collectors. Image courtesy of TÜV Rheinland AG.

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Foreword

It's been a rollercoaster ride of a year for the PV industry, with oversupply problems and order declines affecting even the most stalwart manufacturers. Shaky third-quarter results have given us a taste of the extent of these industry woes, with flat to negative revenue figures resulting in severe downward revisions to full-year projections. And it looks like 2012 might not bring much respite to these straitened times.

They say there's nothing quite like a spot of competition to get the heart racing, and the recent trade dispute between the US and China is doing just that. This potentially counter-productive spat could have a detrimental effect on the industry as a whole, which has proven itself to be closer than ever to retail parity and a global inflection point. For those of you who have missed out on the SolarWorld-led CASM dispute against Chinese manufacturers, we've got a chronological round-up of the events to date on p. 172.

IMS Research has raised its global installation forecast to 24GW for 2011, as we get ever closer to the 30GW annual demand milestone that could very well signal the turning point for new capacity additions from tier-1 suppliers. European markets are in slow retreat mode, being replaced by potentially massive fast emerging markets such as North America, China and Japan, which is still reeling from the Fukushima nuclear episode earlier this year.

In this edition of *Photovoltaics International*, you can learn more about laser edge isolation of mc-Si solar cells, as presented by **Laser Zentrum Hannover** (p. 69). We have acronyms aplenty in the PECVD of ZnO for TCO application paper by **Fraunhofer IKTS** and **TU Dresden** (p. 93), while **TÜV Rheinland** provides a look at the methodologies involved in type approval testing on junction boxes for PV modules on p. 114.

On the more downstream side of things, **EPIA** gives us a glimmer of hope for PV, detailing the logistics of its becoming a viable mainstream player in Europe's energy field before 2020 (p. 156). And **Gartner's** projection (p. 178) of 100GW installed being a reasonable goal for the industry is reiterated on the PV-Tech.org website, where we recently hosted a guest blog by Keiser Analytics. This unique bottom-up analysis of retail electricity prices across the US claims that the country's solar module demand could top 100GW over the next five years – which would spell exciting times ahead.

We've launched several new products this year, such as the PV-Tech Newscast, our weekly video news round-up, and the new-look PV Directory, which houses a detailed and easily navigable one-stop shop for information on some of the industry's major companies, sorted by both sector and region.

And we're excited to announce that we are rebranding and relaunching the PVI Lite publication, which will now be known as *Solar Business Focus*. This new digital and physical publication will form an indispensable guide for doing solar business on a global scale, featuring regular sections including Finance & Legal, Project Focus, Marketplace and Technology & Manufacturing. Be sure to keep an eye out for the first edition, which will be on the PV-Tech website in February!

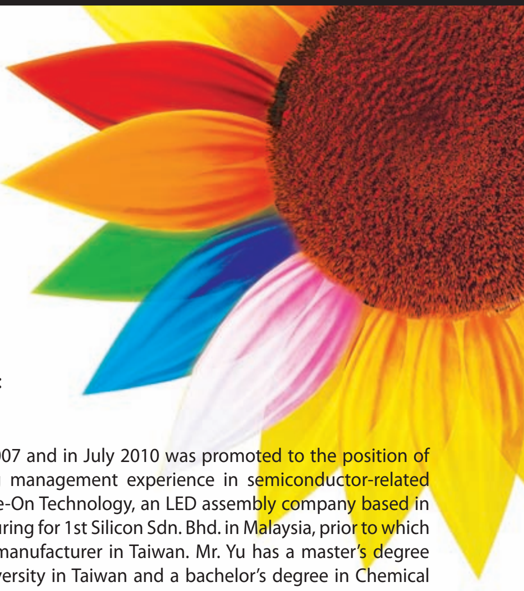
As this is the last edition of the year, we wish to thank all of our authors, advisors, advertisers and everyone that has contributed to our publications and websites over the course of the past year. We're looking forward to a 2012 that defies the pessimistic – or perhaps realistic – expectations of many.

Here's to a prosperous 2012!

Síle Mc Mahon
Managing Editor
Photovoltaics International

Photovoltaics International

Photovoltaics International's primary focus is on assessing existing and new technologies for "real-world" supply chain solutions. The aim is to help engineers, managers and investors to understand the potential of equipment, materials, processes and services that can help the PV industry achieve grid parity. The Photovoltaics International advisory board has been selected to help guide the editorial direction of the technical journal so that it remains relevant to manufacturers and utility-grade installers of photovoltaic technology. The advisory board is made up of leading personnel currently working first-hand in the PV industry.



Editorial Advisory Board

Our editorial advisory board is made up of senior engineers from PV manufacturers worldwide. Meet some of our board members below:

Gary Yu, Senior Vice President, Operations

Mr. Yu served as Trina Solar's Vice President of Manufacturing since May 2007 and in July 2010 was promoted to the position of Senior Vice President of Operations. Mr. Yu has 17 years' manufacturing management experience in semiconductor-related industries. Before joining Trina Solar, he was Managing Director of Wuxi Lite-On Technology, an LED assembly company based in China. Prior to Wuxi Lite-On Technology, he served as a Director of Manufacturing for 1st Silicon Sdn. Bhd. in Malaysia, prior to which he worked at Macronix International, a semiconductor integrated device manufacturer in Taiwan. Mr. Yu has a master's degree in Industrial Engineering and Management from National Chiao Tung University in Taiwan and a bachelor's degree in Chemical Engineering from Tunghai University.

Takashi Tomita, Senior Executive Fellow, Sharp Solar

Takashi Tomita has been working at Sharp for 34 years and is widely recognised as a fore-father of the solar industry in Japan. He was responsible for setting up Sharp's solar cell manufacturing facilities in Nara and silicon production in Toyama. Takashi's passion for solar power has led him to hold numerous posts outside of his roles at Sharp, including: Vice Representative at the Japan Photovoltaic Industry Association; Committee Member of Renewable Energy Portfolio Standard of METI; Adviser Board Member of Advanced Technology of Nara; Visiting Professor of Tohoku University; Adviser of ASUKA DBJ Partners (JAPAN) and Adviser of Global Catalyst Partners (US).

Dr. Kuo En Chang, President of Solar Division, Motech Industries, Inc.

Dr. Kuo En Chang joined Motech in 1999 as Chief Technology Officer and became President of the Solar Division in 2008, with responsibility for all technology and manufacturing. Motech is the sixth largest solar cell producer in the world. Before Dr. Chang joined Motech Solar, he worked on secondary battery research at the Industrial Technology Research Institute (ITRI) for more than three years. Dr. Chang holds a Ph.D. degree in Metallurgical & Materials Engineering from the University of Alabama.

Professor Eicke R. Weber, Director of the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg

Professor Eicke R. Weber is the Director of the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg. Weber has earned an international reputation as a materials researcher for defects in silicon and III-V semiconductors such as gallium arsenide and gallium nitride. He spent 23 years in the U.S. in research roles, most recently as Professor at the University of California in Berkeley. Weber is also the Chair of Applied Physics, Solar Energy, at the University of Freiburg, and during his career has been the recipient of several prestigious awards including the Alexander von Humboldt Prize in 1994, and the German Cross of Merit on ribbon in June 2006.

Dr. Zhengrong Shi, Chief Executive Officer, Suntech

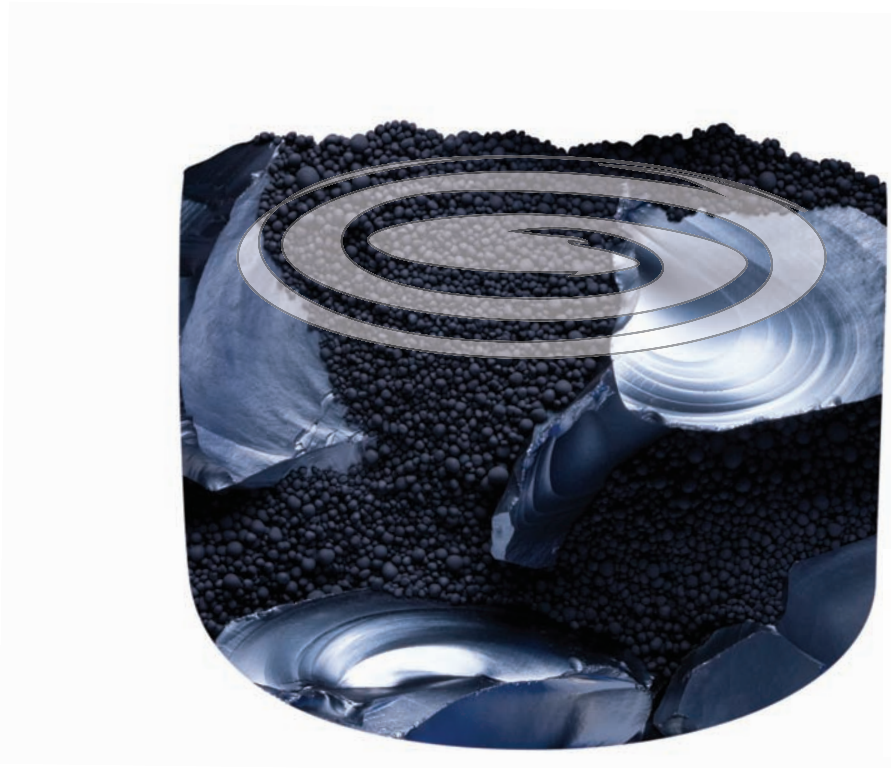
Dr. Zhengrong Shi is founder, CEO and Chairman of the board of directors of Suntech. Prior to founding Suntech in 2001, he was a Research Director and Executive Director of Pacific Solar Pty., Ltd., the next-generation thin-film technology company, before which he was a Senior Research Scientist and leader of the Thin Film Solar Cells Research Group in the Centre of Excellence for Photovoltaic Engineering at the University of New South Wales in Australia. Dr. Shi holds 11 patents in PV technologies and is a much-published author in the industry. His work has earned him such accolades as "Hero of the Environment" (TIME magazine 2007) and "Corporate Citizen of the Year" at the China Business Leaders Awards 2007. A member of the NYSE advisory board, Dr. Shi has a Bachelor's degree in optical science, a Master's degree in laser physics and a Ph.D. in electrical engineering.

Dr. Sam Hong, President and COO of Neo Solar Power

Dr. Hong has more than 30 years of experience working in the solar energy industry. He has served as the Research Division Director of Photovoltaic Solar Energy Division at Industry Technology Research Institute (ITRI), a research organization that serves to strengthen the technological competitiveness of Taiwan, and Vice President and Plant Director of Sinonar Amorphous Silicon Solar Cell Co., which is the first amorphous silicon manufacturer in Taiwan. In addition, Dr. Hong was responsible for Power Subsystem of ROCSAT 1 for the Taiwan National Space Program. Dr. Hong has published three books and 38 journal and international conference papers, and is a holder of seven patents. Dr. Hong was the recipient of Outstanding Achievement Award from the Ministry of Economic Affairs, Taiwan, and was recently elected as chairman of the Taiwan Photovoltaic Industry Association.

Dr. G. Rajeswaran, President and CTO of Moser Baer Photovoltaic Ltd

Raj served as President and CTO of Moser Baer Photovoltaic Ltd. from July 2007 until October 2008, since which time he has been Group CTO for all the Moser Baer business units and holder of the CEO function for launching new businesses. He spent 22 years with Eastman Kodak Company as the Vice President of Advanced Development & Strategic Initiatives, where he managed Kodak's Japan display operations including technology & business development in Japan, Taiwan, Korea and China. He has also served as Vice President and on the board of SK Display Corporation, and worked in technology development with Brookhaven National Laboratory. Raj has a Ph.D., an M.Tech. and a B.E. in electrical engineering. A much-published author, speaker and patent holder, Raj is a member of the Society for Information Display (SID) and has chaired several international conferences in the field of OLEDs.



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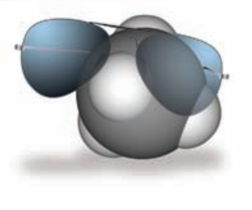

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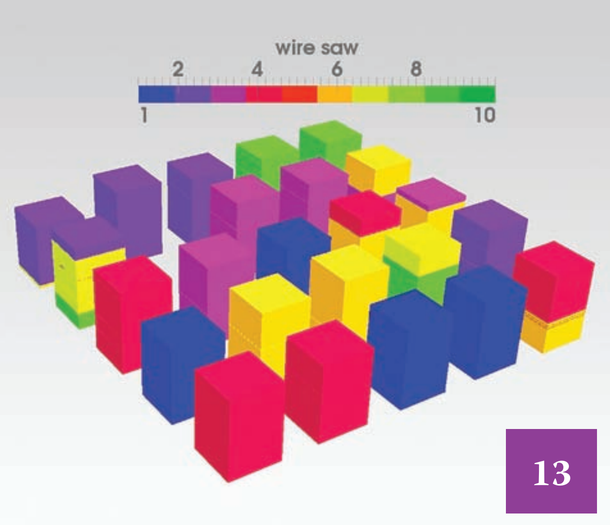

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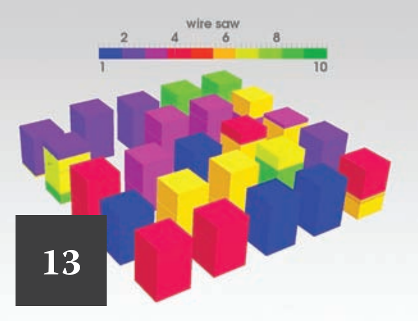

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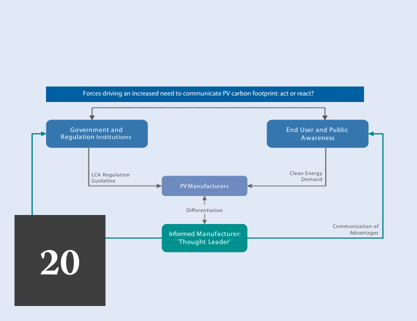

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News

First Solar doubles production in Germany

In June, First Solar predicted its plant in Frankfurt (Oder) would reach full capacity during the third quarter of 2011. This prediction was realised in October when the plant reached full production.

However, the cause célèbre was the production of the plant's one millionth module, commemorated at an opening ceremony attended by Brandenburg Minister President Matthias Platzeck, Katherina Reiche, State Secretary in the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and Jürgen Trittin, chairman of the parliamentary faction of the Greens / Bündnis 90 Party in the German Parliament.

Covering an area of roughly 50,000m^2, the thin-film solar PV module manufacturer will produce 250MW of solar modules per annum. The expansion doubles First Solar's annual production capacity in Germany to 500MW. The new plant became fully operational on schedule after just one year of construction and an overall investment of more than €170 million. First Solar's employment in Frankfurt (Oder) has almost doubled to more than 1,200 from 650.

"With the inauguration of our second German plant in Frankfurt (Oder), we're operating Europe's largest and most modern production site for advanced, thin-film solar modules," said Tymen DeJong, senior vice president for global operations. "Our additional investment shows: Germany is a key market for solar energy and an important production location for First Solar."

First Solar has also voluntarily established the industry's first comprehensive, prefunded solar module collection and recycling program and operates a recycling facility in Frankfurt (Oder).


Source: First Solar

First Solar's Frankfurt (Oder)s plant reached full capacity in October.

Capacity & Production News Focus

Silicio Solar stops production in Puertollano

Concern is growing amongst the 800 employees of silicon wafer manufacturer Silico Solar which planned to close its 300MW facility in Puertollano at the end of November until February 2012 at the earliest. Silico has blamed the need for the closure on the adverse PV market conditions.

According to sources, the Silicio Solar board estimates that the decline of wafer prices within the last 12 months has been between 50 and 60%. Puertollano, one of the solar industrial clusters of Spain, is located near Ciudad Real in the Autonomous Region of Castilla-La Mancha.


Source: Silico Solar

Silico Solar's facility in Puertollano, Spain.

Nigeria's NASENI to develop 7.5MW solar panel manufacturing plant in Karshi, Abuja

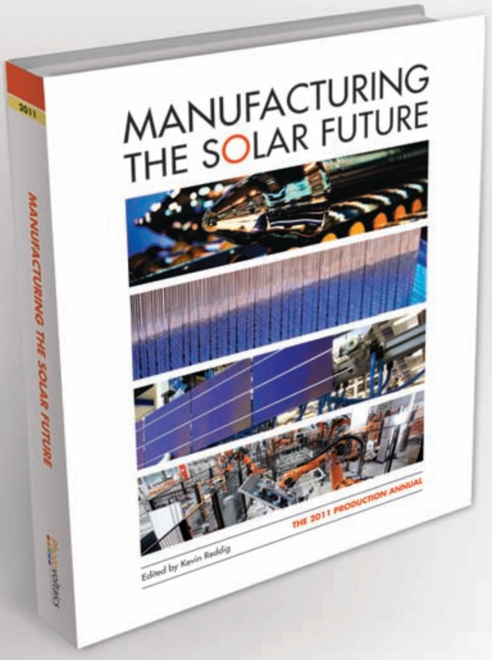
Nigeria's National Agency for Science and Engineering Infrastructure (NASENI) recently revealed plans to develop a 7.5MW solar panel manufacturing plant in Karshi, Abuja. The project, which will allow Nigeria to start the process of cutting its dependency on the importation of solar panels, is being developed through a joint venture with an undisclosed foreign partner.

NASENI commented that as well as helping Nigeria become less dependent on imported solar panels, the manufacturing facility would lead to solar street lighting, water pumping for irrigation, powering repeater and telecommuting stations, powering traffic lights and the small scale processing of farm products. The plant is said to have been tested and is ready for commissioning.

SilexSolar suspends manufacturing at Sydney facility

SilexSolar has suspended all manufacturing as it continues to restructure in response to the downturn in Australia's solar industry. The company has placed its Homebush Bay facility into 'care and maintenance' mode and in the process made all employees in production, as well as several engineering, technical and administrative staff, redundant.

Silex has operated out of the Homebush Bay facility, located within the Sydney Olympic Park, since 2009, when it acquired the site from BP Solar. Its closure is the latest step of a cost-reduction programme, which began in August with the replacement of the in-house cells in its modules with those of new strategic partner Hareon Solar. The company has sufficient inventory to support sales over the next few months, and will focus its efforts on the residential rooftop and medium-scale commercial project markets.


MANUFACTURING THE SOLAR FUTURE
THE 2011 PRODUCTION ANNUAL
Edited by Kevin Reddig
2011


KUKA
KUKA

Source: SilexSolar

Production demonstration at SilexSolar's Homebush Bay, Sydney facility.

While Silex contemplates the future of the manufacturing side of its business, another company, Tindo Solar, is gearing up to start production at a new factory in Mawson Lakes, South Australia. The factory is expected to be operational by the end of the month and when it reaches full capacity it will produce around 250,000 panels annually.

Sunpreme closes on US$50 million in financing round for construction of new solar cell facility in China

Sunpreme revealed that in its latest financing round the company secured over US$50 million, which will go towards the construction of a new solar cell manufacturing facility in Jiaxing, China. The financing round was led by the International Finance Corporation (IFC), a private entity of the World Bank Group. Capricorn Investment and Environment Fund III, managed by Tsing Capital, also contributed to the funding round.

Upon completion of its new solar cell facility, Sunpreme intends to expand the production of its SmartSilicon cells. "Over the past 18 months, Sunpreme has demonstrated for the first time a commercially viable metallurgical Silicon solar cell technology. Our first three US patents for the innovative device structure have been granted and we are now moving to scale production of the SmartSilicon cells in the new Jiaxing facility, near Shanghai," said Ashok Sinha, Sunpreme's chairman and CEO.

Hyundai Heavy Industries suspends production at PV panel facility in Korea

Hyundai Heavy Industries has suspended production at its 50MW solar cell and module plant in Eumseong, South Korea. Manufacturing at the site, which was built in 2007 and is the smallest of three Hyundai solar facilities in Eumseong, was actually halted back in June, although the decision was only made public in early November. The move is a response to the solar industry's slowdown over the past 12 months – a by-product of feed-in tariff uncertainty and wider economic difficulties in Europe and the US.

However, Hyundai are eager to outline that the hiatus in production is merely temporary and does not signal the start of a more permanent scaling back of its solar operations. "Amid the declining solar industry worldwide, we suspended the operation of the No.1 plant in June, and workers who had belonged to the facility have moved to the other two plants nearby," said a Hyundai spokesman. "Once the situation improves, we'll restart the operation of the plant.

This decline is likely to scupper the original growth plan for Hyundai's solar and renewable energy divisions; it planned to ramp up combined capacity at its three PV facilities to 1GW – current capacity is 600MW – and to generate sales worth US$1.8 billion from the alternative energy sector by 2012.

Photowatt France files for bankruptcy as ATS Tooling puts Photowatt Ontario up for sale

ATS Automation Tooling Systems' PV module manufacturing subsidiary, Photowatt France, is planning to file for bankruptcy in the French courts. The company cut production in October after attempts to find a buyer proved unsuccessful. ATS Automation said that it hoped the move would lead to a "recovery process" in which potential buyers may be found and jobs retained.

However, ATS noted that it received a non-binding letter of intent for the purchase of an ATS-owned building in France that formerly housed PWF module assembly operations. Should the sale go ahead as expected, the proceeds would go to offset cash outflows resulting from the bankruptcy process.

ATS expects to record impairment

Source: Google

Sunpreme has secured over US$50 million in its latest financing round.

Source: Hyundai Heavy Industries

Hyundai Heavy Industries' solar cell and module plant has suspended production.

Source: ATS

Automation Tooling Systems' module plant in Ontario.

Production at Evergreen Solar's Devens facility.

Source: Globe file photo/Boston.com

charges and write-offs totalling US$64 million related to PWF operations, including US$24 million of charges related to the termination of certain silicon and wafer supply agreements and other charges related to inventories, silicon deposits, and other PWF assets.

ATS said that it had also initiated a formal sale process for Photowatt Ontario, but no further details have yet been provided.

Court decrees Evergreen Solar may proceed with sale of majority of assets to three companies

Evergreen Solar has received permission to proceed with the sale of the majority of its assets from a bankruptcy judge at a Wilmington, Delaware hearing. The bankrupt module manufacturer and co-owner of the proprietary 'String Ribbon' technology is said to have secured a buyer for its core wafer assets to Hong Kong-based Max Era Properties for approximately US$9.2 million – US$6 million in cash and US$3.2 million in unrestricted ordinary shares of China Private Equity Investment Holdings.

The auction of assets was held on November 1, and resulted in the sale of core assets to Max Era, including IP for the company's 'wide wafer' technology and interests in an unnamed China-based JV company. It is also selling a claim against a Lehman Brothers Holdings affiliate company to the tune of approximately US$171 million to its 13% senior secured noteholders for the sum of US$21.5 million in debt forgiveness, and Evergreen has offloaded its inventory of solar modules to Kimball Holdings LLC for around US$3.8 million.

After entering into time-consuming negotiations with holders of its 13% convertible senior secured notes, which had caused the company to delay quarterly SEC filings, Evergreen Solar filed for Chapter 11 bankruptcy in August this year.

Court papers for the transactions did not mention any sale of the company's 450,000-square-foot manufacturing facility in Devens, MA.

Other News

Manz acquires Würth Solar's CIGS thin-film operations

Collaboration has turned to acquisition as equipment specialist Manz is to acquire Würth Solar's CIGS thin-film production line in Schwäbisch Hall, Germany. The deal will include the purchase of all technology IP from the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), Würth Solar's orginal technology partner on CIGS processes. The takeover should be concluded by early 2012 with a total of 116 Würth Solar employees being integrated into Manz as part of the acquisition.

Würth Solar will be responsible for sales and marketing of the panels in the future, while Manz will use this production line as its R&D line.

Source: Google

Manz's HQ in Reutlingen, Germany.

The new deal changes the previous agreement between the parties, in which Manz was contracted to provide further licensing payments when the first complete CIGSfab was sold. Financial details were not disclosed.

Heraeus set to open Asian Photovoltaics Center in Singapore

Heraeus recently unveiled its latest full-service facility in Singapore. In addition to manufacturing Heraeus's front- and back-side silver pastes for crystalline solar cells, the Singapore-based Asian Photovoltaics Center will also house sales, R&D and technical service teams.

Arise's German subsidiary files for insolvency

Arise Technology Centre GmbH, the wholly-owned German subsidiary of Arise Technologies, has initiated structured insolvency proceedings following the company's closure of its German operations in October. The Gelsenkirchen, Germany-based Technology Centre was established under a multi-faceted agreement with Scheuten Solar in October 2009.

Arise was then instructed by an arbiter to pay €920,066 to Scheuten Solar as a result of lease disputes related to the Technology Centre. Consequently, the Canadian PV module manufacturer has made the decision that it is no longer feasible to continue to run its German operations.

Source: Arise Technologies

The Canadian PV module manufacturer has made the decision that it is no longer feasible to continue to run its German operations.

SolarWorld's Deutsche Cell subsidiary celebrates 10 years of operation

Deutsche Cell, the German subsidiary of SolarWorld, has logged 10 years of cell production in Freiberg and Saxony. Founded in 2001, the company's multicrystalline solar cell production capacity has increased tenfold since the company's inception, currently standing at 260MW per annum.

Deutsche Cell's 10-year celebration will be closely followed by companies such as Suntech with its own celebrations. However, it remains to be seen how many of these cell manufacturers will survive another 10-year milestone, given the economic uncertainty, oversupply situation and trade disputes currently dominating the PV news airwaves.

Solaria employs Camstar's software to manage manufacturing practices at Fremont headquarters

Solaria has begun use of the Camstar Enterprise Platform at its Fremont, California headquarters to help maintain quality initiatives throughout its manufacturing process. Solaria's use of Camstar Manufacturing has allowed the company to access real-time product and process data as well as process and quality control across its global locations.

"The Camstar Platform drives our virtual factory with closed-loop quality processes for continuous improvement by enforcing best practices, and enabling constant visibility and coordination among R&D, contract manufacturing and field use," said Helen Milani, senior director of IT at Solaria.

Source: Solaria

Solaria's solar trackers.

BTU International reduces headcount on weak solar equipment sales

Thermal processing equipment specialist BTU International is reducing its US-based workforce in response to the slowdown in demand from PV manufacturers. Workforce reductions started in June 2011, and included full-time and contracted workers, although the company did not disclose the actual number of jobs lost. Temporary furloughs were also being initiated.

BTU reported third quarter net sales of US$16.9 million, down from US$19.0 million in the preceding quarter and compared to US$19.0 million for the same quarter a year ago. Net loss, including a restructuring charge of US$352,000, was US$2.0 million, compared to a breakeven position in the preceding quarter.

Source: BTU

BTU International's Meridian In-Line Diffusion System.

Integral characterization: Traceability from feedstock to cell

Dennis Schaffarzik & **Dirk Zickermann**, Calisolar GmbH, Berlin, Germany; **Jean Hummel**, Calisolar Inc., Sunnyvale, USA

ABSTRACT
For a vertically integrated solar cell production starting with purification of silicon feedstock and ending with the production of solar cells, it is necessary to have control over all possible parameters that may affect yield, efficiency and product quality. This paper presents an approach for tracking products with minimal effort using a contactless technique. The method allows wafers to be virtually reconstructed into bricks and ingots, as well as recognizing the precursor wafer for each solar cell.

Introduction

Increasingly, cost reduction plays a major role in solar cell production, and yet there are also demands for continuous improvement of the quality of the cells. Yield improvement is one approach to tackling this balancing act: it has been used in the semiconductor industry but is also transferable to solar cell production. Yield improvement can be done by effective process optimization, but is only possible if the boundary conditions are well known and if as many parameters as possible are measured and can be assigned to individual products. In addition, it is necessary to separate the whole solar cell process into single process steps in order to realize the full potential of the benefits of process control and optimization. The knowledge of all parameters – including production- and material-related properties, measurements, electrical data, and quality data for each single wafer and cell – allows an insight into the complex interaction between feedstock quality, crystallization, wafering and cell processes. For example, the influence of defect density in the wafer in connection with the feedstock used, and of crystallization parameters and process steps later in the cell process, can all impact final cell performance.

Detailed product tracking becomes quite complex because production scenarios often interrupt a perfect linear product flow. Disturbances occur when splitting wafer batches or when changing from batch to in-line processes. If detailed product history is needed, complex recording is usually required at each production stage.

Single wafer tracking in the semiconductor industry [1] is the traditional approach used to improve quality and therefore yield and production cost. Laser-marking methods [2,3] are known techniques for tracking solar cell production from ingot crystallization to single wafer and/or cell. This paper presents a novel approach permitting traceability from feedstock to finished solar cell, allowing simple data collection across the production line and then identification and optimization of the relevant and important process parameters.

Tracking solution

The tracking begins with the application of product identifiers to each feedstock batch so that all detailed process and measurement data (e.g. ICP-MS data) can then be saved and tagged with the corresponding feedstock number. After crystallization, an ingot is created and each one gets a unique ingot identifier, which is saved with all its corresponding process data. At the bricking process step, the ingot number is used when saving the process data, and an additional brick-identifier suffix is applied to each of the 25 bricks. The wafering process data are saved with the corresponding ingot and brick identifier. All the combined data are transferred and saved to a manufacturing execution system (MES).

After wire sawing, the wafers are separated singly from the stack using a machine that has two loading entries for the sawed bricks. Each brick of wafers is loaded into four lanes (see red and green wafers in Fig. 1a). In summary, all wafers are transported in eight lanes into a wafer clean bench and recombined into a single lane at the exit of this wafer clean system. Due to the manner of this handling, the order of the wafers is lost: this is illustrated by different colours of the wafers in Fig. 1(a). The blue wafers of one brick from the right-hand side are completed, and the green wafers follow at the right-hand side. During this time, the red wafers from the left-hand side are still being processed. In this case the system mixes wafers from three different bricks (see blue, red and green wafers in Fig. 1a).

> “The complete wafer-tracking system consists of a matrix camera, special illumination to obtain a high contrast of the grain structure of the wafers, and proprietary software.”

The important information on the position of the wafers within the bricks and the tracking of the wafers gets lost. To recover this information, a system called Gemini [4] was implemented. Developed by Intego GmbH, a specialist in vision systems, Gemini essentially

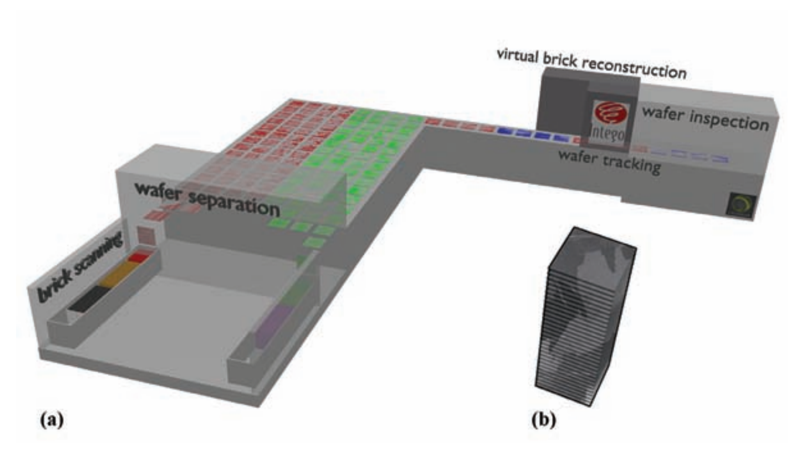


Figure 1. (a) Wafer separation. (b) Drawing of similar grain structure in a sawed brick.

delivers virtual brick reconstruction using intelligent image recognition. This system is able to virtually re-sort the wafers into the sequence of their precursor brick by using the principle that the grain structures of neighbouring wafers within a brick are almost identical (see illustration of wire-sawn brick in Fig. 1b). The complete wafer-tracking system consists of a matrix camera, special illumination to obtain a high contrast of the grain structure of the wafers, and proprietary software. The integration of a brick-scanning system at the entry of the wafer separation is used to transfer the brick and ingot number of loaded bricks to the wafer-tracking system. The pictures of each wafer at the end of the single lane are taken by the wafer-tracking system and transferred to the brick-reconstruction system, with an additional arbitrary incremental virtual serial number for each wafer, and the corresponding ingot and brick number. The software of the brick-reconstruction system is able to detect the grain structure of the wafers and summarizes this feature in a compact file. A fast recognition algorithm is able to calculate a correlation value between any two images and thus allow the system to reconstruct the order of the wafers within a brick and also distinguish different bricks. The information on the position and serial number of each wafer, together with the ingot and brick number, is then transferred by the brick-reconstruction system to the MES. With the stored information of ingot number, brick number and wafer position within the brick, a virtual rebuild of single wafers into the brick's precursor ingot is possible.

The wafer-tracking station transfers the arbitrary serial number of each wafer to the wafer-inspection system as well, which itself associates this serial number with the corresponding wafer measurement data prior to transferring to the MES.

> "Even though a lot of the information of the surface is lost, the system is still able to find the correct precursor wafer for each cell."

Because of the combination of in-line and batch processes in cell production, the order of the wafers will get lost within the process. The in-line process needs a constant flow and a carrier change is needed after the filling of one carrier at the end of the in-line process. During this period of time the in-line process must store some wafers in buffers and will reload them if space becomes available due to process-related missing wafers (see Fig. 2).

Figure 2. Change from in-line to batch.

Due to the change of the aspect (colour, contrast, morphology, reflection, etc.) of the wafer surface through the different processes, the recognition rate becomes very low with this brick-reconstruction system. However, a correlation between cells and wafers is sufficient at this stage of production. To this end, a cell-to-wafer tracking system has been co-developed with Intego GmbH. Based on the brick-reconstruction software, the detected patterns of the wafers after each process step are compared with the as-cut wafers to determine the correlation between cells and wafers.

The largest impact on the wafer appearance is acidic texturization. This process dramatically reduces the contrast of the grain structure of the wafer surface, compared to the as-cut wafer. The software detects and identifies the grain structure of the acidic-texturized wafers as well, but, compared to the grain structure of the as-cut wafers, much information of the grain structure is lost. This loss of information is reflected in the correlation values after the texturization, which are lower than those of the as-cut wafers (see Fig. 3).

Each consecutive process reduces the information that can be derived from the wafer surface and with it the matching correlation values. Nevertheless, the comparison of processed wafer 3 with as-cut wafers 1, 2 and 3 after each process step still shows the highest correlation value for only the as-cut wafer 3 comparison (see Fig. 3). Even though a lot of the information of the surface is lost, the system is still able to find the correct precursor wafer for each cell. The matrix camera for the cell-to-wafer matching system is utilized in the print/colour inspection. For each detected cell, the system uses the same serial number as the one for the wafer, and transfers this number and the print/colour measurement result of each cell to the MES. In the same way, the serial number is also transferred to the cell tester unit, which then uses it in saving all measurement values of each cell and transfers the data to the MES.

Visualization

For a better visualization of all process parameters and process steps, especially for the ingot crystallization, it is helpful to generate a 3D model of the whole ingot using data from wafers or cells. Therefore a procedure has been developed that allows the creation of a 3D representation of wafers or cells with the given coordinates

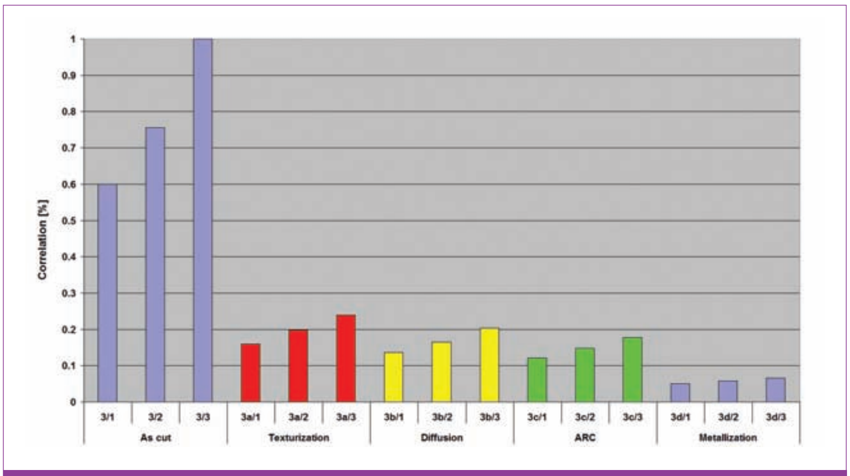


Figure 3. Comparing as-cut and processed wafers with as-cut wafer 3.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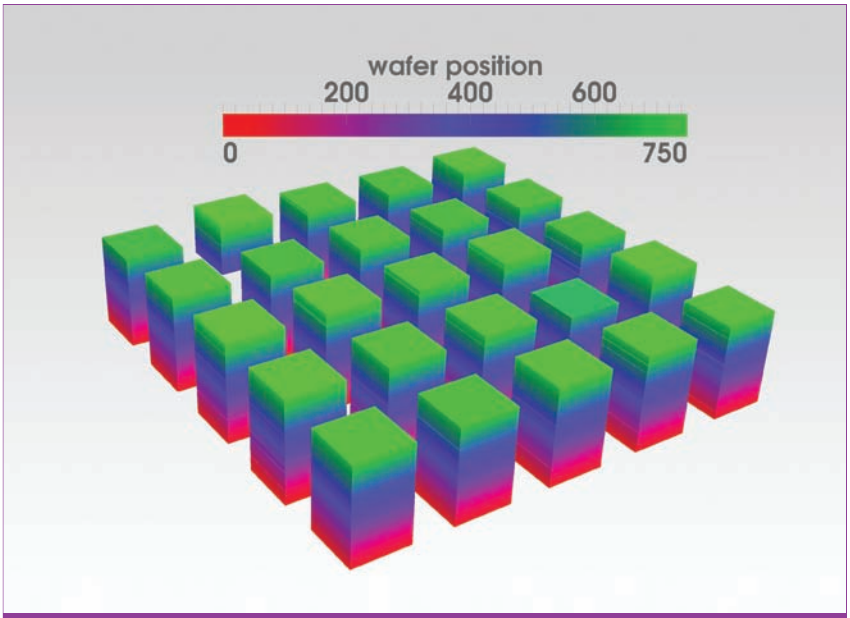

Figure 4. 3D view of an ingot rebuilt from single wafers.

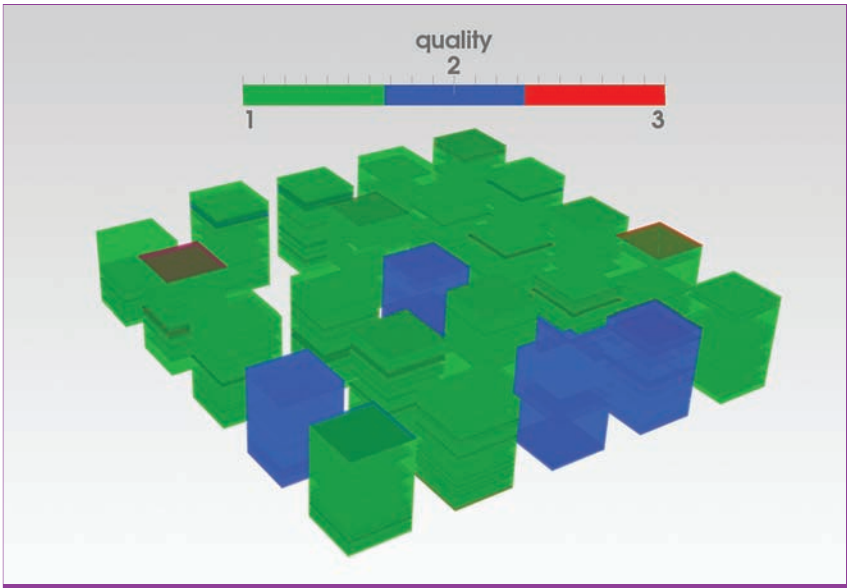

Figure 5. Wafer quality – Example 1.

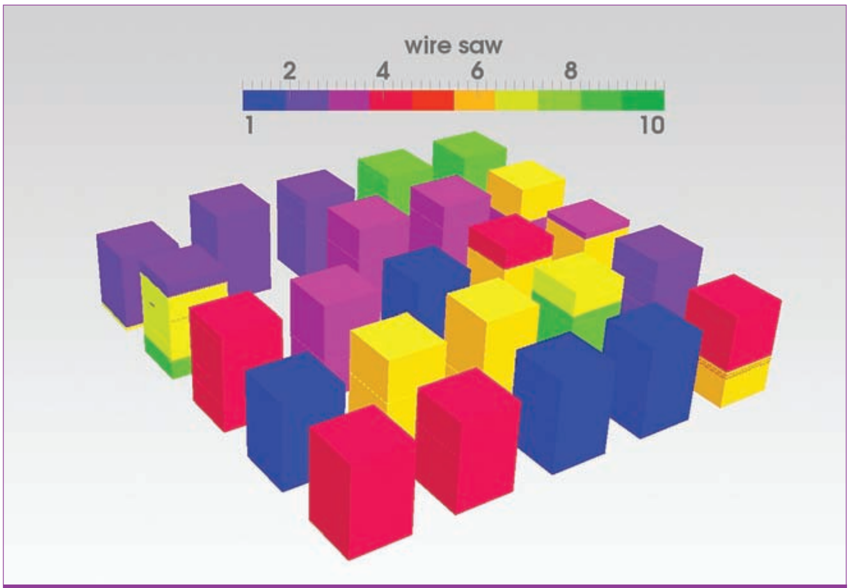

Figure 6. Wire saw number – Example 1.

x and *y* from the brick number and *z* from the height position within the brick. For each wafer or cell, a virtual ingot data model will be automatically constructed with the calculated information of its height within the brick and its position in the ingot. In addition, a colour range can be applied to one parameter to encode measurement results on wafers and cells or process data at single product stages. In Fig. 4 such an ingot reconstruction is shown for the wafer position parameter of each wafer within the 25 bricks.

Results

Example 1: Failure analysis

With this full-tracking solution it is possible to analyze all process parameters, measurement data and binning information corresponding to each wafer or each cell re-positioned into its precursor ingot. Continuous access of these data enables real-time assessment of yield and quality-controlling factors, allowing a fast analysis of the yield/loss mechanism and a fast corrective action in manufacturing.

An example of a yield analysis of low wafer quality is shown in Figs. 5 and 6. The wafer quality parameter is plotted for one ingot in Fig. 5. Most of the quality 2 wafers are located in the four blue bricks. Due to the fact that four bricks are cut at once with each wire saw, it could be that the process of wafering was not under control for a particular wire saw. This can be easily checked if the same wafers of the ingot are plotted against the information on the wire saw with which the wafers were cut (see Fig. 6).

By analyzing in this manner, the correlation between quality 2 and wire saw number 1 (blue bricks) is confirmed and the problem with the wire saw can be investigated and solved. Without such spatial differentiation, the identification of the problem would be rather difficult because the only available information would be that roughly 2500 wafers have quality 2.

Example 2: Experiment observations

To improve production yield some experiments in the production process are necessary. Such experiments may significantly disturb the production because a special handling and tracking of test lots within the production line is necessary. In contrast, the availability of a full-tracking system can avoid additional work within the production, and experiments are easily performed and data extracted using only the MES, as shown in this example (Fig. 7).

A variation of different wire diameters and different pitches was evaluated for wire saws 6 and 9 (dark green and orange bricks, respectively, in Fig. 7). To verify the resulting wafer thickness, the same ingot need only

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be visualized with a colouring scheme for the measured wafer thickness obtained from the wafer-inspection system. In Fig. 8 the resulting thicker wafers (dark red) can be identified and traced back to the wire saws. Furthermore, the possible influence on cell performance, for example the resulting efficiency, of the same ingot can be checked as shown in Fig. 9.

Example 3: Reverse analysis

An analysis such as previously described can be also done in reverse to detect the process influence at the level of single 'products', these being feedstock, ingot, bricks, wafers and cells. The reverse analysis starts from the results of the cell efficiency plotted per ingot. In this example of one ingot, a slight decrease in efficiency was observed in the bottom region of some of the bricks (see Fig. 10). Since each parameter at each product stage can be controlled, it can be seen how the slight decrease in efficiencies matches the lower lifetime values obtained for the wafer level in the bottom region of the bricks (see Fig. 11).

> "Integral tracking of feedstock, crystallization, wafer and cell data is a powerful tool for quality management, process control, process development, and research and development tasks."

Conclusions

3D models of ingots were reconstructed from brick, wafer and cell tracking data. The advantages are found in the visualization of process parameters through brick and ingot reconstruction. This allows a differentiation of the effects of the different components, such as feedstock, crystallization characteristics, wafer processes and cell processes. The quality of the cells can be directly compared to the properties of the corresponding wafers. It is possible to extract the influence of the precursor feedstock on solar cells from the brick and ingot information. Integral tracking of feedstock, crystallization, wafer and cell data is a powerful tool for quality management, process control, process development, and research and development tasks. The influence of feedstock and process parameters on the end product – the solar cell – can be quickly ascertained (and corrective action taken) by one-to-one tracking of wafer and cell data.

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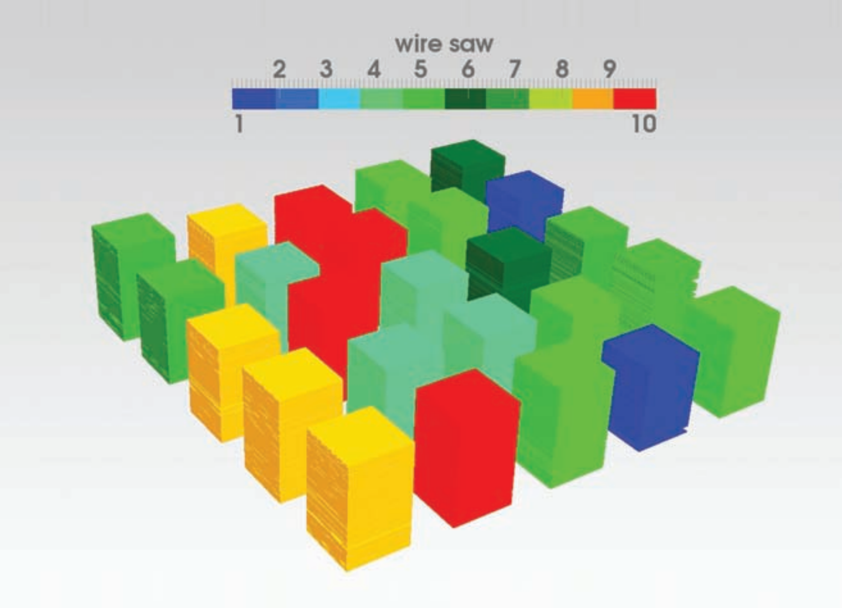

Figure 7. Wire saw number – Example 2.

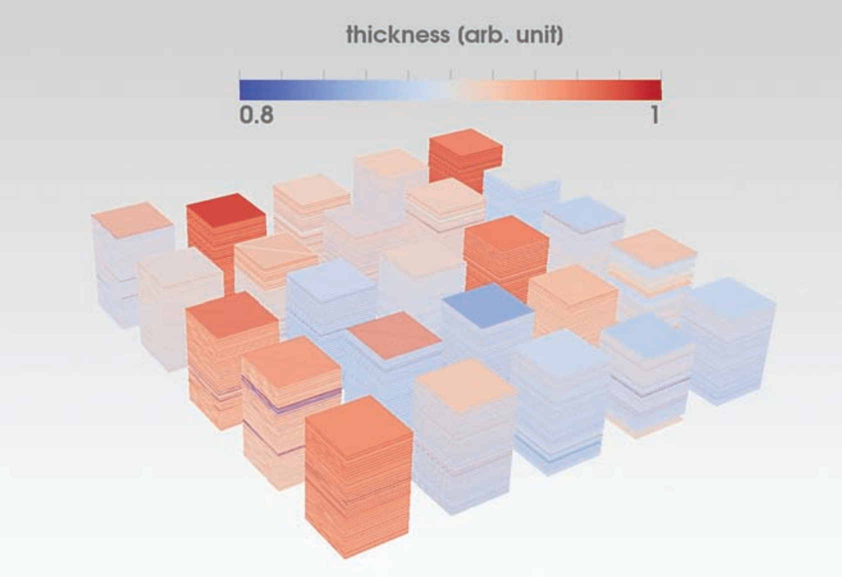

Figure 8. Wafer thickness – Example 2.

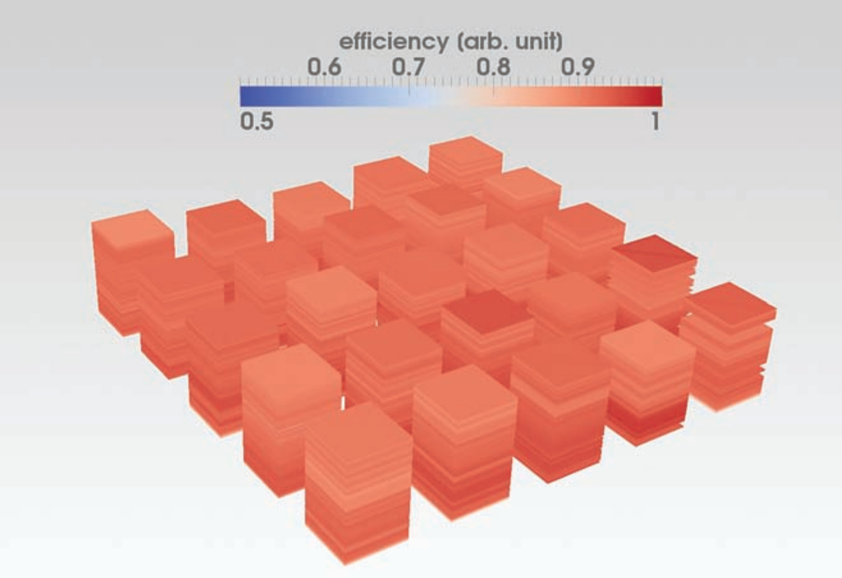

Figure 9. Cell efficiency – Example 2.

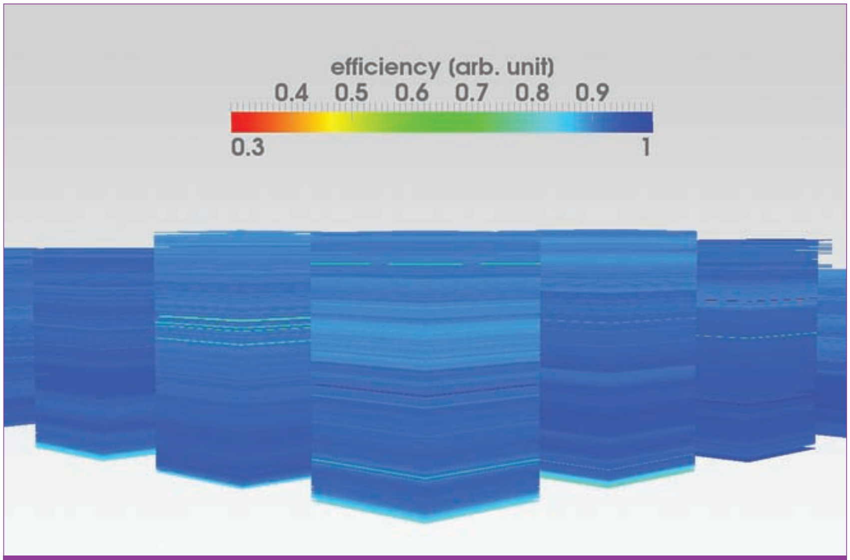

Figure 10. Cell efficiency – Example 3.

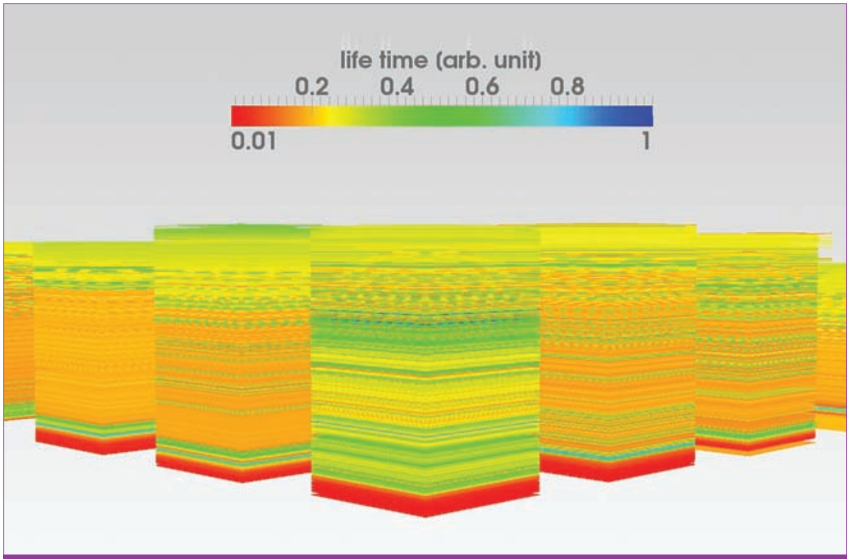

Figure 11. Wafer lifetime – Example 3.

(formerly of Calisolar Inc.) for additional implementation into the cell production and M. Heuer (Calisolar GmbH) for fruitful discussions.

References

[1] Scher, G. 1991, "Wafer tracking comes of age", *Semicond. Internat.*, May.
[2] Müller, J. and Patzlaff, T. 2009, "Solar cell marking method, and solar cell", Patent No. US 2009/0050198 A1.
[3] Richter, A., Krenzin, M. and Moecke, J. 2010, "Ingot marking for solar cell determination", Patent No. US2010/0237514 A1.
[4] Intego GmbH, Gemini system [details available online at http://www.intego.de/en/gemini].

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Dennis Schaffarzik worked on surface photovoltage based characterization of silicon solar cells at the former Hahn-Meitner-Institute, after studying physics at Humboldt University, Berlin. Dennis has been with Calisolar Berlin since 2007, and his current work includes new metrology implementation for process and product control at Calisolar's integrated plant in California.

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True sustainability in the PV industry: The case for carbon footprint certification

Rob van der Meulen, EuPD Research, Bonn, Germany

ABSTRACT
How much carbon is emitted in producing a solar PV module and launching it on the market? This could be an important question which project developers, installers, investors, government agencies and end customers might ask solar PV manufacturers in the future. To answer it, producers need to know the direct emissions from the manufacturing process, as well as those generated from the activities of manufacturers in the upstream supply chain (including raw material acquisition, upstream energy use, packaging, transportation and procurement), and also those arising from module usage and eventual recycling. This paper, written in a cooperation between EuPD Research and Deutsches CleanTech Institut (DCTI), presents an overview of PV's carbon footprint.

Background

PV is seen by the general public as an environmentally friendly source of energy, but little attention is paid to the PV production process and its impact on the environment. Proactively pursuing environmentally sound production practices and communicating this to environmentally aware customers provides an opportunity for manufacturers to differentiate their products from those of their competitors. However, in the future it may not only be a differentiation strategy but also a cost-reducing measure: as carbon regulations are implemented across the globe, the work on improving the carbon footprint can often lead to a reduction in process costs.

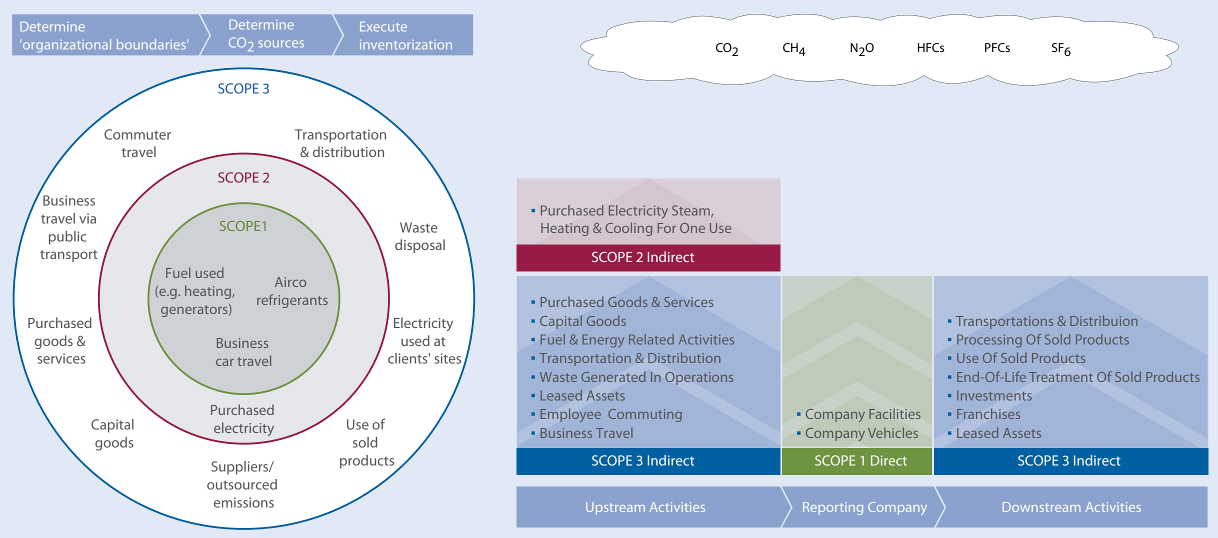
This section presents a discussion of the tools available for calculating and validating the carbon footprint of a product and an analysis of the current status, in general, of the carbon footprint of PV technologies. Furthermore, these results are placed in the context of fossil fuels and competing renewable energy sources. The question of what the current demand from end customers is for carbon footprint practices is also looked at, and how upcoming legal frameworks could change this demand.

Carbon footprint: differentiator, cost reduction driver or both?

By the end of 2012 the PV market will cease to be bottlenecked; offering a competitive, cost-effective and high-performance product will therefore be even more important in the future. Focusing on product competitiveness alone will no longer be a sufficient strategy, and product differentiation will become a higher priority for manufacturers than at present. Product technologies can help to differentiate in terms of conversion efficiency or real-life performance, but within a technology, these differences are considered to be marginal. For example, there are currently 16 manufacturers of µc-Si modules, but no manufacturer's flagship panel offers a substantial technological advantage over any other.

> "Focusing on product competitiveness alone will no longer be a sufficient strategy, and product differentiation will become a higher priority for manufacturers than at present."

In 2010 the buying decisions of customers did not depend on technical matters; instead, price level and product availability were the most important factors influencing purchasing decisions. As of 2012, however, marketing and



Source: World Resources Institute (WRI)

Figure 1. The Greenhouse Gas Protocol Initiative.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sales will gain in importance in order to communicate a manufacturer's distinct product differentiation. This is where carbon footprinting holds the promise of becoming a competitive advantage that can be communicated easily to customers.

Carbon footprinting could become a marketing tool that creates a unique selling point (USP) and helps to build up a premium brand, as well as being proactive in relation to upcoming legislation on this topic. This agrees with findings in the current study by EuPD Research [1]. Project developers and installers state that the carbon footprint is a decisive buying argument (under conditions of similar price and technology offers).

PV received much support and public attention initially because it promised to be a sustainable energy source with low carbon emissions. That is why customers bought it before competitive ROI periods and will do so again in the future. Currently, customers perceive that manufacturers are not active in reducing carbon emissions, but providing more information on carbon footprints of modules could help to educate the customer. Those manufacturers who fail to act in this way will be missing an opportunity, as there exists a huge potential for differentiating between products. Communicating and certifying the carbon footprint of modules could lead to direct benefits for the manufacturers. These benefits may represent an improvement of competitive position through a USP that leads to increased sales (as suggested by this market research) and premium brand building, allows for premium pricing, quality improvement and energy cost reductions, and contributes to the corporate image, to name just a few of the advantages.

The competitive advantage of a low carbon footprint is highlighted in the following example. The direct on-site electricity requirement for manufacturing a µc-Si laminate is estimated to be $44kWh/m^2$; the grid emission factor for producing a laminate is 0.54t/MWh for Germany and 0.89t/MWh for China. Using this information, and all other factors being equal, the CO_2 emissions for a $1.4m^2$ laminate produced in Germany would be 22kg lower than for a laminate produced in China – a significant difference. Customers thinking more about the environment than about a return on investment (ROI) will then obviously lean towards purchasing the German product. As shown by the recent results of an end-customer market analysis, this shift in customer thinking is now taking place.

Methodologies, tools and global standards

In recent years, thinking about the impact of a product on the environment throughout its entire lifetime has become a key focus in environmental policymaking. A wide variety of tools and standards for evaluating such impacts have been developed: the worldwide leading standards adhere to the ISO Life Cycle Assessment standards 14040 and 14044, as well as following the leading Greenhouse Gas Protocol Initiative of the World Resources Institute for calculating a company footprint.

ISO defines life cycle assessment (LCA) as a 'compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle.' In general, an LCA consists of the following four steps:

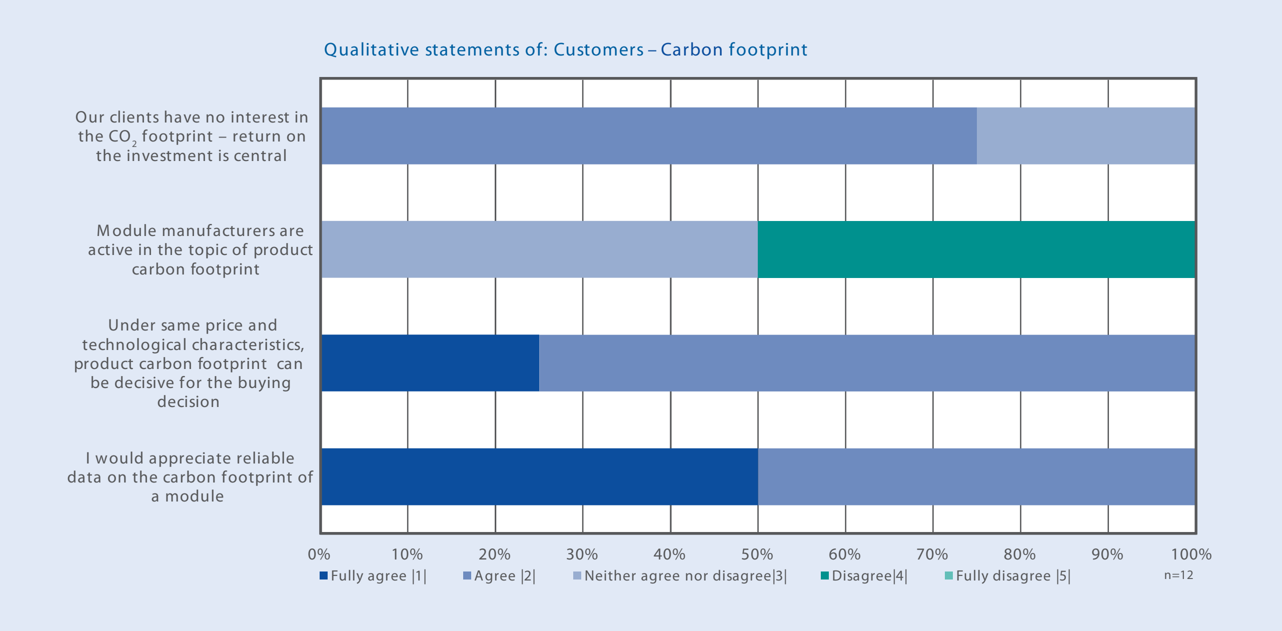
1. Goal and scope definition: defining where the boundary of a product's impact lies.
2. Inventory analysis: accounting for all energy, materials and other inputs required in a process.
3. Impact assessment: calculating direct emissions and environmental impact.
4. Interpretation: analyzing results to deduce solutions for reduction of environmental impact.

One type of LCA is carbon footprinting, in which the analysis is limited to greenhouse gas (GHG) emissions that have an effect on climate change. A product carbon footprint (PCF) can therefore be defined as the GHG emissions produced throughout the entire life cycle of a product in a defined application and expressed using a specific functional unit. In relation to PV, emissions are measured in units of CO_2 equivalent (CO_2-eq) and expressed on a per kWh basis using an estimation of the kWh to be produced for the lifetime of a PV module. This type of assessment is used to:

- investigate sustainability of different PV technologies;
- make fair comparisons between energy technologies;
- identify areas for improvement in PV production processes.

The main challenge for PCF methodologies, in general, is to achieve the right balance between practicality and environmental integrity/credibility, and PV is no exception to this.

In non-scientific terms, the evaluation of the carbon footprint can be described as the difference between the CO_2 emissions



Source: EuPD Research 2011

Figure 2. Market research into the attitudes of PV module customers towards carbon footprint certification.

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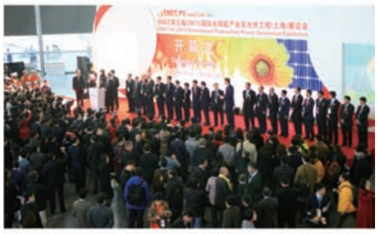

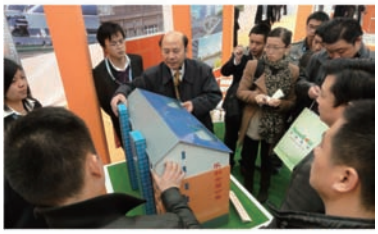

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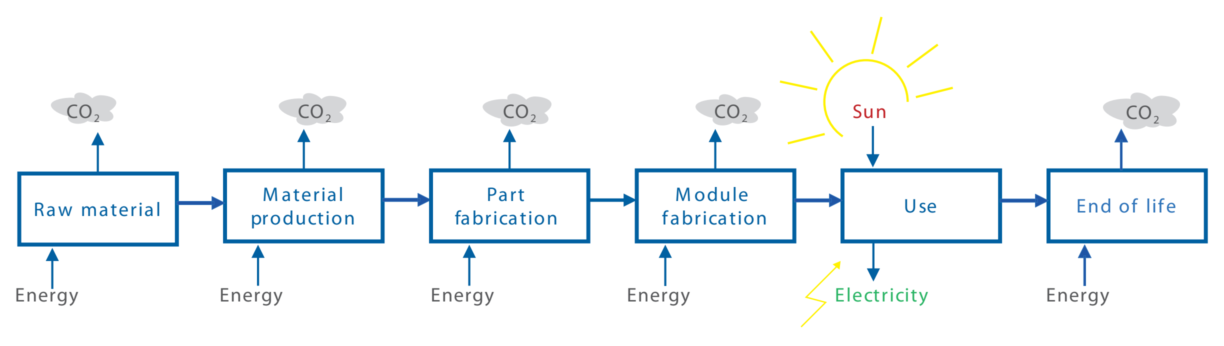

Figure 3. Flow chart of an emissions analysis of a PV module life cycle.

caused by production, transportation, operation and disposal of a product and the CO_2 emissions saved by its operation.

An LCA carbon footprint is the CO_2 emission balance sheet of a product. Within a PV-specific context, the question arises as to how this 'product' can be defined. From a module manufacturer's point of view the 'product' is the module. The 'main task' of a module manufacturer is assessing the CO_2 emissions caused by module production. A proper choice of units for such an assessment could be CO_2-eq per Wp or per m^2. However, a module does not save any CO_2-eq if it is not installed in a PV system. Therefore, when assessing the CO_2-eq emissions of PV, it is necessary to think in terms of systems. Accordingly, emissions caused by the production, transportation, operation and disposal of all components must be considered. In this case, the usual unit for reporting the impact on global warming is CO_2-eq per kWh. When considering the entire system, it is also possible to calculate the energy payback time – another key indicator.

How to reduce the carbon footprint

Determining a company's CO_2 footprint is a first step towards a carbon management system that reduces its footprint by implementing CO_2 (and cost) reduction measures, and by monitoring, reporting and communicating CO_2 performance. The business objectives of a manufacturer can be the following:

- to quantify the total carbon impact of the company and its products (CO_2 footprint verification);
- to identify the low-hanging fruits along with the major opportunities for reducing a carbon footprint (interestingly this can generally be done with a positive ROI);
- to monitor scope 1, 2 and 3 emissions and report them to, for instance, the Carbon Disclosure Project and other international standards;
- to build a brand and increase competitiveness by certifying the full life cycle CO_2 footprint of a PV module in order to create an additional USP.

This life cycle PV module CO_2 footprint is a standardized (ISO 14025/TR) third-party product certificate that allows customers to compare the full module CO_2 footprint (from cradle to grave). It shows the direct emissions from produced modules (scopes 1 and 2), and indirect CO_2 emissions (scope 3) from life cycle stages such as raw material acquisition, upstream energy use, packaging, transportation, product use, and recycling. Offering PV modules that hold a trustworthy certificate will encourage customers to buy modules whose production is environmentally sound.

> "Offering PV modules that hold a trustworthy certificate will encourage customers to buy modules whose production is environmentally sound."

Status quo – where does PV stand today?

LCA calculations for PV technologies have been conducted within the industry for more than 15 years, whereas energy payback times of modules have been subject to scrutiny as far back as 1975. At that time, payback was projected to be around 20 years, but today it ranges from 1 to 2 years. In 2005 there was still a lack of updated data on life cycle inventory for PV. Some data for crystalline technologies was 15 years out of date, whereas thin-film data was around 5 to 10 years old. These facts contributed to the popular and rather unfavourable environmental assessments and comparisons of PV technology. This situation is, however, improving rapidly as LCA is becoming increasingly important in the PV industry.

EuPD Research, together with Deutsches CleanTech Institut (DCTI), has observed a significant variation in CO_2 footprints: from 20 to 220g CO_2-eq per produced kWh of solar electricity. Biomass and wind technologies have been reported as yielding life cycle greenhouse gas emissions of 45g and 11g CO_2-eq per kWh electricity, respectively. Of course these results compare favourably against fossil-based options, for which best practices are rated at 400g CO_2/kWh levels (e.g., gas-fired combined-cycle power plants) [2]. Modules based on a-Si show an exceptionally high variation, which results from the difference between the production of a-Si and μ-Si technologies and the manufacturers' usage of strong GHGs in the production process (e.g. the GHGs SF_6 and NF_3 are approximately 20,000 times stronger than CO_2). Only a handful of companies are active in this field, using varying standards. In evaluating the current landscape, it appears that out of all manufacturers, First Solar places the most emphasis on this topic; however, other manufacturers are catching up.

Outlook – the influence of regulations on PV's carbon footprint

Systems based on green certificates or emissions trading are often mentioned as alternatives to FiTs, and both these systems would be directly relevant to the topic of CO_2 reduction. Revenues for power producers under these schemes would depend directly on the amount of CO_2 emission savings achieved. But FiT programmes can also be said to be associated with the topic, as the implementation of renewable energy laws has been driven by environmental issues as well. High internal rates of return (IRRs) might have obscured this link in recent years, but it nevertheless still exists. The discussion about advantages, disadvantages and interdependencies among the different support schemes is ongoing and will continue intensively in the future. While a comprehensive review of this discussion goes beyond the scope of this article, it is crucial to stress the point that there is an inherent interdependence between the public support of renewable

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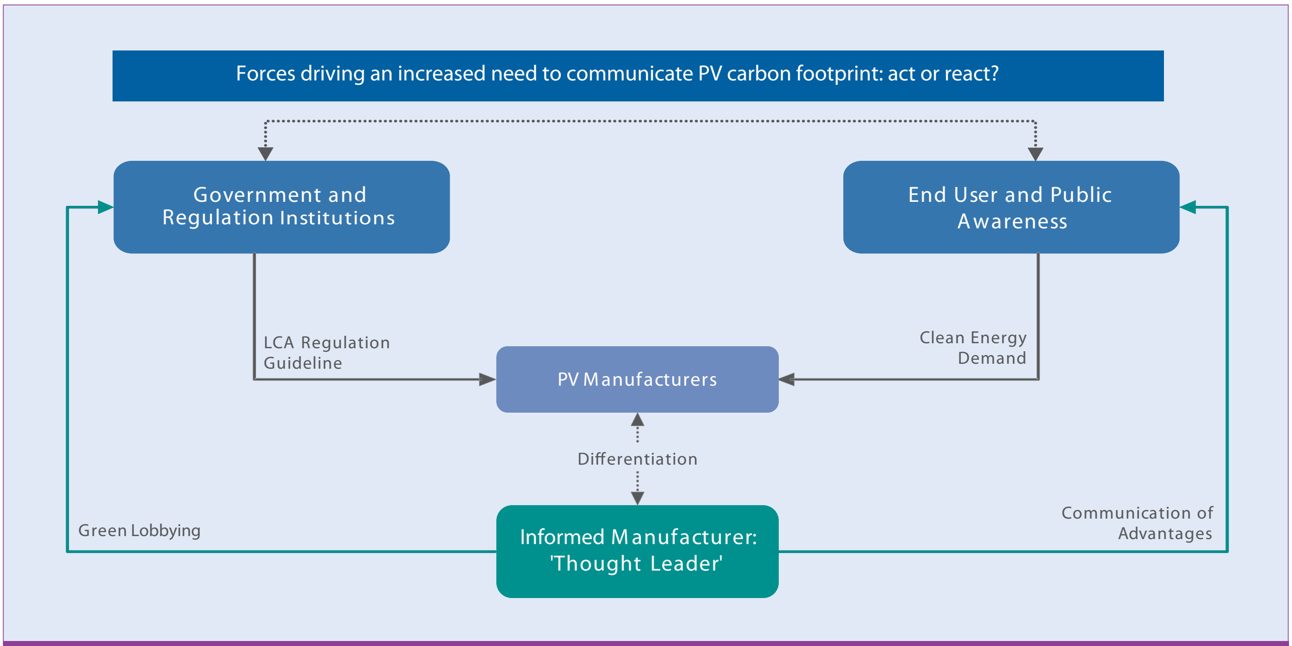

Source: EuPD Research 2011

Figure 4. Drivers for communicating a PV module carbon footprint.

energies and LCA. Some of these interactions can be seen in Fig. 4.

Carbon footprint certification – from a 'nice to have' to a 'must have'

Gradually, the argument is prevailing that grid parity will at best reduce, but not fully eradicate, dependency on political support. This dependency will not be solved until PV is competitive in relation to generation costs. Thus, from a medium-term perspective, PV market development will remain dependent on support mechanisms. Consequently, the positive environmental impact of PV is the main argument for further political financial support. From a politician's point of view, it seems reasonable to require some evidence regarding the LCA of a subsidized product that is supposed to achieve some environmental benefits.

Meanwhile, there is the urgency of differentiating products and offerings, since the industry dynamics will no longer accept a 'stuck in the middle' or 'me too' approach. Now is therefore the time for PV manufacturers to make use of the concept of LCAs to their own advantage. Those who do so can use the opportunity to position themselves as 'thought leaders' and gain considerable market power through the communication of advantages and differentiation that a low carbon footprint provides.

References

[1] Otto, V. et al. 2011, "PV Thin Film Guidebook 2011", EuPD Research report.

[2] de Wild-Scholten, M.J., Alsema, E.A. and Fthenakis, V.M. 2006, "Environmental impact of PV electricity generation – a critical comparison of energy supply options", *Proc. 21st EU PVSEC*, Dresden, Germany.

About the Author

Rob van der Meulen studied physics, economics and environmental engineering at Utrecht University and TUDelft in the Netherlands, and Columbia University in New York. He has published several scientific papers in the area of clean processing in PV solar production. Prior to joining EuPD Research, Rob worked in the Netherlands as a corporate social responsibility consultant with a focus on clean technology. At EuPD Research, he specializes in the fields of thin-film industry analysis and carbon consulting for the PV industry.

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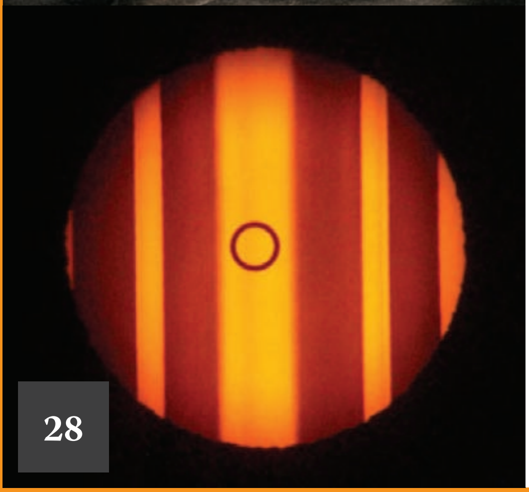
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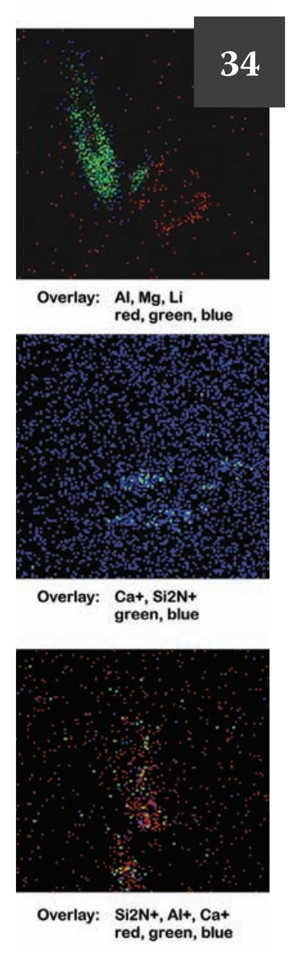
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Trace element analysis in crystalline silicon

Sylke Meyer[1], Susanne Richter[1], Matthias Balski[2] & Christian Hagendorf[1]
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Progress in cost reduction in silver pastes for crystalline silicon cells

Mark Thirsk, Linx Consulting LLC, Mendon, Massachusetts, USA

News

GT Advanced Technologies remains buoyant over shift to technology buy cycle

GT Advanced Technologies issued revenue results ahead of guidance for its second quarter (FY) results. The company posted US$217.7 million in revenue, compared to US$231.1 million in the first quarter of fiscal 2012. Revenue by business segment was led by photovoltaic with revenue of US$111.2 million, due to large number project completions in the quarter. However, GTAT noted that it cancelled several customer orders and experienced shipment push-outs, while citing weaker than expected demand that would impact annual revenue guidance and backlog.

GTAT revised annual revenue down 5% (US$50 million), compared to previous guidance. Fiscal 2012 guidance for revenue is now in the range of US$950 million to US$1.05 billion. The company maintained its gross margin guidance range of 43% to 45%. Gross profit for the first six months of fiscal 2012 was US$208.5 million or 46.5% of revenue, compared to US$139.0 million or 38.2% of revenue for the first six months of fiscal 2011.

Source: GTAT

GTAT's sapphire production facility.

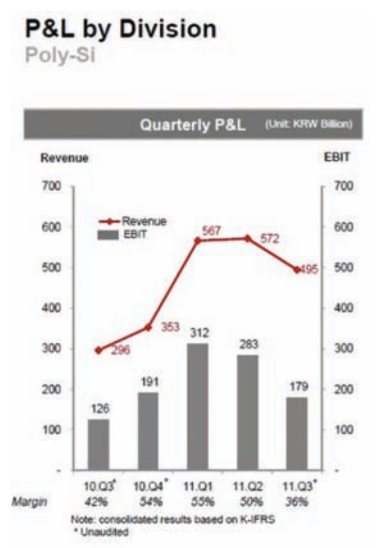
Tom Gutierrez, president and CEO, noted that PV segment sales will not recover until the second half of the year, driven by new innovations in cell efficiencies. These will be spearheaded by a significant move led by GTAT to 'MonoCast' (quasi-mono) technology, which is said to be producing high yields. GTAT will be offering field upgrades to its installed base of DSS furnaces to help move the PV industry to the monocast technology.

Furthermore, the company's acquisition of Confluence Solar, a developer of the 'HiCz' continuously-fed Czochralski (CCz) growth technology for US$60 million, has led to strong interest for this lower-cost Czochralski method. Gutierrez said that he expected the order ramp to start in mid-2012.

Polysilicon News Focus

Polysilicon price declines hit revenue and margins at OCI

Strong quarterly shipments failed to offer respite from a rapid decline in revenue and profit margins within OCI Chemicals, polysilicon production division in the third quarter of 2011. Revenue in its polysilicon segment fell from KRW572 billion in Q2 to KRW495 billion in Q3. Margins fell from 50% in Q2 to 36% in Q3, according to the company.



Source: OCI Chemicals

Revenue in its polysilicon segment fell from KRW572 billion in 2Q to KRW495 billion in Q3. Margins fell from 50% in 2Q to 36% in Q3, according to the company.

Significant overcapacity throughout the PV industry supply chain was cited as the key reason for the plummeting prices and the squeeze on many mid-stream companies margins and profitability.

OCI management expected the overcapacity situation to last between 12-18 months or at least until end-market demand reached 30GW, to return to a better supply and demand balance.

The company conceded that the industry was facing the next two quarters business environment being worse than seen in the third quarter of 2011.

OCI said that due to the continued weak industry demand, customers were showing a preference for high-quality (10N+) polysilicon, reinforcing the stronger shipments and lack of inventory build at OCI.

Not surprisingly with continued price declines, OCI noted that they expect further industry consolidation, especially amongst high-cost and small-scale players.

OCI also noted that an extra 7,000MT of polysilicon capacity would start to come on-stream in November after successful debottlenecking of new facilities, further supporting ongoing cost reduction strategies.

Source: LDK Solar

LDK Silicon's Mahong polysilicon plant.

LDK Solar subsidiary begins work on 30,000MT poly factory in Inner Mongolia

LDK Solar subsidiary LDK Silicon & Chemical Technology has been invited by the City Government of Hohhot, the capital of the Inner Mongolia Autonomous Region, to construct a 30,000MT polysilicon manufacturing facility in the region's Jinsan Development Zone. The groundbreaking ceremony took place today, and the additional capacity will take LDK Silicon's total polysilicon production capacity to 55,000MT per annum by the end of 2013.

The company has existing polysilicon production capacity of 17,000MT per annum, taking into consideration the outputs of the Mahong and Xiacun polysilicon plants in Xinyu, Jiangxi Province, in China. This figure is expected to increase to 25,000MT by mid-2012.

Daqo New Energy sees quarterly revenues, margins slide; guides lower Q4 polysilicon shipments

Daqo New Energy's third-quarter 2011 financial results showed that the company's revenues and margins were lower than in previous quarters. The company finalized its revenues for the third quarter at US$59.6 million, profits at US$19.9 million and its gross margin at 33.3%.

Daqo's US$59.6 million in revenues for Q3 2011 took a hit compared to the US$70.7 million it posted in Q2 2011 and US$63.2 million in Q3 2010. The company advised US$53 million of its revenue came from 1,022MT of polysilicon sold during Q3, compared to US$63 million in revenues for 1,001MT

of polysilicon sold in Q2 2011. Daqo noted that the volume of polysilicon in Q3 increased by 2.1% and 5% compared to Q2 and Q3 volumes, respectively, however, a lower average selling price (ASP) contributed to lower revenues.

Daqo's wafer and module shipments, 6.5MW and 1.9MW, respectively, were short of the company's original 10MW guidance. In Q4, the company expects to ship 800MT to 850MT of polysilicon after a periodical two-week maintenance shutdown of its production facility in December. The company anticipates shipping 16MW of wafers and 14MW of modules, with 8MW coming from its brand name modules.

REC to bag US$66 million after wafer supply deal terminated by customer

REC has agreed to the termination of another long-term wafer supply contract, receiving a US$66 million (NOK370 million) one-time payment in compensation. The company had recently noted that several more contract cancellations could be concluded in the fourth quarter. REC did not disclose the customer involved.

With polysilicon and wafer prices in freefall, despite penalties and bank guarantees in place - PV manufacturers are increasingly finding it cost effective to purchase on the spot markets to gain access to cheaper prices. REC is one of many wafer suppliers finding it can receive cancellation payments on long-term contracts and sell product elsewhere or on more flexible terms.

PV Crystalox suspends polysilicon production in Germany and cuts wafering jobs in UK

Citing some customer cutbacks in module manufacturing levels and continued pressure on wafer prices, PV Crystalox Solar is taking drastic measures to reduce cash burn in these difficult times for the global PV industry. The company is operating at a significant reduction in wafer shipments, compared to previous forecasts, and is implementing job losses and reduced working hours for staff.

The wafer supplier announced a temporary suspension of polysilicon production at its facility in Bitterfeld, Germany. The biggest impact will be on ingot and wafer production in the UK. PV Crystalox said in a statement that it was reducing production output, without providing further details, yet also announced that this would lead to "significant job losses in the UK." Again, the actual number of job losses was not disclosed.


Source: PV Crystalox

Polysilicon production has been temporarily suspended at PV Crystalox's facility in Bitterfeld, Germany.

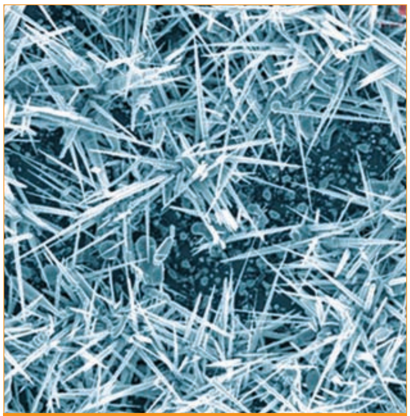
With some of its customers cutting production of cells and modules in response to weak demand, especially in Germany, PV Crystalox drastically revised down shipment guidance. Shipments for the full year are expected to be in the range of 360–390MW, down from previous guidance in August of around 400–450MW. PV Crystalox shipped 378MW in 2010, but has significantly ramped ingot/wafer and polysilicon production since.

Business News Focus

CVD Equipment plans to expand materials business unit

CVD Equipment recently advised of its plans to increase its materials business through its wholly owned subsidiary CVD Materials. The company will be focusing on both traditional and non-traditional chemical vapour deposition-related markets with its marketing and sales efforts targeting researchers at universities, governments and industrial R&D facilities.

Leonard Rosenbaum, president of CVD Equipment, stated, "We believe that now is the right time to build on the processing capability, material manufacturing, marketing and business growth success of our Application Laboratory... [w]e will further develop our in-house next generation material manufacturing capabilities and capacities and expand our marketing and sales efforts directly to researchers and innovators at universities, government and industrial R&D facilities that are working on application development for tomorrow's next generation products in semiconductors, solar, batteries, capacitors, water filtration, catalysts composites and other traditional and non-traditional chemical vapor deposition applications through CVD Materials.


Source: CVD Equipment

CVD Equipment's gallium nitride nanowires.

Rosenbaum continued, "These applications will primarily utilize graphene, carbon nanotubes (CNT), nanowires (NW), and other 1D, 2D and 3D surface and surface area enhanced materials. CVD Materials will primarily focus on 1) contract CVD related process development, 2) research material manufacturing, 3) CVD and other nano-enabled material manufacturing licensed from third parties and 4) on CVD Equipment's proprietary materials and material processing platforms."

Solutia sets price hike on PVB interlayer materials for January 1, 2012

Citing increasing costs of high quality raw materials throughout 2011, Solutia has advised that as of January 1, 2012, its Saflex polyvinyl butyral (PVB) product line will see a price increase. Solutia noted that prices for currently contracted business will be adjusted as individual contracts allow.

"As a leading supplier of PVB interlayer, we are fully committed to meeting the current and future needs of our customers. We are exploring new pricing models to lessen the exposure that raw material pricing brings to our business and our customers," says Eric Nichols, president and general manager of Solutia's advanced interlayers division.

Solutia commences tender offer to acquire Southwall Technologies

Following Solutia's cash tender offer to purchase all outstanding shares of common stock of Southwall on October 7, 2011, it has now been announced that the tender was finalized on November 22, 2011. Southwall is a film and glass producer for the automotive and architectural industries.

The materials and chemicals company Solutia is filing the tender offer statement with the US Securities and Exchange Commission (SEC) with the terms and conditions.

Upon the successful closing of the tender offer, stockholders of Southwall will receive US$13.60 in cash, for each share of Southwall common stock.

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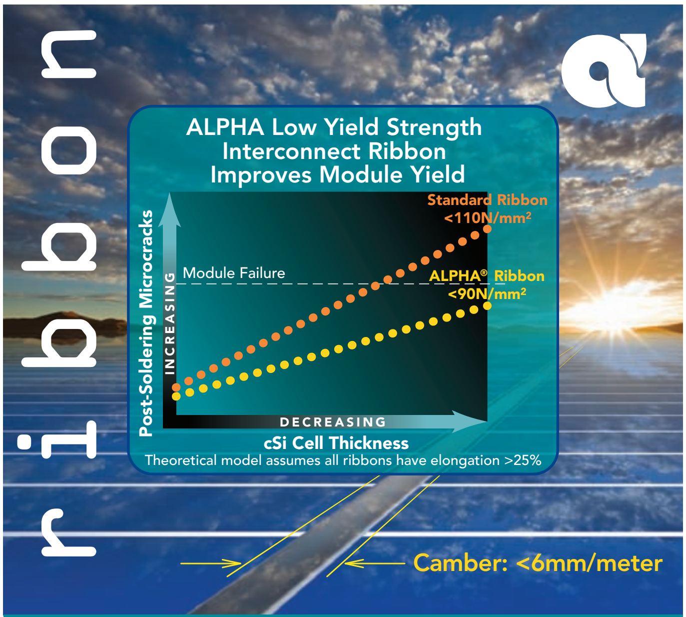

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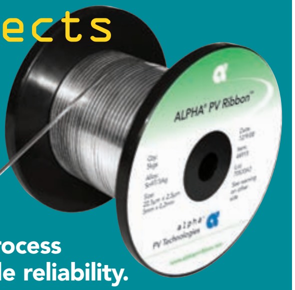

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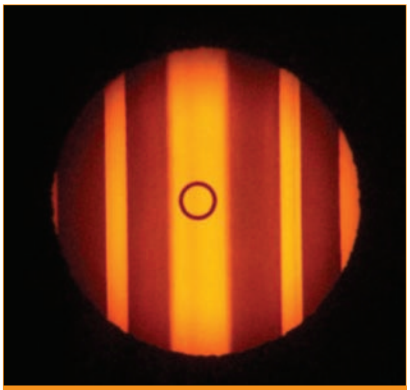
Following the completion of the tender offer and the receipt of stockholder approval, Southwall will merge with a subsidiary of Solutia and become a wholly-owned subsidiary of Solutia.

Polysilicon Technology places US$47.7 million order for reactors from GTAT

GT Advanced Technologies and Saudi Arabia-based Polysilicon Technology (PTC) have signed a US$47.7 million deal, which will see GT supply its SDR 400 reactors to PTC. The order will enhance GT's polysilicon bookings to over US$500 million since the beginning of this fiscal year and will be included in GT's backlog for its Q3 FY12.

The supply order is a continuation of a technology agreement that the two companies first signed in 2009. This is the first order GT has received for its reactors from a Saudi Arabia company and notes that this is currently the only active polysilicon production project in the Middle East.



GTAT will supply its SDR 400 reactors to Polysilicon Technology in a US$47.7 million deal.

The plant will be located in Jubail Industrial City, Kingdom of Saudi Arabia. The equipment is expected to begin delivery in the late half of 2012, with final deliveries completed by the end of the year.

Praxair China to supply oxy-fuel technology for CNBM production line

Praxair China has signed a long-term contract to supply oxygen and oxy-fuel technology for China National Building Materials (Hefei) New Energy's PV glass production line.

Under the terms of the contract, Praxair China will build two vacuum-pressure-swing-adsorption plants and one air separation unit at CNBM's glass production site in the eastern Chinese city of Hefei. It will also supply the oxy-firing technology and accompanying equipment to successfully run the manufacturing line.

China Sunergy reaches final settlement with REC Wafer

The ongoing dispute between China Sunergy and REC Wafer has seen the companies frequent courts in Norway and China in the hope of reaching a settlement over the termination of a supply contract by REC Wafer. China Sunergy has announced that it has agreed to settle all disputes with REC Wafer and that REC Wafer has released the US$50 million bank guarantees.

In 2009, REC Wafer entered into an agreement with China Sunergy to supply it with 156mm wafers over a seven-year period from early 2009 to 2015. China Sunergy paid in excess of US$400 million for the wafers.

The complication occurred when REC Wafer dissolved REC's SiTech unit, with which China Sunergy had the original contract, resulting in REC Wafer's being served a writ for claiming rights to the contract. In 2009, these events were commonplace due to the dramatic drop in polysilicon prices and an increase in poly supply changing the market's supply-demand dynamics. REC Wafer then cancelled the contract following a non-payment by China Sunergy.

2010 saw both companies appeal against rulings passed in their respective countries. In parallel to the main dispute, China Sunergy was granted an injunction with regard to a US$50 million bank guarantee raised according to the contract between China Sunergy and the dissolved REC SiTech AS. The Court of Appeal decided that the injunction was to remain in force until the Court of Appeal passed the judgment on the main case in June 2011.

On October 28, China Sunergy made a settlement payment to REC Wafer. The settlement amount is not being disclosed.

Source: REC Wafer

REC's wafer production facility in Herøya, Norway.

Product Reviews

Arnold Gruppe

New grinding machine for silicon ingots from Arnold offers shorter cycle-times

Product Outline: For extremely high product quality and productivity for treatment of silicon bricks, Arnold Gruppe has introduced the type 72/865 machine, which is a high-end combination of a surface and chamfering machine. Arnold claims that it now has a balanced production range in the grinding field with this high-end grinding machine which can serve the most different requests of customers.

Problem: Optimal yield for ingots and wafers is a key metric for cost reduction strategies. Reduction in material loss and material usage such as water consumption is required.

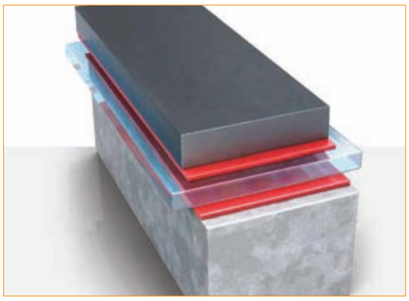
Solution: The machine has four parallel mounted grinding aggregates suitable for grinding of lateral surfaces and for chamfering of squared silicon workpieces in the formats of 125 × 125mm and 156 × 156mm with an automatic format change. The machine processing parts are casted with mineral composite. This high-end grinding machine is claimed to pave the way to 'Zero Error' strategies, as demanded by wafer manufacturers. A process capability of >1,67 Cpk at a tolerance of +/-0.05 mm on a permanent basis is claimed.

Applications: Silicon ingot grinding requirements.

Platform: Current production and process data are stored, visualized and analyzed with the Arnold remote process analysis tool, Arpat, and are the basis for the continuous optimization of production and process parameters. Arpat is a database that is controllable via Web-Browser and is available for all Arnold machines.

Availability: Since September 2011.

Henkel



Henkel's hot water debondable epoxy simplifies solar silicon wafer slicing while reducing wafer damage

Product Outline: Henkel has introduced Loctite 3382 in an effort to simplify silicon ingot bonding and protect against wafer breakages. Loctite 3382 provides improved bonding strength of the ingot in the sawing process and is debondable in hot water. This new bonding solution helps to avoid corrosion of the equipment and is free of caustic odour.

Problem: Loctite 3382 replaces traditional epoxies that require caustic acids for debonding. This adhesive breaks down easily on exposure to hot water, eliminating corrosive debonding solutions and minimizing silicon waste that occurs during the wafer cleaning process.

Solution: Henkel's new bonding solution is a water de-bondable epoxy adhesive providing bond strength to both silicon and the glass and metal mounting substrates used during the ingot sawing process. As this two-part epoxy is pink when cured, it is easy to distinguish from the silicon ingot and the metal and glass mounting substrates during visual inspections. Homogenous and stable, Loctite 3382 sets up in just five to seven hours and is claimed to provide a consistent cutting layer that reduces edge damage and wafer breakage. This epoxy's improved bond strength means the adhesive will not prematurely debond during the sawing process, protecting the ingot and the wafers from damage.

Applications: Silicon ingot bonding for wafer slicing.

Platform: Easy to dispense using meter-mix equipment, Loctite 3382 is packaged in cartridges, pails and drums. This adhesive emits no caustic odour, will not corrode equipment, and is fully compatible with current wafer cleaning solutions and processes.

Availability: Currently available.

Op-tection GmbH

Op-tection offers PL-based wafer inspection platform for efficiency

Product Outline: Germany-based Op-tection GmbH has recently launched a new inspection platform based on photoluminescence technology. The PL inspection platform was developed in cooperation with Schott Solar Wafer and is claimed to be capable of quantifying the achievable efficiency of solar wafers before they enter into the cell process line.

Problem: Solar cell makers sell their solar cells based on efficiency. Higher cell efficiency in general equals more money earned for the cell batch at hand, the wafer itself is often the limiting factor for achievable final solar cell efficiency. A reliable forecast of the achievable efficiency that a wafer can achieve is important for both wafer and cell makers to help wafer makers prove the value of their product to cell makers.

Solution: To enable wafer and cell makers to achieve this goal, Op-tection offers a PL-based sorting platform that automatically inspects and segregates wafers. A sensitive and high-resolution camera records the PL image to analyze the various defects and structures, such as dislocations and material contaminations, with proprietary algorithms that calculate metrics such as edge contamination fractions, dislocation clusters, PL intensity and distribution. Based on the calculated and individually marked wafer metrics, an efficiency forecast can be made.

Applications: Op-tection's PL technology can be used for all types of solar wafers.

Platform: Op-tection Wafer-PL Sorter Series.

Availability: Currently available.

Trace element analysis in crystalline silicon

Sylke Meyer[1], **Susanne Richter**[1], **Matthias Balski**[2] & **Christian Hagendorf**[1]
[1]Fraunhofer Center for Silicon Photovoltaics CSP, Halle; [2]BAM Federal Institute for Materials Research and Testing, Berlin, Germany

ABSTRACT

The reliable analysis of trace elements in silicon is of fundamental importance for the understanding of material properties and quality control of solar cells. This paper presents a demonstration of the power of two analytical techniques for the determination of trace elements in solar silicon: inductively coupled plasma mass spectrometry (ICP-MS) and time-of-flight secondary ion mass spectrometry (ToF-SIMS). These techniques are among the few that achieve sufficiently low detection limits and they may complement each other because of their specific performance. Examples are given of the quantitative chemical analysis of boron, phosphorus and iron in different types of solar silicon, as well as of the enrichment of metals and alkali metals in Si_3N_4 precipitates.

Introduction

The impurities and contaminants in feedstock material and crystallized silicon blocks are a major source of defects and electrical losses in the later solar cells. Starting with the as-cut raw wafer, all subsequent solar cell processing steps rely on the prerequisites defined at the very beginning of the production chain.

> “The impurities and contaminants in feedstock material and crystallized silicon blocks are a major source of defects and electrical losses in the later solar cells.”

Figure 1. ICP-MS facility at Fraunhofer CSP.

It is known that the majority of contaminants found in ingots and wafers migrate into the silicon material from the crucible and the surrounding gas atmosphere during the crystallization process. Moreover, the distribution of the contaminating elements is not homogeneous, because of segregation between solid and liquid phases during crystallization, diffusion processes in the crystal, and local enrichment at grain boundaries and other defective structures. Therefore, a reliable analysis of trace elements in silicon is very important for understanding silicon material properties and quality control. This analysis includes analytical methods that can be applied for a local analysis in the volume and at the surfaces. However, only a few analytical techniques achieve the very low limits of detection and local resolution necessary for this task. Among these are the mass spectrometry techniques ICP-MS, GD-MS and ToF-SIMS, which may complement each other due to their specific performance.

Inductively coupled plasma mass spectrometry (ICP-MS) is currently the most powerful and useful trace-analysis tool capable of quantitatively measuring the total elemental impurity concentrations in solar silicon down to ppbw level. The advantages of ICP-MS analyses, besides the high sensitivity, are flexibility and relatively low costs per sample. A limitation compared to GD-MS or neutron activation analysis (NAA) is the need for chemical decomposition of the samples, which can be a source of external contamination. However, coupling of ICP-MS with laser ablation (LA-ICPMS) can be used for direct sampling of solid silicon and avoids the contamination-prone decomposition procedure [1,2]. But there are drawbacks with LA-ICPMS: it has lower sensitivity and requires a matrix-matched reference material for quantification.

High-resolution glow discharge mass spectrometry (GD-MS) is used more and more in the photovoltaic and semiconductor industry as a technique for surveying most elements in the periodic table with detection limits in the ppbw range. The measurement is independent of chemistry and electronic state, and requires minimal (only mechanical) sample preparation. A broad variety of sample shapes – such as chunks, granules, wafers and even powders – are suitable. An international standard test method (SEMI PV1-0309) for the determination of boron and phosphorus in solar silicon using GD-MS was approved in 2008.

Time-of-flight secondary ion mass spectrometry (ToF-SIMS) is an analytical method suitable for investigating surface contamination since the technique is quasi non-destructive and has a local resolution in the low µm range [3]. Additionally, ToF-SIMS has a detection limit in the ppm range for many elements and a high mass resolution that also permits the detection of whole molecules and molecule fragments. The yield of measured ions and molecules can be increased by applying secondary sputter guns. The secondary sputter sources Cs^+ and O_2^+ are used for negative and positive ion polarity, respectively, and accelerated with 2keV each time, with a sputter target of 300×300µm up to 500×500µm, depending on the analysis area. To eliminate remaining surface contaminants, the Bi-cluster liquid metal ion gun (Bi_1^+, 25keV) is used while observing the decrease in the intensity of typical contaminants.

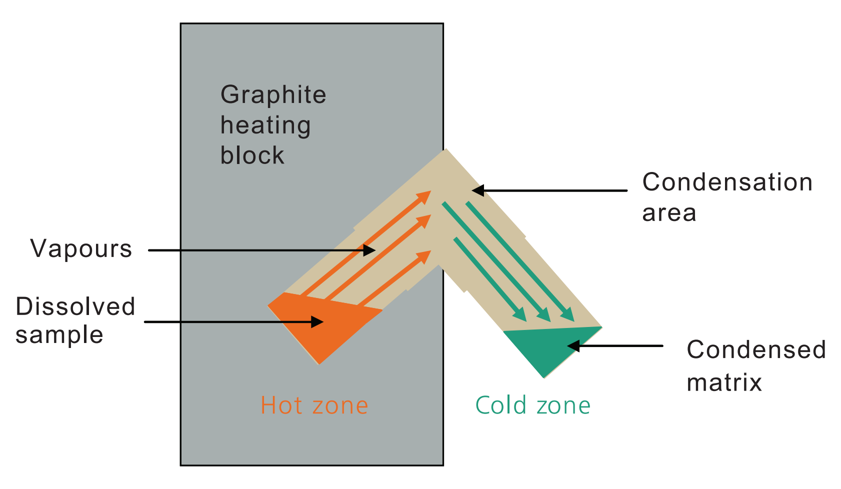


Figure 2. Schematic of the evaporation apparatus.

Results

Chemical decomposition and ICP-MS analysis of silicon

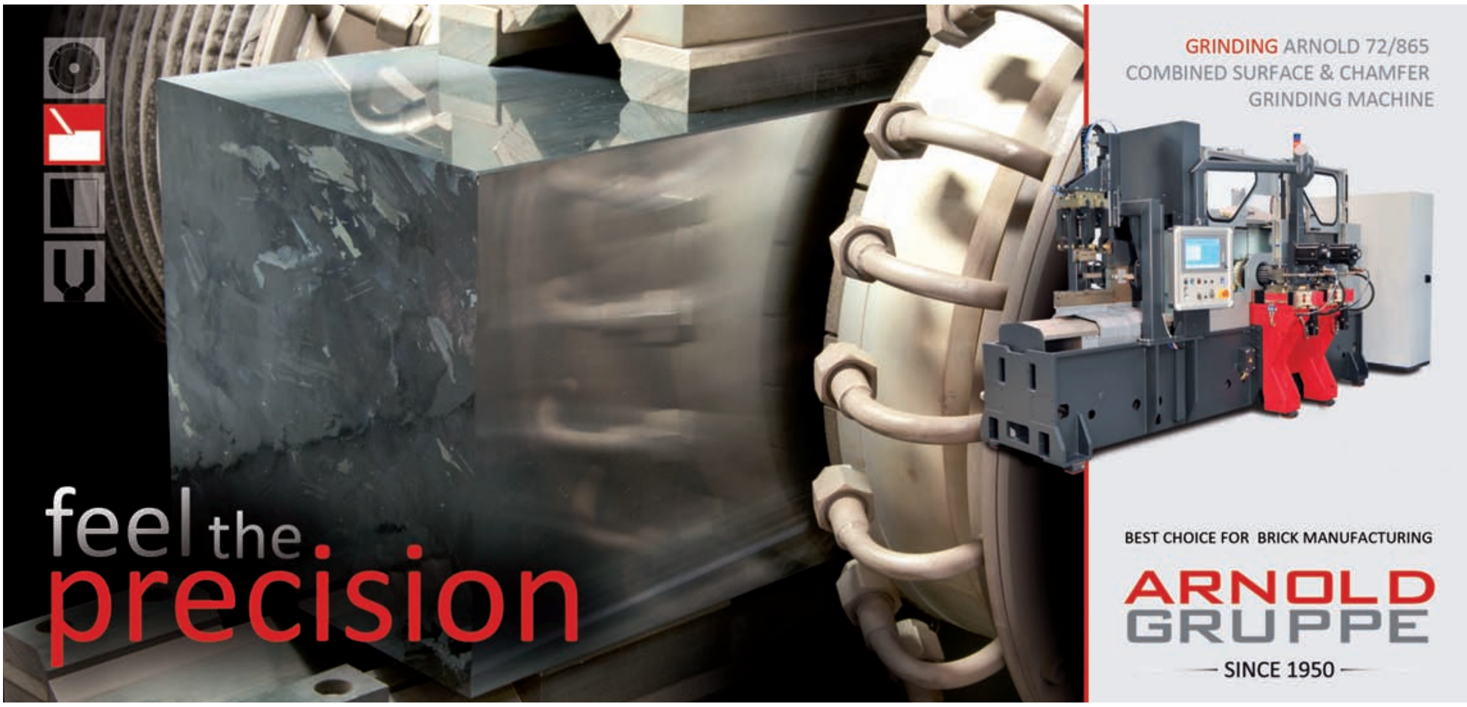
Sample preparation has to be thoroughly optimized because of the relatively high risk of contamination during the procedure. Ultrapure reagents and water, vessels made of material of the highest quality (perfluoroalkoxy – a type of fluoropolymer, otherwise known as PFA) and at least a partial clean-room environment are essential. Surface contaminants must be removed by acid etching prior to the decomposition reaction. The silicon is completely dissolved during an exothermic reaction with HF and HNO_3. Finally, the reaction mixture has to be evaporated until almost dry in order to remove acids and the matrix. Best results were obtained using the Evapoclean apparatus, which operates in a closed system with low risk of external contamination.

Following this optimized protocol for sample preparation, ICP-MS can be successfully used for trace element analysis with detection limits down to the ppbw level. Limits of detection between 0.05ppbw (Ga) and 30ppbw (Ca) were achieved, depending on the particular element (see Table 1). For iron, which is one of the most critical contaminants in solar silicon, concentrations down to 2ppbw (5×10^{13} atoms/cm^3) could be measured with ICP-MS.

A feedstock material with lower purity (upgraded metallurgical grade) was used to perform comparative trace

Element		B	Na	Al	P	Ca	Ti	Cr	Mn	Fe	Ni
LOD	[ng/g]	10	15	40	10	30	5	1	0.1	2	1
LOD	[atoms/cm^3]	1×10^{15}	9×10^{14}	2×10^{15}	5×10^{14}	1×10^{15}	1×10^{14}	2×10^{13}	2×10^{12}	5×10^{13}	2×10^{13}
Element		Co	Cu	Zn	Ga	Sr	Mo	Pb	K	As	Ge
LOD	[ng/g]	0.2	1	1	0.05	1	1	0.1	15	0.3	0.04
LOD	[atoms/cm^3]	4×10^{12}	2×10^{13}	1×10^{13}	1×10^{12}	2×10^{13}	1×10^{13}	6×10^{11}	5×10^{14}	5×10^{12}	7×10^{11}

Table 1. Limits of detection (LOD) for the most important contaminating elements in solar silicon as measured with ICP-MS.



element analyses using ICP-MS, NAA and GD-MS. As seen in Fig. 3, there is a very good correlation between the results of all three techniques. Bearing in mind that NAA is time consuming and cost intensive, and requires larger samples of silicon, it is clear that mass spectrometry techniques are preferable. Although ICP-MS is the more flexible method and can be easily calibrated by using single-element standard solutions, GD-MS is less labour intensive and contamination prone, but its accuracy is tied to reference materials.

> "ICP-MS is a rapid and reliable tool for the quantitative determination of the total boron and phosphorus content in a silicon material."

Boron and phosphorus profiles

The concentration and distribution of the dopant elements boron and phosphorus has a significant effect on the efficiency of the solar cell. It is shown here that ICP-MS is a rapid and reliable tool for the quantitative determination of the total boron and phosphorus content in a silicon material. It is possible to obtain elemental profiles by taking samples from different positions of an ingot. Fig. 4(a) shows a vertical cut from a silicon ingot (compensated material) that was analyzed by chemical decomposition and ICP-MS; the positions of the samples are indicated in the drawing. The resulting concentrations shown in Fig. 4(b) correlated well with a theoretical profile calculated from Scheil's equation using the added dopant concentration C_0 and the segregation coefficients k_{boron} = 0.8 and $k_{phosphorus}$ = 0.35. Similar results can be obtained by using GD-MS and have been reported elsewhere [1].

Determination of the total iron content

As mentioned earlier, the sensitivity of both of the mass spectrometry methods (ICP-MS and GD-MS) is too low to measure iron concentrations lower than 10^{13} atoms/cm^3. However, crystalline silicon is expected to have iron concentration below this value. Nevertheless, ICP-MS can be used to characterize crystallization processes, that is ascertain the influence of different crucibles or coatings. Fig. 5(a) shows mechanically prepared samples from the lateral edge of a typical ingot; typically, this area of the ingot is called the 'bad region' based on measurements of carrier lifetimes. After chemical decomposition the total iron concentration was determined in these samples. Decreasing concentrations in the range 10^{13} to 10^{15} atoms/cm^3 show the influence of the

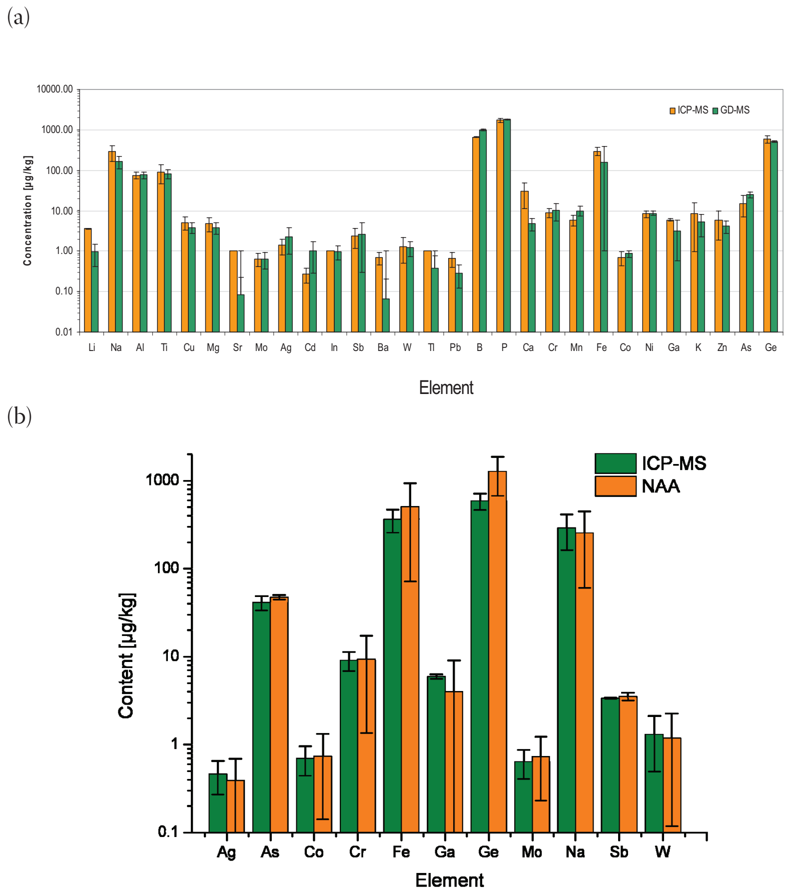


Figure 3. (a) Comparison of trace element and dopant concentrations measured with ICP-MS and GD-MS. (b) Comparison of trace element concentrations measured with ICP-MS and NAA.

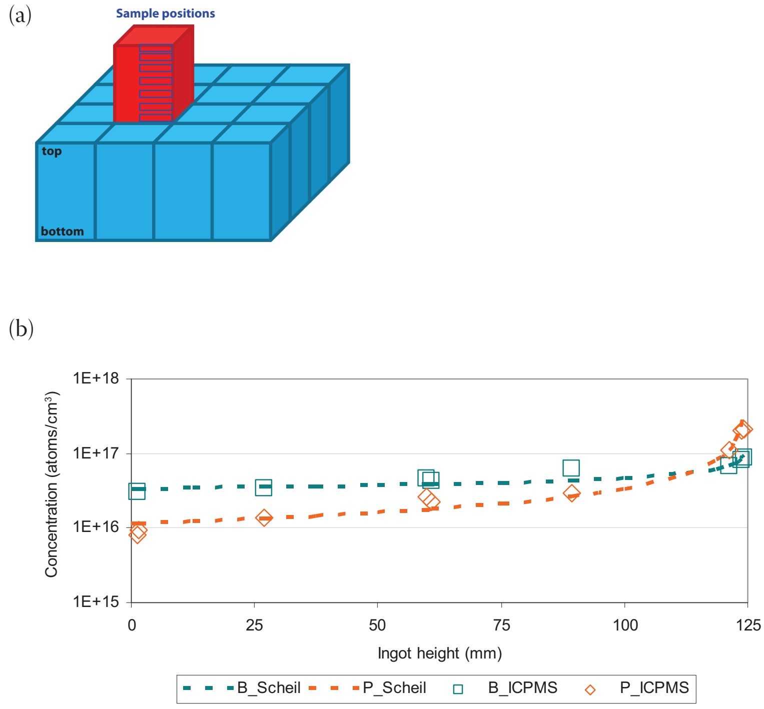


Figure 4. (a) Positions of the samples in the ingot. (b) B and P concentrations determined by ICP-MS and calculated from Scheil's equation.

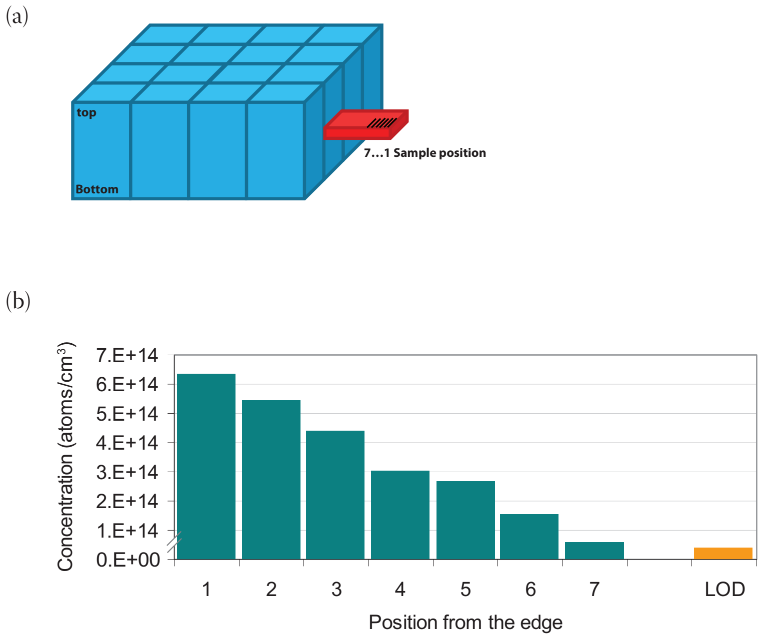


Figure 5. (a) Positions of the samples in the ingot. (b) Iron concentrations in samples from the electrical 'bad region' of the lateral edge of a multicrystalline ingot, determined by ICP-MS.

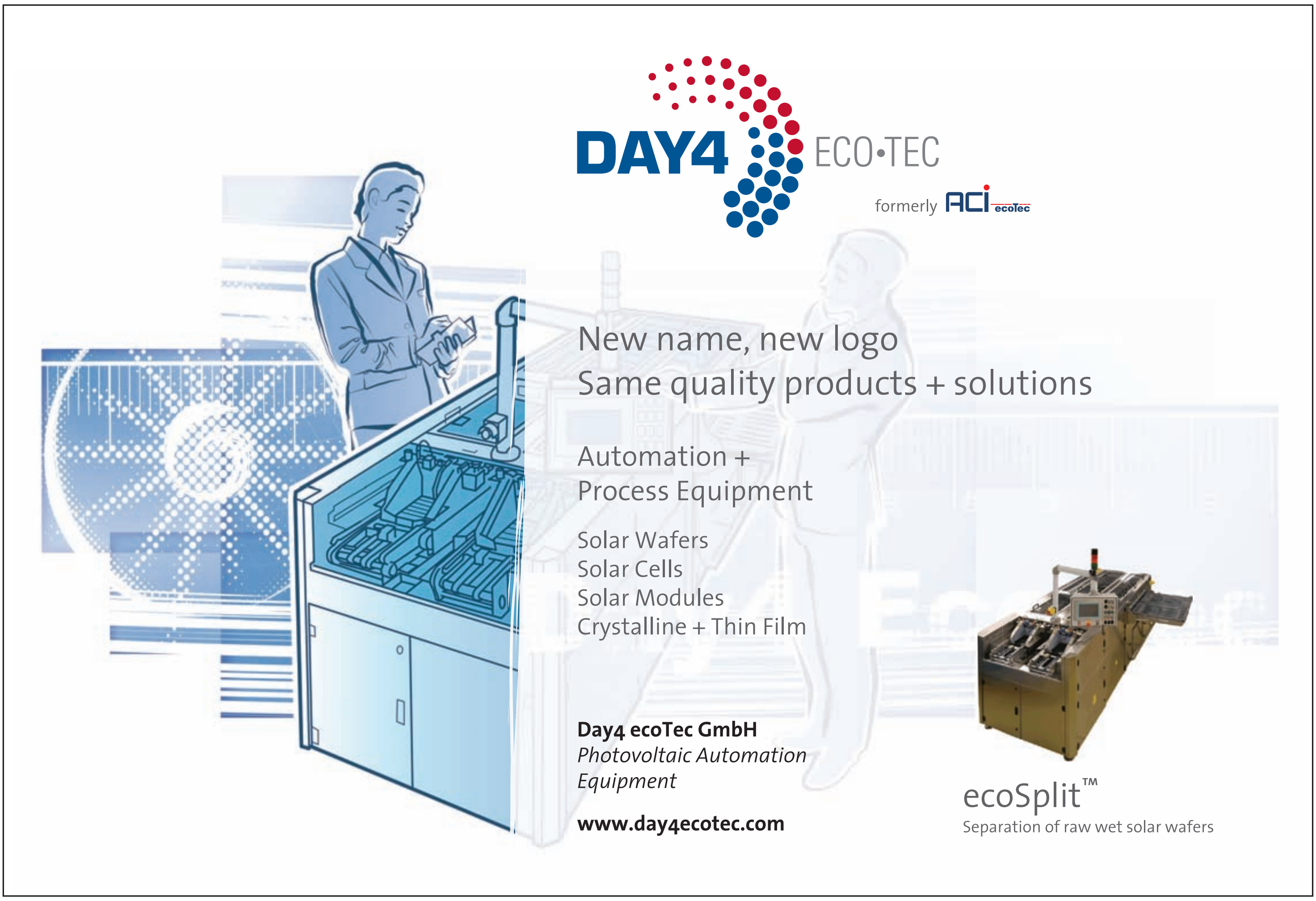
crucible during crystallization (Fig. 5b). As expected, the iron concentrations in the central part of the ingot are below the detection limit of the ICP-MS method.

Trace element analysis of precipitates

ToF-SIMS was performed with an Iontof TOF.SIMS V apparatus for the investigation of the trace element composition of characteristic precipitate clusters down to the ppm range. For this purpose, the dual-beam interlaced mode was used with Bi^+ (25keV) as the primary ion gun working as the analysis beam, and, optionally (for better yield of the analyzed ions), the different Cs^+ or O_2^+ secondary ion guns were used for negative or positive secondary ion sputtering, respectively. An acceleration voltage of 2keV was chosen for the sputter sources.

ToF-SIMS is a suitable analytical method for determining the chemical composition of microscopic structures because of its high mass and high lateral resolution down to 60–100nm, depending on the measurement mode. In accordance with the size of the investigated precipitate, the sputter target (up to 400×400µm^2) was selected to be larger than the analysis target (up to 250×250µm^2). Prior to data acquisition, surface contaminants were removed by low-energy sputtering.

In this study, precipitates were investigated in the dual-beam and Bi^+ bunched mode (with a pulsed Bi^+ gun) for high mass resolution and low detection limit. A surface preparation of precipitates by means of transmission infrared microscopy was performed before the localized ToF-SIMS analysis. Fig. 6 depicts the investigated precipitation types containing a SiC particle with a Si_3N_4 rod, Si_3N_4 fibres and a Si_3N_4 net. The identification of the structures was



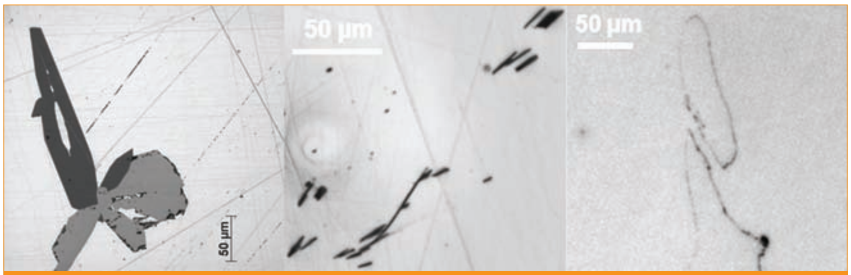


Figure 6. Reflected light images of a SiC particle with a Si_3N_4 rod (left), Si_3N_4 fibres (centre) and a Si_3N_4 net (right).

supported by determining the elemental composition using nanospot EDS.

To obtain a detailed chemical characterization with high local resolution, ToF-SIMS was performed on each structure. Ion images were obtained using the O_2^+ sputter source for enhanced positive ion yield. It was observed that Si_3N_4-like precipitation types contain the alkali metals Li, Mg and Ca. In addition, metals such as Al can be found at the interface position of the SiC and Si matrix as well as at the position of the Si_3N_4 nets (Fig. 7). The alkali metals probably only have a small influence on the electrical properties of the precipitates, as previously shown by Richter et al. [2,3]. The main influence can be explained by the n-doping. Nevertheless, recombination effects and breakdown mechanisms due to the trace elements cannot be excluded.

> “ICP-MS may be used for quantitative determination of total metal and dopant concentrations because of its high sensitivity, whereas the power of ToF-SIMS is its high local resolution.”

Conclusion

It has been shown that ICP-MS and ToF-SIMS are suitable techniques for

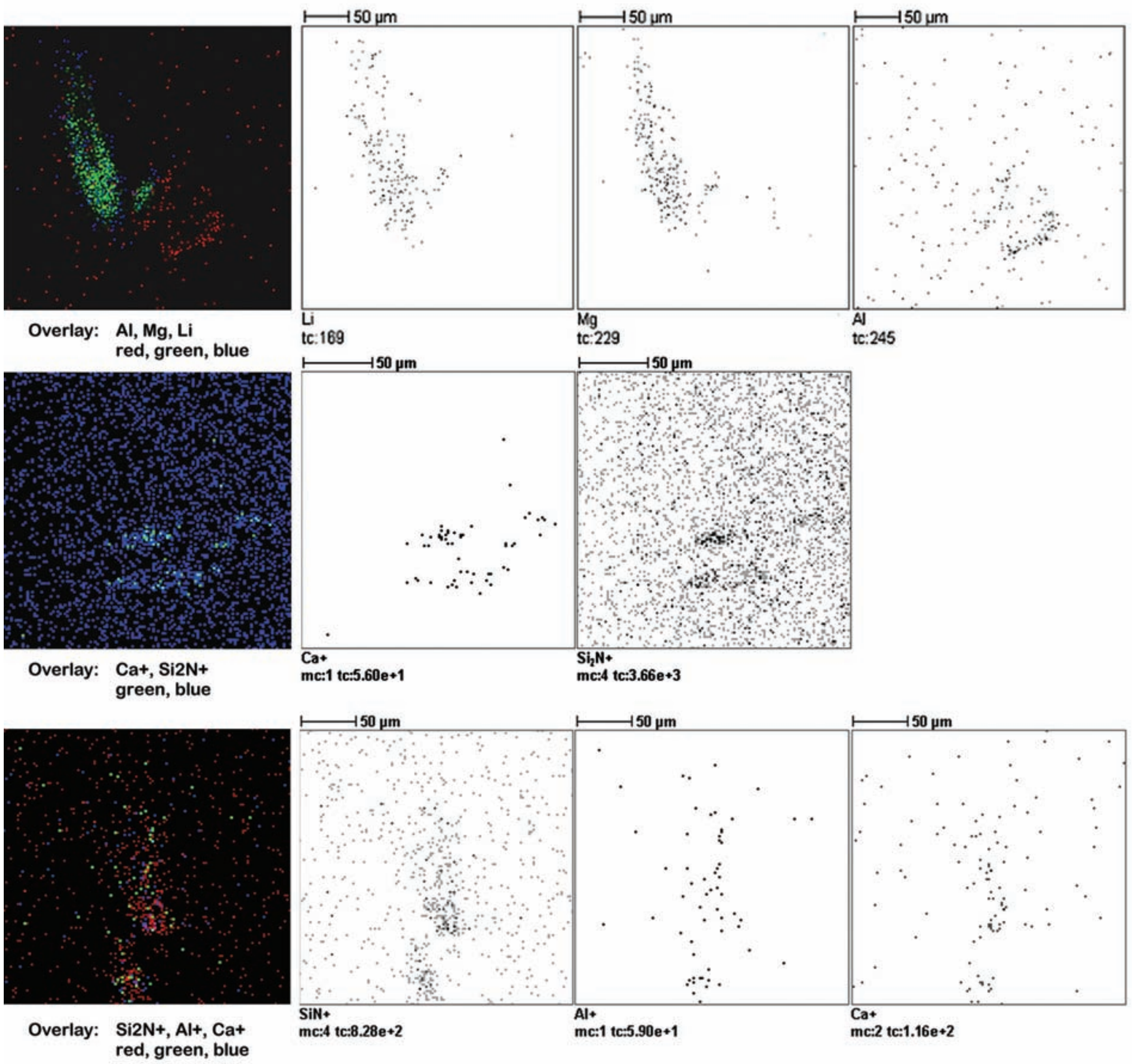


Figure 7. Positive ToF-SIMS ion images of trace metals and alkali metals of a SiC particle with a Si_3N_4 rod (top), Si_3N_4 fibres (centre) and a Si_3N_4 net (bottom). The overlay is shown in the first column.

analyzing trace elements in silicon material. ICP-MS may be used for quantitative determination of total metal and dopant concentrations because of its high sensitivity, whereas the power of ToF-SIMS is its high local resolution. Therefore, both techniques may complement each other in studying the material properties of solar silicon.

Acknowledgements

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References

[1] Wang, L. and Hockett, R.S. 2008, "Quantitative measurement of dopants (sub-ppba), oxygen, and carbon (sub-ppma), and metals (sub-ppma) in PV Si feedstock and wafers by SIMS", *Proc. 23rd EU PVSEC*, Valencia, Spain, pp. 1209–1212.

[2] Richter, S. et al. 2011, "Trace elemental and structural analysis of different types of Si_3N_4 precipitates grown in block-cast multicrystalline solar silicon", *Proc. 21st Workshop Cryst. Silicon Solar Cells & Modules*, Breckenridge, Colorado, USA, pp. 28–34.

[3] Richter, S. et al. 2010, "Trace elemental analysis of precipitates in multicrystalline silicon and investigation of solar cell shunting", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 1254–1258.

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Progress in cost reduction in silver pastes for crystalline silicon cells

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ABSTRACT

Silver paste is a key component of the design of nearly all silicon wafer solar cells manufactured in 2011. The high cost of the precious metal in the paste formulation means that silver paste is also the second-highest component of the total cost of materials. This article reviews the silver paste supply chain and the challenges in silver paste formulation and manufacture, and discusses some of the approaches for reducing or removing entirely the use of silver in crystalline silicon cell manufacture.

Introduction

Silver pastes have been the mainstay of crystalline silicon solar cell interconnection for the past 40 years. The unique benefits in making reliable, low-resistance connection to crystalline silicon, as well as forming low-resistance grids and busbars, make silver an excellent technical solution for solar cell manufacture. Unfortunately, the nature of silver as a noble metal gives its value in global markets significant volatility that is unconnected to local PV market conditions. In the past two or three years this has meant that the percentage of the bill of materials (BOM) for solar cells which relates to silver paste has increased dramatically as silver bullion prices have climbed.

> "Solar cell manufacturers have identified the reduction of the silver paste contribution to the BOM as a key requirement for lowering the overall price of solar modules."

Solar cell manufacturers have identified the reduction of the silver paste contribution to the BOM as a key requirement for lowering the overall price of solar modules. While significant progress has been made in optimizing both silver paste formulations and printing processes to reduce overall cost, significant challenges remain if cost targets are to be met.

Current trends in silver paste

Silver paste is used as a high-conductivity metal on both the front and the back of many solar cell designs in production today. The functionality of paste differs somewhat on the front and back sides of the cell, and thus the formulation of the paste changes. All pastes are based on silver particles that are delivered with functional components in a solvent or oil-based carrier.

For front-side applications, glass frit is combined in the paste to facilitate an aggressive etching process during firing to make contact through the antireflective coating layer with the underlying silicon. The fired paste must make a low-resistivity contact with the underlying silicon through the etched antireflective coating, for high-conductivity grid lines to carry current away from the cell. Different doping levels and antireflective coating materials lead to optimized formulations for each cell type.

For back-side pastes, the glass frit content can be reduced since no etching property is required, but the back-side busbar geometry is often larger than on the front and must make good electrical contact with the aluminium paste that forms the back-surface field. In the past, back-side pastes often contained significant quantities of aluminium powder, but this is less common today.

Generally about 0.2g of silver paste is used on the front side, whereas 0.05g is used on the back. In addition, approximately 1.2 to 1.5g of aluminium paste may be used to form a back-surface field. Functionality of the paste is driven by the silver particle size and its distribution and morphology, by the composition and chemistry of the glass frit, and by processing conditions. Front-side silver pastes are commonly optimized for various levels of doping and different antireflective coating materials, and even for n-type and p-type silicon.

Environmental concerns have also driven a reduction of lead and cadmium content in the glass frit. While the removal of these elements initially led to some compromises in functionality, more recent formulations appear to have addressed these concerns.

The problem with silver paste

The supply chain for silver pastes has one significant problem to overcome. The base material for the manufacture of any silver paste is electronic-grade silver, a material that is both extremely valuable and prone to price variations on global markets on a day-to-day basis.

As has been well documented, the cost of silver spiked in May 2011 at almost 300% above the price of January 2009, before falling again to between $30 and $35 per ounce today. The usual product pricing schemes for precious metal products rely on passing the market cost of the precious metal content to the next owner at the time of sale.

The value added in the creation of the product by the supplier is often a small and fixed part of the final selling price. The total paste price volatility leaves little room for cost reduction efforts on the part of the paste supplier and user.

Companies who manufacture products using precious metals must find business structures that can cope with the significant working capital demands and market risks of holding silver metal during the manufacturing process. These concerns imply that large well-capitalized companies with experience in handling precious metals are often advantaged in the supply of paste.

Technology trends

The 2011 International Technology Roadmap for PV calls for a reduction of 50% in the cost per watt of consumables from 2010 to 2020. As part of this cost reduction the roadmap envisages reducing the silver consumption per cell from 0.3g per cell in 2010 to 0.025g per cell in 2020 – an order of magnitude reduction in one decade. This can only be achieved through a significant redesign of silicon cell architecture, removing much of the silver on the front and back sides of the cell.

Although other high-conductivity metals exist, the direct replacement of silver in screen-printing paste formulation is not straightforward. The most obvious replacement – copper – does not make satisfactory paste. Copper is not a precious metal and brings with it oxidation problems, as well as being incompatible with a functioning silicon diode. The lack of a

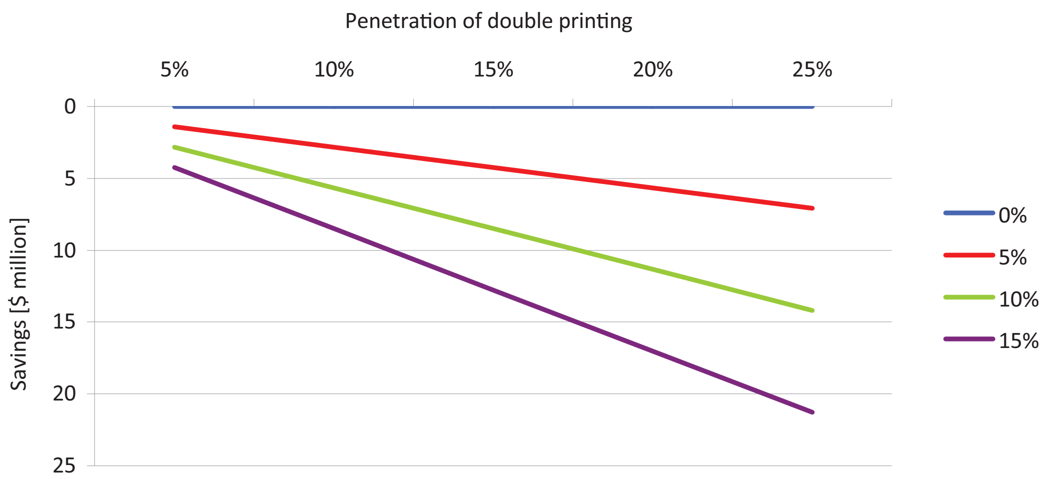

Figure 1. Forecast savings in 2011 from the implementation of double printing.

simple replacement for silver is driving silver reduction efforts in cell-making technology.

Paste reformulation that maintains good ohmic contact with the underlying silicon, and high conductivity of the fired grid lines and busbars, is critical. Reduced silver content pastes have been formulated by all major suppliers in the last 12 months; these pastes can reduce the amount of silver in front-side printing by as much as 20% while maintaining other functional properties.

> "For back-side silver busbars, a reduction in paste usage has been achieved by decreasing the thickness of the print, as well cutting down the silver content."

Double printing attempts to overcome one of the limitations of the screen-printing process, namely the difficulty of producing structures with a high aspect ratio. Since the paste is liquid at the time of printing and can slump after screen snap-off, in addition to its reduction in thickness upon firing, it has proved difficult to formulate standard pastes that can print a thickness-to-width ratio greater than 0.3. Hot-melt pastes printed at high temperature and using a wax-based carrier to achieve high aspect ratios have met with only limited success. Significant efforts in the last two years to develop processes that lay down a second paste print on top of the first have been successful in both reducing finger width and increasing aspect ratio. Matching of pastes for the first and second prints has allowed optimized contact resistance and finger conductivity while offering overall paste consumption reductions. However, the penalty of adding high-precision alignment for the second print, and the extra drying capacity required in the screen-printing line, offset some of the overall advantages of double printing.

Layout changes are a simple technique for reducing paste consumption through an optimization of the printed pattern of the grid and busbars. As cell efficiency increases, a higher density of grid fingers is necessary to carry current away from the cell. Reducing the finger width can offset the increased shadowing that results with more fingers. In current cell designs three 2mm-wide busbars are printed across the front of a cell instead of two. Inaccuracies in attaching stringers require continuous solid lines to ensure good solder joints of the stringers. With improved accuracy of stringer soldering equipment, busbar patterns can be reduced to islands or ladder-shaped structures that significantly reduce paste requirements while allowing reliable stringer connection. Even for high-efficiency cells, copper stringers can offer enough current-carrying capability to offset the need for solid busbars.

For back-side silver busbars, a reduction in paste usage has been achieved by decreasing the thickness of the print, as well as cutting down the silver content. An obvious limit to this occurs as the print thickness approaches the silver particle size used in the paste.

These techniques for reducing the amount of silver paste used and the total silver content per cell have yielded significant reductions in precious metal consumption per cell, but are nearing the practical limit of the savings they can offer. Further techniques – such as silver augmentation by plating, light-induced plating, and direct plating on silicon – offer ways of further reducing silver consumption per cell, although at the cost of increased complexity in processing and addition of new equipment. Alternative plating schemes include the following:

- Silver augmentation: an electroless silver deposition is plated onto a reduced-thickness paste line after firing. The plated silver is of higher density than that of the paste and consequently has a higher conductivity. The total silver used in the grid line can then be reduced.

- Light-induced plating: a metal stack is plated onto the silver using a thin silver-paste seed layer that has been fired to make contact with the front side of the cell. Commonly this stack includes a nickel diffusion barrier, a thick copper conduction layer, and a tin or silver flash for silver wettability. The plated layers are deposited with either galvanic or electroless plating, whereby in the latter case no back-side contact is required. The overall result uses significantly less silver but adds process complexity and new equipment, and requires careful control of nitride integrity to avoid metal deposition in pinholes.

- Direct plating on silicon: to avoid the use of the thin silver seed this technology directly plates metal onto silicon. Laser ablation is required to remove nitride from the front of the cell before plating. Once the direct-plated metal, usually nickel, has been deposited, light-induced plating can be used to build up the grid and busbars. Even though this process completely eliminates silver, it does add costs<AQ4> from laser patterning and a further plating process.

While all of these processes have been demonstrated they are usually only applicable to the front-side metallization, and do not remove the need for silver and aluminium paste on the back side. Although significant plating capacity has been installed, there remains relatively little manufacturing that uses this technology. Many challenges have been resolved but there is still uncertainty about implementing plated grid and busbars in high-volume manufacturing.

Despite several metal wrap-through and emitter wrap-through designs being introduced in 2011, the most effective cell architecture change to remove silver remains the implementation of back contacts. Most designs for back-contacted cells called for aluminium metallization, deposited either as paste or by evaporation. It is possible that aluminium will require an intermetallic contact layer at the silicon interface, although successful cells have been demonstrated without such diffusion barriers. These designs have the potential to be completely manufactured without the requirement for silver, but may need high-resolution patterning processes and are several years away from implementation on a large scale. An additional innovation for back-side contact architectures is that of integrating the cell interconnect in the backsheet. This technology incorporates a copper layer into the backsheet, which is stamped to produce the lead-outs for removing power. Connection with the cells can be done by various methods, including the use of a conductive adhesive, or a solder paste that is then laser heated after module lamination.

> "In 2011 most large cell producers implemented silver paste reduction programs that have yielded significant savings in the quantities of silver paste required in advanced PV modules."

Source: iStock

Figure 2. Silver's unique properties as a highly conductive metal that forms stable connections to crystalline silicon means it is very hard to replace with another single material.

Conclusions

The use of silver as an interconnect metal for PV cells remains as critical as ever. The unique properties of silver as a highly conductive metal that forms stable connections to crystalline silicon means that replacing it with another single material is very difficult. A large and stable supply chain for silver paste has emerged, and optimized formulations to meet the needs of many different cell designs have been proved. The high cost of using a precious metal as an interconnect material on silicon PV wafers remains a significant problem that is only made worse by the volatility of the price of silver on the world's metal markets. The uncertainty and risk in the cost of such a key component in the BOM is the driving force for finding replacement materials and technologies.

In 2011 most large cell producers implemented silver paste reduction programs that have yielded significant savings in the quantities of silver paste required in advanced PV modules. Many of these silver reduction schemes have reached the limit, and the next steps will include some redesign of the cell architecture or significant changes in the metallization processes.

The challenge of developing robust high-volume grid and busbar technologies remains a significant one. Both equipment makers and cell makers continue to develop alternative technologies, but in an industry where product lifetime and reliability are so critical, resistance to significant process change remains high. Major cell architecture changes that will replace the silver grids and busbars with metals such as aluminium and copper are several years off, but should be mature within the time frame identified by roadmap efforts. Whether or not these architecture changes can deliver long module lifetime and high reliability will become a significant focus for process developers, and an opportunity for all participants in the supply chain.

About the Author

Mark Thirsk is a managing partner and co-founder of Linx Consulting, which provides market-defining analysis and strategic insights across major markets in electronic materials. He has over 25 years' experience in economic and business forecasting, strategic planning, technical marketing, product management and M&A, spanning many segments and processes in electronic materials. Mark has served on the SEMI Chemicals and Gases Manufacturers Group (CGMG) since 1999, acting as chairman between 2001 and 2003. He holds a B.Sc. (Hons.) in metallurgy and materials science from Birmingham University and an MBA from The Open Business School, and has authored multiple publications in both academic and trade publications, as well as contributing to several patents.

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Cell Processing

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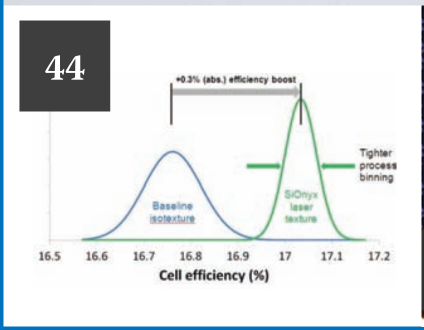

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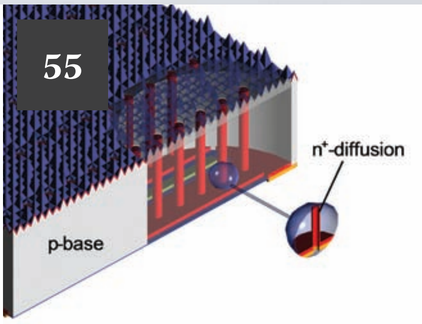

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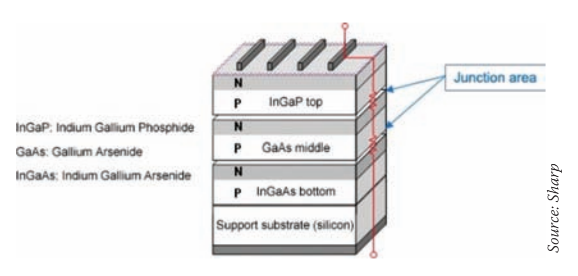
News

Sharp develops solar cell with world's highest conversion efficiency of 36.9%

After 11 years of research and development, Sharp Corporation has achieved the world's highest solar cell conversion efficiency of 36.9% using a triple-junction compound solar cell in which the solar cell has a stacked three-layer structure. Measurement of this value, which sets a new record for the world's highest non-concentrating conversion efficiency, was confirmed at the National Institute of Advanced Industrial Science and Technology (AIST).

Compound solar cells utilize photoabsorption layers made from compounds consisting of two or more elements, such as indium and gallium. Due to the high conversion efficiency, compound solar cells have been used primarily on space satellites.



Source: Sharp

Structure of Sharp's triple-junction compound solar cell.

In 2009, Sharp succeeded in improving cell conversion efficiency to 35.8% based on proprietary technology that enabled efficient fabrication of a stacked triple-layer structure with InGaAs (indium gallium arsenide) as the bottom layer. This latest increase in conversion efficiency was achieved by improving the maximum power output of the solar cell by reducing the resistance of the junction areas necessary to connect the solar cell layers in series.

Japan's New Energy and Industrial Technology Development Organisation (NEDO), which promotes research and development as well as disseminating industrial energy and environmental technologies, aided this breakthrough.

In the future, processes for transferring ultra-thin PV layers onto film substrates will make lightweight, flexible solar cells possible.

Cell Production News Focus

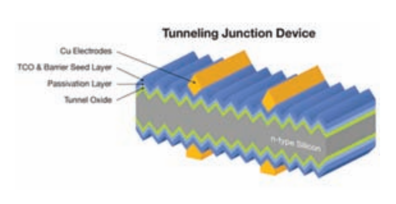
Samsung invests €50 million in Isofoton selective-emitter PV cell production capacity expansion

Korea-based Samsung is said to be providing a €50 million loan to Spain's Isofoton. Company representatives from both firms signed an agreement recently that will see Isofoton use the investment towards a capacity expansion of its selective-emitter PV cell production.

The investment is structured to be dispersed in two separate instalments. The first €30 million will be delivered in 2012 and will go towards the startup of a new selective-emitter solar cell production line with a 100MW capacity. The remaining €20 million will be distributed in 2013 for the expansion of the solar cell manufacturing capacity to reach 300MW.

Silevo comes out of stealth with "breakthrough" hybrid crystalline, thin-film PV module technology

Silevo advised that it had exited its stealth mode with its new proprietary Triex technology. The hybrid solar solution is said to combine high-performance crystalline silicon N-type substrates, thin-film passivation layers and a tunneling oxide layer in one solar module. The solar module is powered by the company's tunneling junction, which it states allows for the three materials to cohesively work together and produce high-efficiency, competitive module costs with optimum energy yield.



Source: Silevo

Silevo's Triex cell structure.

Silevo's corporate headquarters in California's Silicon Valley are supported by its R&D and manufacturing operation base in Asia. The company recently finalized US$33 million in financing with New Margin, a new lead investor, which was joined by GSR & DT Capital. The company intends to use the financing to develop a high-volume manufacturing facility in Hangzhou, China and explore advanced research to bring Triex to 24% conversion efficiency.

The company has modules in pilot production with the Triex cells said to be showing between a 20% and 21% conversion efficiency on full-size substrates with proven production materials. Customer qualification samples were shipped today from its pilot production centre in Fremont, California with high-volume commercial production slated to begin in the first half of 2012.

Sunpreme closes on US$50 million in financing round for construction of new solar cell facility in China

Sunpreme revealed that in its latest financing round the company secured over US$50 million, which will go towards the construction of a new solar cell manufacturing facility in Jiaxing, China. The financing round was led by the International Finance Corporation (IFC), a private entity of the World Bank Group. Capricorn Investment and Environment Fund III, managed by Tsing Capital, also contributed to the funding round. Upon completion of its new solar cell facility, Sunpreme intends to expand the production of its SmartSilicon cells.

Source: SunPreme

SunPreme's headquarters in Sunnyvale, California.

SiOnyx's Black Silicon process boasts 17%-plus-efficient multicrystalline-silicon PV cells

SiOnyx has advised that its patented ultrafast laser texturing technology, Black Silicon, has reached 0.3%, absolute, efficiency growth over typical industry baseline solar cells. The company's 156mm multicrystalline silicon cells, which are manufactured under a partnership with ISC Konstanz, are said to have attained average absolute efficiencies over 17%.

SiOnyx noted that its Black Silicon technology bolsters the efficiency in thinner wafers. Average efficiencies of 16.9% were realized for 150µm-thick multicrystalline cells that were 20% thinner than wafers in current production.

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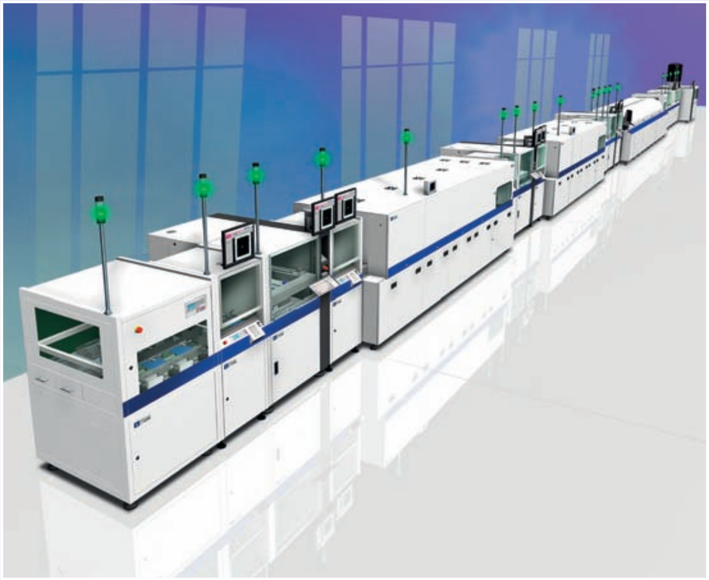

Offering both scalable production solutions and high-speed technologies, ASYS is the ideal partner for cost-efficient metallization. The ULTRAline Metallization Lines are available in single, dual and triple lane configurations with throughput rates from 1200 up to 4600 cells per hour. Comprehensive inspection solutions as well as the implementation of advanced process technologies such as Double Print or Dual Print extend the high level of performance of the ASYS metallization concept well into the future.

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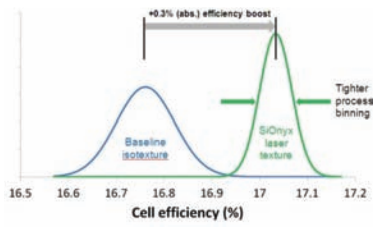

Source: SiOnyx

SiOnyx's standard 156mm multicrystalline Si cells, processed and tested at ISC Konstanz.

The cells were processed and tested at ISC Konstanz with a standard emitter, screen-printed metal and aluminium back surface field. Black Silicon texturing was completed by utilizing a Coherent Aethon tool with a Talisker picosecond laser.

The company further mentioned that its process results led to a definite improvement in process uniformity and cited standard deviations for cell efficiency and current being reduced by a factor of two with its Black Silicon.

Varian implanters help Astronergy achieve 19% conversion efficiency on c-Si PV cells

Varian Semiconductor and Astronergy have noted that just two months into their partnership to improve cell efficiency and to streamline the solar cell manufacturing process, they have developed and characterized a new production process using Varian's Solion ion implant system.

The process is in full production and is said to provide nearly a 1% gain in crystalline silicon solar cell efficiency while also abridging the manufacturing process by decreasing the process steps.

Q-Cells reduced to two-member management team as CFO resigns

More trials and tribulations at struggling Q-Cells have resulted in the resignation of its CFO, who has barely been in the job for 18 months since her appointment in April 2010. Effective from November 14, coinciding with the release of the company's third-quarter results, Marion Helmes's position will be taken by CEO Nedim Cen, former holder of the CFO role, but who was appointed CEO to support initial restructuring efforts that led to a complete management change. Cen remains as CEO, while Andreas von Zitzewitz will take on the position of CSO in addition to his role as COO, resulting in an executive board of just two members.

"In the current situation, Nedim Cen, with his in-depth knowledge of restructuring processes, will take over the task of providing a solid medium-term financial basis for the company, pushing these activities forward in his double role as CEO and CFO," commented Karlheinz Hornung, chairman of the supervisory board, on the re-allocation of responsibilities on the executive board. "Andreas von Zitzewitz will take on the position of CSO in addition to his role as COO. With this streamlined management organisation, the company is set up to operate effectively."

In a statement, Q-Cells said that it regretted Helmes's resignation, citing her contributions in development of the company's financial organisation since joining the company.

Source: Varian

Varian Semiconductor Equipment Associates' Solion ion implant tool.

Indeotec receives new order for Octopus II tool

Indeotec has received the first order and down payment for its Octopus II plasma processing equipment. Octopus II was first unveiled at PVSEC in Hamburg and is the successor to Indeotec's popular Octopus I. The new tool measures 300mm × 400mm and is characterized by eight PECVD, PVD, heating and customised chambers clustered round a central unit.

Following on from this successful round of testing, PV-Lab-EPFL has placed a follow-up order for two additional PECVD to help with its development of heterojunction c-Si and TF-Si.

Meyer Burger halts control transfer proceedings as Roth & Rau issues profit warning and loss of €76 million

Citing difficulties in the market environment and customer project delays as a reason for the company's poor third-quarter figures, Roth & Rau has reported an expected loss at EBIT level of €76 million for the three-month period. In response to this news, Meyer Burger has decided to cease steps it had been taking towards a control and/or profit transfer agreement, while Roth & Rau takes steps to regain financial stability.

According to the company's news release, Roth & Rau will place "all of its efforts into adapting its cost and organisational structures as quickly as possible to secure a rapid, sustainable improvement in its earnings and financial position."

Equipment sign-off delays due to customers impacted by weak demand and overcapacity within the PV industry led to the lower than expected sales in the quarter. Impairment charges on inventory and adjustments being made to the value of individual receivables due to certain customer creditworthiness changes contributed to EBIT losses for the first nine months of 2011 of €76 million. One-off items of €58 million were said to be the prime cause of losses for the current financial year to date.

Based on preliminary figures, Roth & Rau consolidated sales for the first nine months of 2011 amounted to €146 million, compared to €189.2 million in the same period in 2010.

Sequential revenues rise, as PV cellmaker Motech girds for further price erosion

Motech Industries released its Q3 2011 financial results, which saw the company's revenue grow 17% over Q2 2011's results to US$251.83 million. Additionally, the company's net losses went down to US$19 million, from the second quarter's US$21.47 million.

Motech advised that its net losses were lower due to diminishing materials costs, coupled with an enhanced number of shipments. Motech additionally noted that it expects prices to continue dropping in Q4 and possibly throughout 2012 due to what it perceives as a lopsided amount of supply and demand in the market.

During Q3 2011, Motech's cell capacity reached 1.5GW per year with its in-house wafer capacity amounting to 500MWp. The company shipped 330MW during the third quarter and advised that it saw the strongest demand during the quarter coming from Europe.

centrotherm's preliminary figures for first 3 quarters lead company to adjust outlook for full 2011

centrotherm photovoltaics has released its preliminary financial figures with revenue being finalized at €635.7 million for the first nine months of 2011. Operating earnings (EBIT) reached €25.2 million correlating with a 4% EBIT margin. The company noted that from these figures, €65.3 million in revenue was generated by its silicon and wafer unit with an EBIT of -€61.1 million.

centrotherm's batch-type system for nitride deposition in c-Si solar cell processing.

Source: centrotherm

centrotherm's solar cell and module division reported revenues of €546.5 million and an EBIT of €102.3 million while its thin-film segment collected €23.9 million in revenue with €-16 million in EBIT. The company additionally advised that its new order intake for the first three quarters of 2011 hold a provisional figure of €410.7 million.

The company's management board advised that it would be adjusting its full-year forecast due to the fragile sector environment. The board is now estimating that higher revenue and a slightly positive EBIT margin will be attained for the 2011 financial year.

Singulus Technologies' Singular PECVD tool is used for the application of ARCs on crystalline silicon solar cells.

Source: Singulus

SERIS places order for Singular PECVD tool for ARC coating applications

German manufacturer Singulus Technologies has received an order for its Singular PECVD tool, a coating tool for the application of ARCs on crystalline silicon solar cells, from the Solar Energy Research Institute of Singapore (SERIS). The Singular is part of a multi-million dollar project headed by SERIS focusing on silicon wafer heterojunction solar cells and their mass production.

SERIS operates pilot lines for both silicon wafer solar cells and silicon thin-film solar cells. The Singular tool has already demonstrated capabilities for silicon nitride ARCs, achieving excellent efficiencies and colour uniformity for current solar cell technologies. In the SERIS project, these capabilities will be expanded to the deposition of active layers for heterojunction silicon wafer solar cells. The key of the tool is the PECVD inductively-coupled plasma excitation, which is said to allow ideal control over film composition and density at high deposition rates.

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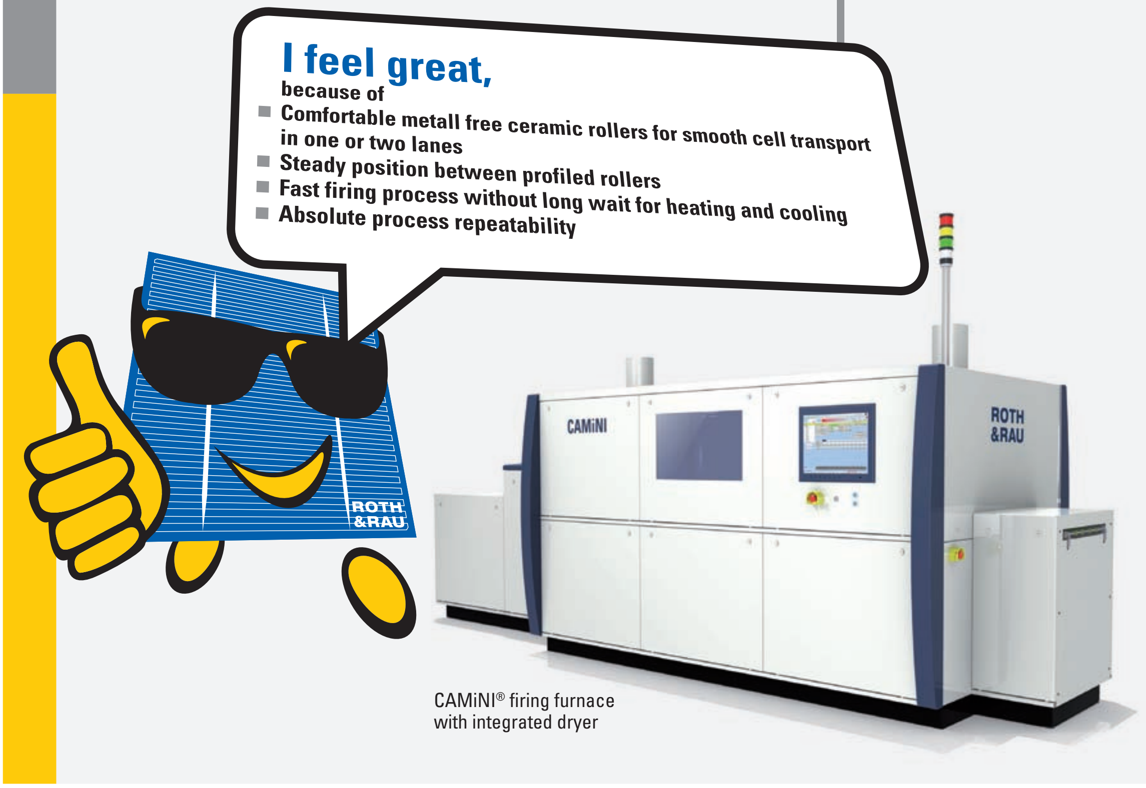

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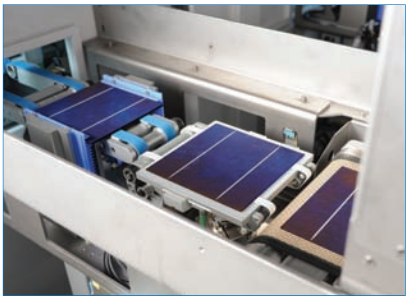
Product Reviews

Applied Materials



Applied's Baccini Pegaso screen-printer enables long-term cell processing

Product Outline: Applied Materials has launched the 'Applied Baccini Pegaso' solar cell manufacturing platform enabling novel, high-efficiency cell designs to be brought into mass production. It fabricates electrical circuits on both sides of a solar cell. Its dual-lane processing layout and adaptive wafer handling techniques provide high throughput and high precision with minimal wafer breakage.

Problem: The next wave of cost-per-watt reduction in the solar PV industry will be achieved through major changes in cell technology and manufacturing sophistication to simultaneously improve efficiency and factory output.

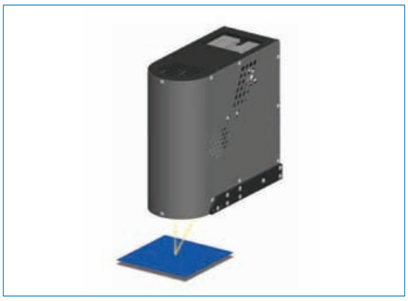
Solution: The system's wafer-handling mechanism is based on planar motor technology, which offers increased speed and accuracy for the wafers being shuttled between two independent tracks. The dual print 'Pegaso-XP' head incorporates a closed-loop optical vision metrology system that adjusts printing parameters from wafer to wafer. The results are claimed to provide near micron-level accuracy and repeatability, which enables higher and repeatable cell efficiencies. Combined with a laser ablation step, the double-sided passivation capability could offer a 0.7–1% cell efficiency gain.

Applications: The platform can handle advanced back contact and selective emitter schemes as well as double printing, allowing additional process units and metrology requirements, especially for unique cell designs and applications.

Platform: The Pegaso platform features 'future-proof' modular architecture enabling modules to be added quickly for additional processing capability.

Availability: Since September 2011.

Aurora Control Technologies



Aurora Control Technologies' in-line emitter dopant measurement system features whole-wafer mapping

Product Outline: Aurora Control Technologies has launched Decima CI, a new in-line emitter dopant measurement system that is claimed to be the industry's first featuring whole-wafer mapping at full production throughput for 100% of manufactured cells. Designed specifically for the PV production environment, the Decima provides 24/7 continuous measurements, requires no production line modifications for installation, and allows easy operator access.

Problem: With the industry's high-throughput, continuous production methods, tight real-time measurement and control of emitter fabrication variability is necessary to enable low cost and optimal power output of the solar cell.

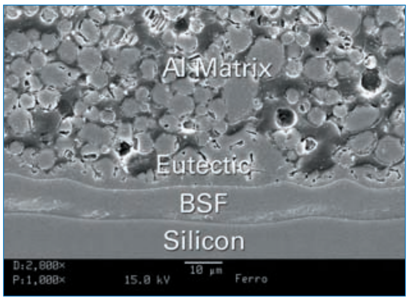
Solution: The Decima CI measures the diffused dopant within a polycrystalline silicon wafer, similar to sheet resistance. Featuring single or multi-lane measurement capability, the Decima's patent pending sensors and analysis technology provide accurate real-time measurements for process control and optimization. The Decima is said to be tolerant to production line faults such as misaligned, shingled or broken wafers. The modular head that sits above the production line connects to Aurora's PMC, a central controller for line-wide measurement integration and operations.

Applications: Measurement of diffused dopant within a polycrystalline silicon wafer.

Platform: The scalable architecture allows it to be economically applied from the smallest of production lines to the largest. The ergonomically designed Human-Machine Interface provides operators and engineering staff easy access to the required critical data.

Availability: Currently available.

Ferro Electronic Materials



Ferro offers cost-saving, high-efficiency rear aluminium conductor pastes

Product Outline: Ferro Electronic Materials has introduced two new rear aluminium conductor pastes to reduce manufacturing costs, while improving electrical efficiency and adhesion compared to currently available commercial products. AL 5130 and AL 5131 have pure aluminium metallurgy with high solids content, and are claimed to enable fast printing at speeds of more than 200mm per second.

Problem: The purpose of the aluminum is to reduce the ohmic contact resistance between the thick film material and the p-doped silicon surface. However, material costs are inhibiting the required reduction in overall cell production costs.

Solution: Ferro's new products allow cell manufacturers to reduce paste consumption by up to 20% and form a uniform BSF that increases absolute electrical efficiency by as much as 0.2% compared to competing products. They provide high adhesion to silicon and EVA film and enable the use of thinner cells that cut silicon costs. The products are compatible with a host of back surface silver pastes from Ferro, form a bump- and bead-free surface over a wide co-firing process window, and are dust-free and scratch resistant for ease of wafer handling.

Applications: Back surface field on crystalline silicon photovoltaic devices.

Platform: AL5130 and AL5131 aluminium pastes are RoHS- and REACH-compliant; AL 5130 is free of lead, cadmium and phthalates. The pastes were developed to accommodate a range of texturization processes used by customers.

Availability: Currently available.

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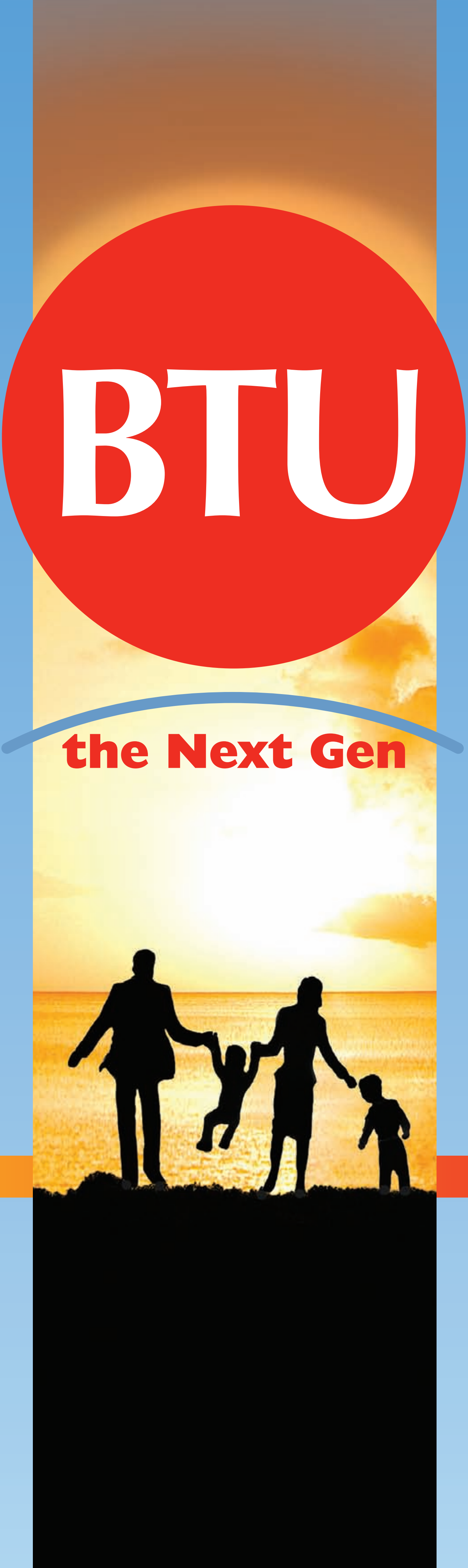
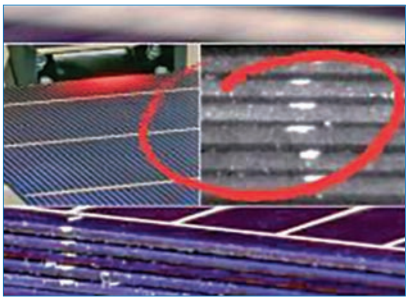


Product Reviews

Isra Solar Vision



Isra Vision's 'SOLARSCAN-Bevel' system provides short-circuit protection and optical cell quality

Product Outline: Isra Solar Vision has introduced a unique defect inspection system for compound spots on cell edges, which can cause short-circuits when the cells enter the flashing process. The new 'SOLARSCAN-Bevel' system is designed to prevent wafer/cell scrap and provides the possibility to react immediately with protective or maintenance actions.

Problem: In order to optimize production efficiency, to increase machine uptimes and to reduce manufacturing costs, one major goal is to detect defects such as contamination and unclean coating in the manufacturing process as early and as fast as possible.

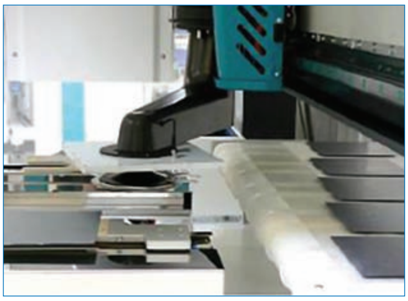
Solution: SOLARSCAN-Bevel inspects the c-Si cells after the printing process but before the firing process. This enables manufacturers to clear compound spots on cell edges that could lead to short-circuits in all subsequent cells in the process flow. The system also provides a reliable inspection alarm for the maintenance staff. The system is claimed to provide the optimum solution for this problem, enabling early detection of edge defects such as contamination or spots.

Applications: Cell inspection for the prevention of compound spots on cell edges post metallization and prior to the firing step.

Platform: Isra Solar Vision claims that the SOLARSCAN-Bevel inspection system provides a return on investment on a single system in an hour or less.

Availability: Since September 2011.

Manz



SpeedPicker 1.1 from Manz offers throughput rate of 5,000 wafers per hour using carbon arms

Product Outline: Manz has made significant updates to its SpeedPicker series system for high-volume crystalline solar cell manufacturing applications.

Problem: Manz's automation system technology had reached its limits in terms of size, speed, and costs and, as a result, has now been superseded by the reengineered SpeedPicker 1.1.

Solution: The new system is claimed to be highly accurate, while being half the size of other systems on the market. SpeedPicker 1.1 requires a maximum of only seven square metres of space, depending on its configuration, helping to significantly reduce its upfront investment cost. In addition, the new generation of the system is claimed to be more intuitive, and therefore easier to operate and with an attractive price.

Applications: C-Si solar cell handling.

Platform: The SpeedPicker 1.1 works with one or two carbon arms which rotate at a high speed and are mounted and pivot on a linear axis, guaranteeing precision placement. A newly developed Bernoulli gripper and a special image processing system ensure that the wafers are perfectly aligned and together offer 100% breakage control when loading and unloading process machines. The system can be configured in a wide variety of ways and easily integrated into existing production lines.

Availability: Currently available.

Trident Solar

Trident Solar offers non-contact inkjet-based selective emitter for c-Si front contacts

Product Outline: Trident Solar has launched its new single-step 'VersaEtch' Etchant / n-Dopant material for inkjet selective emitter application of solar front contacts (c-Si).

Problem: According to Trident Solar, solar cell manufacturers want a single-step, non-contact process that would enable more efficient front contacts by etching through the SiN_x ARC layer then diffusion doping the silicon emitter. A selective emitter approach that could decouple the metallization process from the etching / doping process could potentially maximize the results of both areas.

Solution: The etching material can be jetted from the Trident 256Jet-S printhead and etch through the SiN_x ARC layer when heated to 350°C. When heated to 800°C the n-dopant diffuses into the silicon active emitter. All that is needed to complete the process is a post water rinse. As a non-contact process, use of the VersaEtch Etchant/n-Dopant is claimed to result in up to a 10x reduction in costly wafer scrap. Scrap rates range from 0.5–1.0% and can be reduced to as low as 0.1%.

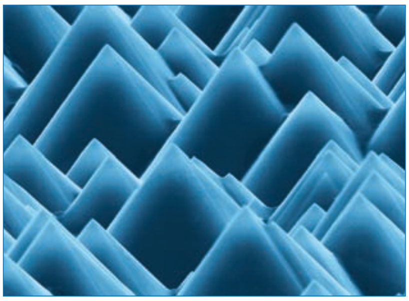
Applications: Single-step, non-contact process for front contacts by etching through the SiN_x ARC layer followed by diffusion doping of the silicon emitter.

Platform: Specifically designed for solar applications, the printhead features stainless steel construction for chemical inertness and a unique repairable design allowing the nozzle plate to be disassembled, ultrasonically cleaned and reassembled.

Availability: Since September 2011.

Product Reviews

RENA



TetraSun and RENA highlight 20% cell efficiency path using IPA-free monoTEX texturing

Product Outline: RENA has launched its monoTEX, IPA-free alkaline texturing process for solar cells, establishing the importance of this process for their breakthrough monocrystalline cell concept. RENA's combination of pre-cleaning and monoTEX texturing is claimed to provide a homogeneous surface with a distribution of pyramid sizes that, together with an optimization of the complete process sequence, enables a cell efficiency that is well beyond the 20% mark.

Problem: IPA-based KOH texturing of monocrystalline Si-wafers causes not only environmental and cost problems but also micro- and macro-inhomogeneities influencing the efficiency of the cells.

Solution: monoTEX is a new type of moderating and wetting agent for IPA-free alkaline texturing operating far below the boiling point of its components. RENA's combination of pre-cleaning and monoTEX texturing leads to a uniform texturing start and a controlled pyramid distribution. It also has very short process times of less than 15 minutes, with bath lifetimes over 40 runs and >95% tool uptime. The tuning of the complete process sequence with upstream and downstream processes enables the monoTEX user to achieve efficiencies beyond 20%.

Applications: IPA-free texturing of monocrystalline Si-wafers.

Platform: The elimination of IPA from both the exhaust and fluid waste streams further supports TetraSun's focus on cost of ownership (CoO) concerning both environmental and manufacturing cost.

Availability: Currently available.

Singulus Technologies

ICP-PECVD tool from Singulus enables development of passivation layers for new cell concepts

Product Outline: Singulus Technologies has launched the 'SINGULAR ICP-PECVD' platform for the development and production of high efficiency silicon solar cells, requiring passivation layers for R&D and production applications. The platform has been applied at research centres and institutes in Europe, America and Asia.

Problem: To reduce the costs of PV electricity, continuous improvements with respect to efficiency and manufacturing cost of PV cells and modules are necessary.

Solution: SINGULAR is an ICP-PECVD coating tool for crystalline silicon solar cells which is used for the mass production of silicon solar cells. The tool is based on static in-line production, which combines the advantages of in-line substrate transport and static processing. It allows the coating of complex layer systems, such as layer stacks or gradients consisting of different materials. The process variability, the small tool footprint and high reliability are said to be required for high cell efficiencies, while providing improved total cost of ownership and high uptime. The key feature of the machine is the ICP–PECVD technology. The inductively coupled plasma (ICP) excitation allows ideal control of film composition and density at high deposition rates.

Applications: Crystalline solar cell passivation layers for R&D and volume production.

Platform: The system is of a modular design, consisting of several vacuum chambers which can be customized. Due to this high flexibility, new manufacturing processes for cell efficiencies above 20% can be developed on a manufacturing platform. This is intended to guarantee a fast and easy transfer to production.

Availability: Since September 2011.

STRAMA-MPS

STRAMA-MPS offers multicolour LED sun simulator for cell testing

Product Outline: STRAMA-MPS has introduced its third-generation 'ProMoSim evo^3', an LED-based sun simulator for improved solar cell testing that includes quality checks, high-precision IV curve measurement and steady state light soaking and cell degradation measurements.

Problem: Instability of spectra due to thermal and aging effects at classic bulb-based flashers cause mismatches in PV cell efficiency measurement. Additionally, deviation in P_{max} is caused by transient effects. Here the charging of a capacity in the specimen needs an appropriate time to allow precise sweeping through the IV curve.

Solution: With ProMoSim evo^3, the company claims to offer a highly accurate efficiency measurement by minimum non-uniformity (<0.4%) and spectral match (±10%). Intensity variation and programmable spectra allow for additional tests, e.g. degradation or light soaking in the steady-state mode, made possible by a multicolor LED illumination array, offering a life time of over 50,000,000 flashes. Together with the long-term conditions (temporal long-term instability of irradiance <0.5%), the system offers the opportunity to cover classical flasher applications and innovative steady-state features into an all-round test system.

Applications: Simulating real sun irradiation.

Platform: ProMoSim evo^3 is a table-top test system for PV cells up to eight inches. According to IEC 60904-9, it offers precision and much better class AAA. The system includes a 4Q-amplifier plus software and monitoring cell.

Availability: Currently available.

Emitter wrap-through solar cells – status and perspectives

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ABSTRACT
Crystalline silicon wafer technology currently dominates industrial solar cell production. Common devices feature opposing electrodes situated at the front and the rear surface of the wafer, and subsequent front-to-rear interconnection is used for module assembly. This paper describes the status and perspectives of the emitter wrap-through (EWT) cell concept, which is a fully back-contacted solar cell. The functions which have to be fulfilled for this concept, as well as the corresponding challenges and advances, are discussed.

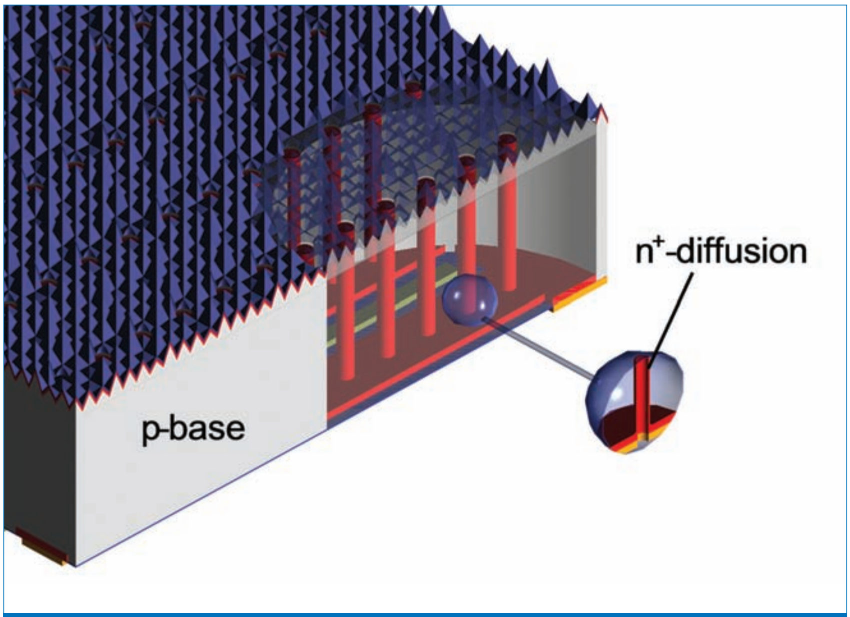


Figure 1. A 3-dimensional schematic view of an EWT solar cell [10].

Introduction

Today crystalline silicon solar cells with classical front contacts form more than 80% of the market share of all PV technologies. The classical approach with a metallization grid on the front side, which in most cases consists of screen-printed silver, leads to shading losses. With the emitter wrap-through (EWT) solar cell concept, which was first published by Gee et al. [1] in 1993, these shading losses can be avoided and a larger amount of current can be extracted. Back-contact back-junction solar cells also avoid shading losses but feature more demanding requirements in terms of material quality, such as a high diffusion length of several times the cell thickness, which is necessary for achieving high efficiencies [2]. EWT cells already have an advantage over conventional cells when the diffusion length is about half the cell thickness [3]. This is due to the double-sided collection, made possible by front and rear emitters. An additional advantage offered by the full rear contacting is that an advanced module assembly can be used. This permits, for example, the use of wider tabs or foils for the cell interconnections, thus reducing the series resistance losses in the module [4,5].

> “With the emitter wrap-through (EWT) solar cell concept, shading losses can be avoided and a larger amount of current can be extracted.”

Another way of increasing the conversion efficiency of conventional solar cells is to introduce passivation layers and local contacts as in the passivated and rear-emitter cell concept [6]. This can be combined with wrap-through concepts such as EWT. A combination of these improvements seems to be the most desirable for achieving high efficiencies beyond 20%. In the next section, the challenges and perspectives of manufacturing EWT solar cells will be addressed. Then, a review of recent cell results concerning the EWT concept will be presented, followed by a description of suitable cell design and module integration.

Challenges in manufacturing EWT solar cells

Manufacturing EWT solar cells is quite challenging, as their structure is more complex than that of conventional solar cells. A 3-dimensional schematic view of the EWT cell structure is shown in Fig. 1. To achieve the interconnection of the front emitter to the rear emitter, a set of densely placed via-holes (approximately 24300–48600 holes for a 243cm^2 wafer) has to be drilled. This is possible with today’s advanced laser technology, as laser systems are already able to drill 5000 holes/s [7]. Considering the advances in laser technology, higher drilling rates than this will be likely in the future.

No laser-induced damage must remain inside the via-holes after the drilling step, since this leads to increased recombination [8,9]. The absence of damage can be ensured through a regular saw-damage removal step, which can also be used to achieve a flat rear surface.

Different approaches can be used to form the characteristic interdigitated pattern of the emitter on the rear side. Most publications report the formation of the grid using a patterned diffusion barrier of silicon dioxide or silicon nitride, for example. Of course, photolithography can be used to pattern this barrier; it makes the process rather expensive but the alignment accuracy is more precise. Other techniques – such as laser structuring [11], screen printing [12,13] or inkjet printing of an acid-resistant material – can be used to form the interdigitated pattern. To further reduce the number of process steps, direct printing of a diffusion barrier as shown by Spribille et al. [14] or Gee et al. [15] can be used.

The passivation of the pn-junction bordering the surface on the rear side is also an important issue. The length of the pn-junction can reach several metres on a wafer with an edge length of 125 or 156mm, depending on the distance between two fingers of the same polarity (often referred to as 'pitch'). As Kühn et al. [16,17] state, this leads to enhanced recombination depending on the quality of the surface passivation. It is therefore important to achieve a good passivation of the pn-junction on the rear side to achieve high efficiencies. Minigirulli [18] showed that an EWT cell with a passivated pn-junction has an increased conversion efficiency.

Another important issue is the metallization. Engelhart [11] showed a sophisticated self-aligned process using evaporated aluminium with a subsequent etching step. In this case the aluminium is used to contact both polarities. Account must therefore be taken of the fact that aluminium spiking effects on the emitter area might occur in subsequent low-temperature steps, leading to a decrease in cell efficiency [19,20]. Manole et al. [21] showed how the thermal stability of an evaporated aluminium contact can be increased using a thin tunnelling oxide layer or an aluminium-silicon alloy as a intermediate layer. Spiking effects can be circumvented by using screen-printed contacts. As already shown by several authors [15,18,22], screen printing with a subsequent co-firing step leads to functional EWT solar cells.

> "Precise alignment is a challenge that has to be met by the via-drilling and all patterning steps, to avoid possible shunting of the solar cells."

Precise alignment is a challenge that has to be met by the via-drilling and all patterning steps, to avoid possible shunting of the solar cells. In these terms a photolithographic patterning seems most desirable but on the other hand adds to the additional process complexity and costs. As Woehl et al. [23] state, with the screen-printing equipment and pastes used at Fraunhofer ISE, a pitch of 2mm for back-contact back-junction cells can be obtained with four alignment steps. For EWT cells, three alignment steps are possible but the alignment accuracy of the laser has to be taken into account as well. Fraunhofer ISE [23] have shown that pitches of 500µm width are possible using inkjet printing for back-contact back-junction cells.

With regard to all cell types reaching maximum cell efficiencies, the main optical and electrical loss mechanisms must be significantly reduced. While reducing the optical loss mechanisms is fairly simple, due to the absence of shading losses, the electrical loss mechanisms need to be looked at more closely. These losses can be split into electrical resistance and recombination losses and will be discussed next.

Electrical resistance

As in the case of all cell concepts, the electrical losses due to series resistance have to be kept as small as possible, which is rather challenging because lateral effects play an important role in the EWT cell. Lateral series resistance losses can be very high within the base, depending on the pitch of the interdigitated finger grid and the base resistivity: therefore the base resistivity and/or the pitch have to be quite low. If point contacts, for example laser-fired contacts [24], are used these losses will be even higher than for line contacts. Spreading resistance effects occur, leading to an enhanced series resistance of the cell [25]. On the other hand, a low base resistivity enhances the recombination in Cz silicon material due to the boron-oxygen complex [26]. The right choice of base material is therefore very important and depends on the pitch that can be realized with the patterning technology used.

Even more complex is the influence of the emitter sheet resistance in an EWT cell. Current crowding at the via-hole, which takes places at the front side [27], as well as series resistance losses due to the via-hole, increases the series resistance losses. According to Dicker [28] the series resistance losses due to the via-hole are one of the main loss mechanisms. But these losses can be reduced by increasing the number of via-holes. The arrangement of the via-hole pattern is also an important factor. Non-square via-hole patterns feature a larger amount of current transport in a single direction, which increases the contribution of the series resistance of the front side emitter to the total series resistance [29]. Therefore a square or hexagonal via-hole pattern with a high density of via-holes seems to be the most favourable. However, small pitches increase the length of the pn-junction on the rear surface and make the alignment more difficult.

The metallization on the rear side is another issue. For wafers with an edge length of 156cm, an interdigitated grid with one busbar on each side leads to high series resistance losses due to the large finger length. In this case the finger conductivity needs to be very high to reduce these losses to a minimum. A design with two busbar pairs as proposed by Kress et al. [22] can be used to reduce the finger length. Since the busbar is in most cases expanded, the current within the semiconductor has to travel a greater distance to reach the next contact, and consequently the region underneath the busbar contributes a larger portion to the total series resistance [30]. An alternative approach is therefore to use a busbar-less concept featuring conductive adhesives with a structured metal foil as proposed by Eickelbroom et al. [31]. This reduces the series resistance losses in a large-scale EWT solar cell and is one of the advantages over conventional cells.

Recombination

The emitter diffusion process is the key process, since it determines a great deal of the recombination losses.

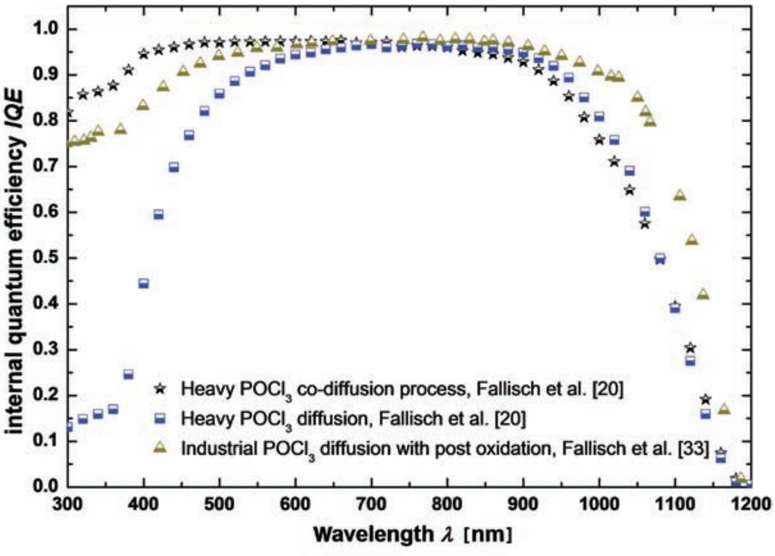


Figure 2. Measured IQE of an EWT cell for different diffused emitter profiles: a heavy diffusion process with and without a side selective emitter [20], and an industrial diffusion process with a subsequent oxidation [33].


when footprint matters...

Auger recombination is the main loss mechanism within the emitter because of the high density of charge carriers nearby. Therefore a low doping is preferable, which is in contradiction to a low series resistance. Furthermore, it has been shown by simulation that a high rear-emitter coverage is beneficial for the collection of minority charge carriers for low-quality material [32]. Hence it is even more important to have a very low emitter saturation current density. Engelhart [11] achieved emitter saturation current densities of approximately 130fA/cm^2 on a textured passivated front side and about 80fA/cm^2 on a planar oxide passivated rear side using a highly doped emitter. This leads to a peak open-circuit voltage of 668mV for the processed EWT cells.

> “The emitter diffusion process is the key process, since it determines a great deal of the recombination losses.”

Moreover, a higher phosphorus doping and deep emitter on the front side not only enhances the Auger recombination, thereby reducing the open-circuit voltage, but also reduces the short-circuit current density due to reduced quantum efficiency in the short-wavelength range. This can be seen in Fig. 2, which shows three different internal quantum efficiency (IQE) measurements for different diffused emitter profiles.

Using a heavy diffusion process to obtain a high conductivity results in a low internal quantum efficiency in the short-wavelength range. If a co-diffusion process is used with a moderately doped front side emitter [20], the quantum efficiency can be significantly increased, leading to a higher short-circuit current density and in turn to a higher cell efficiency. Such a heavy diffusion process, however, is not necessary: an industrial diffusion process, which is used for conventional cells, can also be used for EWT cells. In this case a short oxidation step after the diffusion process and phosphosilicate glass (PSG) removal reduces the series resistance losses and the emitter recombination, and also passivates the pn-junction. Compared to cells featuring a heavy diffusion, an improved quantum efficiency is achieved, leading to short-circuit current densities of up to 39.5mA/cm^2. Of course, this industrial diffusion process can also be used as a co-diffusion process to further increase the quantum efficiency in the short-wavelength range.

Additional fill factor losses occur if the potential difference between the front and the rear of the pn-junction increases. This is an effect not only of an increased series resistance but also of an enhanced recombination. Due to the potential difference across the front and rear of the pn-junction, charge carriers in the front emitter are reinjected into the base material, where they diffuse to the rear side and are collected by the rear junction. This enhances the possibility of recombination, which leads to an additional decrease in fill factor. This effect appears particularly in the p-busbar regions, as the distance to the first row of via-holes is greater, which results in a larger difference in the voltage potential [30]. The same effect can appear if the base resistivity is too high and the potential difference in the lateral direction within the base increases. These via-resistance-induced recombination enhancements [34,35] or non-generation losses [36] depend on the geometrical parameters – such as pitch, number of holes and so on – as well as on the emitter resistivity and the base resistivity of the manufactured EWT cell. These effects can be avoided by choosing the right materials and geometries.

Review of EWT research

Since 1993 a lot of research has been done concerning the potential of EWT silicon solar cells. Gee et al. simulated a maximum efficiency of 21.6%, assuming Cz p-type material with a rather low value of 0.25Ωcm^2 for the lumped series resistance [1]. Several groups have since issued reports about the processing of EWT cells: a selection of these publications will now be reviewed.

In 1998 Smith et al. demonstrated an efficiency of 18.2% on an area of 41cm^2 – a record result at the time. The cells were made of float zone (FZ) silicon material. Photolithographic patterning of silicon dioxide was used to create the interdigitated grid on the rear side, and a heavy diffusion process was used to obtain a high conductivity. For metallization, an evaporated metal stack was used. In 2000 Kress et al. [37] reported an EWT solar cell efficiency of 16.1% on 10×10cm^2 Cz silicon material. This process sequence included two diffusion steps to achieve a moderately doped front emitter and a heavily doped emitter on the rear side and the via-holes. Screen printing was used for the metallization.

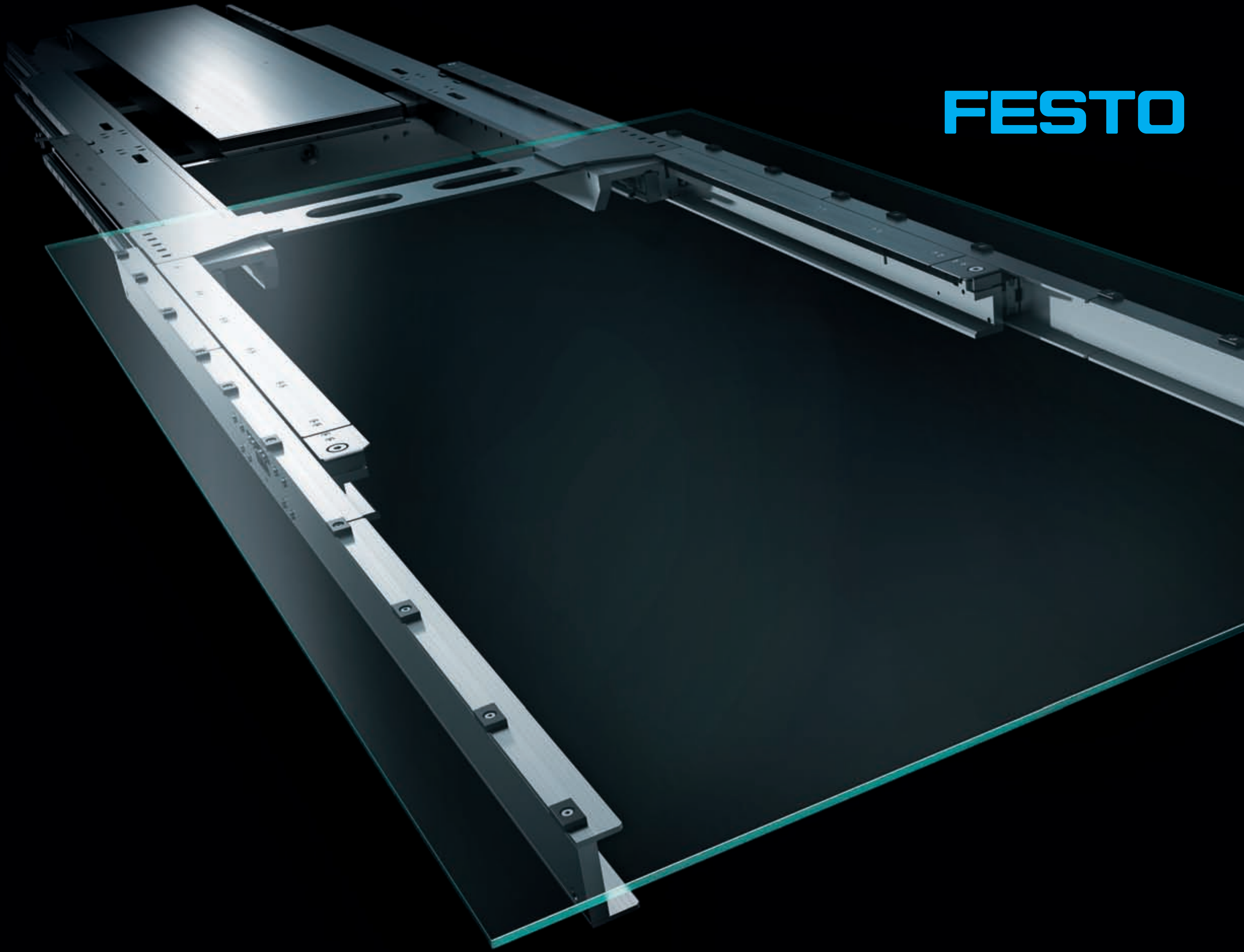
Just one year later, in 2001, Glunz et al. [38] presented the first EWT cell with a conversion efficiency exceeding 20%. On FZ silicon material, efficiencies of 21.4% have been achieved with an active cell area of 6cm^2. This cell featured a very high open-circuit voltage of 685mV and a short-circuit current density of 40.9mA/cm^2, but included a complex cell process with multiple diffusion and oxidation steps, and patterning using photolithography. Some years later, Kray et al. presented an EWT cell with an efficiency of 18.7% on Cz silicon with an active cell area of 6.23cm^2 after light-induced degradation [39]. However, these EWT cells also featured a cell process including photolithography patterning, several high-temperature steps and an evaporated metallization. These processes make the EWT cell rather expensive and not suitable for industrial production, but demonstrate the potential of the EWT structure in real devices.

In 2007 Engelhart [11] presented a calibrated measurement of 21.4% efficiency on an area of 92cm using FZ silicon. This cell had a very high short-circuit current density of 41.5mA/cm^2, which impressively showed the absence of shading losses and the advantages of the EWT cell concept. An open-circuit voltage of 668mV and a fill factor of 77.1% were also obtained. The patterning of the emitter and dielectric layers was performed using mask-free laser technology, and laser-fired contacts [24] were used on an evaporated aluminium metallization for the base contacts. As the process sequence also included four high-temperature steps (two diffusion and two oxidation steps) it was still very complex and therefore expensive. With a simpler process sequence that only included one oxidation and one diffusion step, a peak efficiency of 20.0% was achieved on the same area and material. On a large area of 125×125cm^2, the Institute for Solar Energy Research Hamelin (ISFH) reported a peak efficiency of 20.4% on FZ silicon material [40].

Mingirulli et al. presented a fully screen-printed EWT solar cell with 18.8% conversion efficiency on an area of 16.65cm^2 in 2009 [12,13]. Similar to the simpler fabrication process of Engelhart, the process sequence included only two high-temperature steps (one oxidation and one diffusion step). An industrial screen-printing process was used for the metallization. In the same year, Hacke et al. [5] reported results of a peak efficiency of 18.2% for an EWT cell on 156mm pseudo-square Cz silicon. On an area of 243cm^2, 17.2% has been achieved for multicrystalline material and 16.6% for upgraded metallurgical grade (umg) silicon (untextured).

Just recently, in 2011, Fallisch et al. [33] reported on an EWT cell on FZ silicon yielding a conversion efficiency of 18.7%, using a homogeneous industrial emitter diffusion process with a subsequent short oxidation after the PSG removal. The metallization consisted of a combination of screen printing and an evaporation process; this allowed a subsequent plating step for reducing series resistance losses. Both contacts were plated with silver, so soldering should be possible. On the other hand, an additional patterning step to isolate the evaporated contacts was necessary, which increased the process complexity.

Also in 2011, Gee et al. presented a peak conversion efficiency close to 19.8% before



light-induced degradation on a large area of 156×156cm^2 using Cz material [15]. The process sequence was rather short – it included an industrially-applicable back-to-back emitter diffusion step and screen-printed contacts. The process sequence included only a few extra process steps, such as laser drilling, protection of the rear side from an alkaline texturization process by a PECVD layer, printing of a diffusion barrier and a silicon nitride deposition on the rear side. These make the process sequence already usable for industrial application.

A little earlier in the year, the first n-type EWT cell with a peak conversion efficiency of 21.6% on a small area of 2×2cm^2 was presented by Kiefer et al. [41]. This cell featured a short-circuit current density of 40.4mA/cm^2, an open-circuit voltage of 661mV and a very high fill factor of 80.8%, which demonstrated that the EWT cell concept can also be successfully applied to n-type silicon material.

Cell design and module integration

Conventional silicon solar cells have their electrical contacts arranged in busbars on the front and rear surfaces that span the length of the cell. The cells are interconnected with flat Sn-coated Cu ribbon wire. To minimize optical losses, the ribbon must be made narrow; however, it cannot be made very thick, because the stiffness of thicker Cu ribbon will increase yield loss [42]. The compromise is to accept a rather high resistance loss of around 2% in conventional modules when using three busbars and 156mm cells. The optical loss is around 3% when using 1.6mm-wide Cu ribbon interconnects, three busbars and 156mm cells. The total loss associated with the interconnects is therefore approximately 5%.

One of the main advantages of back-contact cells is the minimization and/or elimination of the optical and resistive losses due to the interconnects when assembled into a module. Nevertheless, it is crucial to carry out the design of the cell and module together to maximize the cell and module performance. It should be remembered that most of this discussion is relevant to any back-contact solar cell technology – including back-contact back-junction cells and metallization-wrap-through (MWT) cells.

The first concepts of EWT cells used the same design paradigm as conventional cells. Busbars that ran the length of the cell were envisioned so that flat Cu ribbon interconnects could be used for module assembly [1]. The busbars could be placed at just the edges of the cell, or they could be included in the interior of the cell to reduce the average gridline length. A major problem was identified with busbars, specifically the regions of high resistance associated with the geometry [30]. The region over the busbars has a longer path length for current collection compared to the remaining active-area region. The equivalent circuit for a back-contact cell includes a solar cell with a high series resistance (representing the busbar regions) in parallel with a solar cell with low series resistance (representing the active-area regions). Some authors have since referred to this effect as 'electrical shading', although this term is also frequently used to refer to limitations in current collection due to finite diffusion lengths in back-contact back-junction solar cells [43]. It should be noted that some reported results for research devices use a 'designated area' measurement where the busbar regions are not illuminated during the measurement or included in the efficiency calculation to circumvent this loss mechanism. Such an approach, however, is obviously not applicable to commercial devices [44].

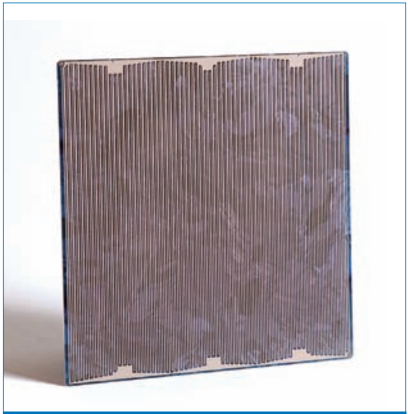


Figure 3. Rear surface of a 125mm EWT mc-Si cell.

"Good progress from both a cell and a module perspective has been made, bringing the EWT cell concept close to entering the market."

The series resistances losses can be minimized by reducing the area of the high-resistance regions, but this geometry change necessitates an alteration of the module assembly technology. The busbar dimensions can be minimized while still leaving pads for the electrical connections. An example of this geometry is shown in Fig. 3 for a 125mm EWT cell [45]. The tapering of the busbars allows current to be collected from the pads while minimizing the size of the busbars. This edge-connect geometry uses short, flat Cu interconnects between adjacent solar cells and for which modified stringer/tabber tools can be used. However, the series resistance of the solar cell is increased because of the very long grid lines.

Optimized for cost and performance, the design enables current to be collected and extracted from the solar cell in uniformly distributed locations throughout the interior of the cell [45]. Through refinement of this interior current-collection geometry and other improvements in the processing [15], efficiencies of up to 19.8% have been demonstrated for 156mm Cz EWT cells using only screen-printed metals and patterning. The cell layout was optimized for high efficiency, and the Ag metal usage minimized for cost reduction. The cell layout was also designed for use with a 'monolithic module assembly' that employs a large-area flexible circuit integrated with the module backsheet materials [46]. Many technical advantages of this approach have been previously described [47]. Rigorous (and in some cases new) testing procedures were implemented to ensure the reliability of such a new module assembly technology [45]. Modules built with a monolithic module assembly and EWT cells have passed and received IEC certification [46].

Conclusion

This article has shown which challenges have to be met for manufacturing EWT solar cells; the current status of EWT development has been reviewed. Most of the challenges, such as series resistance and recombination issues, are already known and, as pointed out, can be overcome by a suitable cell design and process sequence. One of the main advantages – the reduced shading losses – has been successfully demonstrated in several publications, with short-circuit current densities over 40mA/cm^2 being achieved. These current densities can be obtained using industrially diffused emitters.

Conversion efficiencies above 21% have already been realized on a small scale using mask-free patterning technology. On larger areas, the conversion efficiency achieved is close to 20% using a simple process sequence with only a few additional extra process steps. New approaches relating to the module assembly of back-contacted solar cells have produced suitable results, and monolithic module assemblies of EWT cells have received IEC certification. All these advances demonstrate that good progress from both a cell and a module perspective has been made, bringing the EWT cell concept close to entering the market.

References

[1] Gee, J.M., Schubert, W.K. and Basore, P.A. 1993, *Proc. 23rd IEEE PVSC*, Louisville, Kentucky, USA, p. 265.

[2] Granek, F. 2009, Ph.D. dissertation,

Institut für Mikrosystemtechnik, Albert-Ludwigs-Universität Freiburg, Freiburg, p. 209.

[3] Kerschaver, E., van Zechner, C. and Dicker, J. 2000, *IEEE Trans. Electron Dev.*, Vol. 47, p. 711.

[4] Clement, F. 2009, Ph.D. dissertation, Fakultät für Angewandte Wissenschaften, Universität Freiburg, Freiburg, p. 1.

[5] Hacke, P. et al. 2009, *Proc. 34th IEEE PVSEC*, Philadelphia, Pennsylvania, USA, p. 2102.

[6] Blakers, A.W. et al. 1989, *Appl. Phys. Lett.*, Vol. 55, p. 1363.

[7] Mayerhofer, R., Müllers, L. and Becker, A. 2006, *Proc. 4th WCPEC*, Waikoloa, Hawaii, USA, p. 1115.

[8] Mingirulli, N. et al. 2007, *Proc. 22nd EU PVSEC*, Milan, Italy, p. 1415.

[9] Mingirulli, N. et al. 2007, *Appl. Phys. Lett.*, Vol. 91, p. 183512/1.

[10] Glunz, S.W. 2007, *Adv. in OptoElectronics 2007*, p. 97370/1.

[11] Engelhart, P. 2007, Ph.D. dissertation, Fakultät für Elektrotechnik und Informatik, Universität Hannover, Germany, p. 162.

[12] Mingirulli, N. et al. 2011, *Prog. Photovolt. Res. Appl.*, Vol. 19, p. 366.

[13] Mingirulli, N. et al. 2009, *Proc. 24th EU PVSEC*, Hamburg, Germany, p. 1979.

[14] Spribille, A. et al. 2010, *Proc. 25th EU PVSEC*, Valencia, Spain, p. 2654.

[15] Gee, J.M. and Wang, M. 2011, *Proc. 26th EU PVSEC*, Hamburg, Germany.

[16] Kühn, R. et al. 1998, *Proc. 2nd World Conf. PV Energy Conver.*, Vienna, Austria, p. 1390.

[17] Kühn, R., Fath, P. and Bucher, E. 2000, *Proc. 28th IEEE PVSC*, Anchorage, Alaska, USA, p. 116.

[18] Mingirulli, N. 2009, Ph.D. dissertation, University of Konstanz, Konstanz, p. 54.

[19] Fallisch, A. et al. 2010, *Proc. 5th World Conf. PV Energy Conver.*, Valencia, Spain, p. 1991.

[20] Fallisch, A. et al. 2010, *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA, p. 791.

[21] Manole, M. et al. 2005, *Proc. 20th EU PVSEC*, Barcelona, Spain, p. 1391.

[22] Kress, A. 2001, Ph.D. dissertation, Fachbereich Physik, Universität Konstanz, Konstanz, p. 131.

[23] Woehl, R. et al. 2010, *AIP Conf. Proc.*, Freiburg, Germany, Vol. 1277, p. 53.

[24] Schneiderlöchner, E. et al. 2001, *Proc. 17th EU PVSEC*, Munich, Germany, p. 1303.

[25] Fischer, B. 2003, Ph.D. dissertation, Fachbereich Physik, Universität Konstanz, Konstanz, p. 198.

[26] Schmidt, J., Aberle, A.G. and Hezel, R. 1997, *Proc. 26th IEEE PVSC*, Anaheim, California, USA, p. 13.

[27] Hall, R.N. and Soltys, T.J. 1980, *Proc. 14th IEEE PVSC*, San Diego, California, USA, p. 550.

[28] Dicker, J. 2003, Ph.D. dissertation, Fakultät für Physik, Universität Konstanz, Konstanz, p. 201.

[29] Fallisch, A. and Biro, D., *IEEE J. Photovoltaics* [forthcoming].

[30] Smith, D.D. et al. 1999, *IEEE Trans. Electron Dev.*, Vol. 46, p. 1993.

[31] Eikelboom, D.W.K. et al. 2001, *Proc. 17th EU PVSEC*, Munich, Germany, p. 1547.

[32] Hilali, M.M., Hacke, P. and Gee, J.M. 2006, *Proc. 4th World Conf. PV Energy Conver.*, Waikoloa, Hawaii, USA, p. 1299.

[33] Fallisch, A. et al. 2011, *Proc. 26th EU PVSEC*, Hamburg, Germany.

[34] Ulzhöfer, C. et al. 2010, *J. Appl. Phys.*, Vol. 107, p. 104509.

[35] Ulzhöfer, C. et al. 2008, *physica status solidi (RRL)*, Vol. 2, No. 6, pp. 251–253.

[36] Greulich, J. et al. 2011, *Proc. 1st Internat. Conf. Silicon PV*, Freiburg, Germany.

[37] Kress, A. al. 2000, *Proc. 28th IEEE PVSC*, Anchorage, Alaska, USA, p. 213.

[38] Glunz, S.W. et al. 2001, *Proc. 17th EU PVSEC*, Munich, Germany, p. 1287.

[39] Kray, D. et al. 2003, *Proc. 3rd World Conf. PV Energy Conver.*, Osaka, Japan, p. 1340.

[40] Institute for Solar Energy Research (ISFH) Hamelin 2007, Report, p. 92.

[41] Kiefer, F. et al. 2011, *Proc. 37th IEEE PVSC*, Seattle, Washington, USA.

[42] Zhao, J., Qi, W. and Ni, Z. 2011, *Photovoltaics International*, 12th Edn.

[43] Hermle, M. et al. 2008, *Proc. 33rd IEEE PVSC*, San Diego, California, USA, p. 1.

[44] Peters, C. et al. 2008, *Proc. 23rd EU PVSEC*, Valencia, Spain, p. 1010.

[45] Gee, J.M. et al. 2009, *Proc. 34th IEEE PVSC*, Philadelphia, Pennsylvania, USA, p. 002133.

[46] Meakin, D.H. et al. 2010, *Proc. 5th World Conf. PV Energy Conver.*, Valencia, Spain, p. 3858.

[47] De Jong, P. 2010, *Photovoltaics International*, 7th Edn.

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A novel technological process for p-type back-contact solar cells

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ABSTRACT

A new production process for crystalline silicon (c-Si) solar cells, specifically p-type back-contact solar cells, is proposed. In contrast to the conventional c-Si solar cell manufacturing method, this new technology eliminates the etching process and reduces the industrial three-step electrode printing to only one step, greatly improving the technological process. Furthermore, the proposed process is also largely compatible with a traditional c-Si solar cell production line. Oxidation technology for producing the SiO_2 film on a c-Si wafer, together with corrosive window technology, such as through HF corrosive paste screen printing, for creating the patterning on the wafer covered with SiO_2 film, are used in the fabrication of the p-type back-contact solar cells.

Introduction

In recent years, many solar cell technologies have been developed, such as dye-sensitized solar cells [1,2], film solar cells [3,4] and crystalline silicon (c-Si) solar cells [5–8]. The photovoltaic (PV) industry has experienced a rapid rate of development, particularly in the number and scale of enterprises producing c-Si solar cells. However, conventional c-Si solar cells [9] have two sides with electrode grid lines, and the electrode grid lines on the side facing the sunlight can create a shadow, thus reducing the effective area that receives sunlight. It is therefore clear that back-contact solar cells [10–12] can increase solar efficiency compared to conventional c-Si solar cells. In back-contact solar cell technology the positive and negative electrodes are both formed on one side of the p-type silicon wafer doped with boron, enhancing the effective surface for receiving sunlight and avoiding any shielding by the electrodes. To increase efficiency in capturing electrons and holes, there are many p-n junctions on the reverse of the back-contact solar cell.

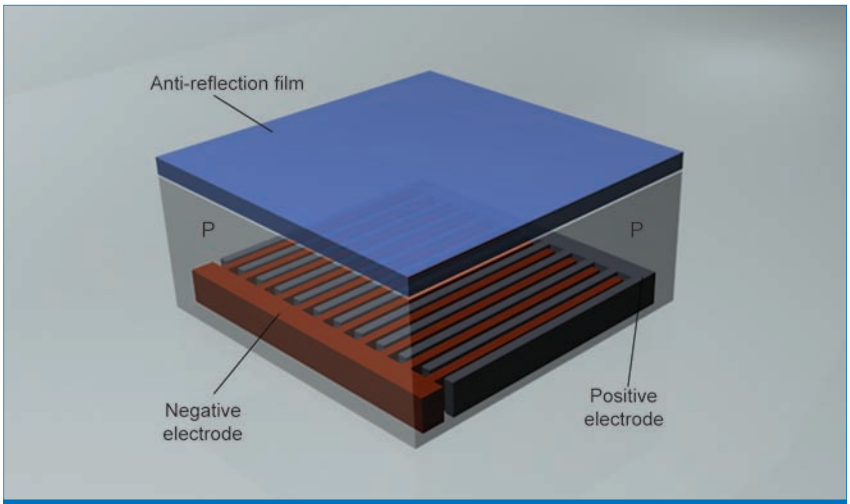

Figure 1. The p-type back-contact solar cell.

This paper presents a new technology for manufacturing p-type back-contact solar cells, in which the costly etching step is eliminated and the electrode printing is carried out in one step rather than three. This new manufacturing technology therefore greatly simplifies the process steps and minimizes the production costs, making it extremely attractive to conventional c-Si solar cell manufacturers all over the world. Moreover, this new process is largely compatible with traditional c-Si solar cell production lines, which means that it can be adopted with only minor modifications of the current manufacturing process.

Principle

The p-type back-contact solar cell is composed of an anti-reflection film, a pyramid layer, a p-type boron-doped wafer, several p-n junctions, and positive and negative electrodes (Fig. 1). An anti-reflection film made up of Si_3N_4 can reduce the reflection of the incident sunlight and improve the sunlight absorption for this particular type of solar cell. Without electrode shading on the sunlight-facing surface, the p-type back-contact solar cell is able receive more sunlight than a traditional c-Si solar cell. Under and adjacent to the Si_3N_4 film lies the pyramid layer, which increases the probability of incident sunlight because of the particular pyramid structure. This structure can change the transmission direction of the sun's rays and double the probability of incidence.

The c-Si wafer is doped with boron and referred to as a *p-wafer*, which is currently used universally for making solar cells in the field of photovoltaics. In order to maintain compatibility with industrial p-wafer supplies and conventional solar cell production lines, a p-wafer has been chosen and used for the p-type back-contact solar cell.

On the reverse of the p-type back-contact solar cell, there are many p-n junctions with electrodes to obtain high efficiency in capturing electrons and holes. The number of p-n junctions and electrodes can be optimized without the need to consider sunlight shading. These p-n junctions can reduce the combination of electrons and holes and improve the collection of these. By using a silver electrode material, the electrode resistance can be reduced because of the high number of finger electrodes. All these factors have the potential to improve the efficiency of the p-type back-contact solar cell.

Technological process

The process for manufacturing conventional c-Si solar cells with two-side electrodes, from the texture-making stage to testing, is illustrated in Fig. 2(a). For comparison, the p-type back-contact solar cell technological process is shown in Fig. 2(b). Although the new process has the additional steps of oxidation and corrosive window, there is no costly etching step; moreover, the conventional three-step electrode printing has been reduced to a single step. The new production process is therefore simplified but still compatible with a conventional c-Si solar cell production process.

> “Although the new process has the additional steps of oxidation and corrosive window, there is no costly etching step; moreover, the conventional three-step electrode printing has been reduced to a single step.”

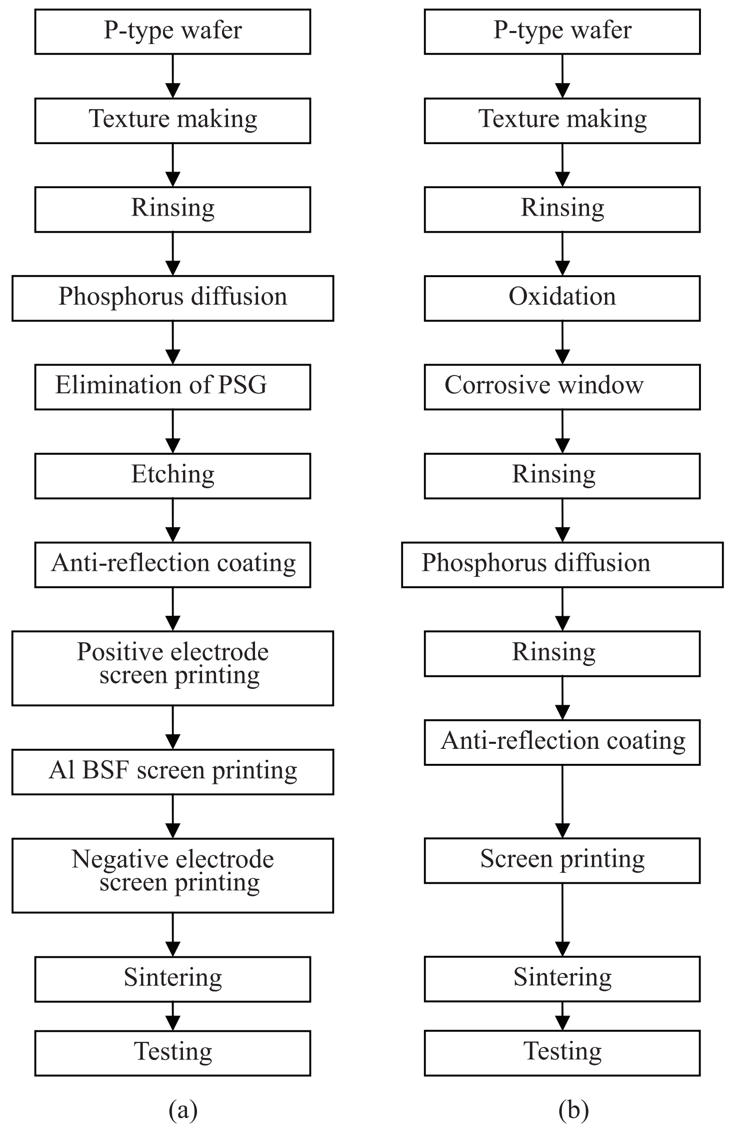

Figure 2. Production processes for (a) conventional c-Si solar cells, and (b) new p-type back-contact solar cells.

P-type c-Si wafer

P-type c-Si wafers of conventional dimensions, doped with boron, can be purchased on the market (commercially produced by, for example, LDK or Motech); these include polycrystalline, quasi-monocrystalline and monocrystalline silicon wafers as illustrated in Fig. 3.

Texture making

The pyramid-like texture of a monocrystalline silicon wafer can be created using an alkali method; the texture of a polycrystalline silicon wafer, by an acid method. The texture structures can change the sunlight transmission direction and increase the probability of incident sunlight falling on the solar cells by a factor of two or more. These texture structures can reduce the sunlight reflection and improve the spectrum response and short-circuit current.

Alkali method

Using a low concentration of NaOH aqueous solution, the production of monocrystalline silicon wafers and quasi-monocrystalline wafers starts with anisotropic corrosion that produces an intensive pyramid structure. The chemical reaction [9] is:

$$Si + 2NaOH + H_2O = Na_2SiO_3 + 2H_2$$

and the resulting pyramid structure is shown in Fig. 4.

Acid method

At a certain concentration of nitric acid and hydrofluoric acid in aqueous solution, the production of polycrystalline silicon wafers begins with a chemical reaction that produces the texture of a wormhole structure (for example, using a device such as RENA). The chemical reaction is:

$$3Si + 4HNO_3 + 18HF \rightarrow 3H_2[SiF_6] + 8H_2O + 4NO\uparrow$$

and the texture of the polycrystalline silicon wafer [13] is shown in Fig. 5.

Oxidation

In forming the SiO_2 film, the chemical reactions are as follows:

$$Si + O_2 \rightarrow SiO_2$$
$$Si + 2H_2O \rightarrow SiO_2 + 2H_2.$$

The chemical reactions take place industrially at a high temperature of approximately 950°C in an oxidation furnace such as a Seven Star or a CECT. The oxidation film of SiO_2, having a reddish-purple appearance and a thickness of around 50nm, can effectively prevent phosphorus from diffusing into the silicon.

Figure 3. The appearance of p-type c-Si wafers: polycrystalline (left), quasi-monocrystalline (centre) and monocrystalline (right).

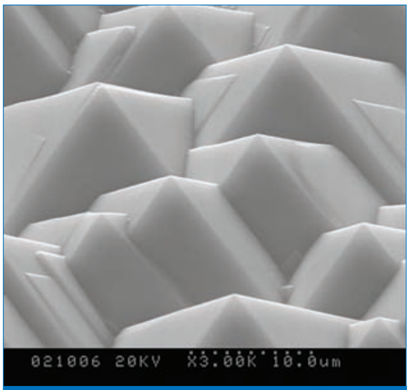

Figure 4. Pyramid texture of a monocrystalline silicon wafer, created by the alkali method.

> “The oxidation film of SiO_2, having a reddish-purple appearance and a thickness of around 50nm, can effectively prevent phosphorus from diffusing into the silicon.”

Corrosive window

The SiO_2 oxidation film can be corroded by using a paste containing HF. The reaction is:

$$SiO_2 + 6HF \rightarrow H_2[SiF_6] + 2H_2O.$$

The corrosive patterning (window) is formed by screen printing. Fig. 6 shows the oxidized wafer with patterning, where the red grid lines comprise the corrosive window and the grey area is covered with SiO_2 film. In Fig. 6 the number of grid lines needs to be optimized with the patterning. The negative electrode should be aligned within the grid line during the screen printing of the metal electrode.

Phosphorus diffusion

The p-n junctions are made using hot phosphorus diffusion on the corrosive window, referred to as *patterning* where the silicon wafer area is exposed. The reaction [14, pp. 94–95] is:

$$5POCl_3 \rightarrow P_2O_5 + 3PCl_5$$
$$4PCl_5 + 5O_2 \rightarrow P_2O_5 + 10Cl_2$$
$$2P_2O_5 + 5Si \rightarrow SiO_2 + 4P.$$

At around 850°C, liquid $POCl_3$ decomposes and reacts with oxygen and silicon, thus generating phosphorus. The phosphorus can diffuse into the silicon wafer through the patterning not covered by the SiO_2 oxidation film and can form many p-n junctions of the design shown in Fig. 7. On the other hand, the phosphorus does not diffuse into the area covered by the SiO_2 film, since the film obstructs the diffusion. A diffusion furnace (such as the CECT, Tempress Systems or Seven Star brand) is normally used for this process.

Rinsing

After phosphorus diffusion, the wafer needs to be cleaned to eliminate phosphorus silicon glass (PSG), the SiO_2 oxidation film and metal ions. Removal of PSG and the SiO_2 oxidation film can be done simultaneously [14, p. 100]:

$$SiO_2 + 6HF \rightarrow H_2[SiF_6] + 2H_2O.$$

Metal ions can be removed using hydrochloric acid (HCl) and a metal ion complexation reaction.

In a solar cell production line, a washing machine with many tanks is normally used for rinsing. After reactions have taken place in one tank, the wafers are washed and cleaned by spraying them with deionized water in other tanks.

Anti-reflection coating

A Si_3N_4 anti-reflection film is coated on the sunlight-facing top surface without electrodes by plasma-enhanced chemical vapour deposition (PECVD) or physical vapour deposition (PVD). PECVD and PVD are the most common processes used in the photovoltaic industry (Centrotherm and Applied Materials are two examples of suppliers).

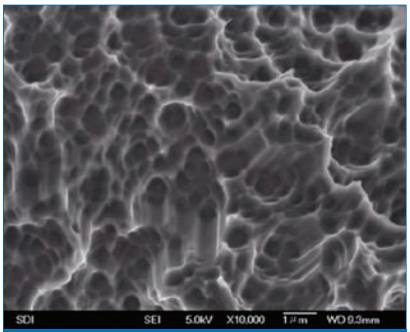

Figure 5. SEM image of a polycrystalline silicon surface, textured using the acid method.

In the case of PECVD, the reaction is:

$$3SiH_4 + 4NH_3 \rightarrow Si_3N_4 + 12H_2.$$

Taking into account the glow discharge, gas flow, reaction time, temperature and electric field, a Si_3N_4 film is formed. The detailed parameters should be optimized according to the on-site production.

For PVD, the reaction is:

$$4NH_3 + 3Si \rightarrow Si_3N_4 + 6H_2.$$

A silicon (Si) bar, NH_3, Ar (argon) and

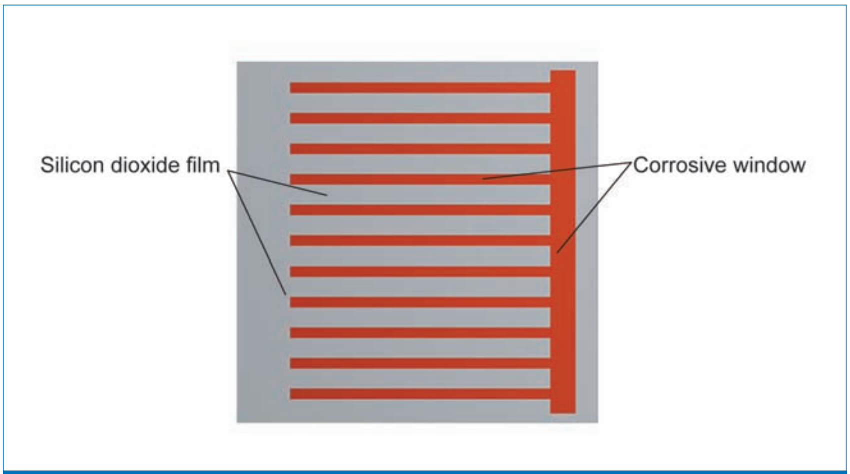

Figure 6. Corrosive patterning (window) on the oxidized wafer.

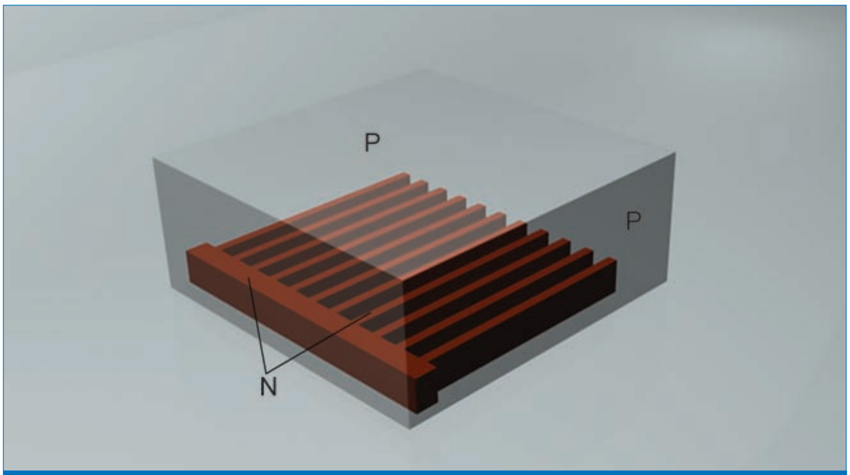

Figure 7. Phosphorus diffusion on patterning.

N_2 are used in the PVD process. Under the conditions of a strong electric field and magnetic field, at a temperature of around 500°C, the gases ionize, whereby highly dynamic Ar ions hit the Si bar and sputter Si ions. The Si ions then react with N (nitrogen) ions to generate Si_3N_4, which is deposited on the wafers. The thickness of the anti-reflective coating film is usually measured by ellipsometry.

Screen printing

In accordance with the design of the p-type back-contact solar cell, a special screen needs to be made for the metal electrode printing. The negative electrode pattern should align with the previous pattern for phosphorus diffusion. An example of screen-printed electrodes is shown in Fig. 8. The electrode paste (such as silver paste) can be purchased on the market and is available from, for instance, DuPont and Ferro; common suppliers of screen printers are ASYS GmbH, Baccini and Manz Automation.

> “In accordance with the design of the p-type back-contact solar cell, a special screen needs to be made for the metal electrode printing.”

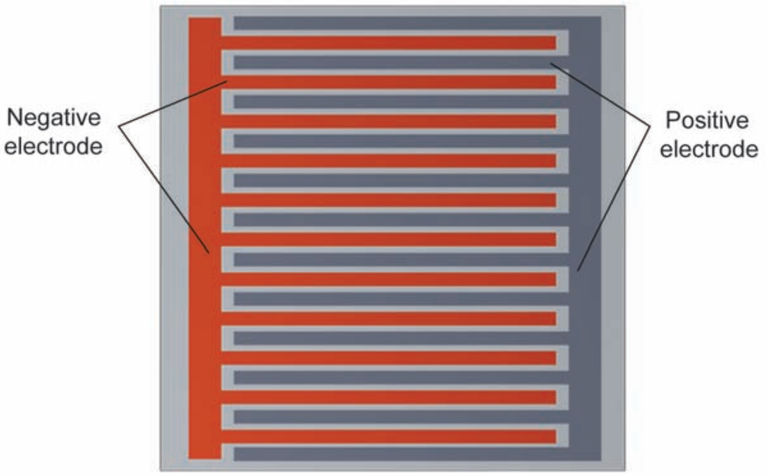

Figure 8. Screen-printed back-contact positive and negative electrodes.

Sintering

After the electrode paste screen print, the paste needs to be sintered to get rid of the impure ingredients, such as organic material, as well as to form metal electrodes on the p-type back-contact solar cell. Generally, a welding furnace is used for sintering in the photovoltaic industry, taking nitrogen as the protective gas at around 950°C. (Some commercial welding furnace suppliers are BTU, Despatch Industries and Roth & Rau.)

Testing and sorting

In conformity to the solar cell test standard IEC60904, the p-type back-contact solar cells are tested for their electrical characteristics. The cells are then classified and sorted according to the test results and ratings. For classification, it is better to take into account the efficiency and short-circuit current simultaneously. Using solar cells of the same or similar current values can minimise potential problems of mismatch and power loss when they

are used together in PV modules. Well-known suppliers of cell testers and sorters are Berger Lichttechnik, ASYS GmbH and Applied Materials.

Conclusions

A new process of manufacturing p-type back-contact solar cells has been described, which, compared to the traditional solar cell production process, has the advantages of eliminating the etching process and reducing the number of steps in the electrode printing process from generally three to just one. Oxidation technology for the creation of the SiO_2 film on the c-Si wafer, and corrosive window technology in the HF corrosive paste screen printing, are both used in the new process. Not only is this method compatible with the conventional solar cell production process, but also the p-type back-contact solar cell with many p-n junctions is expected to increase efficiency in capturing electrons and holes.

References

[1] Nazeeruddin, M.K., Baranoff, E. and Grätzel, M. 2011, "Dye-sensitized solar cells: A brief overview", *Solar Energy*, Vol. 85, pp. 1172–1178.

[2] Grätzel, M. 2001, "Photoelectrochemical cells", *Nature*, Vol. 414, pp. 338–344.

[3] Romeo, N. et al. 2004, "Recent progress on CdTe/CdS thin film solar cells", *Solar Energy*, Vol. 77, pp. 795–801.

[4] Rech, B. et al. 2006, "Challenges in microcrystalline silicon based solar cell technology", *Thin Solid Films*, Vol. 511–512, pp. 548–555.

[5] Aberle, A.G. 2000, "Surface passivation of crystalline silicon solar cells: A review", *Prog. Photovolt: Res. Appl.*, Vol. 8, pp. 473–487.

[6] Green, M.A. et al. 2001, "Progress and outlook for high-efficiency crystalline silicon solar cells", *Solar Energy Mater. & Solar cells*, Vol. 65, No. 1–4, pp. 9–16.

[7] Green, M.A. 2003, "Crystalline and thin-film silicon solar cells: State of the art and future potential", *Solar Energy*, Vol. 74, No. 3, pp. 181–192.

[8] Breitenstein, O. et al. 2004, "Shunt type in crystalline silicon solar cells", *Prog. Photovolt: Res. Appl.*, Vol. 12, pp. 529–538.

[9] Guo, Zh. et al. 2005, "Progresses in preparation of crystalline silicon solar cells", *New Energy and Technol.*, Vol. 3, pp. 20–24.

[10] Kerschaver, E.V. and Beaucarne, G. 2006, "Back-contact solar cell: A review", *Prog. Photovolt: Res. Appl.*, Vol. 14, pp. 107–123.

[11] Mulligan, W.P. et al., "Manufacture of solar cells with 21% efficiency"[available online at http://www.tayloredge.com/reference/Electronics/Photonics/HighEfficiencySolarCells].

[12] Huljić, D.M. et al., "Development of a 21% back-contact monocrystalline silicon solar cell for large-scale production" [available online at http://www.q-cells.fr/medien/produkte_prozesse/publikationen/downloads].

[13] Park, S.W. and Kim, J. 2003, "Application of acid texturing to multi-crystalline silicon wafer", *J. Korean Physical Society*, Vol. 43, No. 3, pp. 423–426.

[14] Yang, J., Yu, H. and Ge, J. 2009, *Solar Photovoltaic Power Generation Application Technology*. Beijing: Publishing House of Electronics Industry.

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Investigations into laser edge isolation (LEI) of mc-Si solar cells using ns- and ps-laser radiation

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ABSTRACT

In the photovoltaic industry, laser edge isolation (LEI) is a well-established process at the end of the process chain. However, because the cell properties vary from one cell producer to the next, no systematic approach is defined in industry for establishing an efficient isolation groove. Nevertheless, a general approach has to be defined for analyzing the LEI process for silicon solar cells. Besides the material aspects and laser parameters, atmospheric boundary conditions must be considered. This paper presents investigations into the ablation of a specific type of mc-silicon solar cell, and the most suitable laser, as well as the ambient parameters, is determined based on the results of the experiments.

Introduction

Lasers are currently used within the photovoltaic industry for edge isolation, and for marking and cutting silicon solar cells. In the case of edge isolation, the n^+-doped surface layer has to be removed to guarantee the isolation of the pn-junction. The laser edge isolation (LEI) process is applicable for mc-Si solar cells using different types of laser sources. To increase the efficiency of a crystalline solar cell, high shunt resistances are necessary, and damage within the irradiated areas must be avoided. A set of laser parameters – such as wavelength λ, pulse duration t_p and laser fluence H_p – have already been investigated for LEI processes [1–6], with wavelengths ranging from near-infrared (NIR) to ultraviolet (UV) and pulse durations from a few picoseconds to several hundred nanoseconds. Damage can occur in the heat-affected zone during laser irradiation [7,8] and reduces the efficiency of the cell.

In order to separate the pn-junction and increase the shunt resistance to a maximum value, a theoretical minimum ablation depth of 0.5µm is derived from the n^+-doped diffusion profile. Therefore a large absorption coefficient for ablation is required, and suitable laser sources, such as UV-lasers [9,10], must be used. In addition to wavelength, ablation for laser edge isolation depends on t_p and repetition rate f_{rep}, and results in heat load of the material. The heat penetration depth is an approximate measure of the penetration of the heat load, and possibly induces laser damage of a thin layer. The potential of selected laser sources for use in laser edge isolation will be demonstrated using distinct laser parameters.

The LEI process for silicon solar cells cannot be completely described by the laser parameters – an additional investigation of the dependence on the process gas is necessary. The main additional process parameter is the concentration of oxygen in the process atmosphere [11]. Thus the quality of the edge isolation is highly dependent on the concentration of oxygen within the irradiated area.

Experimental

Solar cell specifics

Standard industrial-type isotextured mc-Si solar cells of dimension 156×156×0.18mm^3 and featuring double-side diffusion and screen-printed metallization (Fig. 1) were laser edge isolated on the front side by applying laser radiation from different sources. In the case of picosecond laser radiation, process atmospheres were also tested for their suitability in laser edge isolation.

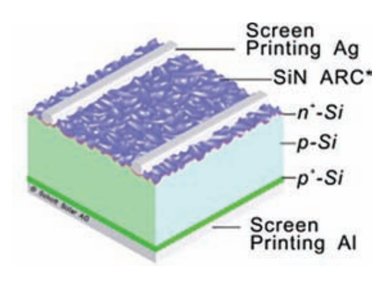

Figure 1. Structure of a mc-Si solar cell with an n^+-doped surface layer.

The ablation depth required for effective laser edge isolation can be derived from the n^+ (phosphor) dopant concentration distribution. In the case of the investigated solar cells, the dopant concentration decreases to the ground-doped level at a depth of approximately 0.5µm, and corresponds to the minimum

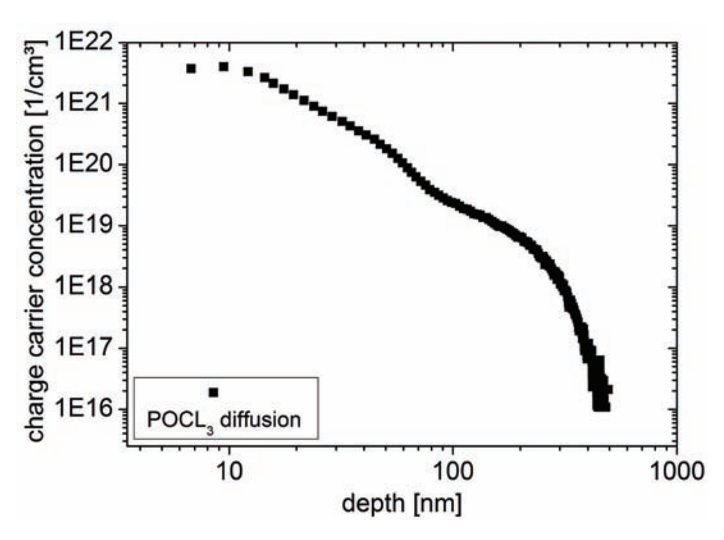

Figure 2. n^+-dopant (phosphor) concentration of mc-Si solar cells versus depth (data from Schott Solar AG), showing the ground-doped level at a charge carrier concentration of approximately 10^{16}cm^{-3}.

required ablation depth at a charge carrier concentration of approximately 10^{16}cm^{-3} – the so-called 'ground-doped level' (Fig. 2).

A typical dopant concentration profile of phosphorous in silicon depends on two diffusion mechanisms during production, which are dominant at different charge carrier concentrations and diffusion velocities. The highly doped regime is dominated by vacancy diffusion, whereas the poorly doped regime is dominated by interstitial diffusion. The well-known kink-and-tail carrier distribution results because of the different diffusion mechanisms of phosphor in silicon [12]. The charge carrier concentration converges asymptotically towards the ground-doped level [13].

"The parallel resistance of a silicon solar cell depends on the dopant profile and the corresponding specific resistivity at this charge carrier concentration."

The parallel resistance of a silicon solar cell depends on the dopant profile and the corresponding specific resistivity at this charge carrier concentration. Both these dependencies have to be related in order to determine the correlation between the shunt resistance and the ablation groove depth. Therefore the n^+-dopant concentration as a function of depth is the crucial parameter and determines the ablation depth for sufficient laser edge isolation. The specific resistivity ρ of phosphorous-doped silicon depends on the charge carrier concentration Λ, and the achievable shunt resistances can be estimated at a certain groove depth by plotting Λ versus ρ (Fig. 3). The dependence of the specific resistivity on the charge carrier concentration can potentially be described by the expression

$$\rho\,(\Lambda) = a\cdot \Lambda^{b} \qquad (1)$$

where a and b are numerical fit parameters. The Λ-ρ dependence, taken from Beadle et al. [14], is fitted in three regimes shown in Fig. 3, and the fit parameters for the three regimes are listed in Table 1.

Regime	a [Ω·cm^4]	b
1	1015	-0.9549
2	568.25	-0.2253
3	1014	-0.8599

Table 1. Fit parameters for the three regimes in Fig. 3.

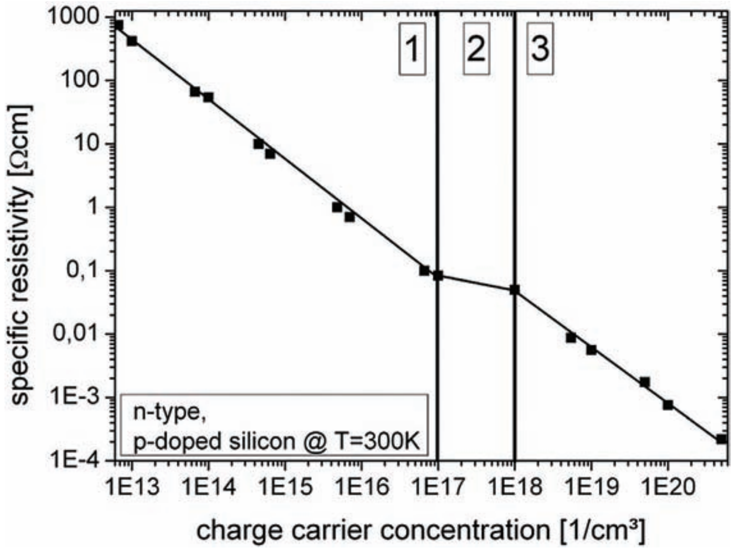

Figure 3. Specific resistivity of n-type phosphorous-doped silicon at room temperature versus charge carrier concentration (data taken from Beadle et al. [14]).

From Figs. 2 and 3, the dependence of specific resistivity $\rho(z)$ on depth can be derived as shown in Fig. 4.

Laser set-up specifics and parameters

The laser edge isolation process was investigated by applying ns- and ps-laser radiation to mc-Si solar cells. The cells were processed at identical ambient conditions to allow an evaluation of shunt resistance as a function of laser ablation depth to be made.

Laser scanners were used to position the focused laser radiation along the desired path. For the investigations, optics with focal lengths of 255mm and 250mm were used. The relevant parameters for different laser systems are listed in Table 2. Different groove depths were generated by laser ablation using the laser sources indicated in the table. The groove depth was measured by optical microscopy, and the corresponding shunt resistance was determined by dark I-V measurements.

In addition, several gases were tested (at 1 bar at room temperature in normal ambient atmosphere, oxygen, nitrogen and argon) for their suitability as processing atmospheres in the laser edge isolation process. These experiments were carried out with Laser 1, and three characteristic laser parameter sets were tested for edge isolation. The structural and chemical investigations of the laser grooves were conducted using scanning electron

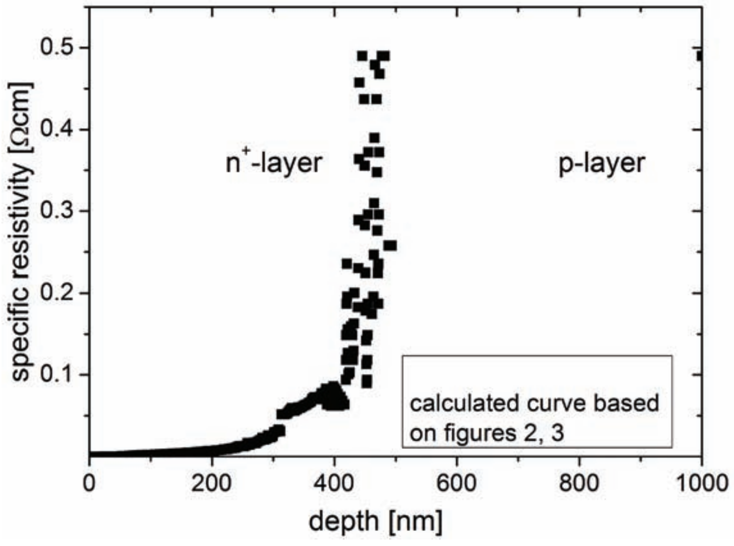

Figure 4. Specific resistivity of n-type phosphorous-doped silicon at room temperature versus depth, based on Figs. 2 and 3.

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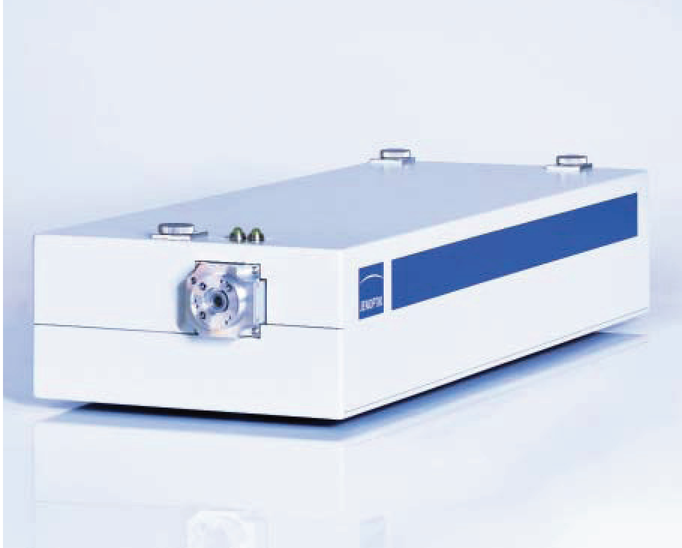

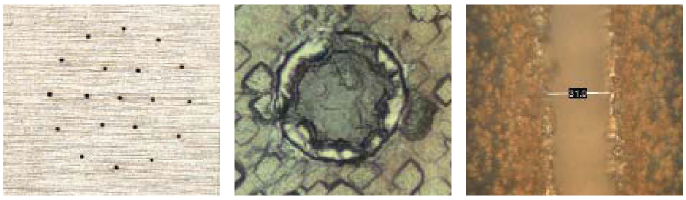

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	Laser	λ[nm]	t_P[ns]	$H_{P,max}$[J/cm^2]	f_{rep}[kHz]	f_{foc}[mm]
1	Trumpf: TruMicro 5X50 2ω	515	0.007	14	400	255
2	Trumpf: TruMicro 5X50	1030	0.007	6.2	400	255
3	Rofin: RSM E20	532	7	21.7	15	250
4	Rofin: RSM E20	532	13	14.4	40	250
5	IPG: YLPM-1-A4-20-20	1064	20	7.6	100	255
6	IPG: YLP-1-120-50-50	1064	120	31.3	50	255

Table 2. Laser systems and relevant laser parameters.

microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX).

Characteristics of the laser edge isolation process

A small specific resistivity – the initial potential – at the top of the solar cell can be identified. With increasing depth the specific resistivity increases to its maximum – the capacity limit (Fig. 4). The resistivity is then determined from the specific resistivity, using the general equation

$$R_{sh}(z) = \rho(z) \cdot \frac{A(z)}{L} \qquad (2)$$

where R_{sh} represents the resistivity, $\rho(z)$ is the depth-dependent specific resistivity, L is the length of the edge of the solar cell, and $A(z)$ is the product of the groove width (d_{gr}) and residual thickness (difference of the thickness z of the solar cell and the ablation groove a).

> “With increasing depth the specific resistivity increases to its maximum.”

The variation of R_{sh} as a function of groove depth can be mathematically described using an empirically derived logistic growth approach. This type of growth is best described by the differential equation [15]

$$\frac{dR_{sh}(z)}{dz} = k \cdot R_{sh}(z) \cdot (R_{sh,\max} - R_{sh}(z)) \qquad (3)$$

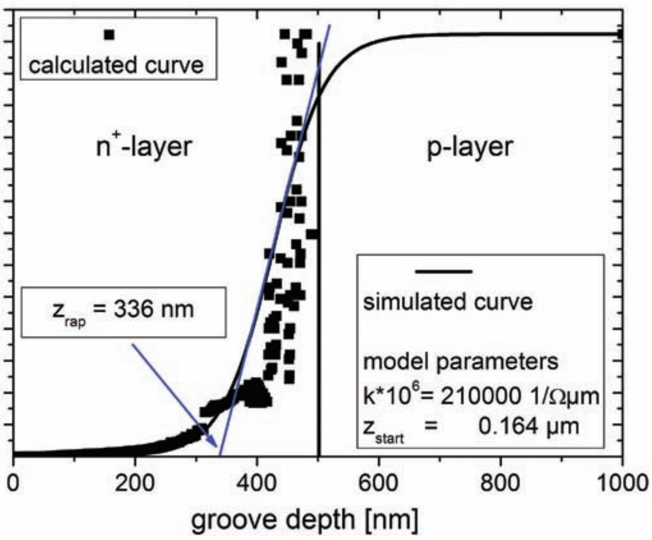


Figure 6. Resistivity as a function of groove depth, determined from Figs. 2 and 3 and modelled using Equation 4 (edge length of the solar cell L = 156mm; area of laser beam diameter and solar cell thickness A = 4212μm^2).

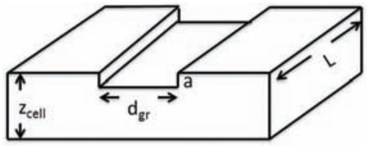


Figure 5. Schematic of the laser-generated groove for evaluating Equation 2.

where the parameter $R_{sh,max}$ represents the shunt resistance capacity limit of the solar cells, and the logistic parameter k is a measure of the change of the groove depth-dependent shunt resistance. A solution of the differential equation is given by

$$R_{sh} = R_{sh,\max} \cdot \frac{1}{1 + \exp[-k \cdot R_{sh,\max} \cdot (z + z_{start}) \cdot (\frac{R_{sh,\max}}{R_{sh,N=0}} - 1)]} \qquad (4)$$

where $R_{sh,N=0}$ represents the initial shunt resistance, z the depth and z_{start} the depth value at which the shunt resistance starts to increase with depth (and therefore depends on the underlying dopant profile). Another, more convenient, value for determining the rapid start of growth of the shunt resistance with depth is defined by z_{rap}, and will be used to empirically determine the carry-over of the dopant profile. The intersection of the tangent of the model curve of Equation 4 at the turning point with the abscissa defines z_{rap}, and is given by the equation

$$z_{rap} = \frac{\ln[\frac{R_{sh,\max}}{R_{sh,N=0}} - 1] - R_{sh,\max} \cdot k \cdot z_{start} - 2}{R_{sh,\max} \cdot k} \qquad (5)$$

Based on the described model, the data taken from Fig. 4 and Equation 2 can now be modelled using Equation 4. This is an idealized graph of shunt resistance versus groove depth. The minimum charge carrier concentration is taken as a reference for the ground-doped level as it is not measured (Fig. 2). The ideal case defined by the dopant profile in Fig. 2 is $z_{rap,ideal}$ = 336nm and shown in Fig. 6.

The efficiency of the laser edge isolation process in terms of ablation depth required to reach the intersection of the tangent and the abscissa is then defined as

$$\eta = \frac{z_{rap,ideal}}{z_{rap,laser}} \cdot 100\% \qquad (6)$$

In order to compare the results with different repetition rates, the normalized laser edge isolation efficiency η_{norm} is introduced and defined through a normalized $z_{rap,laser,norm}$ as

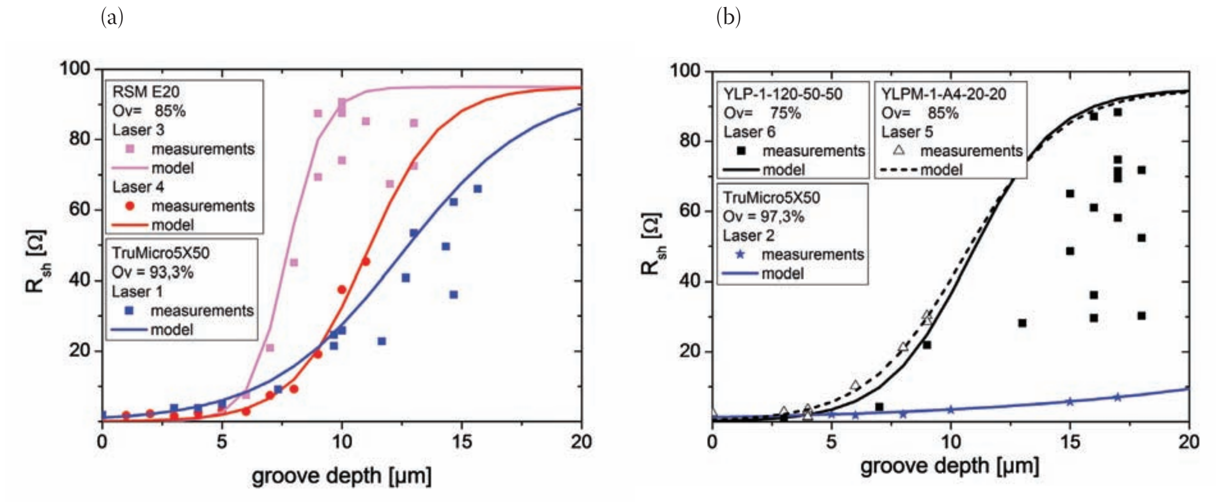


Figure 7. Shunt resistance versus groove depth for various laser systems and modelled logistic functions.

$$\eta_{norm} = \frac{z_{rap,ideal}}{z_{rap,laser,norm}} \cdot 100\% \qquad (7a)$$

$$z_{rap,laser,norm} = \frac{z_{rap,laser}}{N_{ppp}} \qquad (7b)$$

$$N_{ppp} = \frac{d_{gr} \cdot f_{rep}}{v} \qquad (7c)$$

where the parameter N_{ppp} is the number of laser pulses per point.

Results and discussion

Shunt resistance as a function of laser-ablated groove depth

The shunt resistance as a function of groove depth was determined for five laser systems, and different laser pulse durations, wavelengths and repetition rates were investigated. The measured shunt resistances were fitted to the developed logistic model (Equation 4); also, the relevant model parameters, specifically k and z_{rap}, were determined to estimate the efficiency of the laser edge isolation process. The limitations of these laser systems can be determined by plotting the logistic model curve against groove depth per pulse. By doing this, it is possible to determine the most feasible laser parameters that will minimize damage to the solar cell in the laser edge isolation process. The relevant derived model parameters are

Laser	$z_{rap,laser}$ [µm]	$z_{rap,laser,norm}$ [µm]	η [%]	η_{norm} [%]
1	6.9	0.490	4.9	68.6
2	20.4	0.503	1.7	66.8
3	6.2	0.897	5.4	37.5
4	7.5	1.160	4.5	30.0
5	6.5	0.963	5.2	34.9
6	9.0	1.877	3.7	17.9

Table 3. Relevant model parameters for different laser systems and corresponding laser edge isolation efficiencies ($z_{rap,ideal}$ = 0.336µm).

$z_{rap,laser}$, $z_{rap,laser,norm}$ and $z_{rap,ideal}$ (see Table 3), and accordingly the laser edge isolation efficiencies η and η_{norm} can be determined.

The differences between the theoretical predicted groove depth of 0.5µm for complete edge isolation and the values obtained experimentally can be explained by thermodynamic assumptions and, to a lesser extent, by impurities, redeposition of particles, surface topology and a non-ideal behaviour of mc-Si solar cells.

In the first step, the laser radiation is partially absorbed by the silicon. The optical energy is transformed into phonon energy, e.g. oscillation energy of atoms of the compound, which is, from a macroscopic perspective, a heat load. The heat dissipates afterwards by diffusion. The laser energy in the material accumulates by consecutive laser irradiations, until energy input and energy losses equalize. However, the temperature of the material rises steadily as a consequence of energy accumulation, thus producing diffusion of the dopants into the bulk material according to Fick's laws. The diffusion constant of phosphor in silicon rapidly increases with rising temperature [16]. With a series of large energy laser radiation pulses, a surface temperature close to the melting point of silicon is reached in a timescale of tens of microseconds. At this diffusion time, the diffusion length is of the order of several micrometres, based on equations in [16]. As a consequence, the model parameters k, $R_{sh,max}$ and z_{start} are also functions of the thermodynamic properties of silicon.

The statistical spreading of the measured shunt resistances at certain groove depths is due to local shunts in the cell area, which result in a decrease in R_{sh}. Nevertheless, with the laser parameters used, the logistic curve (Equation 4) satisfactorily describes the maximum achievable shunt resistances as a function of depth. In all cases, improvements are possible whereby the energy losses due to heat dissipation are reduced. Shorter pulse durations and shorter wavelengths, resulting in a smaller ablation rate, are preferable for the edge isolation process: first, there is less heat load and a smaller heat-affected zone; and second, there is a larger absorption of laser radiation. By using wavelengths and pulse durations that ensure a heat-affected zone in the region of $z_{rap,ideal}$, a saving of laser power is indicated for the laser edge isolation process. With a smaller $z_{rap,laser}$ (see Table 3), less carry-over of the dopants is induced by the solar cell and therefore higher maximum laser edge isolation efficiencies are achievable.

> "Shorter pulse durations and shorter wavelengths, resulting in a smaller ablation rate, are preferable for the edge isolation process."

Solar cells could not be isolated by a 500nm deep groove using laser radiation with a laser wavelength of λ = 515/1030nm; even with ultra-short laser pulses in the optical ablation regime [5,6,15], for which the heat load is minimal, it still was not possible. The ablation rate for laser radiation with a pulse duration of t_p = 7ps in the optical ablation regime of silicon is smaller than 200nm. As a result, additional laser pulses are required to remove the n$^+$-layer completely, leading to a thermal load of the silicon and diffusion of the dopants. In consequence, ns-laser pulses are preferable in the case of pulse energies which support an effective melt ejection and because of their larger thermal penetration depth of approximately d_{th} = 1µm, occurring at a pulse duration of t_p = 7ns at T = 300K. This corresponds to a value that is at least twice as large as the doped depth, and is therefore, in a first approximation, sufficient for removing the n$^+$-layer with a limited amount of laser pulses.

Shunt resistance as a function of different ambient gases and topologies

Different characteristic laser processing parameter sets (H_p, Ov) were used for the laser edge isolation with different ambient

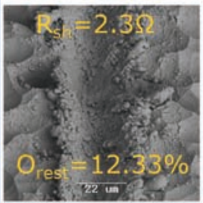
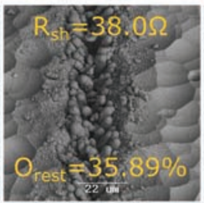
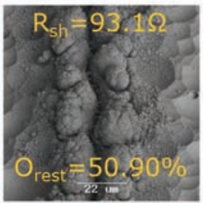
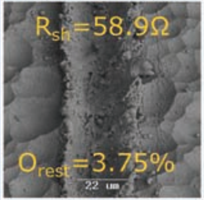
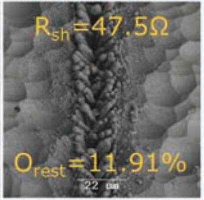
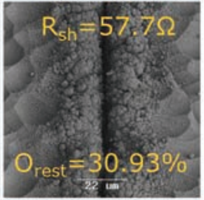
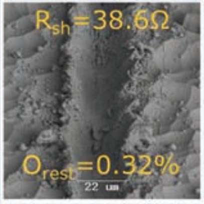
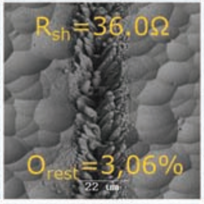
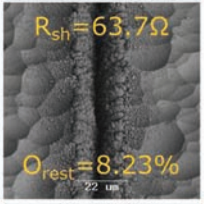
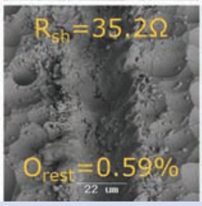
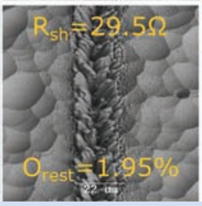
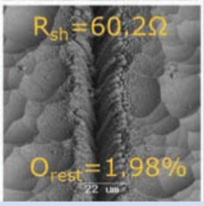
H_p [J/cm^2]	14	1	1
Ov [%]	93.33	99.63	99.91
O_2			
Ambient atmosphere			
N_2			
Ar			

Table 4. Different groove types generated in an ambient atmosphere, O_2, N_2 and Ar for three characteristic laser parameters (where f_{rep} = 400kHz, d_f = 23.4µm and O_{rest} is the remaining atomic oxygen concentration in the laser groove).

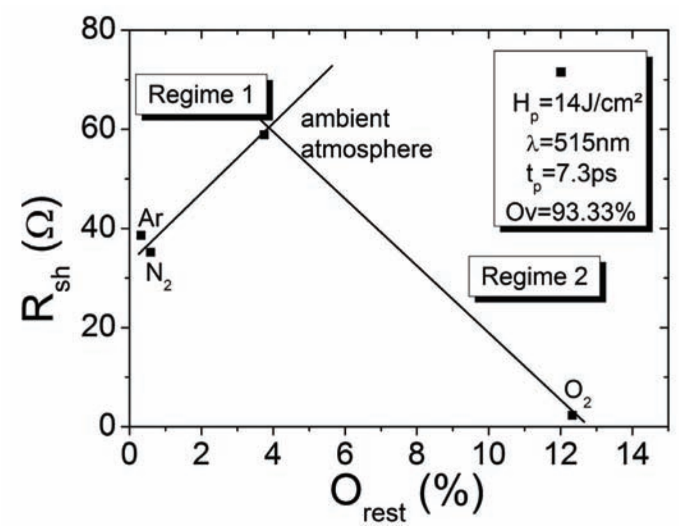


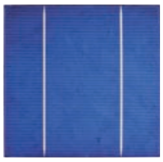
Figure 8. Shunt resistance as a function of remaining oxygen concentration O_{rest}.

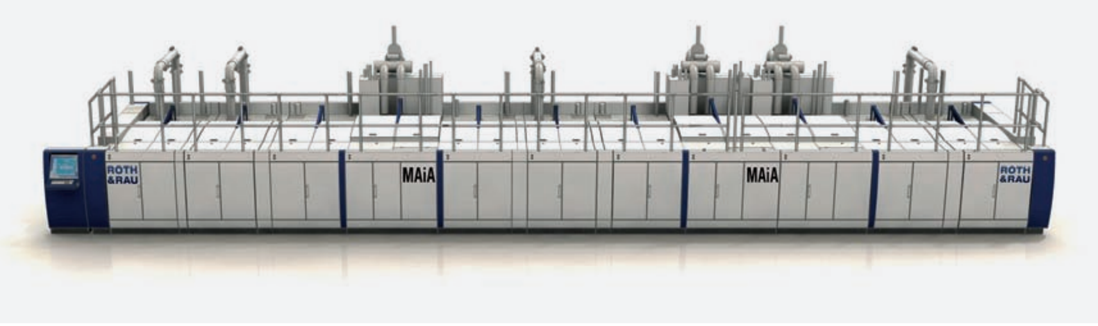
gases. With these parameter settings, three groove structure types are distinguished.

Generation of grooves by laser ablation with a fluence of H_p = 14J/cm^2 and an overlap of Ov = 93.33% results in typical v-shaped groove geometries as shown in Table 4. However, the measured groove depths of approximately 15μm at H_p = 14J/cm^2 do not depend on the investigated atmospheres. At a fluence of H_p = 1J/cm^2 and overlaps of Ov = 99.63% and Ov = 99.91%, a cone-like structure and a deep, narrow groove are generated respectively [11]. The characteristic geometrical structures at H_p = 1J/cm^2 and different overlaps do not depend on the process gas type and the geometry does not change. The main observed differences are electrical and chemical in nature. The shunt resistances and the remaining oxygen concentration in the groove vary over a wide range for different laser parameters and gases (Table 4).

As seen in Table 4, laser processing in argon and nitrogen atmospheres results in smaller shunt resistances. In the case of industrially-relevant laser parameters, such as velocity (v ≥ 0.624m/s), the most suitable process gas is in fact ambient atmosphere. Increasing the oxygen content causes, at a scanning velocity of v = 0.624m/s (corresponding to Ov = 93.33%), a reduction of the shunt resistance of the solar cells. Edge isolation in the optical regime and at a smaller scanning velocity (and therefore at larger overlaps) yields larger shunt resistances, but isolating with these parameters corresponds to an insufficient throughput. Increasing the remaining oxygen concentration increases the shunt resistance to a maximum; a further increase of the oxygen concentration then causes the shunt resistance to decrease significantly (Fig. 8).

The increase of the shunt resistance due to a larger oxygen concentration (regime 1 in Fig. 8) is possibly due to passivation of the ablation edges after irradiation; on the other hand, the decrease of the shunt resistance with further increase in oxygen concentration (regime 2 in Fig. 8) can be explained by diffusion of impurities. This is based on the different characteristic process timescales for the passivation and diffusion during laser edge isolation. Secondary ion mass spectroscopy (SIMS) measurement of the tentative dopant profile in the laser-





ablated grooves (which are necessary for edge isolation) failed due to the roughness of the bottom of the groove. To evaluate these proposed mechanisms, passivation and diffusion, other characterization tools need to be used.

Conclusion

The shunt resistance of mc-Si solar cells after laser edge isolation is characterized by three process mechanisms, each with a different emphasis. In general the value of the shunt resistance is a function of the three process mechanisms: ablation depth, passivation of ablation edges and diffusion of impurities.

In the case of depth-dependent shunt resistance, a logistic model approach has been derived which satisfactorily describes the shunt resistance as a function of ablation depth. In the other two cases – passivation and diffusion – preliminary results have been presented. Based on these empirical investigations and the developed logistic model, it is possible to determine optimal laser parameters for laser edge isolation at a specific charge carrier distribution. The dominant process during laser edge isolation depends on the three characteristic process times for heat diffusion, phosphor diffusion and passivation.

> “The best-suited atmosphere is standard ambient atmosphere.”

A theoretical representative set of efficient laser parameters for achieving higher solar cell efficiencies is given for a certain optical set-up. A typical optical set-up is equipped with an f-theta lens with a focal length of z_{lens} = 292mm and a collimated raw beam diameter of d_{raw} = 5.5mm at 1/e^2. Complementing this optical set-up, the laser source should provide an output power of $P_{\text{m}} \geq$ 23.1W at a repetition rate of f_{rep} = 30kHz. Furthermore, a pulse duration of t_{p} = 7ns at a laser wavelength of λ = 532nm and a beam quality factor $M^2 < 1.5$ will be required. With these parameters it is possible to ensure a scribing velocity of $v \geq$ 624mm/s for a 6-inch solar cell having a charge carrier concentration distribution comparable to that shown in Fig. 1. The scaling of the required laser power for sufficient edge isolation increases in a non-linear way for faster scribing velocities and larger focal diameters, and especially for higher repetition rates. Moreover, the best-suited atmosphere is standard ambient atmosphere.

Acknowledgment

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References

[1] Emanuel, G. et al. 2001, “High throughput laser isolation of crystalline silicon solar cells”, *Proc. 17th EU PVSEC*, Munich, Germany, pp. 1578–1581.

[2] Muellers, L. et al. 2008, “Analysis of different laser concepts for edge isolation of crystalline solar cells”, *Proc. 23rd EU PVSEC*, Valencia, Spain, pp. 1670–1672.

[3] Kray, D. et al. 2007, “Study on the edge isolation of industrial silicon solar cells with waterjet-guided laser”, *Solar Energy Mater. & Solar Cells*, Vol. 91, No. 17, pp. 1638–1644.

[4] Hauser, A. et al. 2001, “Comparison of different techniques for edge isolation”, *Proc. 17th EU PVSEC*, Munich, Germany, pp. 1739–1741.

[5] Haupt, O. et al. 2009, “Improved laser edge isolation of crystalline silicon solar cells using a high power picosecond laser”, *Proc. ICALEO*, Orlando, Florida, USA.

[6] Haupt, O et al. 2009, “Excellent edge isolation of crystalline silicon solar cells obtained by high power picosecond laser”, *Proc. 24th EU PVSEC*, Hamburg, Germany.

[7] Haupt, O. 2008, “Laser dicing of silicon: Comparison of ablation mechanisms with a novel technology of thermally induced stress”, *Proc. 9th Int. Symp. on Laser Prec. Microfab.*, Quebec City, Canada.

[8] Schoonderbeek, A. et al. 2006, “Laser technology for cost reduction in silicon solar cell production”, *Proc. ICALEO*, Scottsdale, Arizona, USA.

[9] Bäuerle, D. 2000, *Laser Processing and Chemistry*, 3rd edn. Heidelberg: Springer Verlag.

[10] Colville, F. 2009, “Laser scribing tools edge in front”, *Global Solar Technology*, March/April, pp. 12–15.

[11] Schütz, V. and Stute, U. 2011, “The influence of atmospheric components during laser edge isolation”, *Proc. 26th EU PVSEC*, Hamburg, Germany.

[12] Uematsu, M. 1997, “Simulation of boron, phosphorus, and arsenic diffusion in silicon based on an integrated diffusion model, and the anomalous phosphorus diffusion mechanism”, *J. Appl. Phys.*, Vol. 82, No. 5, pp. 2228–2246.

[13] Kränzl, A. 2007, “Industriesolarzellen auf dünnem multikristallinem Silizium: Diffusionsverfahren, neue Materialien und bifaciale Strukturen”, Dissertation, Universität Konstanz.

[14] Beadle, W.E. et al. 1985, *Quick Reference Manual for Silicon Integrated Circuit Technology*. New York: Wiley.

[15] Schütz, V. et al. 2010, “Laser edge isolation with a focus on damage reduction by the use of ultra-short pulse lasers”, *Proc. 25th EU PVSEC*, Valencia, Spain.

[16] Fair, R.B. 1981, “Concentration profiles of diffuse dopants in silicon”, in Yang, F.Y.Y., Ed., *Impurity Dopant Processes in Silicon*. Amsterdam: North Holland.

About the Authors

Viktor Schütz graduated from the Photonics programme at the University of Applied Sciences Oldenburg/Ostfriesland/Wilhelmshaven in 2008. He has been working as a scientist at LZH in the field of photovoltaics, semiconductors and simulations since October 2008.

Alexander Horn studied physics in Siegen, Germany, and graduated in 2003. After that he became senior scientist holding the chair in Laser Technology (LLT) of the RWTH Aachen, and then leader of the Ultrafast-Technology group in 2004. In 2008 he took up a new position as a representative professor at the Institute for Physics of the University of Kassel, Germany. Dr. Horn is now the head of the Photovoltaics group at LZH, where his main field of research is the ultra-fast detection of laser-induced processes, especially the development and usage of novel pump and probe techniques. He has authored more than 56 scientific publications.

Uwe Stute was awarded a Ph.D. in physics in 2001. Since then he has worked on laser production technology at LZH, followed by photovoltaic applications in industry. In 2010 Dr. Stute went back to LZH as manager of the department of technologies for non-metals, which incorporates laser applications relating to glass, photovoltaic and carbon-reinforced plastics.

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Thin Film


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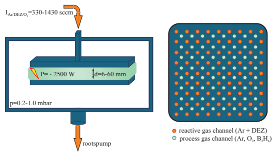

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Critical subsystems for thin-film PV manufacturing equipment

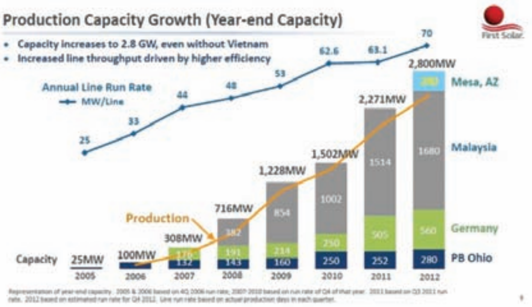
John West, VLSI Research UK

Return of ship's captain to the helm of First Solar sets new course

In another sign of trouble in the PV capital equipment sector, Veeco has decided to exit the CIGS solar systems business. Announced as part of the company's second-quarter financials, the move results in a combined negative impact and backlog removal of approximately US$71 million on its Q2 GAAP results.

Source: Endeavor.org

First Solar chairman Michael Ahearn took over the CEO role from ousted Rob Gillete recently.



Source: First Solar

First Solar's production capacity growth projection to 2012.

CEO John Peeler cited "various reasons," for the decision, "including" the improved performance of mainstream solar technologies and the lower-than-expected end-market acceptance for CIGS technology to date. While CIGS remains an important thin-film solar technology, we have determined that the timeframe and cost to successful commercialization are not acceptable to Veeco."

The company had been active in the sector, making several acquisitions and product launches over the past four years, including the purchases of toolmaker Mill Lane and CIGS developer DayStar Technologies assets in New York state and the rollout of its FastFlex and FastLine equipment systems. Veeco had also landed Global Solar, Daiyang Metal, GroupSat and others as customers.

Effective Q3 2011, the company said it will treat its CIGS solar systems business, which operated at a loss, as a discontinued operation.

Production News Focus

CNSE opens CIGS-focused Solar Energy Development Center near Albany, NY

Earlier this year, Veeco announced its impending exit from the CIGS thin-film PV business and with its announcement advised of its intentions to transfer its R&D facility and pilot line in New York to the College of Nanoscale Science and Engineering (CNSE) at the University of Albany. Three months after the initial declaration, Dr. Alain Kaloyeros, Senior VP and CEO of CNSE, and Congressman Chris Gibson, came together to formally launch CNSE's new Solar Energy Development Center in Halfmoon, New York, which has taken over the facility once occupied by Veeco.

CNSE manages and operates the New York facility, which features a 100kW prototyping and demonstration line for next generations CIGS thin-film solar cells. Additionally, the Halfmoon site has a pilot line for proof-of-concept prototyping, which will allow preliminary performance data to be gathered before a full-scale manufacturing line is developed.

Source: CNSE

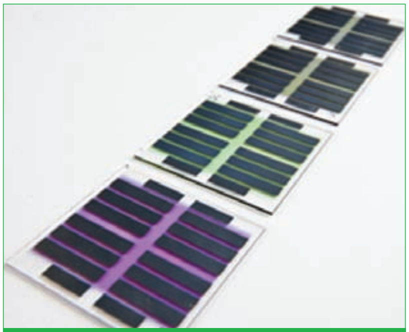
College of Nanoscale Science and Engineering.

CNSE also noted that the work completed at its new centre would support the US Photovoltaic Manufacturing Consortium. The US$300 million public-private collaboration is headquartered at CNSE and was created as part of the US DOE's SunShot Initiative under a partnership between CNSE and Sematech.

Imec launches project X10D for development of OPV cells with increased efficiency at lower costs

Working with its 16 project partners, imec has launched the European FP7 project X10D. The collaboration will see the companies working towards the development of tandem organic solar cells that boast increased conversion efficiency, a longer lifetime and a smaller production cost. Imec advised that the overarching goal of the project is to bring OPV technologies into the competitive thin-film PV market.

X10D aims to increase the power conversion efficiency to achieve at least 12% on cell level (1cm^2), and 9% on module level (100cm^2). Additionally, the project aims to guarantee a minimum 20-year lifetime for OPV modules on glass and 10 years on foil while dropping the cost below €0.70/Wp.



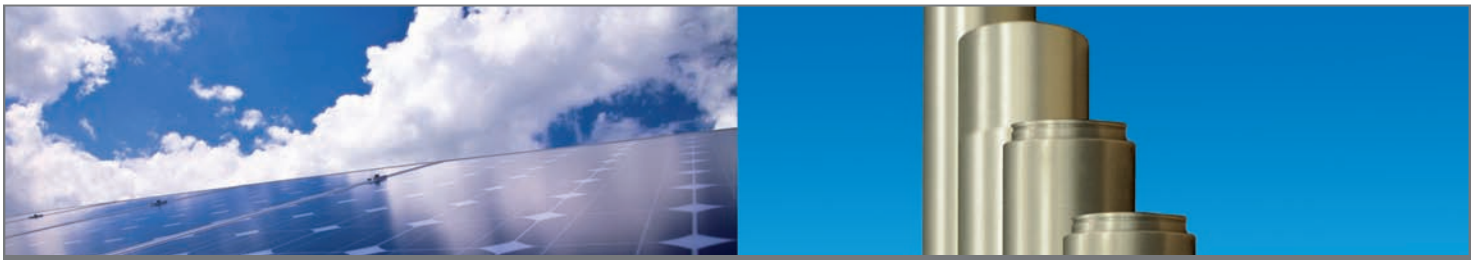
Source: Imec

Imec's tandem organic solar cells on glass plates have a power conversion efficiency of 5.15%.

CIGS PV manufacturer MiaSolé claims 13% module efficiencies in volume production

MiaSolé is claiming that its CIGS thin-film solar technology has reached 13% efficiency in volume production at its Silicon Valley facility – a 30% improvement since the beginning of the year.

In early October, Mississippi-based thin-film PV company Stion advised that the DOE's National Renewable Energy Laboratory had verified its monolithically integrated CIGSSe modules with 14.1% conversion efficiency while Manz laid claim to its CIGS fab in Hamburg producing thin-film modules with an



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Other direct costs	0.054 $/W	0.039 €/W	7.81%
Personnel costs	0.020 $/W	0.015 €/W	2.89%
Maintenance costs	0.010 $/W	0.007 €/W	1.45%
Depreciation of the utilities (7 years)	0.008 $/W	0.006 €/W	1.16%
Depreciation of the building (25 years)	0.003 $/W	0.002 €/W	0.43%
Total Cost of Ownership	**0.691 $/W**	**0.504 €/W**	**100%**

Cost of ownership calculation example of a factory with capacity of 30MWp per year, with automated production lines, and exchange rate = 0.73 €/$.

PE-CVD reactor for thin layers.

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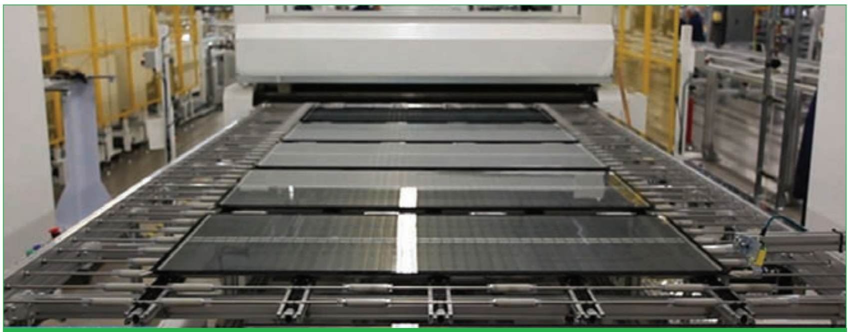


Source: MiaSolé

MiaSolé's production line.

aperture efficiency of 15.1%, equivalent to 14% module efficiency.

MiaSolé also recently celebrated manufacturing its 50 millionth cell since its inception. Earlier this year the company, which uses 88 cells per PV module, teamed up with Intel's Technical Manufacturing Services practice to accelerate its production ramp from 50MW to 150MW per annum capacity by the end of 2011.

Emcore lands contract from ARTS for design and delivery of solar panels to NASA

Emcore announced that ASRC Research and Technology Solutions (ARTS) has entered into a contract with the company for the design, manufacturing and delivery of solar panels for NASA's Ames Lunar Atmosphere and Dust Environmental Explorer (LADEE) mission. Thirty-two solar panels will be built by Emcore for the LADEE mission at its Albuquerque, New Mexico facility.

LADEE is a robotic mission that will orbit the moon in order to study and characterize the lunar atmosphere, including fine dust particles that are suspended over the lunar surface. NASA's spacecraft is set for a launch date in early 2013.

Source: NASA

NASA's LADEE mission will orbit the moon to characterize the atmosphere and lunar dust environment in the Minotaur V launch vehicle.

Soitec, Reflexite join forces to manufacture CPV lens plates

Soitec and Reflexite Energy Solutions have joined forces to create a new company dedicated to producing silicone-on-glass (SOG) Fresnel lens plates for concentrated photovoltaics (CPV) modules. The company, which has been christened Reflexite Soitec Optical Technology and is to be based in Soitec's new San Diego manufacturing facility, will also focus on increasing the efficiency and lowering the cost of the lens plates.

Under the terms of the agreement, Reflexite is supplying the technology and manufacturing expertise to produce the SOG lens plates, while Soitec provides the design expertise and business contacts, as well as the factory itself. Discussion is currently underway on the layout of the factory, which, when operational, will employ 100 people.

"This joint venture is unique in the CPV industry and represents a very important step in our commitment to the San Diego region and the US market," said Andre Jacques Auberton-Herve, Soitec's president, CEO and chairman. "By working together under the same roof, we can ensure the continuous supply of superior-quality lens plates at the most competitive cost, and our future product development programs will be much more efficient by working in such close proximity."

Soitec has been a pioneer of SOG lens plate design and, as its long-term supplier, Reflexite has played a key role in helping Soitec secure contracts to equip more than 300MW of CPV projects throughout the southwest US.

Manz adjusts revenue and EBIT figures for FY 2011

The management board of Manz has responded to the worldwide fall in demand for PV equipment by reducing its revenue and earnings expectations for the 2011 fiscal year. The decision, which will see forecasted revenues adjusted to €220–230 million, was made at a recent board meeting, where it was also revealed that earnings before interest and taxes (EBIT) are likely to be positive or at break-even level.

Manz's management team is also anticipating a final fiscal year revenue figure of €240-250 million and an EBIT margin of at least 5%. Although these figures are dependent on there being no further deterioration in the overall macroeconomic and sector-specific conditions for the remainder of the year.

Konarka and Webasto partner on organic solar cells for auto roof systems

Konarka Technologies and automobile supplier Webasto Roof Systems have

Source: Konarka

Konarka's organic solar cells will be incorporated into Webasto's automobile roof systems.

announced their partnership on the integration of organic solar cells in automobile roof systems. Webasto plans to integrate the organic cells from Konarka while additionally working to increase their efficiency so that they can be used on various models of cars.

Testing & Certification News Focus

Amonix earns pair of LEED certifications for facilities, will power Nevada site with own CPV system

Amonix's Seal Beach, California and North Las Vegas, Nevada facilities have earned gold-level certification for their low environmental impact from the US Green Building Council's Leadership in Energy and Environmental Design (LEED) program. The company's buildings were rated in 13 environmental impact categories, including climate change, indoor environmental quality, resource depletion and water intake.

Amonix additionally revealed that as part of its LEED certification, its Nevada facility would be powered with eight of its own CPV solar systems providing 100% of the site's energy needs, approximately 1,500MWh per year. The North Las Vegas lighting array is said to surpass LEED requirements by 15% to 20% with high-performance plumbing fixtures reducing water usage 41%.

HelioVolt earns UL, IEC certifications for CIGS PV modules; first commercial panels now available

HelioVolt's HVC-170X modules have been granted ANSI/UL-1703, IEC-61646 and IEC-61730 certifications after testing was completed by Intertek-ETL. The company's monolithically integrated panels are manufactured at its Austin, Texas plant using HelioVolt's proprietary CIGS technology.


Source: HelioVolt

Production of HelioVolt's CIGS modules.

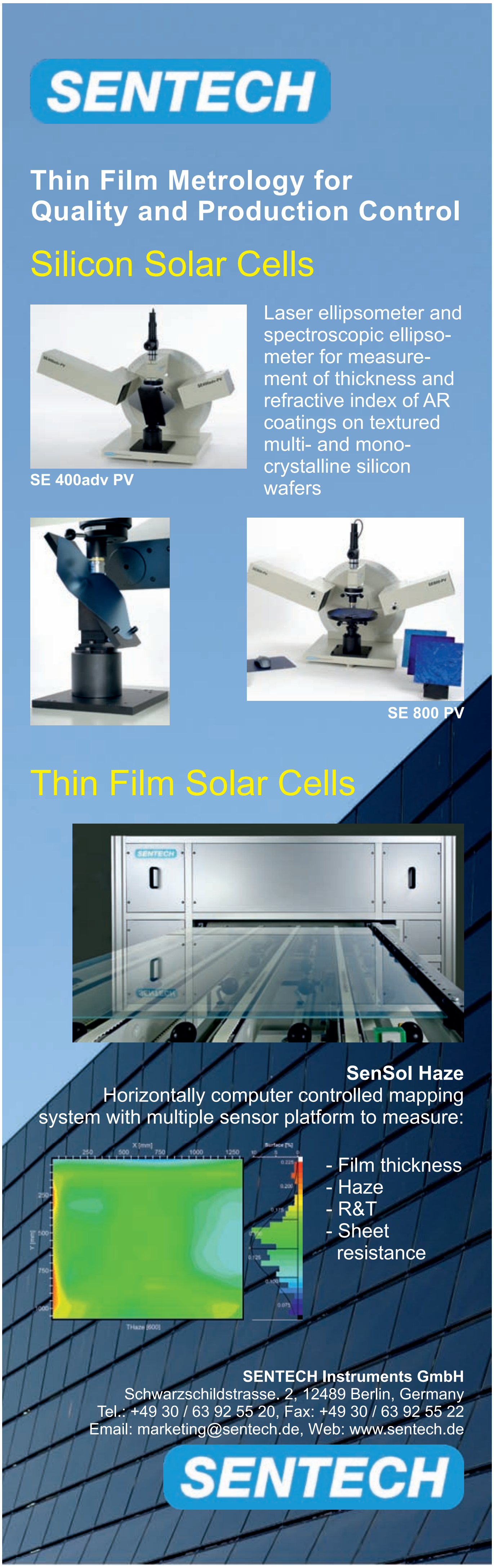
"The rigorous outdoor testing and reliability programs we have invested in over the past three years have given us great confidence in the superior performance of our modules. We are pleased to offer the first in a rapidly developing series of commercially available products to our strategic customers," said Dr. BJ Stanbery, HelioVolt's founder and chairman.

The announcement comes just a few months after the company revealed the US$50 million investment made by SK Group in September for the expansion of HelioVolt's Austin facility.

Odersun's PV modules receive "Made in Europe" certificate, qualify for Italian solar power tariff

Odersun's thin-film solar cells will now carry the "Made in Europe" certificate, which was confirmed by the VDE Institute. The certificate allows solar plant operators using Odersun's modules to participate in a 10% higher feed-in tariff from Italy's Conto Energia IV.

In collaboration with energy agency GSE, the certificate for "Made in Europe" ensures that at least 60% of a module or its system components have been manufactured in Europe. GSE advised that it would pay the 10% higher subsidy for projects that use the EU components.



Thin-Film Order Focus

Leybold to supply PECVD tool for thin-film silicon PV research at Next Energy EWE

Next Energy, the independent EWE Research Centre for Energy Technology has asked Leybold Optics to provide its Phoebus lab tool by the beginning of 2012 for Next Energy's R&D purposes involving thin-film solar cells. As Next Energy is concerned with silicon thin-film technology, its scientists are looking to increase the efficiency of the cells, which they state would then lead to a reduction in the cost of the technology.

The Phoebus lab tool is said to be able to coat substrate with up to a 5mm thickness and a surface of up to 300 × 300mm in addition to any other small substrate in different shapes.

Nanometrics' TSM metrology system installed by "major solar PV manufacturer"

Nanometrics, a supplier of metrology systems, has announced that a major manufacturer of advanced thin-film solar PV cells successfully installed the latest generation of the Trajectory Solar Monitor (TSM) metrology system for in-line process monitoring and control of CIGS films. Exact details of the transaction were not disclosed.

A tool for rapid film thickness measurement, the TSM system was installed as a complement to TSM reflectometry tools currently used for in-line buffer, TCO and CIGS thickness monitoring, providing a comprehensive, integrated process control solution for advanced PV cells.

Nanosolar supplies 6MW of CIGS PV panels for projects in France, Oregon

Thin film PV company Nanosolar said it has supplied close to 6MW of its CIGS utility panels for two installations in France and Oregon, as part of its partnership with EDF Energies Nouvelles and its US subsidiary, enXco.

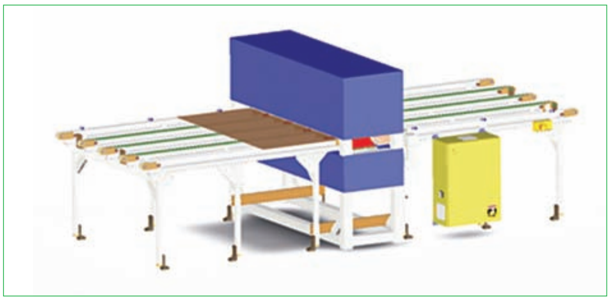
Approximately 3MW were installed this summer and commissioned in September in a larger EDF EN solar power plant in Gabardan, France. The Oregon project, built this summer and commissioned in November, is located near Amity and consists of two systems comprising almost 3MW of Nanosolar modules.

Mainstream Energy to distribute 5MW of Solar Frontier CIS modules in North America

Solar Frontier has entered into a distribution agreement with Mainstream Energy that will see Mainstream sell and install 5MW of Solar Frontier's CIS modules beginning in the fourth quarter of 2011. The CIS thin-film modules in the distribution agreement will be manufactured at Solar Frontier's CIS factory in Miyazaki, Japan. Solar Frontier noted that the agreement would increase its presence throughout the North American market.

Product Reviews

Dr Schenk



Dr Schenk's SolarMeasure I-V Curve Tracer offers individual cell electrical characterization

Product Outline: Dr Schenk has developed a high-speed, non-destructive system for measurement of I-V curves of thin-film modules prior to the lamination step. The SolarMeasure I-V Curve Tracer evaluates the characteristics of every individual cell on the complete thin-film panel and detects local variations. These measurements can be taken in-line and the results serve as a GO/NO-GO test of whether a panel should be processed further.

Problem: Indirect metrology tests such as measurement of pinhole density, layer thickness or haze are not sufficient to predict a solar panel's final electrical efficiency.

Solution: The I-V Curve Tracer measurements can be correlated with preceding optical inspection data (e.g. local defects, layer thickness, haze) to characterize and improve processes. The I-V Curve Tracer offers stable and homogenous measurements without light power fluctuations across the measurement plane. Unique electrical characterization is achieved through space-resolved, wavelength-resolved and irradiance-resolved measurements. Unlike conventional flasher-tests, this measurement can be performed in-line before the lamination step and can thus serve as a GO/NO-GO tester to decide whether a panel should be further processed. The I-V curve tracer can also be used as an off-line tool.

Applications: Evaluation of individual electrical characteristics of every cell on the complete thin-film panel.

Platform: Based on a proprietary LED illumination technology, the fully automated system features a three-quadrant, four-point measurement for optimized determination of the serial and parallel resistance as well as an I-V measurement in forward direction without light.

Availability: Since September 2011.

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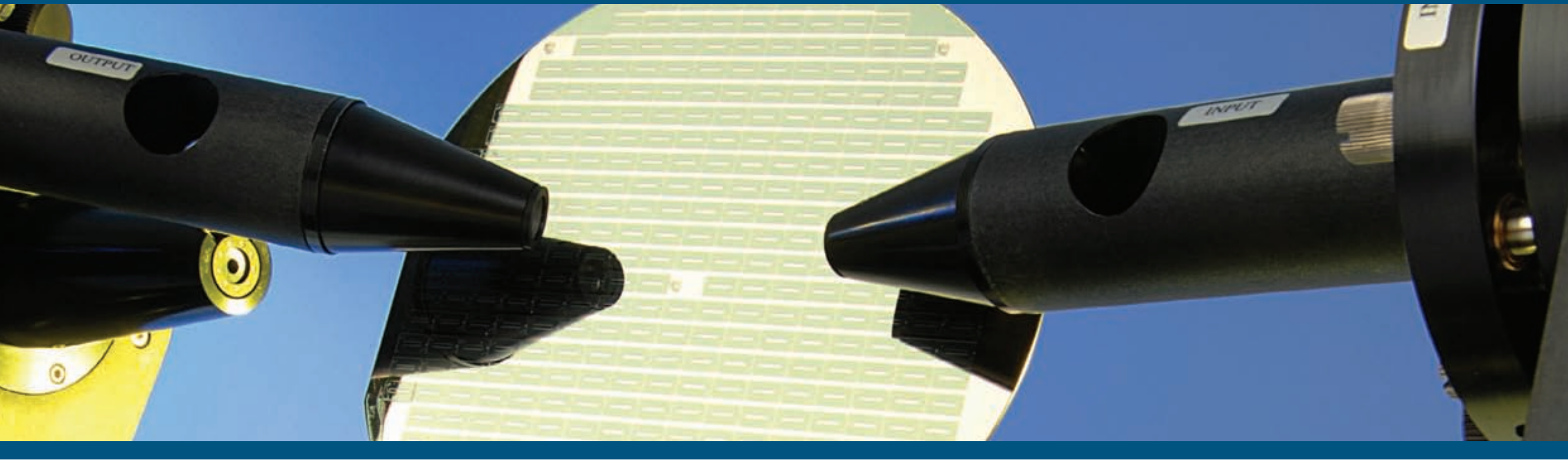

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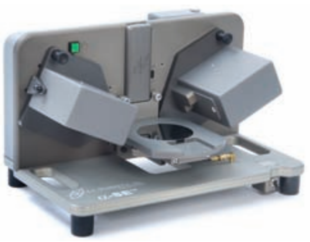

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Product Reviews

Singulus Technologies

Tenuis Gen 2 system from Singulus offers process time reduction for CIS/CIGS thin-film solar cells

Product Outline: Singulus Technologies has made significant improvements to its Tenuis platform for wet-chemical coating of thin-film solar modules made of CIGS on glass. The Tenuis Gen 2 system incorporates dosing and temperature control, while reducing the process time by up to 20 %. The floor space requirements of the modular system have also been reduced by 30%.

Problem: It is extremely important for cell manufacturers to continuously advance processes and throughput to gain a competitive advantage. Major improvements to production tool platforms are required that can reduce production costs and intrinsic CoO.

Solution: The new Tenuis Gen 2 is claimed to offer substantial cost advantages in the production of high performance CIS/CIGS thin-film solar cells. The costs are reduced by temperature profiles adjusted to the process and efficient use of chemicals, so that the new system consistently exploits the savings potential in manufacturing. For a higher throughput, several production machines can be combined to a large production complex. The system is also claimed to provide advantages upon commissioning and in the ramp-up stage. The new cluster design can commence modularly after a short installation time and the first substrates can be coated.

Applications: Wet-chemical coating of buffer layers for CIGS on glass. The system provides the possibility of using alternative coating materials such as ZnS.

Platform: The Tenuis Gen 2 system is characterized by stable and reproducible process results and very high up time, according to the company. The re-launch of the Tenuis system is completed by a new software user interface.

Availability: Since August 2011.

Yamaichi Electronics

Yamaichi Electronics' thin-film junction box uses kink protection with Hermetic Sealed technology

Product Outline: Hermetic Sealed technology has been used for the first time by Yamaichi Electronics in a thin-film junction box. In case of shadow, the design permits the over-molded diodes to discharge significantly more heat than a non-over-molded variant.

Problem: The automated fabrication of PV modules improves efficiencies, product integrity and reduces production overhead. By using automated production lines, assembly time of a junction box to a PV panel can be reduced. However, the need to provide 20-plus year field reliability requires zero penetration of moisture or other materials into the box that could cause premature failure.

Solution: With Hermetic Sealed technology, the junction box is not composed of individual 'failing parts.' Instead, the cables and electronics of the box are insert-molded in a single highly efficient work step ensuring freedom from leaks, thus increasing the lifetime and safety of the entire PV installation. The simple mounting of the thin-film junction box on the solar panel with high-quality adhesive pads ensures cost-effective and safe production. The bands of the PV module are contacted through clamping terminals, while mounting can be carried out without the use of tools. The box and cover can be attached simultaneously with the clamping contacts and crimped.

Applications: Junction box for thin-film modules.

Platform: The TF junction box, with a height of only 14mm, is among the flattest boxes on the market and can be used even when space is tight. The TÜV- and UL-listed junction box can be delivered with or without diodes.

Availability: Currently available.

Bystronic glass

Bystronic's photovoltaic-TPA system offers continuous encapsulation and sealing of thin-film modules

Product Outline: The photovoltaic-TPA (Thermo Plastic Applicator) from Bystronic glass group is a machine designed for the encapsulation and sealing of thin-film modules. The machine is claimed to be the first of this type that is capable of working in 24-hour operation without any interruption.

Problem: Whereas the use of the conventional butyl sealant stripes from a reel is permanently linked with production interruptions when the material reel needs to be changed, high-viscous butyl dispensing provides for continuous production and lower energy usage when compared to traditional lamination processes.

Solution: The photovoltaic-TPA applies high-viscous butyl on semiconductor thin-film substrates with high precision. Two high-performance pumps ensure that the viscous sealing material is always available. The dosing pumps are claimed to apply the material accurately to a tenth of a millimetre; depending on the film's thickness, the application thickness of the butyl varies between 0.5 and 1mm. This encapsulating method uses relatively little energy as it operates without any heating or cooling. Depending on the module size, the cycle times are approximately 30 to 45 seconds.

Applications: CdTe, CIS, CIGS, µ-Si or a-Si applications.

Platform: The machine is available in both horizontal and vertical options. Integration into complete back-end lines and existing plants is possible. The machine's dual-drum pump system allows operation 24 hours a day, seven days a week.

Availability: Currently available.

Structure and stability of a-Si/µc-Si tandem solar cells deposited on LPCVD-grown ZnO:B and sputtered ZnO:Al

Brad Tinkham[1], **Clement David**[1,2], **Andreas Neumann**[1], **Daniel Sixtensson**[1], **Thierry Girardeau**[2] & **Fabien Paumier**[2]
[1] Inventux Technologies AG, Berlin, Germany; [2] Institut P PRIME, Département Physique et Mécanique des Matériaux (PHYMAT), Université de Poitiers-CNRS, Poitiers, France

ABSTRACT

Because of its attractive electronic and optical properties, zinc oxide (ZnO) has found widespread use as a front and back electrode in commercial solar cells. ZnO can be deposited on glass using a variety of different methods, of which vacuum-based techniques are the most commonly used in industrial applications. Aluminium-doped sputtered ZnO:Al (AZO) has been studied intensively for use as a front contact in a-Si/µc-Si tandem cells. The implementation of AZO in series production has been hindered by reproducibility issues stemming from the combination of deposition and subsequent etching steps that are necessary to tune the 'haze' of the layers for optimal light scattering. Boron-doped ZnO:B (BZO), deposited by low-pressure chemical vapour deposition (LPCVD), has become a cost-effective option for module manufacturers, since the desired layer morphology can be produced as grown without the need of post-growth chemical etching. This paper addresses the different aspects of using AZO and BZO layers as front contacts for a-Si/µc-Si tandem modules fabricated in series production. The properties of the underlying ZnO layers put restrictions on the layer properties and process parameters that are used in the deposition of a-Si and µc-Si.

Introduction

As the first layer deposited in the superstrate solar cell configuration, the zinc oxide (ZnO) front contact layer is subject to all subsequent post-deposition steps in the manufacturing flow. Post-deposition treatment can have a strong effect on key parameters – such as resistivity and transmittance – that can impact module performance. Despite intensive research efforts directed at elucidating the bulk mechanisms behind the electrical changes in zinc oxide, many questions remain.

> "Post-deposition treatment can have a strong effect on key parameters – such as resistivity and transmittance – that can impact module performance."

Boron-doped ZnO (BZO) grown by LPCVD was developed in the mid-1990s by the Photovoltaics and Thin Film Electronics Laboratory in Neuchâtel, Switzerland [1]. BZO can be deposited at relatively low temperatures (< 200°C), and a pyramidal morphology develops during growth, which provides excellent light-scattering properties. By adjusting the LPCVD process parameters – such as gas flow, temperature and pressure – the haze (fraction of diffusely scattered light) can be tuned to a desired value that proves to be compatible with the overall cell structure and maximizes light trapping in the absorber layers. The transmittance (transparency) of the BZO layers between 400nm and 800nm is typically higher than that of AZO layers, which allows for the use of thinner absorber layers that in turn reduce material consumption and limit the light-induced degradation (LID). Furthermore, the structure of the silicon absorber layers is influenced by the morphology underlying the BZO or AZO template.

Investigation of post-growth treated ZnO grown by LPCVD (BZO)

Experiment

ZnO belongs to a small class of materials, so-called *transparent conductive oxides* (TCOs), that exhibit high transparency as well as high conductivity. The structure of the silicon absorber layers in solar cells is tailored to the electrical and optical properties of the BZO layer. However, the transmittance and resistivity of the BZO layers are typically measured directly after the LPCVD deposition. As shown by Beyer et al. [2], because of post-growth thermal treatment during the manufacturing process, the layer characteristics directly after growth do not necessarily represent those of the BZO layer in the finished product.

Boron-doped ZnO films approximately 1500nm thick were deposited on 3.2mm glass substrates at 180°C by LPCVD using a commercial TCO 1200 manufactured by Oerlikon Solar. Diethyl zinc and water vapour are used as precursor gases for ZnO growth, and the boron doping is provided by the flow of diborane. After growth, samples were annealed in discrete steps to 400°C, and measured *in situ* by X-ray diffraction in a Bragg-Brentano geometry. The X-ray measurements were performed with a continuous temperature ramp, and scans were made at 5°C intervals both for samples in air and for samples maintained under vacuum at a pressure of 0.1 mbar. The changes in conductivity were investigated in parallel by annealing ZnO/glass films to discrete temperatures and subsequently preparing samples for Fourier transform infrared spectroscopy (FTIR) measurements. Hall effect measurements were also performed and confirmed the same trends in carrier mobility (μ_e) and carrier density (N_e) observed in FTIR.

Analysis and discussion

For ZnO/glass samples annealed in a vacuum, the sheet resistance of the layers decreases steadily until around 250°C and then increases thereafter. The same general behaviour is observed for samples annealed in air, although the magnitude of the decrease in resistance in these samples is much lower. Abrupt changes in physical and electronic structure are

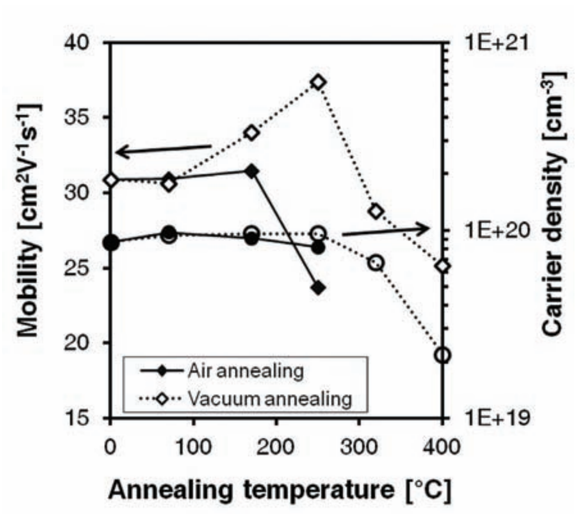

Figure 1. Evolution of mobility and carrier concentration of ZnO:B as a function of annealing temperature measured by FTIR.

noticeable at temperatures closer to 200°C. As given by Equation 1, the bulk conductivity (σ) of BZO for strongly n-type semiconductors is a function of both the carrier concentration (N_e) and the carrier mobility (μ_e):

$$\sigma = q\, N_e\, \mu_e \qquad (1)$$

where q is the unit of elemental charge. Fig. 1 shows values of these parameters as determined by fits to FTIR spectra. The FTIR data points (not shown here) are fitted using the software program RG-VIM [3], which has been developed at Fraunhofer IST. From the data in Fig. 1 it is apparent that both concentration and mobility contribute to the changes in conductivity, with mobility having the larger impact.

When deposited on glass substrates by LPCVD, ZnO exhibits a Wurtzite structure with its (110) planes parallel to the glass surface [4]. This differs from the case of ZnO deposited on Si(100) by LPCVD, where the surface texture is typically (002) [5,6,7]. In order to evaluate thoroughly the effect of heat treatment on the physical characteristics of BZO, X-ray diffraction was performed on samples *in situ* during annealing in both vacuum and atmospheric conditions. Fig. 2(a) shows the relative change in the (110) plane spacing (d_{110}) as the samples are heated to 400°C at a rate of 1°C/min; Fig. 2(b) shows the full-width at half maximum (FWHM) of the (110) diffraction peak as the samples are heated to 400°C at a rate of 1°C/min. The measured contribution of thermal expansion has been subtracted from the data. The initial lattice contraction and subsequent rapid increase in the plane spacing point to a distinct change in the bulk structure. This change is accelerated for the samples annealed in air, which suggests that the oxygen concentration could be playing a role in the transition. The FWHM of the (110) peak is plotted in Fig. 2(b) for the same temperatures. A coarsening of the ZnO grains may explain the peak narrowing, and the transition temperature at 220°C corresponds to the decrease in (110) planar spacing evidenced in Fig. 2(a).

> “Annealing BZO films under vacuum at 250°C can improve the electrical properties of the layer, but for temperatures above 320°C the resistance of the samples increases rapidly.”

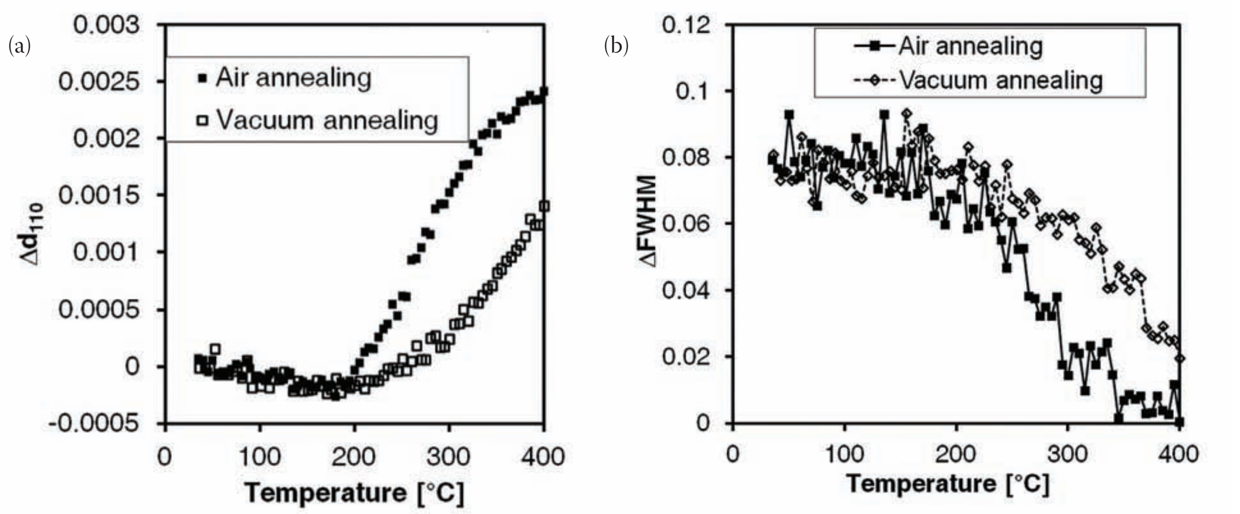

Figure 2. (a) Relative change in ZnO (110) plane spacing, and (b) evolution in FWHM of (110) diffraction peak upon heating in air and in a vacuum environment.

Annealing BZO films under vacuum at 250°C can improve the electrical properties of the layer, but for temperatures above 320°C the resistance of the samples increases rapidly. This behaviour is also observed, but slightly shifted to a lower temperature, in the case of air annealing. Measurement of the ZnO lattice constant during *in situ* X-ray diffraction (XRD) reveals a structural change occurring at temperatures that correspond to changes observed in carrier concentration and mobility as determined by both FTIR and Hall effect. Changes in the concentration of oxygen-related defects in the ZnO lattice could explain the results. Detailed X-ray photoelectron spectroscopy (XPS) measurements for LPCVD-grown ZnO on silicon reveal no change in levels of oxygen vacancies (V_o) or zinc interstitials (Zn_i) after thermal treatment [8]. However, XPS is a surface-sensitive technique and cannot detect changes in oxygen concentration deep in the bulk of the material. At around 200°C, an increase in the (110) peak-integrated intensity together with a decrease in FWHM indicates a recrystallization process. In polycrystalline ZnO, grain boundary scattering is known to be a dominant factor in the limitation of the carrier mobility [9,10,11,12]. FTIR is, however, sensitive only to the in-grain mobility as influenced by ionized impurity scattering, which implies an additional mechanism at work in the evolution of the layer characteristics.

Hydrogen, which is known to enhance the conductivity in ZnO [13] and to desorb above 250°C [14], is a possible candidate for inducing the changes observed in the electrical properties. In the LPCVD growth process, hydrogen is present in all of the precursors employed in the process. At higher temperatures, the (110) interplanar spacing increases, which suggests a modification of the lattice due to structural defects. The origin of these defects that arise at higher annealing temperatures is the subject of ongoing studies.

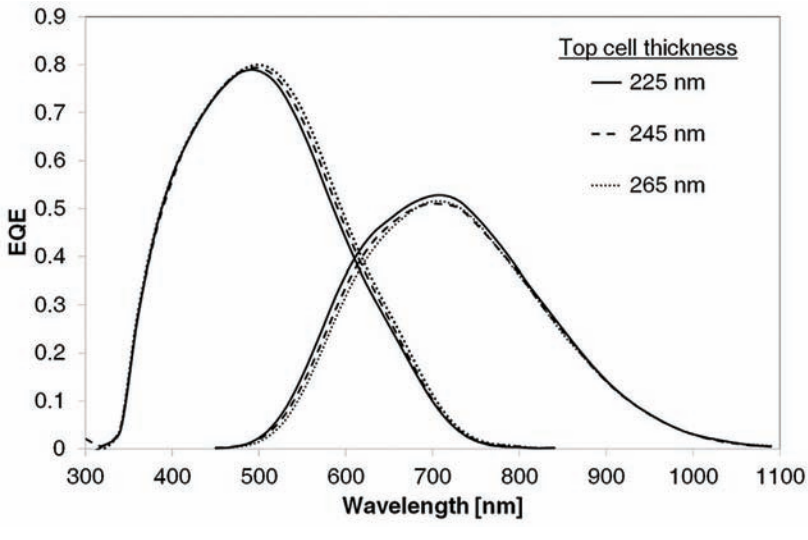

Figure 3. External quantum efficiency spectra for samples grown on AZO for different top cell thicknesses.

Investigation of cells on sputtered and wet-etched ZnO (AZO)

Experiment

The layer morphology of etched ZnO after sputtering differs greatly from that of ZnO grown by LPCVD. The as-grown sputtered layers are smooth and the crater-like morphology responsible for light scattering only develops after wet-chemical etching. Depending on the deposition parameters and duration of the etching treatment, the root mean square (RMS) roughness of the ZnO layers can be very high. Moreover, the transmittance of AZO diverges from that of BZO in both infrared and ultraviolet parts of the spectrum. The optical properties of the AZO layers are mostly dependent on the layer thickness and the composition of the target used during sputtering. The structure, and in particular the thicknesses, of the absorber layers in the solar cell can be optimized accordingly for growth on BZO and AZO layers.

Solar cells and modules employing both AZO and BZO as a front contact layer were fabricated. The BZO layers used in the modules were similar to those described in the previous section, having thicknesses of 1500nm and sheet resistances of about 20Ω/sq. The AZO films were deposited by a commercial

	TC-J_{SC} [mA/cm^2]	BC-J_{SC} [mA/cm^2]	BC-J_{SC}/ TC-J_{SC}	ΣJ_{SC} [mA/cm^2]
LPCVD-225nm	11.67	9.5	0.81	21.17
PVD-225nm	10.52	9.69	0.92	20.21
PVD-245nm	10.76	9.31	0.87	20.07
PVD-265nm	11.02	9.17	0.83	20.19

Table 1. Distribution of current in top cell (TC) and bottom cell (BC), and matching ratio for samples with different top cell thicknesses.

by Von Ardenne Anlagentechnik. Ceramic ZnO (1.5 wt. % Al_2O_3) targets were employed in the nonreactive sputter process to deposit the 1200nm AZO films. The films were grown on 3.2mm-thick low-iron glass substrates. A thin SiO_2 layer was first grown to provide a diffusion barrier between the glass and ZnO layers. The AZO layers were etched in a 0.5% HCL solution for different durations to create morphologies suitable for light scattering into the absorber layer. The etching process removed about 200–300nm of ZnO, which resulted in sheet resistances ranging from 8 to 14Ω/sq. To accommodate the increasing roughness produced by longer etching times, different absorber structures were tested; in particular the top cell thickness was varied for the modules prepared with AZO. The current densities in the amorphous top cell and microcrystalline bottom cell were measured by external quantum efficiency (EQE). Current-voltage (IV) characteristics of the cells and modules were measured by a sun simulator and flasher, both employing air mass (AM) 1.5 spectrums.

Analysis and discussion

As the thickness of the a-Si layer is increased, more light is absorbed in the top cell and in turn less light in the bottom cell. Fig. 3 displays the results of external quantum efficiency measurements in the top and bottom cells for different a-Si thicknesses grown on AZO. Table 1 summarizes the contribution to the total current density from the top and bottom cells as determined by integration of the EQE signal multiplied by the solar spectrum. The result for cells grown on BZO with standard thickness is shown for comparison. All of the data in this table are measured on samples in their initial state, which means they did not experience any LID. For a top cell thickness of 225nm, the current density of the bottom cell is even higher than the BZO sample, but since the top cell current is lower, the total current is less limited by the bottom cell. Setting the appropriate current matching condition is important for maximizing the module output power in the stabilized state. Since almost the entire light-induced degradation takes place in the top cell, it is favourable to intentionally limit the total current with the bottom cell to minimize degradation. The AZO sample with a top cell thickness of 265nm gives a similar matching condition to that of the BZO sample with a 225nm top cell thickness.

> "The AZO sample with a top cell thickness of 265nm gives a similar matching condition to that of the BZO sample with a 225nm top cell thickness."

Fig. 4 shows the I-V characteristics for these samples in their stabilized state after 1000 hours of light soaking. The structure on BZO delivered the best efficiency, despite the thinner top cell thickness. Nevertheless, the development at this stage on AZO is encouraging. Only one process modification to accommodate the different TCO structures has been considered and comparable results have been achieved.

The higher voltage values seen in the AZO structure can be traced back to a favourable morphology for subsequent silicon layer growth. Although the trenches in the AZO are relatively deep, the pyramidal mounds that are present on the BZO structure are absent. For thicker BZO layers, the pyramids assume even steeper profiles, which can cause local stress fields in the silicon layers to develop. This can result in the formation of microcracks in the bulk Si that can be detrimental to the performance of the solar cell [15]. Systematic studies relating crack density to cell efficiency have been performed by other groups. As shown by Python et al. [16], it is possible to model cells with defective regions and defect-free regions as two diodes connected in parallel. In the defective regions the current is independent of the magnitude of the crack density, whereas the current increases linearly with crack density in the regions modelled without defects. The increase in current for samples with thicker BZO layers is due to the increase in haze and enhancement of light trapping for thicker layers. A linear decrease in both open-circuit voltage (V_{oc}) and fill factor (*FF*) as a function of crack density has been observed.

Research groups have considered different theories for the voltage decrease on rough substrates. As the pyramidal structure of the BZO becomes sharper or more V-like, the coverage of the absorber layers becomes less uniform [17]. The p-layer of the amorphous cell is the first layer to be deposited on the transparent front contact and its thickness strongly influences V_{oc}. Some investigations point to an increase in recombination centres in the μc-Si layer caused by impurities accumulating preferentially in low-density defective regions [18]. This same reasoning has been applied to explain the drop in *FF*. The negative impacts of the crack formation can be partially compensated by increasing the growth temperature and therefore

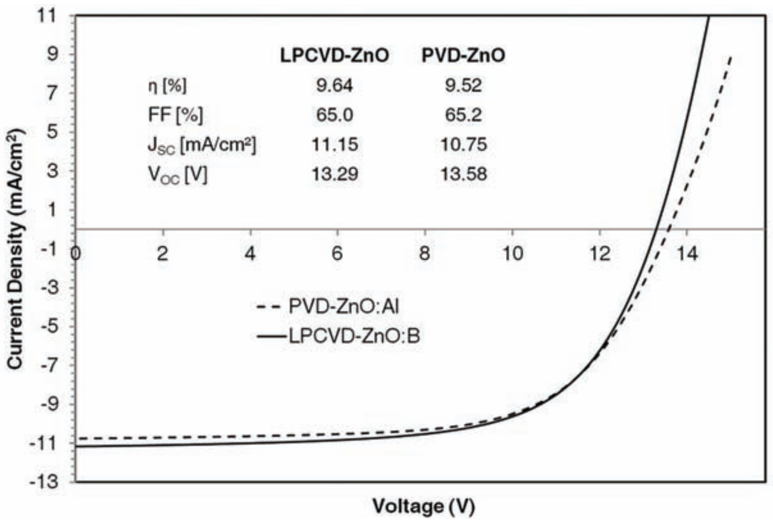

Figure 4. Comparison of IV characteristic for an optimized structure grown on LPCVD with a top cell thickness of 225nm, and for a sample grown on AZO with a top cell thickness of 265nm.

	TC-J_{SC} [mA/cm^2]	BC-J_{SC} [mA/cm^2]	BC-J_{SC}/ TC-J_{SC}	ΣJ_{SC} [mA/cm^2]
LPCVD-225nm	11.67	9.5	0.81	21.17
PVD-225nm	10.52	9.69	0.92	20.21
PVD-245nm	10.76	9.31	0.87	20.07
PVD-265nm	11.02	9.17	0.83	20.19

Table 1. Distribution of current in top cell (TC) and bottom cell (BC), and matching ratio for samples with different top cell thicknesses.

sputter system manufactured by Von Ardenne Anlagentechnik. Ceramic ZnO (1.5 wt. % Al_2O_3) targets were employed in the nonreactive sputter process to deposit the 1200nm AZO films. The films were grown on 3.2mm-thick low-iron glass substrates. A thin SiO_2 layer was first grown to provide a diffusion barrier between the glass and ZnO layers. The AZO layers were etched in a 0.5% HCL solution for different durations to create morphologies suitable for light scattering into the absorber layer. The etching process removed about 200–300nm of ZnO, which resulted in sheet resistances ranging from 8 to 14Ω/sq. To accommodate the increasing roughness produced by longer etching times, different absorber structures were tested; in particular the top cell thickness was varied for the modules prepared with AZO. The current densities in the amorphous top cell and microcrystalline bottom cell were measured by external quantum efficiency (EQE). Current-voltage (IV) characteristics of the cells and modules were measured by a sun simulator and flasher, both employing air mass (AM) 1.5 spectrums.

Analysis and discussion

As the thickness of the a-Si layer is increased, more light is absorbed in the top cell and in turn less light in the bottom cell. Fig. 3 displays the results of external quantum efficiency measurements in the top and bottom cells for different a-Si thicknesses grown on AZO. Table 1 summarizes the contribution to the total current density from the top and bottom cells as determined by integration of the EQE signal multiplied by the solar spectrum. The result for cells grown on BZO with standard thickness is shown for comparison. All of the data in this table are measured on samples in their initial state, which means they did not experience any LID. For a top cell thickness of 225nm, the current density of the bottom cell is even higher than the BZO sample, but since the top cell current is lower, the total current is less limited by the bottom cell. Setting the appropriate current matching condition is important for maximizing the module output power in the stabilized state. Since almost the entire light-induced degradation takes place in the top cell, it is favourable to intentionally limit the total current with the bottom cell to minimize degradation. The AZO sample with a top cell thickness of 265nm gives a similar matching condition to that of the BZO sample with a 225nm top cell thickness.

> “The AZO sample with a top cell thickness of 265nm gives a similar matching condition to that of the BZO sample with a 225nm top cell thickness.”

Fig. 4 shows the I-V characteristics for these samples in their stabilized state after 1000 hours of light soaking. The structure on BZO delivered the best efficiency, despite the thinner top cell thickness. Nevertheless, the development at this stage on AZO is encouraging. Only one process modification to accommodate the different TCO structures has been considered and comparable results have been achieved.

The higher voltage values seen in the AZO structure can be traced back to a favourable morphology for subsequent silicon layer growth. Although the trenches in the AZO are relatively deep, the pyramidal mounds that are present on the BZO structure are absent. For thicker BZO layers, the pyramids assume even steeper profiles, which can cause local stress fields in the silicon layers to develop. This can result in the formation of microcracks in the bulk Si that can be detrimental to the performance of the solar cell [15]. Systematic studies relating crack density to cell efficiency have been performed by other groups. As shown by Python et al. [16], it is possible to model cells with defective regions and defect-free regions as two diodes connected in parallel. In the defective regions the current is independent of the magnitude of the crack density, whereas the current increases linearly with crack density in the regions modelled without defects. The increase in current for samples with thicker BZO layers is due to the increase in haze and enhancement of light trapping for thicker layers. A linear decrease in both open-circuit voltage (V_{oc}) and fill factor (*FF*) as a function of crack density has been observed.

Research groups have considered different theories for the voltage decrease on rough substrates. As the pyramidal structure of the BZO becomes sharper or more V-like, the coverage of the absorber layers becomes less uniform [17]. The p-layer of the amorphous cell is the first layer to be deposited on the transparent front contact and its thickness strongly influences V_{oc}. Some investigations point to an increase in recombination centres in the μc-Si layer caused by impurities accumulating preferentially in low-density defective regions [18]. This same reasoning has been applied to explain the drop in *FF*. The negative impacts of the crack formation can be partially compensated by increasing the growth temperature and therefore

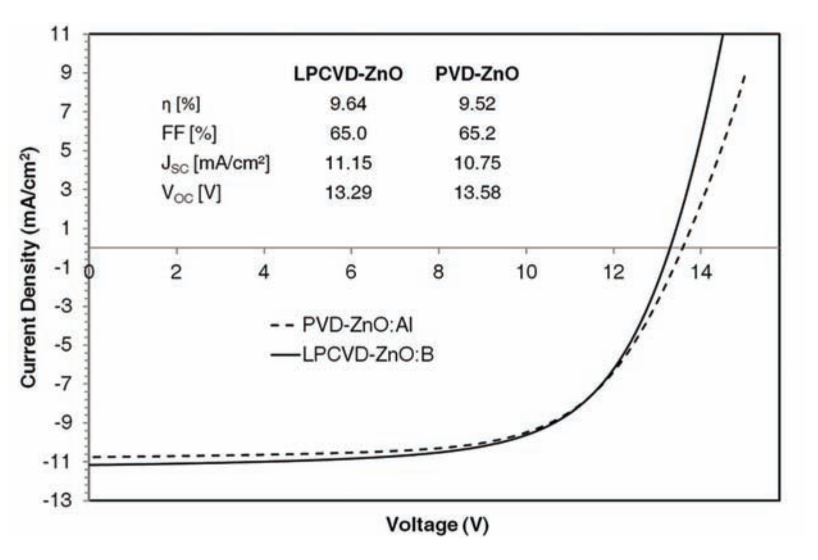

Figure 4. Comparison of IV characteristic for an optimized structure grown on LPCVD with a top cell thickness of 225nm, and for a sample grown on AZO with a top cell thickness of 265nm.

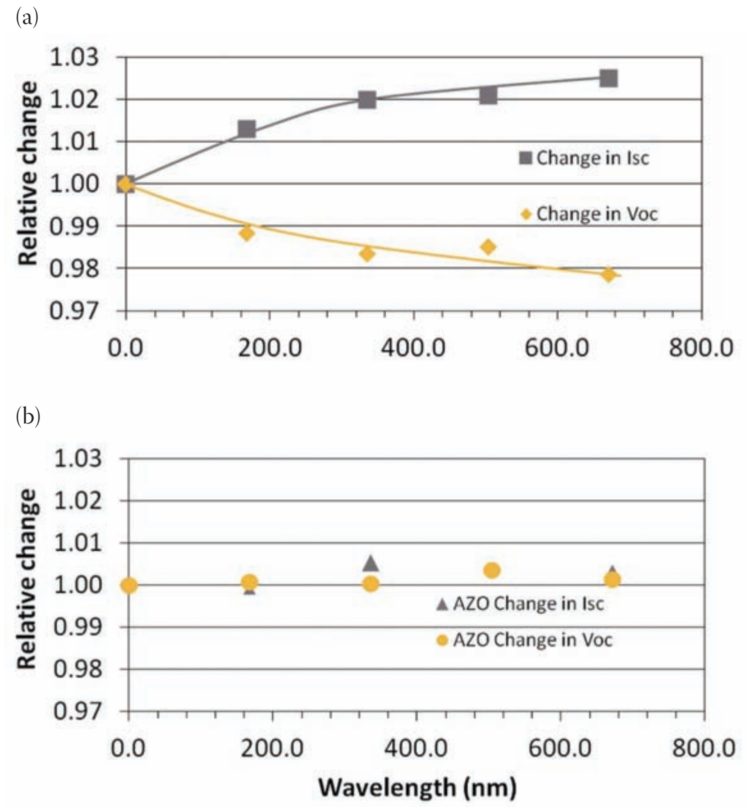

Figure 5. Relative change in I_{sc} and V_{oc} for modules annealed after back contact deposition for samples deposited on (a) LPCVD-grown ZnO:B, and (b) sputtered ZnO:Al.

increasing the adatom mobility of the diffusing Si species. The cracks can then be 'filled' by silicon and the regions are in turn denser and less susceptible to accumulation of impurities. By using a higher temperature in the µc-Si growth, the underlying a-Si cell and TCO are also being heated to higher temperatures. Especially in the a-Si cell, unintentional diffusion of dopants could be activated at higher temperatures, which can lead to a drop in V_{oc}. Therefore, simply increasing the µc-Si growth temperature for the purpose of reducing crack density is not necessarily an option.

Depending on the flow of the production line, modules can experience variable waiting times between process steps. This is often the case in the area where the modules are encapsulated. Several modules fabricated on both BZO and AZO that had been stored without light exposure and in air for up to 1000 hours were investigated. The effects of storage time on current and voltage are shown in Fig. 5; the difference in stability of the current and voltage is obvious. The module power, which corresponds to the product of the current and voltage, is constant over the duration of the experiment for both module types, but the samples with a BZO front contact show a clear increase in current and decrease in voltage for longer storage times. On the other hand, the modules with AZO are observed to be completely stable. All modules were stored with a screen-printed white paint layer with a thickness greater than 10µm covering the absorber and TCO layers. For samples stored without paint, the effects of storage are even more pronounced, and storage in a vacuum almost completely suppresses the observed behaviour on BZO samples.

By similar reasoning to that for the drop in V_{oc} on rough as-deposited BZO, the impurities (in this case oxygen atoms) are believed to concentrate close to and diffuse along the cracked regions. The positive effect on the current for the samples on BZO is rather surprising but can be understood as a passivation of the grain boundary defects that leads to a longer carrier lifetime in the intrinsic region of the absorber layer in the solar cell. It is also believed that the stability of the V_{oc} and I_{sc} values of modules produced with AZO during dark storage can be attributed to the AZO surface morphology that reduces or eliminates the formation of cracks in the µc-Si bottom cell.

Summary

The electrical and structural changes of LPCVD-grown ZnO/glass have been investigated by XRD and FTIR. An increase in carrier mobility as well as carrier concentration upon heating to 200°C was verified. For samples heated in a vacuum, which corresponds to conditions in solar module production, the increase is more significant. Heating to higher temperatures reduces both the carrier mobility and the carrier concentration. Results from XRD suggest a grain-coarsening effect at higher temperatures. Despite the increase in grain size, both FTIR and Hall effect measurements support the conclusion that changes in point defect concentration are the root cause of the observations. The composition analyses inferred from XPS show no evidence of oxygen or zinc stoichiometric modifications; therefore the change in carrier concentration can be attributed to extrinsic defects, most notably hydrogen atoms, which are believed to act as unintentional donors in n-type ZnO.

> "The reduction of cracks in the microcrystalline layers should result in better resistance of the modules to post-growth oxidation and in superior module performance under low-light conditions."

An evaluation of BZO and AZO front contact layers for use in a-Si/µc-Si tandem solar modules was carried out. Owing to its high transmission and good light-scattering properties, Inventux's standard BZO front contact displayed the highest efficiency. Efficiencies only marginally lower than those on BZO could be obtained on AZO substrates; however, slightly thicker top cells were needed to reach these values. Achieving higher transparency in the AZO layers, especially at shorter wavelengths, would boost the current in the device and allow the process to be more cost competitive. The fact that higher voltage values were attained on the AZO layers suggests that modification of the BZO morphology could allow more uniform crack-free layers to be produced, which would lead to higher voltages and fill factors. The reduction of cracks in the microcrystalline layers should result in better resistance of the modules to post-growth oxidation and in superior module performance under low-light conditions. SIMS measurements on post-growth treated BZO layers for various treatment durations indicate that is possible to lower the oxygen concentration in the intrinsic silicon layer by more than an order of magnitude [19]; treating BZO layers to induce a more rounded morphology, while at the same time maintaining the light-trapping characteristics of pretreated BZO, is a possible approach to increasing overall module efficiency and stability.

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References

[1] Shah, A. et al. 1997, "Recent progress on microcrystalline solar cells", *Proc. 26th IEEE PVSC*, Anaheim, California, USA, p. 569.

[2] Beyer, W. et al. 2010, "Annealing effects in LPCVD grown zinc oxide films", *Proc. 25th EU PVSEC*, Valencia, Spain, p. 3094.

[3] Pflug, A. et al. 2004, "Optical characterization of aluminum-doped zinc oxide films by advanced dispersion theories", *Thin Solid Films*, Vol. 455, p. 201.

[4] Fäy, S. et al. 2005, "Low pressure chemical vapour deposition of ZnO layers for thin-film solar cells: Temperature-induced morphological changes", *Solar Energy Mater. & Solar Cells*, Vol. 86, p. 385.

[5] Zhang, Y. et al. 2004, "Effect of annealing on ZnO thin films grown on (001) silicon substrate by low-pressure metalorganic chemical vapour deposition", *Semicond. Sci. Technol.*, Vol. 19, p. 755.

[6] Zhang, Y. et al. 2005, "Properties of ZnO thin films grown on Si substrates by MOCVD and ZnO/Si heterojunctions", *Semicond. Sci. Technol.*, Vol. 20, p. 1132.

[7] Huang, J. et al. 2007, "Microstructure and defect investigations of the as-grown and annealed ZnO/Si thin films", *J. Appl. Phys.*, Vol. 102, p. 053521.

[8] David, C. et al. 2011, "Microstructural and conductivity changes induced by annealing of ZnO:B thin films deposited by chemical vapour deposition", *J. Phys: Condens. Matter*, Vol. 23, p. 334209.

[9] Ellmer, K. 2001, "Resistivity of polycrystalline zinc oxide films: Current status and physical limit", *J. Phy. D: Appl. Phys.*, Vol. 34, p. 3097.

[10] Steinhauser, J. et al. 2007, "Transition between grain boundary and intragrain scattering transport mechanisms in boron-doped zinc oxide thin films", *Appl. Phys. Lett.*, Vol. 90, p. 142107.

[11] Ruske, F. et al. 2010, "Improved electrical transport in Al-doped zinc oxide by thermal treatment", *J. Appl. Phys.*, Vol. 107, p. 013708.

[12] Yamada, T. et al. 2010, "Ingrain and grain boundary scattering effects on electron mobility of transparent conducting polycrystalline Ga-doped ZnO films", *J. Appl. Phys.*, Vol. 107, p. 123534.

[13] Noh, J. et al. 2008, "Reversible change in electrical and optical properties in epitaxially grown Al-doped ZnO thin films", *J. Appl. Phys.*, Vol. 104, p. 073706.

[14] Duenow, J. et al. 2008, "Effects of hydrogen ambient and film thickness on ZnO:Al properties", *J. Vac. Sci. Technol. A*, Vol. 26, p. 692.

[15] Python, M. et al. 2009, "Influence of the substrate geometrical parameters on microcrystalline silicon growth for thin-film solar cells", *Solar Energy Mater. & Solar Cells*, Vol. 93, p. 1714.

[16] Python, M. et al. 2008, "Relation between substrate surface morphology and microcrystalline silicon solar cell performance", *J. Non-Cryst. Solids*, Vol. 354, p. 2258.

[17] Cuony, P. et al. 2010, "Mixed-phase p-type silicon oxide containing silicon nanocrystals and its role in thin-film silicon solar cells", *Appl. Phys. Lett.*, Vol. 97, p. 213502.

[18] Li, H. et al. 2009, "Structural defects caused by a rough substrate and their influence on the performance of hydrogenated nano-crystalline silicon n-i-p solar cells", *Solar Energy Mater. & Solar Cells*, Vol. 93, p. 338.

[19] Python, M. et al. 2010, "Microcrystalline silicon solar cells: Effect of substrate temperature on cracks and their role in post-oxidation", *Prog. Photovolt: Res. Appl.*, Vol. 18, No. 7, p. 491.

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Plasma-enhanced chemical vapour deposition of ZnO for photovoltaic TCO application

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ABSTRACT

In terms of material properties, plasma-enhanced chemical vapour deposition (PECVD) of ZnO has advantages over sputtering techniques, due to the variety of available precursors, and the different dopants for achieving certain levels of n-type and, controversially discussed, p-type transparent conductive oxides (TCOs) on various substrate materials. This paper considers the deposition of boron-doped zinc oxide for n-type TCO-application on substrates of dimensions up to 50×50cm² and at a temperature range of 50 to 450°C using a PECVD reactor with a plasma frequency of 13.56MHz. The materials' characteristics such as transparency, carrier concentration and structural properties are discussed as a function of the deposition parameters. The deposition temperature strongly affects the crystallographic and morphological appearance of the deposited thin films, which was investigated using field emission scanning electron microscope (FESEM) and X-ray diffraction (XRD) methods. The electronic band structure-dependent characteristics were studied using ultraviolet-visible (UV-vis) spectroscopy and Hall measurements. Secondary ion mass spectrometry (SIMS) measurements complete the characterization methods for qualitatively verifying the incorporation of dopants and impurities. Results are reported for columnar-grown boron-doped ZnO with optical transparency greater than 80% in the visible range and a maximum carrier concentration of 10^{20}cm^{-3}.

Introduction

Transparent conductive oxides (TCOs) are known for their use as electrode materials for thin-film photovoltaic devices and other optoelectronics. Their unique properties of sufficiently high electrical conductivity while maintaining high transparency in wide spectral ranges, combined with further enhancing benefits such as stray-light tailoring, have stimulated significant increasing efforts in scientific and technological research. Materials commonly used as TCOs are ITO, SnO_2:F and ZnO:X. Doping zinc oxide with group 13 elements (Al or B) leads to n-type conductivity that is widely known and used [1–3]. To achieve p-type conductivity, many investigations are based on dopants of group 15 elements (N or P) [4–6] or co-doping of group 13 and group 15 elements [7,8] for tailoring the electronic band structure. But, so far, no long-term stable and reproducible results have been demonstrated; in contrast, fundamental physical research supports the assumption that p-type conductivity of ZnO is not feasible [9]. Due to the rising costs of indium, ZnO is increasingly used instead of ITO in photovoltaic TCO applications.

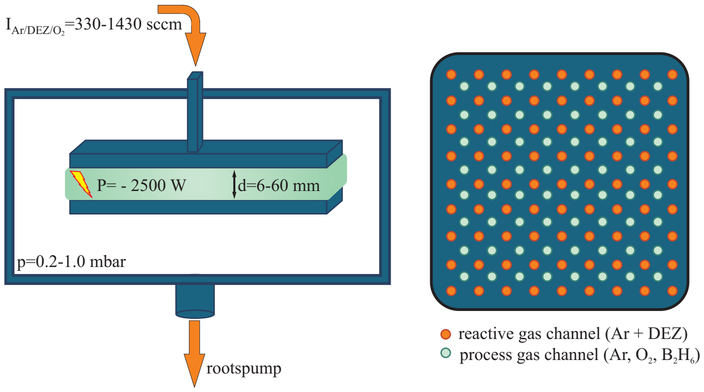

Figure 1. Schematic drawing of the PECVD reactor (left), and a top view of the two-channel direct gas distribution electrode (right).

The deposition of ZnO is carried out by means of a wide variety of physical and chemical methods. Industrially proven techniques are widely and abundantly reported: sputtering, reactive sputtering [2] and chemical vapour deposition (CVD) [10–12]; some wet chemical deposition approaches (e.g. sol-gel [1]); and more scientifically and educationally oriented methods such as molecular beam epitaxy [13], pulsed laser deposition [7], ultrasonic spray pyrolysis [14] and atomic layer deposition [15]. Among these methods, magnetron sputtering and metal organic CVD (MOCVD) are the main techniques for growing ZnO thin films applied to thin-film silicon solar cells [10]. The CVD methods can be classified into two groups: the first comprises the thermal CVD methods, which cover thermally driven reaction kinetics; the second includes the plasma-enhanced methods (e.g. PECVD). Plasma enhancement enables processes to take place below the usual temperatures for chemical reactions [16]. Lower deposition temperatures allow temperature-sensitive substrates such as polymeric foils to be used or the thermal exposure of heterojunction solar cell systems to be minimized. The main process parameters that influence the film properties encompass plasma parameters and chemical reactance flow, as well as the reaction conditions: process pressure and substrate temperature. By adjusting these parameters, the film conductivity and transparency properties, as well as the film morphology, roughness and microstructure, can be varied. The careful preselection of the precursors affects the species formed in the plasma during the process and therefore affects the chemical reaction in the plasma and the film properties.

Deposition set-up

The plasma reaction chamber at Fraunhofer IKTS is part of a plasma CVD tool manufactured by Roth&Rau Microsystems

Parameter	Lower limit	Upper limit
Electrode distance	8mm	60mm
Chamber pressure	0.1mbar	1mbar
O_2:DEZ	0.5	10
Plasma power	50W	2500W
DEZ flow	20 sccm	80 sccm
Substrate temperature	50°C	450°C

Table 1. List of basic process parameters for PECVD deposition of ZnO.

> "To achieve a homogeneous plasma reaction over the whole substrate, the ratio of carrier gas (argon), process gas (oxygen) and reactive gas (zinc precursor diluted in argon) plays a key role."

(Meyer Burger AG). The tool is equipped with a parallel plate electrode assembly (similar to a plate capacitor): the substrate is placed at the bottom electrode and the upper electrode consists of a unique separate gas inlet system (Fig. 1). This gas inlet is designed to avoid the reaction of the educts before being injected into the plasma and ensures that the whole reaction to ZnO begins in the reaction chamber. Using highly reactive precursors such as diethyl zinc (DEZ, $Zn(CH_5)_2$) requires these particular design features in order to prevent a premature chemical reaction in the gas inlet. DEZ is a fluid under normal conditions, and therefore a bubbler set-up is necessary, in which a carrier gas (argon) is passed through the DEZ. The diluted amount of DEZ in argon, and thus the precursor flow in the plasma chamber, is controlled via an argon flow through the bubbler at a certain temperature and specific pressure according to the calculated vapour pressure.

The construction of the chamber (shown schematically in Fig. 1) allows the adjustment of the distance between substrate and showerhead from 6 to 60mm. The substrate sizes can be freely chosen up to 50×50cm^2; depending on the adjustable distance, even substrates thicker than common glass or silicon wafers can be used. All the results reported here pertain to ZnO thin films deposited on n-type silicon substrates at 50W plasma power. The plasma chamber is equipped with a 13.56MHz RF generator, which can be exchanged to provide higher (up to 40 or 100MHz) or lower frequencies. For μc-Si thin-film deposition, higher frequencies lead to higher deposition rates [17,18]; carrying this over to TCO deposition is currently the subject of ongoing research. For the PECVD process, the careful control of process parameters, particularly the electrode distance, strongly influences the deposition rate as well as homogeneity and therefore the economic aspects. To achieve a homogeneous plasma reaction over the whole substrate, the ratio of carrier gas (argon), process gas (oxygen) and reactive gas (zinc precursor diluted in argon) plays a key role. Controlling the applied plasma power and reactor pressure increases the field of parameters but narrows down the process window for appropriate film characteristics.

The possible process conditions for deposition of ZnO with this equipment are summarized in Table 1. Optical emission spectroscopy (OES) and monitoring of the bias voltage facilitates feedback and control of the plasma process. The OES spectra examine light emissions of excited ions that are representative for certain species. Thus, plasma chemical reactions can be deduced as reported by Groenen et al. [19] and the relative density of the species (e.g. Zn) can be calculated as reported by Robinson et al. [20]; from this, a set of parameters can be estimated. The characteristics of the plasma can be indirectly assessed from the bias voltage, which expresses a complex interaction between plasma power, gas flow and geometry of the plasma volume. Therefore, the bias voltage has to be stable over the process time and, for reproducibility, over every single deposition.

Film deposition

In order to deposit zinc oxide during PECVD, a plasma power of at least 50W is required, otherwise no reaction between the metal organic precursor and oxygen is observable, even at temperatures up to

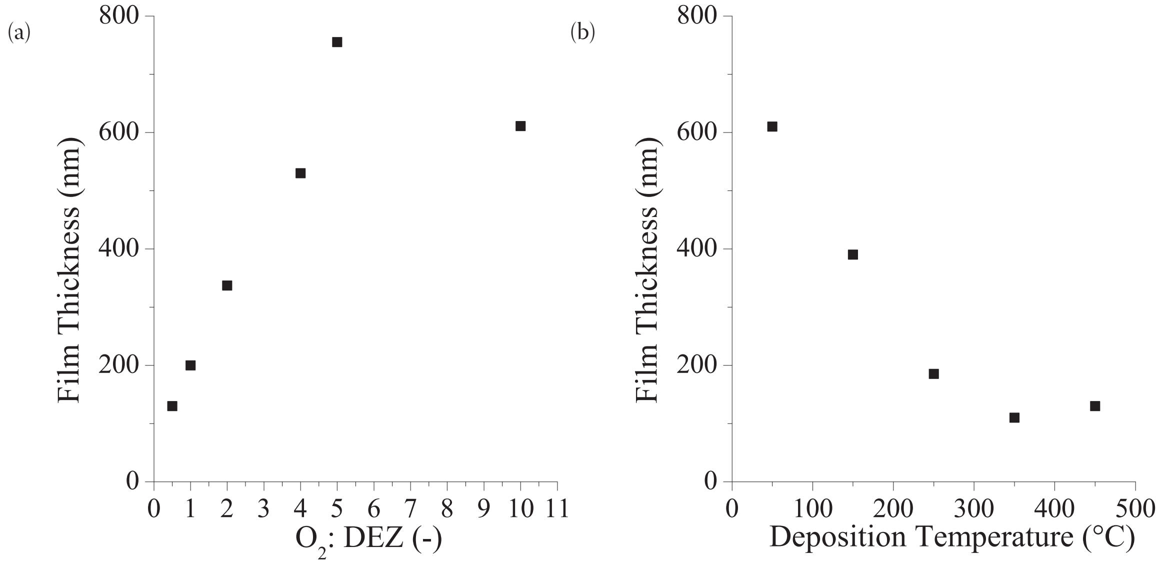

Figure 2. ZnO thickness of undoped films for (a) different O_2:DEZ ratios (at T=300°C), and (b) different substrate temperatures (for O_2:DEZ ratio of 0.5). A higher oxygen flow increases the deposition rate, and higher substrate temperatures lead to lower deposition rates.

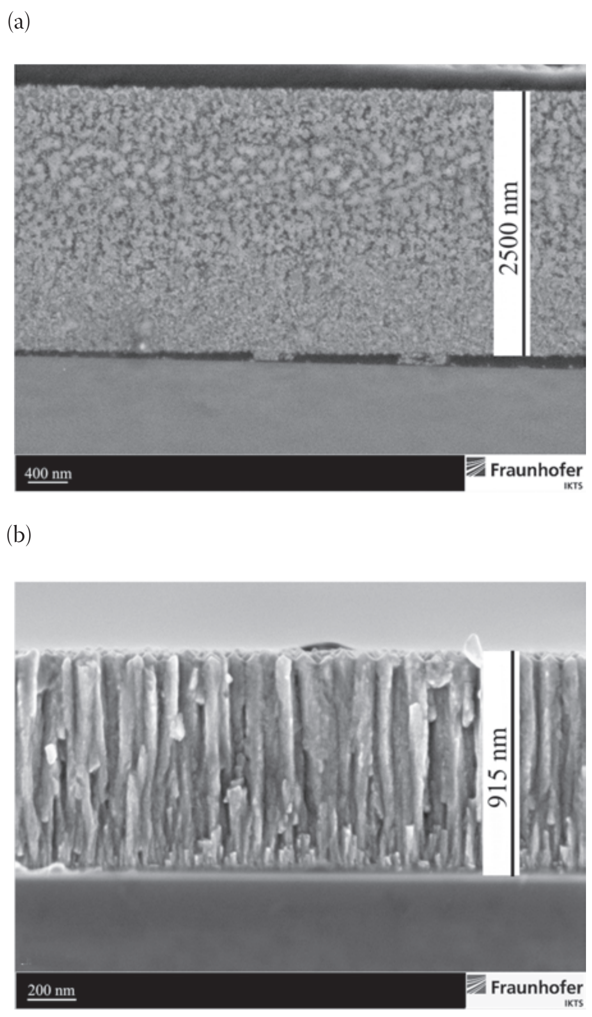

Figure 3. FESEM images of fractured surfaces of undoped ZnO films deposited at temperatures of (a) 50°C and (b) 350°C. Columnar grain growth is revealed at elevated temperatures.

450°C. In CVD processes that use other oxygen sources (e.g. water), this is reported differently in the literature [12]. For thermal expanding plasma CVD processes, Groenen et al. [19] reported that the main reactions (1) and (2) can be expected, driven by charge exchange with argon ions and a dissociative recombination with electrons:

$$Zn(C_2H_5)_2 + 5O_2 \rightarrow 4CO + 5H_2O + ZnO \quad (1)$$
$$Zn(C_2H_5)_2 + 7O_2 \rightarrow 4CO_2 + 5H_2O + ZnO \quad (2)$$

Therefore, an excess of oxygen is necessary to obtain high-quality ZnO films and economic deposition rates. For different ratios of O_2:DEZ, the film thickness increased with increasing amounts of oxygen (Fig. 2a) up to a ratio of 5, and then reached a plateau. When all other process parameters were kept constant, the film thickness decreased with increasing substrate temperature (Fig. 2b).

In a substrate temperature range of 50 to 450°C, the deposition rate, film morphology and microstructure changed dramatically. Low substrate temperatures resulted in high deposition rates, but the deposited films were of low quality and had high porosities (Fig. 3a). Spectroscopic ellipsometry measurements on these porous films reflected the low quality by a low dispersion coefficient *n* less than 1.8. They mainly consisted of nm-scaled and irregularly orientated crystallites. When temperatures rose above 350°C, the ZnO films were deposited uniformly with low porosities and typical columnar grain growth (Fig. 3b), and a dispersion coefficient *n* greater than 1.95.

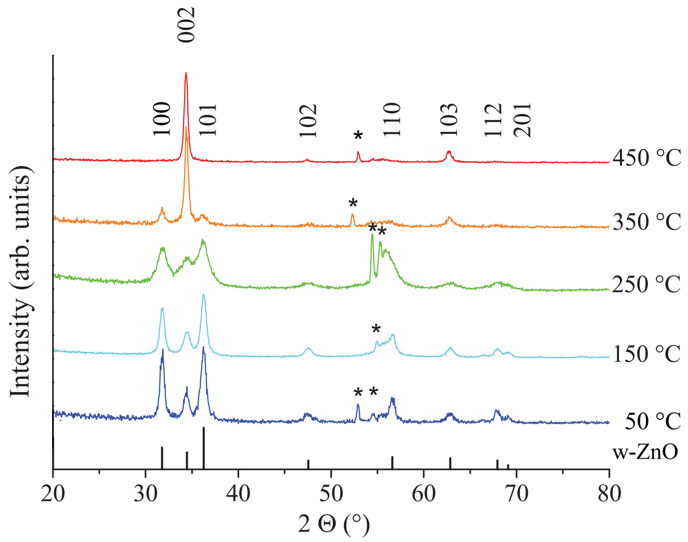

Figure 4. XRD patterns of undoped ZnO layers deposited at different substrate temperatures (for O_2:DEZ ratio of 0.5). Above 250°C, the change in crystal orientation from irregular (powder-like) to the preferred orientation of the c-axis perpendicular to the substrate surface is indicated by an increase of the relative intensity of the 002 reflection. Some silicon reflections, caused by the recording geometry, are visible and indicated by asterisks.

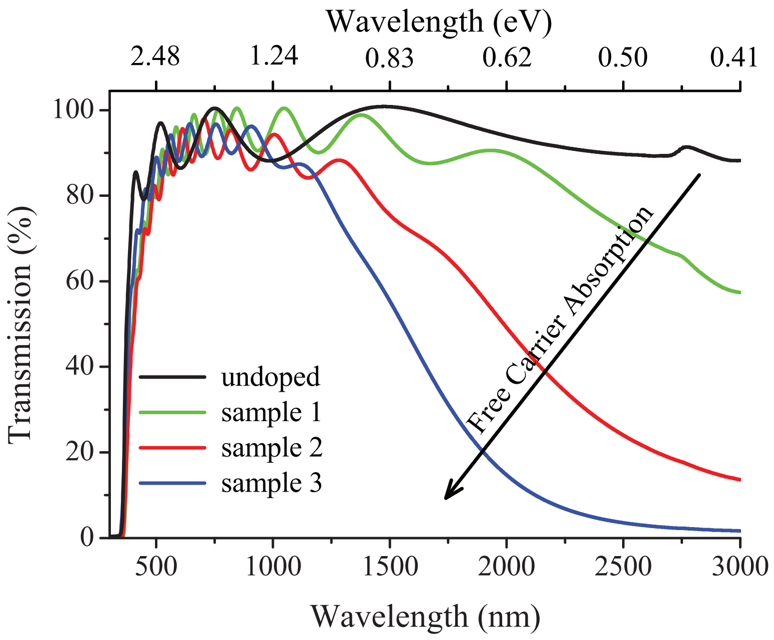

Figure 5. UV-vis transmission measurements of ZnO:B samples. Absorption in the IR region rises with increasing dopant flow, due to the free-carrier absorption.

> "Low substrate temperatures resulted in high deposition rates, but the deposited films were of low quality and had high porosities"

The influences of the substrate temperature on crystal growth direction, crystal habit and preferred orientation were measured using X-ray diffraction (XRD) at grazing incidence (1°). Fig. 4 shows the XRD patterns of a specimen series deposited at different temperatures: a strong crystal orientation with the c-axis perpendicular to the substrate surface at temperatures above 350°C is evident. The XRD patterns below a deposition temperature of 350°C all revealed Bragg reflections of hexagonal wurtzite-structured ZnO powder (according to PDF 00-36-1451 [21]). The crystals were deposited with relatively small crystallite sizes in a randomly orientated fashion, in agreement with the XRD results and the film microstructure (Fig. 3a).

Boron doping

The doping of TCO requires precise control of impurities as well as of dopant flow; otherwise, the transparency and resistivity of the films cannot be reproduced. Therefore, at Fraunhofer IKTS, all gases used in the CVD reactors are of high purity – at least grade 5.0 (99.999%), but usually grade 6.0 (99.9999%), is used. As the dopant source, diborane (B_2H_6) diluted to 2 vol% in argon was injected in various amounts into the plasma through the oxygen channel. High carrier concentrations (> 10^{19}cm^{-3}) in the films were confirmed for B_2H_6:(DEZ+O_2) ratios of 0.05 (sample 1), 0.125 (sample 2) and 0.25 (sample 3), and verified independently by Hall measurements and by analyzing the ultaviolet-visible (UV-vis) spectra by using the Drude model for free-carrier absorption (Fig. 5), as well as by an analysis of the Burstein-Moss shift (Fig. 6).

The carrier concentrations are summarized in Table 2 and agree with results reported in the literature

	Film thickness [nm]	B_2H_6:(DEZ+O_2)	Carrier concentration [cm^{-3}]		
			Burstein-Moss shift	Drude model	Hall measurements
Undoped	420	0	n/a	n/a	n/a
Sample 1	1090	0.05	> 5.0*10^{19}	1.1*10^{20}	n/a
Sample 2	1090	0.125	> 5.6*10^{19}	3.7*10^{20}	9.8*10^{19}
Sample 3	900	0.25	> 1.3*10^{20}	6.5*10^{20}	1.8*10^{20}

Table 2. Comparison of carrier concentrations derived from the UV-vis spectra and Hall measurements for three samples of varying film thicknesses and different dopant ratios (T=350°C, P=50W).

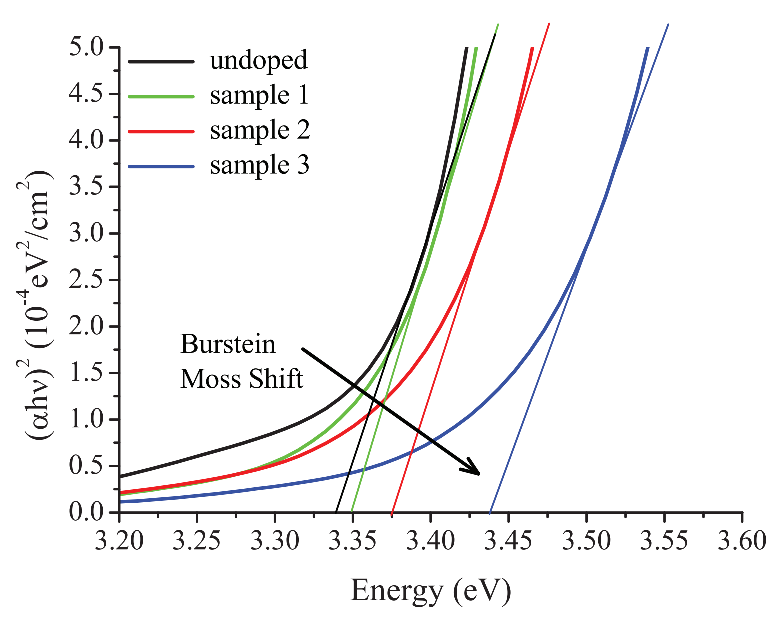

Figure 6. Tauc plot of ZnO:B samples calculated from the UV-vis data in Fig. 5. Note the blue shift of the fundamental band edge (Burstein-Moss shift) with increasing diborane flow.

[3,7,10,22]. The presence of boron throughout the whole ZnO layer was determined qualitatively from SIMS measurements (Fig. 7). The layers consist of a homogeneous distribution of boron over the entire film thicknesses, but a comparison of sample 1 and sample 3 indicates that the overall content of boron differs depending on the boron flow rate during deposition. All results shown were collected on specimens deposited under identical conditions of a substrate temperature of 350°C and an O_2:DEZ ratio of 1: higher carrier concentrations with higher boron content are therefore emphasized.

The strong 002 reflection refers to the growth in the c-axis perpendicular to the substrate surface (Fig. 8). The intensity of the 103 reflection compared to the 002 reflection and the shift of the 2Θ position may indicate an influence of the boron incorporated into the lattice. Investigations to clarify this fact are currently in progress.

> "The main parameter influencing the film morphology and crystal orientation was the deposition temperature."

Conclusion

Homogenous thick crystalline ZnO:B transparent thin films were deposited in a PECVD chamber by a reaction of diethyl zinc with an excess of oxygen in a capacitively coupled argon plasma. Both reaction gases were separately injected into the plasma by a two-channel showerhead. The dopant source B_2H_6 was transported through the oxygen channel in various quantities. Plasma power and electrode distance were optimized to 50W and 16mm, respectively. It was found that the deposition rate was strongly influenced by

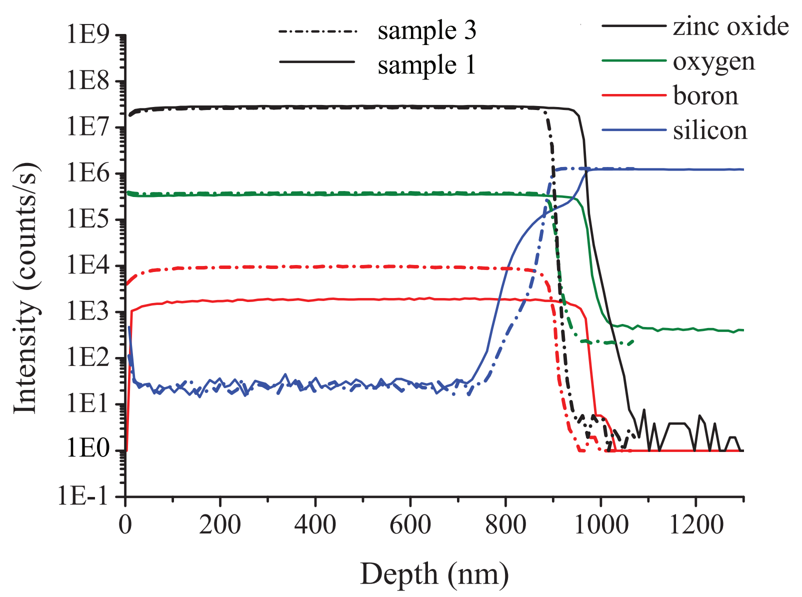

Figure 7. SIMS measurements for sample 1 (continuous line) with a 0.05 (low dopant flow) boron ratio, and for sample 3 (dashed line) with a 0.25 (high dopant flow) boron ratio. The elemental distribution as a function of ZnO layer depth was recorded. Concentrations of different elements are not comparable.

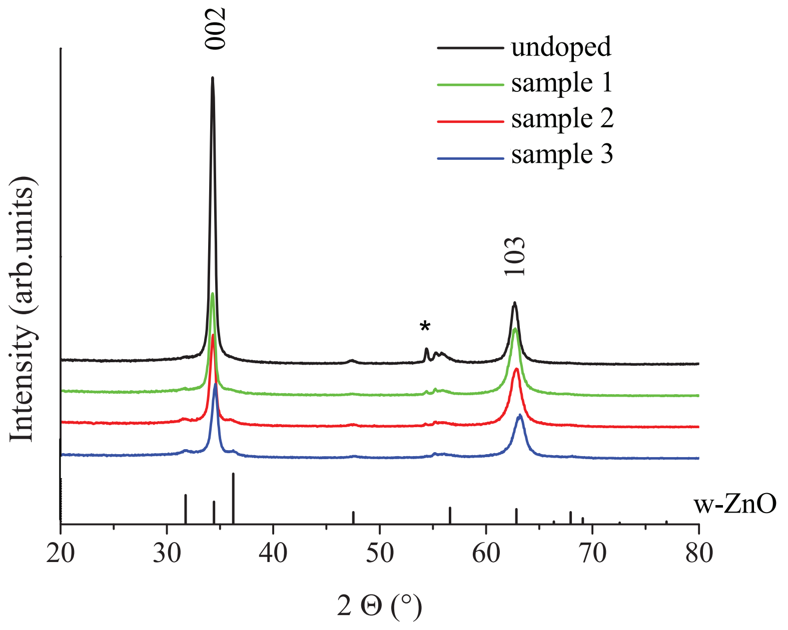

Figure 8. Comparison of the XRD measurements of an undoped sample (black line) with those of samples 1–3. The intensities are normalized to the 103 reflection in order to show more clearly how the relative intensity ratio of the 002 to 103 reflection changes with boron content.

the ratio of O_2:DEZ and by the deposition temperature. A higher temperature decreased the deposition rate, whereas the deposition rate was increased up to the stoichiometric ratio of DEZ and oxygen according to the main reaction in Equations (1) and (2).

The main parameter influencing the film morphology and crystal orientation was the deposition temperature. Above a substrate temperature of 350°C, columnar grain growth with a preferred orientation of the c-axis of hexagonal wurtzitic ZnO perpendicular to the substrate surface was revealed. The resulting boron-doped films exhibited a high carrier concentration of greater than 10^{19}cm^{-3}, which was homogenously distributed in the layer over the whole film depth. An optical transparency of greater than 80% in the visible region was demonstrated by UV-vis spectroscopy.

Acknowledgements

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References

[1] Kumar, V. et al. 2011, "Structural, transport and optical properties of boron-doped zinc oxide nanocrystalline", *J. Mater. Sci. Technol.*, Vol. 27, No. 6, pp. 481–488.

[2] Gao, L. et al. 2011, "Boron doped ZnO thin films fabricated by RF-magnetron sputtering", *Appl. Surf. Sci.*, Vol. 257, pp. 2498–2502.

[3] Addonizio, M.L. et al. 2008, "Doping influence on intrinsic stress and carrier mobility of LP-MOCVD-deposited ZnO:B thin films", *Solar Energy Mater. & Solar Cells*, Vol. 92, pp. 1488–1494.

[4] Jiang, J. et al. 2008, "Effects of phosphorus doping source temperatures on fabrication and properties of p-type ZnO thin films", *Mater. Lett.*, Vol. 62, pp. 536–538.

[5] Xu, W. et al. 2004, "Low pressure MOCVD growth of p-type ZnO thin films by using NO as the dopant source", *J. Crystal Growth*, Vol. 265, pp. 133–136.

[6] Pan, X.H. et al. 2008, "Electrical and optical properties of phosphorus-doped p-type ZnO films grown by metalorganic chemical vapor deposition", *J. Appl. Phys.*, Vol. 103, p. 023708.

[7] Liu, G.X. et al. 2008, "Boron and nitrogen co-doped ZnO thin films for opto-electronic applications", *Ceramics Int.*, Vol. 34, pp. 1011–1015.

[8] Kumar, M. et al. 2009, "Formation of Al–N co-doped p-ZnO/n-Si (1 0 0) heterojunction structure by RF co-sputtering technique", *Appl. Surf. Sci.*, Vol. 256, pp. 1329–1332.

[9] Lyons, J.L. et al. 2009, "Why nitrogen cannot lead to p-type conductivity in ZnO", *Appl. Phys. Lett.*, Vol. 95, p. 252105.

[10] Chen, X.L. et al. 2007, "Boron-doped zinc oxide thin films for large-area solar cells grown by metal organic chemical vapor deposition", *Thin Solid Films*, Vol. 515, pp. 3753–3759.

[11] Myong, S.Y. et al. 2007, "Temperature dependence of the conductivity in large-grained boron-doped ZnO

films", *Solar Energy Mater. & Solar Cells*, Vol. 91, pp. 1269–1274.

[12] Faÿ, S. et al. 2007, "Opto-electronic properties of rough LP-CVD ZnO:B for use as TCO in thin-film solar cells", *Thin Solid Films*, Vol. 515, pp. 8558–8561.

[13] Look, D.C. et al. 2002, "Characterization of homoepitaxial p-type ZnO grown by molecular beam epitaxy“, *Appl. Phys. Lett.*, Vol. 81, No. 10, pp. 1830–1832.

[14] Zhang, C. 2004, "Structural and electrical properties of nitrogen and aluminum codoped p-type ZnO films", *Solid State Commun.*, Vol. 132, pp. 75–78.

[15] Krajewski, T. et al. 2009, "The influence of growth temperature and precursors' doses on electrical parameters of ZnO thin films grown by atomic layer deposition technique", *Microelectron. J.*, Vol. 40, pp. 293–295.

[16] Shimizu, M. et al. 1985, "Growth of ZnO films by the plasma-enhanced metalorganic chemical vapor deposition technique", *J. Crystal Growth*, Vol. 71, pp. 209–219.

[17] Shah, A. et al. 2000, "Intrinsic microcrystalline silicon (μc-Si:H) deposited by VHF-GD (very high frequency-glow discharge): A new material for photovoltaics and optoelectronics", *Mater. Sci. & Eng.*, Vol. B69–70, pp. 219–226.

[18] Smets, A.H.M. et al. 2006, "Optimization of the high rate microcrystalline silicon deposition conditions of the multi-hole-cathode very high frequency SiH_4/H_2 plasma", *Conf. Record 2006 IEEE 4th World Conf PV Energy Conv.*, Vol. 2, pp. 1592–1595.

[19] Groenen, R. et al. 2005, "Plasma processes and film growth of expanding thermal plasma deposited textured zinc oxide", *Plasma Process. Polym.*, Vol. 2, No. 8, pp. 618–626.

[20] Robbins, L.J. et al. 2001, "An investigation of the plasma chemistry involved in the synthesis of ZnO by PECVD", *J. Electrochem. Soc.*, Vol. 150, No. 10, pp. C693–C698.

[21] McMurdie, H.F. et al. 1986, "Methods of producing standard X-ray diffraction powder patterns", *Powder Diffraction*, Vol. 1, p. 76.

[22] Faÿ, S. et al. 2007, "Polycrystalline ZnO:B grown by LPCVD as TCO for thin film solar cells", *Thin Solid Films*, Vol. 515, pp. 8558–8561.

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Critical subsystems for thin-film PV manufacturing equipment

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ABSTRACT

Sales of critical subsystems used in thin-film PV manufacturing equipment are expected to reach $324M in 2011, and the outlook is for this figure to grow by 3.74% in 2012 to $336M. This expectation is going against the trend for the industry as a whole, which is predicted to decline next year as revenues from cell and module manufacturing weaken. The reason for this countermovement is the opportunities available to manufacturers who are willing to invest in the latest thin-film PV equipment to drive down costs and force unprofitable competitors out of business. While the same opportunities exist for crystalline silicon manufacturing, the number of well-resourced companies signalling their intention to invest in thin-film technologies should ensure a positive year for suppliers of equipment and critical subsystems to this segment of the industry.

The critical subsystems market

Critical subsystems are products that have been designed to address specific applications within the semiconductor and related manufacturing industries and actively affect the processing and handling of substrates. They are high-technology and high-value products, and a well-defined group of companies has emerged to serve this market. A defining feature of this market is the level of dependency that equipment companies have on these suppliers for technology developments which enable them to develop the next-generation process tools. The semiconductor industry is clearly the largest market, but in recent years the photovoltaic industry has evolved from being one of several niche thin-film manufacturing industries to become the third-largest market for critical subsystems, just behind the flat-panel display industry. The latter is now fully mature and its growth prospects are limited, so it will not be long before the photovoltaic industry becomes the second-largest market for critical subsystems.

In 2011 the total market for critical subsystems is expected to reach $7.7Bn, just beating the peak value of $7.3Bn achieved in 2000. Critical subsystems for all photovoltaic applications will account for just under 10% of the total at $740M, which is quite an achievement considering the value of critical subsystems sold into the photovoltaic industry was only $10M in 2000. Of the $740M likely to be sold this year, $324M relates to equipment for thin-film PV manufacturing.

> "It will not be long before the photovoltaic industry becomes the second-largest market for critical subsystems."

The main subsystems technologies used are fluid management, integrated process diagnostics, process power, thermal management, vacuum subsystems, substrate handling and other subsystem technologies. The largest segment is for vacuum subsystems, which includes vacuum pumps, pressure gauges and abatement subsystems, and represents 37% of the total in 2011 with a value of $120M. The next largest segment is for process power subsystems, which includes RF, DC and microwave power supplies, matching networks, and fluorine gas generators, and represents 19% of the market at $60M.

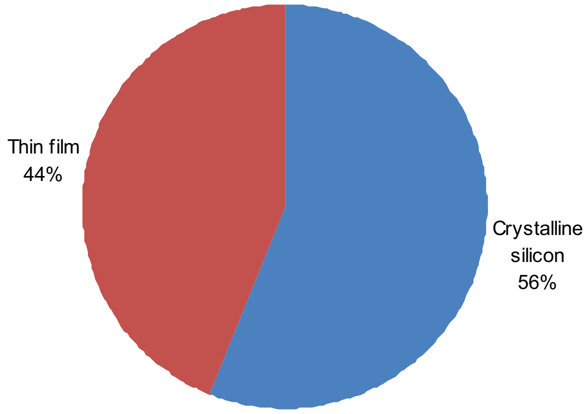

Figure 1. Sales of critical subsystems by cell technology in 2011 ($740M).

In 2012 sales of critical subsystems into the thin-film PV manufacturing industry are expected to grow 3.74% to a value of $336M. The top suppliers of critical subsystems to the PV industry are Advanced Energy, Alcatel (now part of Pfeiffer Vacuum), Edwards, Horiba, and MKS Instruments.

Thin-film manufacturing

The photovoltaic industry, like much of the global economy, is having some difficulties right now and this is forcing change in the industry. There is a strong argument that photovoltaics is now in the third phase of the industry lifecycle, which is all about reducing cost and eliminating unproductive players. This process is becoming clearer as the dominant technologies are emerging and the benefits of economies of scale have been established. The outcome is that smaller players are being acquired or exiting the market and new entrants will be, for the most part, restricted to well-resourced companies. For suppliers of thin-film PV panels this is a very interesting time. Over 30% of PV manufacturers are engaged in the manufacture of thin-film panels, yet as a group they only account for 20% of industry sales. This means that there has to be realignment with the rest of the industry soon. This is already becoming apparent because some of the smaller participants have already exited the market as they run out of time to prove their commercial viability. The highest-profile casualty to date has been Solyndra and, with several others

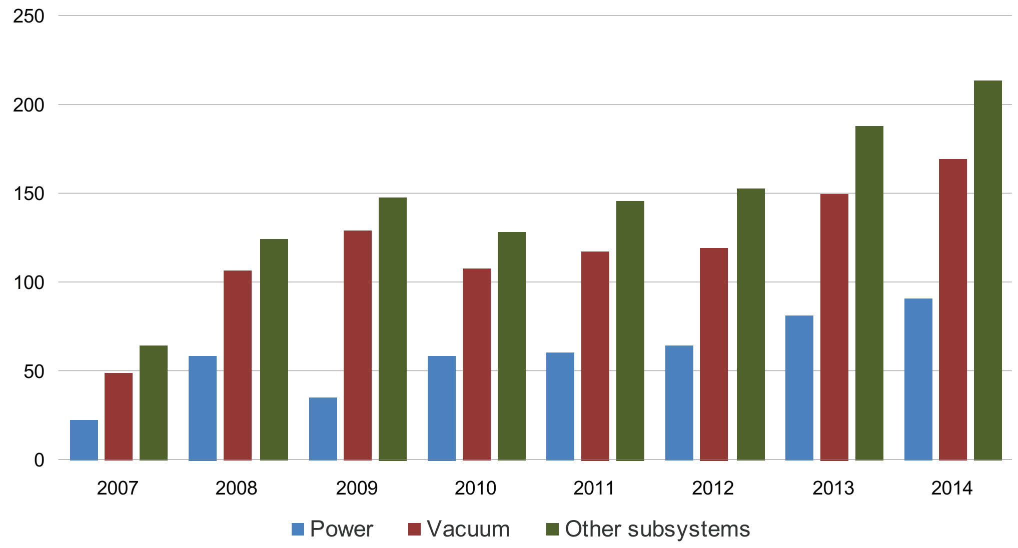

Figure 2. Sales of critical subsystems for thin-film PV equipment 2007–2014 ($M).

at risk, there could be as much as 400MWp of thin-film capacity retired in 2011.

> “The demand for critical subsystems will grow faster than the PV equipment market as a whole.”

While this is sending shockwaves throughout the industry as a whole, it should be noted that First Solar, a thin-film PV manufacturing company, actually has the best track record on profitability of any cell and module manufacturer of any cell technology. This fact has attracted new entrants to the market despite concerns about overcapacity. Last year Solar Frontier came in with a huge 900MWp investment at its CIS fab in Japan, and TSMC are ramping up capacity of their CIGS fab in Taiwan. In addition GE has announced its intention to expand its CdTe fab to 400MWp in the next few years. The list of well-resourced companies with proven thin-film technology extends to around a dozen companies, all of which are scheduled to invest next year and are likely to be in the market for the long term. This is good news for suppliers of critical subsystems, as the proportion of critical subsystems sales per $ spent on thin-film PV manufacturing equipment is higher than that for crystalline silicon. As a result the demand for critical subsystems will grow faster than the PV equipment market as a whole.

Thin-film equipment suppliers

The thin-film PV equipment market is split into two major segments: silicon thin film and non-silicon thin film. Currently, the silicon thin-film PV equipment market is the largest segment, with equipment sales expected to exceed $1100M in 2011. However, silicon thin-film technology has struggled to compete against the steep price declines of crystalline silicon modules for several years. This is unfortunate as silicon thin-film technology has great potential. It is interesting to note that the industry would have been very different if the silicon thin-film equipment suppliers could have brought their technology roadmap forward by just 18 months. As it is, silicon thin film has been just one step behind the cost curve and for this reason it takes second place to crystalline silicon. Accelerated product development at Oerlikon and other equipment suppliers should put this technology back into contention for 2012, assuming that prices for crystalline silicon modules do not collapse. However,

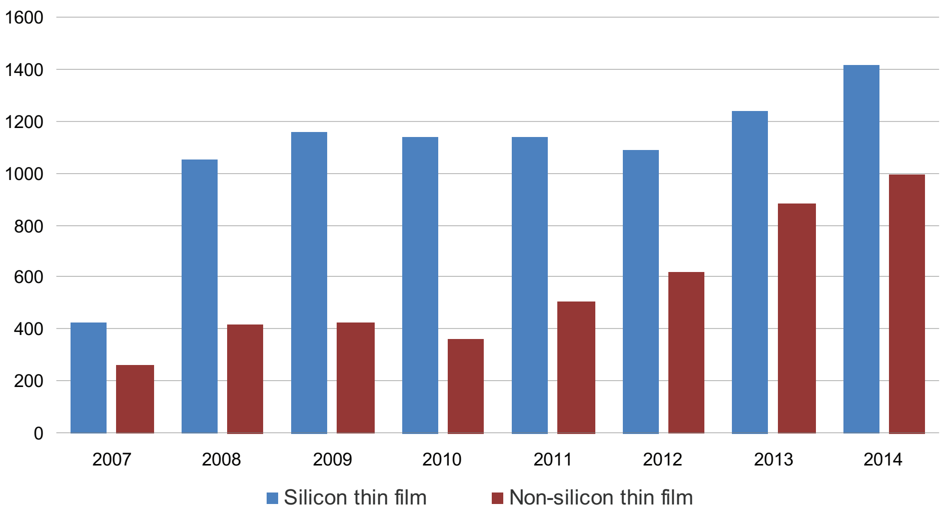

Figure 3. Sales of thin-film PV equipment 2007–2014 ($M).

demand for silicon thin-film equipment in 2012 is dependent on what happens with Hanwa and its plans to complete the investment in its 1GW plant in China. So far, the first phase has been completed and over $400M of equipment has been installed. What happens next depends on how successful Hanwa is in ramping up production and finding large customers. The major suppliers of vacuum processing equipment for silicon thin-film manufacturing are Oerlikon Solar, Ulvac, Jusung and Apollo Solar.

The market for non-silicon thin-film PV manufacturing equipment, on the other hand, is relatively small at $500M. This figure is set to grow in 2012 as First Solar continues to invest and some of the new entrants start to spend heavily. The non-silicon thin-film market is different in that much of the equipment supplied is designed to the panel manufacturer's specifications. This means that there is a relatively large part of the market which is served by captive suppliers. This is something of a problem for equipment suppliers, as it reduces the size of their addressable market, but from the critical subsystems suppliers' perspective this does not matter, as they sell to both captive and merchant markets. The major vacuum processing equipment vendors for non-silicon thin-film manufacturing are centrotherm photovoltaics and Von Ardenne Anlagantechnik.

Conclusion

The photovoltaic equipment industry has undergone explosive growth in recent years to become a significant market which will exceed a value of $7.3Bn in 2011 (excludes polysilicon, ingot and wafering equipment). Suppliers of subsystems and components have been major beneficiaries, as the growth will result in sales of $740M this year and has helped to offset their reliance on the semiconductor and flat-panel display industries. While thin-film PV manufacturing equipment makes up only 22% of the cell and module PV equipment market, it accounts for just under half of the demand for critical subsystems. This is because thin-film PV manufacturing is vacuum process intensive and as such requires more critical subsystems per $ of capital expenditure than crystalline silicon manufacturing.

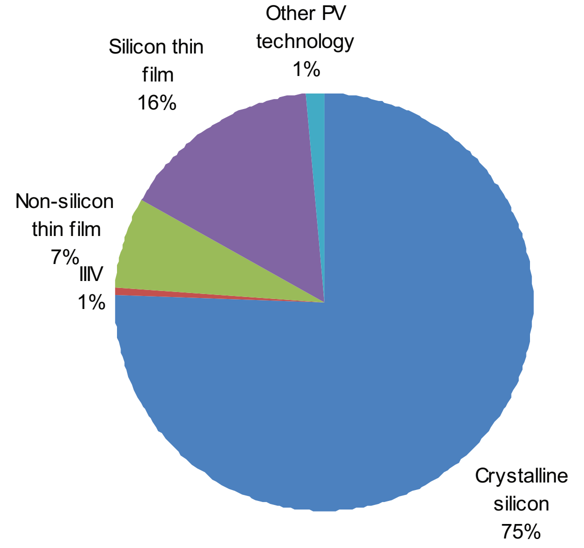

Figure 4. Cell and module manufacturing equipment by cell technology 2011 ($7.3Bn).

Uncertainty in the financial markets is currently tempering the growth in all the PV markets. End demand for PV cells has weakened, and the reduced access to finance has caused the less profitable PV cell and module manufacturers to pull back on their original expansion plans. However, the winners in this industry will be those companies that continue to invest when the market is weak. This means that 2012 will be the year when upgrading existing capacity, and investing in leading-edge manufacturing equipment, will drive demand rather than pure capacity expansions.

> "The likely scenario for next year, despite the threat of falling revenues, is for the profitable and well-resourced companies to invest to stay competitive."

Forecasting the equipment market is difficult, as demand for cells and modules is primarily driven by government targets. Nevertheless, one aspect of the PV industry has been relatively constant and that is the growth in demand in terms of shipments in MWp. This demand has increased continuously over the past 10 years at double-digit rates, even during the financial crisis in 2009. The message is that demand for PV modules and panels in MWp is growing and is set to continue to do so throughout 2012. However, this growth comes at a cost, and this cost is lower revenue growth. The dilemma facing the industry is how to stay profitable as prices fall. It is clear that those companies that are not profitable at today's prices are not going to be profitable at next year's prices unless they invest in new manufacturing technology. The likely scenario for next year, despite the threat of falling revenues, is for the profitable and well-resourced companies to invest to stay competitive. Overall, capital expenditure on equipment is expected to fall by at least a quarter in 2012, although demand for thin-film equipment is predicted to grow modestly by around 3%. This in turn will drive growth of 3.74% for critical subsystems used in thin-film PV manufacturing equipment.

About the Author

John West is the managing director of VLSI Research Europe, a firm focused on market research and economic analysis of technical, business and economic aspects within the photovoltaic, semiconductor, nanotechnology and related industries. He has been analyzing the PV capital equipment market since 2006.

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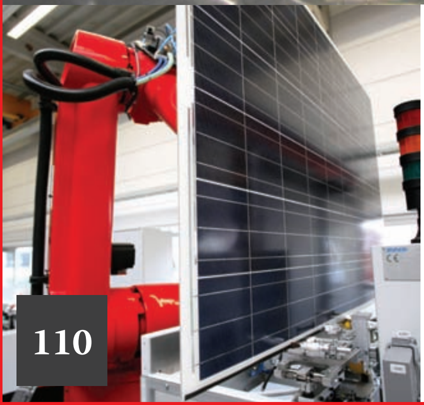

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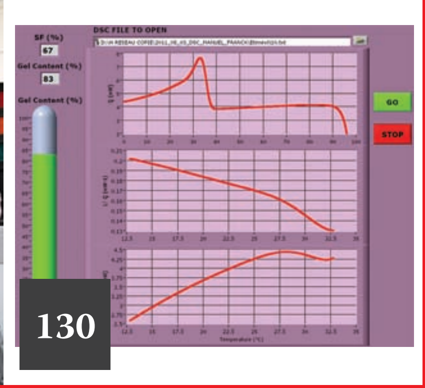

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IMS Research: PV module manufacturing capacity hits 50GW in 2011

After several years of aggressive PV module manufacturing capacity expansions, market research firm IMS Research has reported that global capacity will have reached an astonishing 50GW in 2011. This is especially surprising in light of actual demand this year only growing by 19% to 23GW and an increased capacity of more than 54%.

With a range of market forecasts projecting only a small increase in growth in end-user demand for 2012, IMS said that wafer, cell and module production capacity expansions would slow dramatically in response to the massive oversupply situation. IMS has predicted around 10% growth for 2012.

Sam Wilkinson, report author and senior research analyst at IMS Research, commented, "A number of manufacturers have recently announced suspended production or closure of production facilities… With the supply of these products exceeding demand by such a margin, top-tier branded cells and wafers are available at incredibly low prices and many suppliers are favouring purchasing cells and wafers on the spot market over manufacturing them internally."

This shift towards purchasing cheaper cells and wafers is behind the recent series of polysilicon and wafer contract cancellations. Not surprisingly, IMS noted that many smaller tier-3 Chinese suppliers are ceasing production completely.


Source: Solarbuzz

IMS Research reports global capacity will have reached an astonishing 50GW in 2011, especially in light of actual demand this year only growing by 19% to 23GW

Business News Focus

Suntech surprises with early Q3 preliminary financial results

The world's largest solar module manufacturer issued early preliminary third-quarter results and provided a meagre insight into job losses and restructuring of manufacturing operations in the face of significant overcapacity within the industry.


Source: Suntech

Suntech's Dr. Shi announced that the company is the reduction of operating expenses by at least 20% in 2012.

Suntech said that Q3 shipments were expected to have risen by 15% over the previous quarter, with revenue above US$800 million. Gross margin is expected to be approximately 13%, which is at the high end of the previously guided range of 11% to 13%. Suntech also said it would incur a "significantly larger than expected non-cash foreign exchange translation loss".

"With excess supply and a volatile macroeconomic environment, we recognize that the coming quarters will be challenging; however, with these actions we will become a leaner, more competitive organization," commented Dr. Zhengrong Shi, Suntech's chairman and CEO. "By proactively implementing these initiatives, we are confident Suntech will be able to maintain its financial and operational stability, and emerge in an even stronger market position".

Suntech further announced that it was targeting the reduction of operating expenses by at least 20% in 2012. Capacity expansions would be put on hold in 2012, while the company expected to incur up to US$10 million of severance expenses in the second half of 2011.

In the previous quarter, Dr. Shi had said that the company remained on track to expand cell and module production capacity to 2.4GW by the end of 2011.

Centrosolar demonstrates business model works on third-quarter profit

A clear focus on the roofing systems business and successful regional diversification efforts over the last two years have enabled Centrosolar to eke out a small €1.7 million profit for the third quarter. The company posted revenue of €72.9 million, though the prior-year level of €101.7 million is indicative of the overall challenging business environment and lack of demand elasticity.


Source: Centrosolar

The company posted revenue of €72.9 million, though the prior-year level of €101.7 million is indicative of the overall challenging business environment and lack of demand elasticity.

On a regional basis, Centrosolar said that 74% of revenue had been generated outside of Germany, compared to 64% in the same quarter of 2010. The company noted that it was expanding activities in North America and building out its mounting systems product range in the region to support growth.

Centrosolar also guided full-year revenue to be in the region of €300 million. However, this is considerably down on last quarter when the company had been optimistic of a revenue target of €330 to €380 million with a positive operating result.

ITC to investigate Westinghouse Solar patent infringement claims against Zep Solar, Canadian Solar

The US International Trade Commission (ITC) has voted to begin an investigation on behalf of the US government on a claim filed by Westinghouse Solar that Zep Solar and Canadian Solar are importing solar products that infringe on Westinghouse's patents. The company asserts that Zep Solar and Canadian Solar make and import certain products that infringe its US Patent Numbers 7,406,800 and 7,987,641.

Westinghouse filed a petition with the ITC in order for the commission to look into the alleged infringements and is looking for a permanent exclusion order that would prevent certain Zep Solar and Canadian Solar products from being imported into the US. Additionally, Westinghouse is asking for a cease and desist order that would forbid the importation, sale or advertising of these products.

Barry Cinnamon, CEO of Westinghouse Solar stated, "I want to make our position clear: this ITC patent infringement action is unrelated to the anti-dumping allegations of SolarWorld and several

PV Modules Order Focus

Soltas Energy, CNPV sign module supply contract

Soltas Energy has signed a contract to purchase 175.5MW of CNPV Solar Power's premium range modules. Delivery of the modules will be staggered over the next two years, with the first shipment being received in October. Soltas has previously stated that it intends to achieve 1GWp of installations by 2016.

SolarWorld modules power Phipps Conservator solar project in Pittsburgh

Pittsburgh's Phipps Conservatory and Botanical Garden Centre for Sustainable Landscapes, located in Schenley Park, is being powered by solar panels from SolarWorld. Energy Independent Solutions has installed 125kW worth of SolarWorld's 250W Sunmodule solar panels across three-quarters of the centre's roof and a quarter of the modules on the ground.

The US$24 million Phipps project will be combining solar hot water, natural light capture and geothermal heating and cooling, along with solar, to power the centre. SolarWorld noted that the mounting systems for the solar panels were provided by US-based Solar FlexRack. The Phipps project is anticipated to be completed by next spring.

MEMC to supply 130MW of PV modules to Northland for Ontario power-plant projects

MEMC Singapore, a unit of MEMC Electronic Materials, and Northland Power have signed a master module supply agreement for the purchase of solar PV modules to be manufactured in Newmarket, Ontario. The modules will be used for Northland's 130MW Ontario solar portfolio and as part of a CAD$600 million investment by Northland for the construction of ground-mounted solar projects in Ontario. The monetary value of the deal was not disclosed.

SPI to supply modules for KDC projects; releases Q3 financial results

SPI Solar has signed an agreement to supply KDC Solar with US$42 million of LDK modules for a range of upcoming PV projects in New Jersey. The contract further consolidates the relationship between the two firms; in June, SPI unveiled a three-year partnership with KDC, whereby it would serve as KDC's preferred EPC and operations and maintenance service provider. SPI will supply KDC with LDK modules for a range of upcoming PV projects in New Jersey.

China Sunergy ships 23MW of modules to SUNfarming

China Sunergy has agreed a shipment of 23MW of solar modules to German distributor and project developer SUNfarming Group. SUNfarming will use China Sunergy's modules to design and mount customized PV systems for commercial and residential ground-mount and rooftop projects, mostly in the north and east areas of Germany. Over 18MW of the modules sold will be used in ground-mount projects and others will be used in rooftop projects. The company will deliver the 23MW module shipment within the fourth quarter of 2011.

The US ITC will begin an investigation into Westinghouse Solar's patent infringement claim against Zep Solar and Canadian Solar.

Source: iClarified

other manufacturers. Our goal is quite simply to protect Westinghouse Solar's intellectual property by seeking an order prohibiting the importation of solar products that infringe our US patents," continued Cinnamon. "We will continue to aggressively defend our patent rights, which we believe were first infringed by Zep Solar, a US company."

Further information on the SolarWorld/CASM dispute is available in our special feature on page 172.

Senersun joins CERES module recycling program

Senersun announced that it has officially become a member of The European Centre for the Recycling of Solar Energy (CERES), joining several other EU-based solar companies. CERES is a non-profit association, which aims to create a voluntary commitment take-back program for the PV community.

Innotech Solar launches US sales unit for customers in the Americas

Innotech Solar has officially debuted the US arm of the company, Innotech Solar USA, which will focus on providing sales services to customers in the US and Latin America. Based in Vista, California, the new division extends Innotech's presence into the American market with the office joining other Innotech entities, including its cell processing facilities in Norway and Germany and sales offices in Shanghai and Hong Kong.

ET Solar gains five-year US$1.27 billion credit facility to expand European operations, launches anti-reflective module range

Having previously used the banking services of China CITIC Bank's Nanjing Branch (CITIC), module manufacturer ET Solar has signed a new agreement with the bank, obtaining a US$1.27 billion line of credit to run over the next five years. ET Solar said that the credit facility would support ongoing efforts to capture increased market growth in Europe.

ET Solar has also been increasingly active in the UK market since the UK FiT was established in April 2010. Some 'free solar' enterprises, which had gained strong early adoption in the residential market, used ET Solar modules, and the company has also found success in commercial projects.

The company has also recently launched its range of anti-reflective modules, said to offer higher electricity production, more stable performance and lower unit cost than conventional glass-based modules. The modules are offered under ET Solar's 25-year linear power performance warranty, along with a 10-year workmanship warranty and global technical support.

Sanyo solar module sales stablilise in first six months

Total sales from Panasonic's new subsidiary, Sanyo, were down 19% to ¥669.3 billion, compared with ¥829.7 billion in the same period a year ago. Though the company did not disclose Sanyo's solar PV business figures separately, Panasonic did say that sales were stable in the quarter. Sanyo had previously not disclosed PV sales separately.

Within Sanyo's Energy business segment, sales were ¥210.2 billion, a 4% decline over the same period a year ago, due in part to currency fluctuations and price declines. Operating profit was ¥4.9 billion, down from ¥11.5 billion in the same period of 2010.

Tested in the lab (UL, TÜV) proven in the field.

Sanyo solar module.

Source: Kingsley Group

The sales decline for the Sanyo segment was said to be due to sluggish markets in other electronics-based sectors. Also attributed to Sanyo was ¥26.9 billion of segment loss, compared with a segment profit of ¥6.1 billion a year ago. Panasonic said the losses were also influenced by the amortization of intangible assets recorded at the acquisition.

IBC Solar extends PV module product warranties to 10 years

IBC Solar's MonoSol and PolySol series solar modules have been outfitted with a 10-year product warranty, which supports the modules' 25-year linear power warranty. The new 10-year warranty covers the IBC MonoSol and IBC PolySol series of modules if they show any defects that can be attributed to their manufacturing or materials faults.

IBC Solar has extended its product warranty to 10 years.

Source: Stadt ohne WATT

"We have continuously extended or quality management in recent years for the benefit of our customers and owners of systems", explained Marco Siller, director of product management at IBC Solar. "This extended product warranty reflects our high quality standards and offers our customers more confidence and increased investment protection."

Testing and Certification News Focus

British Standards Institution awards Trina Solar ISO verification statement

The British Standards Institution (BSI) has awarded Trina Solar its ISO 14064-1:2006 verification statement. To qualify for the statement, BSI carried out an audit to ensure Trina conformed to the necessary guidelines. Trina is among the first Asian module manufacturers to be awarded the verification, which is also a boon for its quest of establish itself in the burgeoning UK solar market.

Trina's chairman and CEO, Jifan Gao, said, "This verification is a recognition Trina Solar's ability and commitment to sustainable development and emission reduction efficiency within the PV industry".

Trina Solar's headquarters in Changzhou, China.

Source: Trina Solar

Four aleo solar module types pass ammonia test

PV module manufacturer aleo solar said that four of its module types had passed the ammonia resistance test by SGS Société Générale de Surveillance SA. The ammonia certification adds to previous certification for use in other extreme conditions such as the slat spray test. Polycrystalline-based aleo modules S_16 and S_18 as well as the monocrystalline module types S_17 and S_19 have now been declared ammonia-resistant.

Polycrystalline-based aleo modules S_16 and S_18 as well as the monocrystalline module types S_17 and S_19 have now been declared to be ammonia resistant.

Source: Heinz Liesenberg

The modules' certification to the ammonia resistance test renders them suitable for installation on agricultural buildings where farm animals are held.

SEMI issues new PV standard focused on test methods for shipping crystalline-silicon modules

SEMI's new PV standard, "SEMI PV23-1011 – Test Method for Mechanical Vibration of c-Si Photovoltaic Modules in Shipping Environment", has been released with the intention of reducing the cost of damages associated with the transportation of modules. The standard was mainly authored by the SEMI Taiwan PV Standards Committee and examined by the global SEMI PV Standards Committee.

SEMI noted that since many module manufacturers guarantee a lifetime between 20 and 30 years, tests to certify that the modules can endure environmental conditions before shipment can help decrease the cost to both customers and manufacturers.

Therefore, the new standard outlines a common test method to assess the damage to PV modules due to the mechanical vibration of transportation and shipping. The standard is additionally meant to hasten the development of better module protection to be used for transport.

The standard is intended to help PV cell, module and system makers create internationally-accepted test methods for shipping modules in different conditions and environments. Terry Tsao, president of SEMI PV Group Taiwan and Southeast Asia, stated, "[The standard] will not only improve the credibility of product and its packaging design, but also effectively reduce unnecessary losses related to defects generated during transportation."

CDTC's LSP panels meet Mediocredito Italiano bankability criteria

The insurability of PV projects that use LSP panels have put China Technology (CDTC) in good stead with savings bank, Mediocredito Italiano. CTDC's organizational structure, management team, key performance features, manufacturing processes and quality control programs were some of the principal criteria requirements requested by Mediocredito Italiano.

Odersun's PV modules receive 'Made in Europe' certificate and qualify for Italian solar power tariff

Odersun's thin-film solar cells will now carry the 'Made in Europe' certificate, which was confirmed by the VDE Institute. The certificate allows solar plant operators using Odersun's modules to participate in a 10% higher feed-in tariff from Italy's Conto Energia IV.

In collaboration with energy agency GSE, the certificate for Made in Europe ensures that at least 60% of a module or its system components have been manufactured in Europe. GSE advised that it would pay the 10% higher subsidy for projects that use the EU components.

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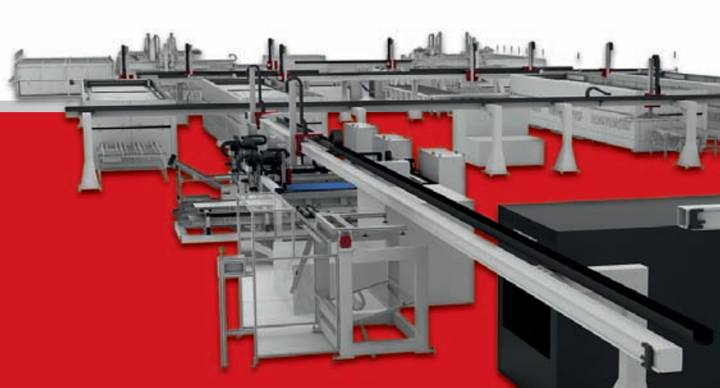


Product Reviews

Dow Corning & Reis Robotics

New liquid encapsulation process from Dow Corning and Reis Robotics improves performance and durability

Product Outline: Dow Corning and Reis Robotics have announced that their solar cell liquid encapsulation process has passed factory acceptance testing and is now available for commercial use. Additional site testing was conducted on the pilot line at the new Dow Corning Solar Solutions Application Center in JinCheon, Korea with a well-known solar product manufacturer.

Problem: Module durability and efficiency have often been at odds with the need to reduce capital and manufacturing costs, while significantly increasing the production rate of solar module assembly steps.

Solution: The new technology features a liquid encapsulation process that provides a clear laminate to protect each solar cell in a panel, thus replacing commonly used ethyl vinyl acetate resin. Panel manufacturers can increase efficiency and reduce total cost of ownership through lower processing temperatures and faster throughput. The system chemistry and process have been fine-tuned to reduce cycle times while maintaining low temperatures. The process is claimed to require lower capital and less factory space, due to the throughput increase.

Applications: Solar cell liquid encapsulation.

Platform: Dow Corning PV-6100 Encapsulant Series relies on the UV stability of the silicone molecule to deliver improved durability and increased efficiency for crystalline modules compared to incumbent organics. The liquid silicone-based material provides an ultra-transparent layer of protection for the solar cell in a panel and is claimed to outperform incumbent organics in durability, efficiency, module life and UV resistance.

Availability: Since August 2011.

DuPont

DuPont's 'TPNext' laminate offers improved adhesion for faster throughput

Product Outline: DuPont Photovoltaic Fluoromaterials has developed a new backsheet technology designed to enhance the quality and manufacturability of crystalline silicon solar modules by improving adhesion to encapsulants, resistance to ultraviolet (UV) light and enabling faster throughput in the backsheet production process. DuPont recently signed a licensing agreement with Taiflex Scientific, who plans to offer its 'Solmate' backsheet in conjunction with DuPont's 'TPNext' laminate, which is based on DuPont's 'Tedlar' polyvinyl fluoride (PVF) backsheet film.

Problem: Increased lifetime of modules is of upmost interest to the industry to reduce the cost of solar electricity. Besides the solar cell string itself, the encapsulating system is the component with the highest responsibility for the lifetime of a PV module.

Solution: TPNext is a proprietary laminate consisting of Tedlar film, polyester and a unique extrusion-coated tie-layer from DuPont that is claimed to reduce the use of organic solvent-based adhesives, and deliver improved and consistent adhesion to EVA encapsulants as well as improved UV resistance. The TPNext laminate is a single protective layer backsheet, designed to complement the standard construction of Tedlar film, polyester and Tedlar film known as TPT. Improved adhesion of the encapsulant to solar cell strings is claimed to increase throughput in lamination.

Applications: Crystalline silicon solar module encapsulation.

Platform: The backsheet is normally made as a laminated film composite, the most common being a trilayer structure of Tedlar/Polyester/Tedlar (TPT). This structure allows the fluoropolymer to protect both sides of the polyester from photo-degradation.

Availability: Since September 2011.

Edwards

Edwards' GXS Series vacuum pumps improve module laminator throughput

Product Outline: Edwards, a global supplier of vacuum and abatement equipment and services, has introduced the GXS 450 and 750 series of dry vacuum pumps optimized for solar laminator applications. The series is claimed to deliver higher throughput and productivity, with a lower cost of ownership.

Problem: Often viewed as a bottleneck within back-end module processing steps, lamination of solar cells within the frame requires correct and consistent operation. Improving chamber evacuation times can improve throughput and productivity of a laminator, reducing manufacturing costs.

Solution: The GXS 450 and 750 pumps provide faster chamber evacuation for enhanced laminator throughput and higher productivity. The pumps incorporate Edwards' proprietary screw technology and high-energy drive. Chamber purge speeds of 450m^3/h and 750m^3/h have been optimized to deliver rapid and robust vacuum performance, low maintenance requirements, long service intervals and advanced temperature control. An optional booster package is also available to further enhance process chamber evacuation times and reduce the lamination cycle time. The closed-loop temperature control prevents pump fouling and the pumps' low running power reduces their overall cost of ownership.

Applications: Solar laminator throughput improvement.

Platform: Its compact size saves valuable fab floor space and allows the pump to be placed closer to the laminator for simpler installation and more efficient operation. The pumps' low noise and low vibration also facilitate placement close to the tool to minimize impact on the fab working environment.

Availability: Currently available.

Reis Robotics

Circumferential uninterrupted tape application from Reis Robotics reduces moisture risk

Product Outline: Reis Robotics has developed a new process that provides a fully automatic, circumferential application of adhesive tape before the module framing process step. Because the process does not need to pause at the module corners when the direction changes, dirt and water penetration is said to be virtually eliminated.

Problem: Conventional adhesive tape placement requires the stopping of the process at each of the four corners of the module, leading to ingress of dirt and moisture that can eventually penetrate the frame over time.

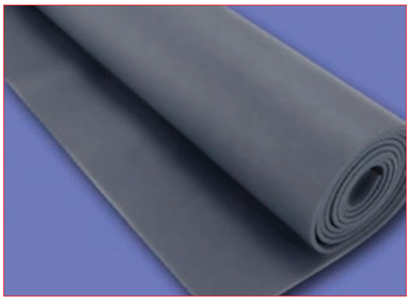
Solution: Reis Robotics' new process involves the continuous application of the foamed tape to prevent dirt and moisture from entering. The new process offers considerably increased safety since gap-free continuous gluing is performed at the corners. Furthermore, the elimination of starting points for the application of adhesive tape on all corners reduces the risk of water entering the space between laminate and frame. This fully automated assembly process is said to allow for a reproducible level of quality in the finished product.

Applications: Extensive tests have shown that various common adhesive tape types from different manufacturers are compatible with this assembly process.

Platform: Reis Robotics emphasizes that the new procedure is of modular design which gives customers the possibility of retrofitting the automated taping system into existing production lines.

Availability: Since September 2011.

Saint-Gobain Solar



Saint-Gobain Solar's solid silicone rubber operates as durable membrane for lamination process

Product Outline: Saint-Gobain Solar has launched its 'SolarBond' Membrane materials for module lamination process in two models, SolarBond Membrane Standard and Membrane Premier. The membrane is designed to protect the module and the lamination equipment in extreme temperatures.

Problem: During the PV module lamination process, module makers seal all components with ethylene vinyl acetate (EVA) adhesive film to ensure that module layers remain secure. High heat levels are needed to melt the EVA (typically 145–155°C). These temperatures call for a flexible, durable membrane for use in the vacuum laminator to provide compression on the module in repeated cycles.

Solution: SolarBond Membranes were developed specifically for the PV vacuum lamination process and act as a vacuum blanket, constructed from high-performance solid silicone rubber, with excellent thermal and mechanical properties, chemical inertness and long service life. This silicone enables the membrane to retain its inherent flexibility and tear resistance through multiple lamination cycles. Manufactured in continuous lengths of 2.8m widths with no seams, both versions eliminate the risk of ghosting on the module, often caused by seams in joined membranes.

Applications: Module lamination process.

Platform: The premier version incorporates unique additives in its formulation to resist the EVA outgassing and can last for up to 6,000 cycles, depending on EVA type, laminator model and process parameters. The membranes are available in a 3mm thickness and widths up to 2.85m.

Availability: Since September 2011.

Bürkle

e.a.sy-Lam SL laminator from Bürkle improves cross-linking speed to reduce process times

Product Outline: Bürkle has developed a new three-step single-opening laminator by focusing on a number of key process parameters to reduce costs and increase productivity. The e.a.sy-Lam SL machine is claimed to reduce unit costs per solar module by up to 25%.

Problem: Uptime and overall reliability in the lamination process are critical factors in high-volume applications. Overall cost reduction requirements are pushing for higher throughput. The need to address to both aspects is now a priority for competitive product with high quality finished product.

Solution: The e.a.sy-Lam SL laminator has been designed to reliably enable the temperature for laminating glass-foil modules to be increased to improve the cross-linking speed. Depending on the foil type, an increase of the operating temperature by 10°C to around 160°C can double the cross-linking speed. Combined with a higher pressure and a reduction of the evacuating time, it is possible to reduce the process time to a claimed 3.5 minutes. The use of one three-step e.a.s.y-Lam SL system could replace up to four single-opening laminators, according to the company.

Applications: Laminating glass-foil modules.

Platform: The laminator ensures the same overall temperature is achieved of the thermal oil so that the module quality is not affected by local temperature deviations in the heating platen by being separated. Conventional heating elements are integrated into the heating platen so that a failure can damage the modules in the affected area.

Availability: Since September 2011.

Snapshot of spot market for PV modules – quarterly report Q3 2011

pvXchange, Berlin, Germany

ABSTRACT
Solar enterprises will each be faced with the occasional surplus or lack of solar modules in their lifetimes. In these instances, it is useful to adjust stock levels for modules at short notice, thus creating a spot market. Spot markets serve the short-term trade in different products, by enabling the seller to permanently or temporarily offload surplus, while buyers are able to access attractive offers on surplus stocks and supplement existing supply arrangements as a last resort.

Price trends

Throughout the year, until the end of the third quarter, prices of solar modules on the spot market have fallen by 22–23%, depending on their technology and origin. The price for Chinese crystalline modules has even dropped by 33.5% between January and September. Prices of crystalline modules made in Japan, Korea and Germany have dropped by 22%.

> "The price of silicon fell below the level of US$50/kg in September."

Due to the current fall in prices along the whole value chain, module prices will also continue to decline until the end of the year. The price of silicon fell below the level of US$50/kg in September and the prices of wafers and cells are also in a free fall, forcing some cell producers to scale down or even stop production to avoid further losses.

Strong pressure on prices and competition by crystalline modules forced manufacturers of thin-film modules to revise their prices downwards by 26–28%.

Demand

Demand in the third quarter has not met expectations at all, especially on the large European PV markets. Even the most optimistic analysts have adjusted their predictions downwards to 5.5–6GW for newly installed capacity in Germany in 2011. Compared to the previous year, demand for thin-film modules on the spot market suffered a sharp decline.

Increasing difficulties in finding financial support for PV projects is the reason for weak demand in Europe, as many analysts explained during PVSEC in Hamburg. Price falls for solar components will not ease the tensions on the financial markets either. Imminent elections in some of the most important PV countries in southern Europe cause even more insecurity among the creditors. In Germany, the largest and most secure PV market for investors, many installers and project developers have been waiting until the end of the third quarter for further price cuts.

The second half of September brought a recovery in demand in Europe, not only in the traditional markets like Germany and Italy, but also in Eastern Europe and the UK, where numerous projects were connected to the grid in recent weeks.

News

High conversion efficiency modules from Suntech Power as well as CSI, Yingli and Trinasolar were the best-selling products on the spot market. CSI and Yingli were two of the few companies reporting an increase in shipments and a positive operating margin in the second quarter of 2011 in spite of strong pressure on margins. The vertically

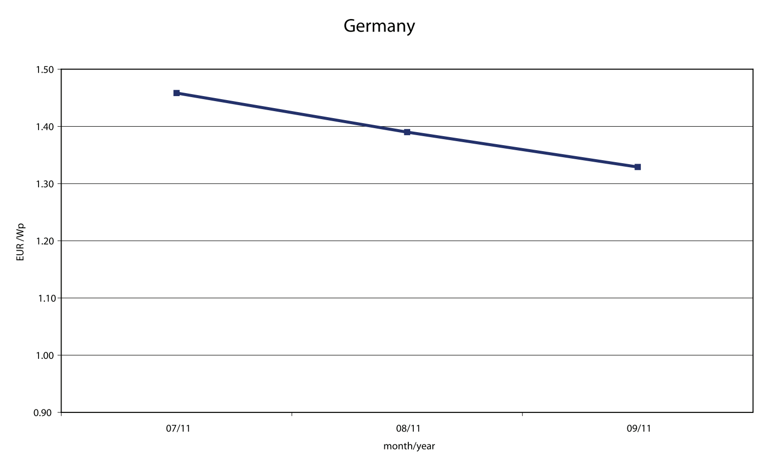


Figure 1. Development of module prices for modules produced by German manufacturers from July 2011 to September 2011.

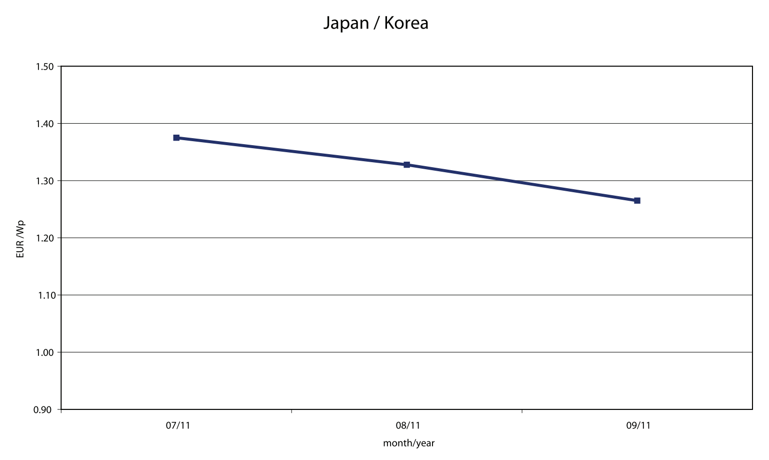


Figure 2. Development of module prices for modules produced by Japanese or Korean manufacturers from July 2011 to September 2011.

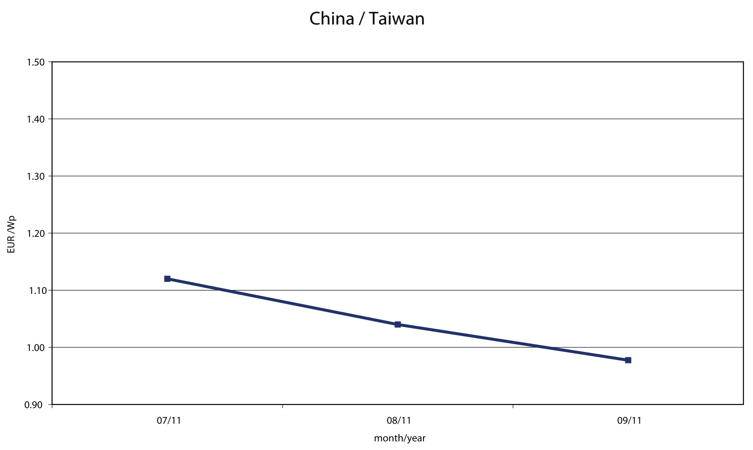


Figure 3. Development of module prices for modules produced by Chinese or Taiwanese manufacturers from July 2011 to September 2011.

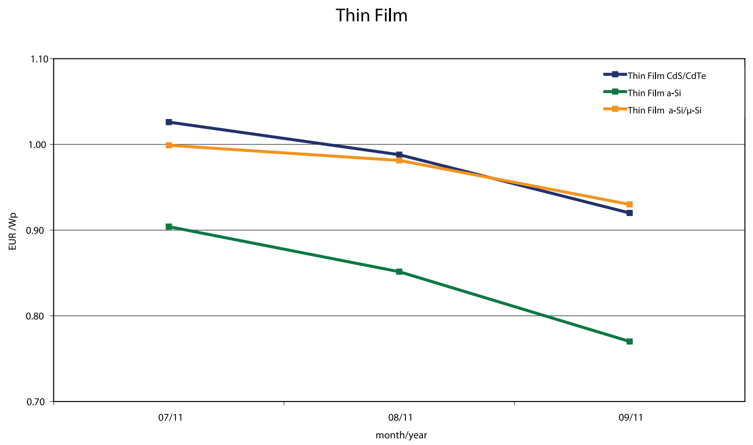


Figure 4. Development of module prices for thin-film modules from July 2011 to September 2011.

integrated production capacities of these companies, as well as their presence in all large and small PV markets worldwide, are some of the reasons for their success in the most difficult times for the PV industry.

Buyers do not seem to be very interested in thin-film manufacturers other than First Solar (Cd-Te modules), even though amorphous and tandem module prices have seen a stronger decline than in previous months.

Cautious optimism prevails with regard to the development of the global market thanks to a few bits of good news: a national feed-in tariff in China and the high demand of the American market (where a 166% higher growth than in 2010 is expected, equating to 2.4 GW of newly installed capacity), as well as a 35% higher growth than in 2010 in Japan because of 1.3 GW of newly installed capacity.

> "The global PV market could grow by 20% compared to the previous year."

Outlook

The news from China, the USA and Japan has led analysts to upwardly revise their demand prediction for 2011. The global PV market could grow by 20% compared to the previous year.

Despite global growth, module manufacturers will have to put up with slumps in profit due to the price decline. Many companies – such as Q-Cells, Solon and Centrosolar – have lowered their expectations for 2011. Nevertheless, for most companies, the outlook for the rest of the year is positive.

About the Authors

Founded in Berlin in 2004, **pvXchange GmbH** has established itself as the global market leader in the procurement of photovoltaic products for business customers. In 2010 the company procured solar modules with an output of around 180MW. With its international network and complementary services, pvXchange is constantly developing its position in the renewable energy market, a market which continues to grow on a global scale. Based in Europe, pvXchange also has a presence in Asia and the USA.

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Junction boxes for photovoltaic modules – qualification and tests

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ABSTRACT
Photovoltaic (PV) modules and components are products which have to withstand the diverse effects of extreme conditions during their lifetime. The wide range of climatic conditions and possible mechanical stresses must be taken into account when designing a PV component. To assess whether the quality of a product is sufficient to withstand such influences, some international standards have been developed. TÜV Rheinland operates several ISO 17025-accredited laboratories worldwide for type approval testing of PV components – such as junction boxes, connectors and cables – as well as concentrating PV modules, flat-plate modules and solar thermal systems. Experience of testing PV components has been gained over the last 12 years, and even over the last 20 years in the case of PV modules. New developments in photovoltaics mean that continuous development and review of standards is necessary.

Introduction

Several national and international type approval standards have been released for PV modules and components, and more recently for concentrating PV modules and assemblies. Third-party testing and certification to these standards is not required by law in most cases. Certificates, however, document the maintenance of a certain level of quality and form the basis for PV project financing. Several test marks have been established to indicate to a buyer the fulfilment of standard requirements. A certificate or quality mark alone, however, does not guarantee the high quality of a PV product. Testing is usually limited to a small number of samples, which in many cases are not even taken from the batch production, but are prototypes of a new series instead. Additional quality assurance measures are therefore needed.

Important standards for PV junction boxes

The type approval test of a PV junction box can be performed according to European standard EN 50548 and to national documents such as DIN V VDE V 0126-5 or UL-subject 3703. Additionally, TÜV Rheinland has created an internal test programme – 2 PfG 1798/11.10 – for PV junction boxes for use with modules qualified to ANSI/UL 1703, which covers requirements drawn from ANSI/UL 1703, complete with the bypass diode test of EN 50548.

Since EN 50548 is currently the only existing and valid international standard for PV junction boxes, and because it is based on DIN V VDE V 0126-5, the following explanations will mainly cover requirements specified in that standard. Working Group 2 of IEC/TC82 is currently creating a proposal for an IEC standard for PV junction boxes.

Type approval tests for PV junction boxes

EN 50548 is interbalanced with current existing and valid PV module IEC standards, such as IEC 61215, IEC 61646 and IEC 61730. It covers most of the safety and qualification tests of these standards.

It is not required that the tests be carried out on complete PV modules. Of course, if a PV junction box is to be tested in combination with a PV module, the tests can be performed on the complete sample. However, in most projects, the junction box will be tested separately because the junction box manufacturer wants to sell his product to different module manufacturers.

Test group	Description
A	Marking, information and documentation
B	Material tests
C	Constructional requirements
D	Mechanical tests
E	Test sequence I – thermal cycle test (tc200)
F	Test sequence II – damp heat test
G	Test sequence III – thermal cycle test (tc50) and humidity freeze test
H	Test sequence IV – bypass diode thermal test
I	Reverse current test

Table 1. Test groups for type approval tests.

The type approval test is divided into nine test groups. Four of these groups (E–H) contain test sequences in which the tests have to be performed consecutively in the specified order. The other five test groups contain single tests.

> “Usually the manufacturer wants to supply its PV junction box to as many PV module manufacturers as possible, so the box has to operate under several combinations of adhesives and backsheet foils.”

If the intention is to test the junction box separately, it must be ensured that the specimen is mounted on the same surface – which may be glass or backsheet foil – with the same adhesive material and under the same conditions as those in an expected installation on the PV module. For example, if the junction box is intended to be potted, the specimen must be prepared in a similar way.

Usually the manufacturer wants to supply its PV junction box to as many PV module manufacturers as possible, so the box has to operate under several combinations of adhesives and backsheet foils. Also different potting materials are often used. In these cases the tests are to be performed in all possible combinations with the relevant number of specimens.

The plates on which the specimens are mounted will be made of glass or similar material. The size of the plates depends on the size of the test chambers. In the case of junction boxes intended to be mounted on

Figure 1. Ball pressure test: material test for resistance to heat.

modules having a backsheet foil, the specimen will be mounted on the same type of backsheet foil, which is bonded to the plate.

Considering that some of the tests are long-term, it is recommended to perform these tests in as many simultaneous combinations of specimens as possible. The number of specimens and their preparation for a type approval test is described in detail in EN 50548 (see table 2 in EN 50548 for an overview).

Test group A: Marking, information and documentation

It must be possible to identify a PV junction box even after it has spent a number of years in the field. This is useful for the replacement of components, such as bypass diodes. Therefore, to allow the identification, a minimum marking on the PV junction box will show the manufacturer's name (this can be a trademark or mark of origin), the type identification (a key code might be helpful for a PV junction box used in several combinations of backsheet foil and/or adhesives, fitted with several types of component, having different ratings, etc.) and, if applicable, the polarity of built-in or integrated connectors (in which case a warning label as shown in annex A of EN 50548 must also be identified near the connector).

The manufacturer must also be able to provide all important data listed in paragraph 4.2.1 of EN 50548 in a data sheet or other technical documentation. Additionally, all other information which is necessary to ensure safe installation and function must be listed in the technical documentation. This can be, for example, information about the termination of cable and/or cell connections, information regarding the connector system, and, of course, all information relating to the mounting, such as the type of backsheet, type and parameters of the adhesive and type of sealing. Installation specifications, such as the pressure needed for fixing the box and the drying time of the adhesive, are also required to be documented.

For the type approval test the applicant must present data sheets or certificates of approval for all components, such as fitted cables, connectors, cable glands or similar. Experience has shown that a lot of delays in projects are caused by missing or incorrect documentation, but this test group would seem to be the easiest one to pass.

Test group B: Material test

In this test group all relevant tests for all materials used are listed. These materials are polymers forming an enclosure or serving as a support for live, current-carrying and other metal parts, and also polymers used in gaskets, if applicable. Testing the durability of labels for markings (if the marking is not performed by impression) and warning labels also forms part of this group. The tests will not be performed on a mounted specimen but on a separate one, or even on a part of one. It is possible that some tests in this group will be modified in future editions or amendments of the standard – the

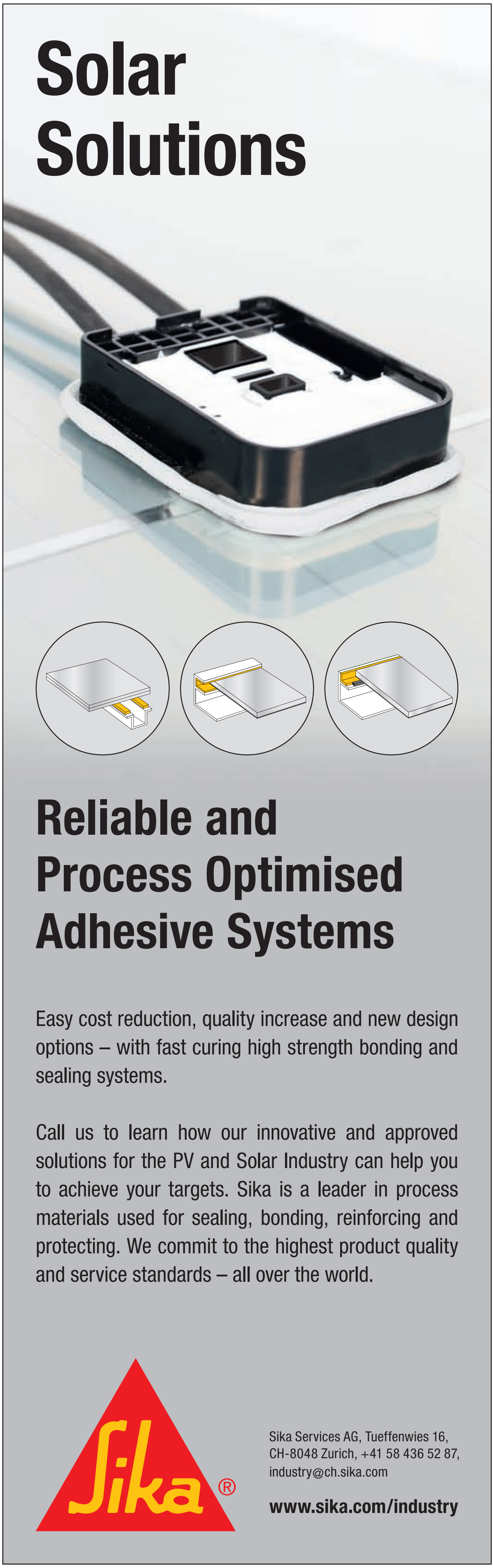

Figure 2. Glow-wire test: test for resistance to ignition.

reasons for this will be explained later. The wet test for durability of marking will be performed with a test apparatus as described in EN 60068-2-70 and with water as the test liquid. A similar test apparatus may produce the same results.

For polymers forming an enclosure, the flammability test according to EN 60695-11-10 will be performed on a sample, unless the applicant can present the manufacturer's approval of the material. Irrespective of this, TÜV Rheinland has decided to always perform the flammability test since the material properties also depend on the parameters during the injection process. If the wall thickness of the enclosure is less than 3mm, the flammability test must be performed according to EN 60695-11-20.

The weather resistance test with a xenon lamp according to ISO 4892-2 or a fluorescent lamp according to ISO 4892-3 will be performed on another sample of the material. The duration of this test is actually 500 hours. Several technical committees are currently discussing an extension to 1500 hours. After the weather resistance test, a glow-wire test with a temperature of 650°C will be carried out on the conditioned sample.

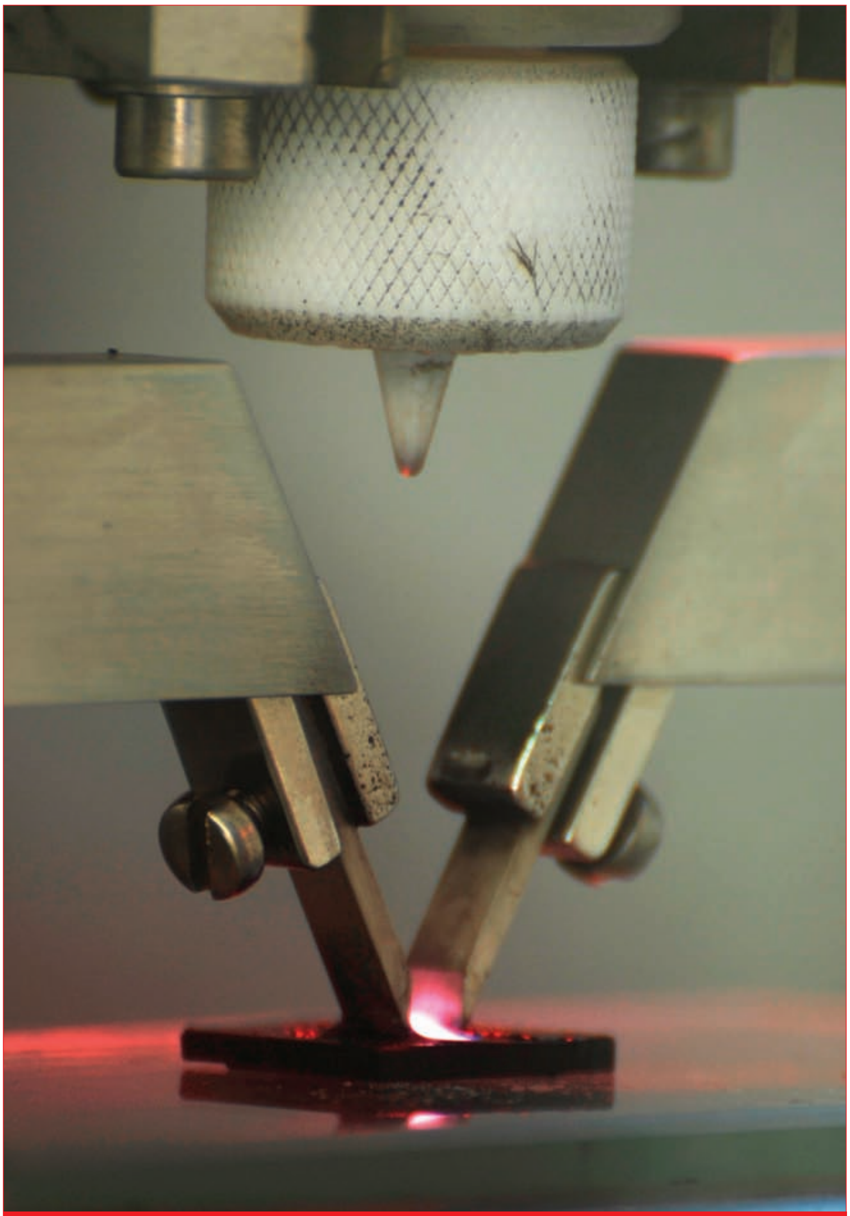

Figure 3. CTI test: proof tracking index (PTI) test for evaluating the CTI value.

The ball pressure test will be done on an additional sample of the material. For this test the temperature used will be either 90°C or *the temperature evaluated during the bypass test (see test group H) + 20°C*, whichever is higher.

Important note: The requirement indicated in italics is different from that specified in DIN V VDE V 0126-5. During the first test projects conducted by others in the TÜV Rheinland lab, it was found that these parameters are not realistic requirements. Since the resistance to heat was also evaluated in the bypass diode thermal test, the German committee decided to apply for an amendment to EN 50548 in which the test temperature will be 90°C for polymers serving as an enclosure. Until the amendment has been agreed and decided on by the European committee (CENELEC), the requirement in paragraph 5.3.13 of EN 50548 must be respected as described, unless DIN V VDE V 0126-5 is to be applied as the test standard.

The same test will be performed on polymers serving as a support for live metal parts, but the test temperature used will be either 125°C or *the temperature evaluated during the bypass test (see test group H) + 20°C*, whichever is higher. The important note mentioned above is also applicable for these materials. In addition, the flammability test according to EN 60695-11-10 will be performed on a sample. The glow-wire test will also be performed, but the test temperature for these materials is 750°C. The glow-wire test also applies to potting material (if applicable) which is in contact with live metal parts. For the testing of potting materials, separate test plates can be used as specimens.

Current-carrying and other metal parts must show no sign of corrosion after storing in a 10% solution of ammonium chloride in water and drying in air with a relative humidity of 91–95% at a temperature of 20°C ± 5°C.

Gaskets will be conditioned by accelerated ageing in a heating cabinet at a temperature of 100°C ± 5°C for 240 hours. After conditioning, the gasket will be used for the specimen for the ingress protection (IP) test described in test group E. A modification of the conditioning is planned for future versions of the test, and there are currently discussions about performing in addition a compression test after ageing. This could be realized by closing and opening the lid ten times after reinstallation of the gasket. If the gasket cannot be separated from the lid or the base of the enclosure, the complete part will be inserted into the heating cabinet.

Test group C: Constructional requirements

Group C consists of single tests involving visual inspections. Most of the tests can be done on separate, non-fixed specimens, but it is recommended to have at least one specimen mounted on a test plate.

A visual inspection and application of test probe 11 in accordance with IEC 61032 (applying a force of 20N) must show that, after mounting, the live parts are not accessible, even if any deformation of the housing and/or cover occurs as a result of mechanical and thermal stress, which may be possible during normal use.

Lids or other parts intended to be removed must only be detachable with the aid of tools. If they are attached without screws, there must be one or several detectable facilities, for example recesses, which enable tools to be deployed in order to remove the lids or other parts. Precautions must be taken for preventing the lid being lost from a PV junction box that is intended to be re-opened. To this effect, the lid must be fixed to the base enclosure by hinges, or by other means that will ensure that the lid cannot be misplaced after opening the junction box in the field.

If barriers are used to provide insulation they must be of an insulating material appropriate for the application. Also an 'adequate thickness' of the barrier is required, but there is no definition of this value. The barrier must only be able to be removed by the use of a tool. In the majority of existing PV junction boxes there is no such barrier, so usually this requirement does not apply.

For rewirable connections of the conductors in the relevant terminals, sufficient volume inside the PV junction box must be provided to avoid any damage to the cable and to ensure adequate termination of the cable. In contrast to UL standards or specifications, no particular volume depending on the cross-section of the cables is stipulated. Sharp edges must also be avoided.

Adequate terminations and connection methods must be used inside the PV junction box. The applicant must provide evidence of approval that the terminals comply with the requirements of their relevant IEC or EN standards, and that they are suitable for the type and range of cross-sectional areas of conductor and cell connections. If no approvals exist for the terminals, perhaps due to the fact that they are special constructions for use in that PV junction box, the terminals can be tested during the PV junction box test. Taking account of the relevant standards, the main aspects of the terminal tests are that:

- adequate material is used;
- there is sufficient retention;
- the contact pressure is not transmitted through the insulating material.

Rated voltage [V DC]	Rated impulse voltage for basic insulation [kV (1.2/50μs)]	Rated impulse voltage for reinforced insulation [kV (1.2/50μs)]
100	1.5	2.5
150	2.5	4
300	4	6
600	6	8
1000	8	12
1500	10	16

Note: values are derived from IEC 60664-1 and IEC TR 60664-2-1 for overvoltage category III.

Table 2. Rated impulse voltage for PV junction boxes.

Required impulse voltage [kV (1.2/50μs)]	Minimum clearance for inhomogeneous field [mm]		
	Pollution degree 1	Pollution degree 2	Pollution degree 3
1.5	0.5	0.5	0.8
2.5	1.5	1.5	1.5
4.0	3	3	3
6.0	5.5	5.5	5.5
8.0	8	8	8
12.0	14	14	14
16.0*	19.4	19.4	19.4

* Values for 16.0kV are evaluated by interpolation.

Table 3. Minimum clearances for PV junction boxes.

Rated voltage [V DC]	Minimum creepage distance for basic insulation [mm]					
	Pollution degree 2			Pollution degree 3		
	Material group I	Material group II	Material group III	Material group I	Material group II	Material group III
100	0.71	1	1.4	1.8	2	2.2
150	0.78	1.08	1.57	1.97	2.17	2.47
300	1.5	2.08	3	3.77	4.24	4.71
600	3.03	4.29	6	7.6	8.56	9.53
1000	5	7.1	10	12.5	14	16
1500	7.51	10.42	15	18.86	20.86	23.57

Table 4. Minimum creepage distances for basic insulation.

Electrical and thermal properties of terminals are also considered during several tests of the PV junction box; mechanical properties are checked by tests in test group D. It must be ensured that terminals are held in position when the conductor or cell connections are attached, and that soldered, welded or similar connections are effected so that they are not held in position by just the connections themselves. For a soldered connection, hooking in an eyelet before soldering, for example, is considered to be a suitable means of retaining the conductor in position.

One important and critical issue is the assessment of the clearances and creepage distances. The description of how to evaluate and measure these distances is quite involved, so only the following brief explanation of these procedures will be given. In general the distances have to be evaluated and assessed according to the requirements of IEC 60664-1 and IEC TR 60664-2-1 (for rated voltages above 1000V DC and up to 15,000V DC). Overvoltage category III and pollution degree 3 (inside the enclosure, the distances must be dimensioned for at least pollution degree

2) must be considered. If additional and special tests according to IEC 60664-3 are met, the pollution degree inside a potted or sealed PV junction box can be considered to be 1.

> “One important and critical issue is the assessment of the clearances and creepage distances.”

For an evaluation of creepage distances it is important to know the material group. Materials are classified into four groups according to their comparative tracking index (CTI) values. These values are determined in accordance with IEC 60112 using solution A for every insulating material that could form part of the creepage pathway.

Clearances as well as creepage distances have to be dimensioned for reinforced or double insulation between live parts and accessible surfaces. This also applies to the distances between the terminals for rewirable connections. All other clearances and creepage distances must meet the requirements of basic insulation in relation to the maximum working voltage as specified by the manufacturer.

The adhesive area between a module and a junction box is considered to be a cemented insulated joint provided that all relevant tests, especially those according to test groups E and F, have been passed. Since it is difficult to evaluate the minimum distances in IEC 60664-1, the distances have been calculated and listed in Tables 2–6.

Of course, other constructional requirements must be considered too. It is very important that fitted components such as PV connectors and PV cables are suitable for use in photovoltaic systems and have at least the rated values of the PV junction box. All PV connectors must comply with the requirements of EN 50521; the PV cable must comply with the requirements of 2 PfG 1169/08.2007.

Test group D: Mechanical test

For the single tests of test group D, separate, non-fixed samples could be used, but it is recommended to check a specimen mounted on a test plate. Some of the tests that consider the mechanical properties of terminations and connections are described in paragraph 5.3.19 (of EN 50548), which refers to requirements of other relevant test standards for terminals, depending on the type of connection.

If the junction box has knock-outs (which is usually not the case for most existing types of PV junction box), the retention and the removal of the knock-outs will be tested. It must be ensured that the knock-outs still remain in place without degradation of the IP protection after applying a specified force under special conditions. It must also be ensured that, after removal of the knock-outs with a tool, no sharp edges remain that could cause damage to the cable or other parts.

Rated voltage [V DC]	Minimum creepage distance for reinforced insulation [mm]					
	Pollution degree 2			Pollution degree 3		
	Material group I	Material group II	Material group III	Material group I	Material group II	Material group III
100	1.42	2	2.8	3.6	4	4.4
150	1.56	2.16	3.14	3.94	4.34	4.94
300	3	4.16	6	7.54	8.48	9.42
600	6.06	8.58	12	15.2	17.12	19.06
1000	10	14.2	20	25	28	32
1500	15.02	20.84	30	37.72	41.72	47.14

Table 5. Minimum creepage distances for reinforced insulation.

Rated voltage [V DC]	Minimum creepage distance for basic insulation [mm]	Minimum creepage distance for reinforced insulation [mm]
100	0.25	0.5
150	0.30	0.6
300	0.7	1.4
600	1.68	3.36
1000	3.2	6.4
1500	5.2	10.4

Table 6. Minimum creepage distances for basic and reinforced insulation (pollution degree 1 and all material groups).

Another mechanical test concerns cord anchorage. The relevant paragraph 5.3.21 of EN 50548 is divided into two sections: one for a junction box intended to be used with specified cables, and the other for a box intended to be used with generic cables. If the cables are specified, the PV junction box will be tested with these types of cable in all possible combinations to take account of the worst case – this is usually the smallest diameter of the cross-

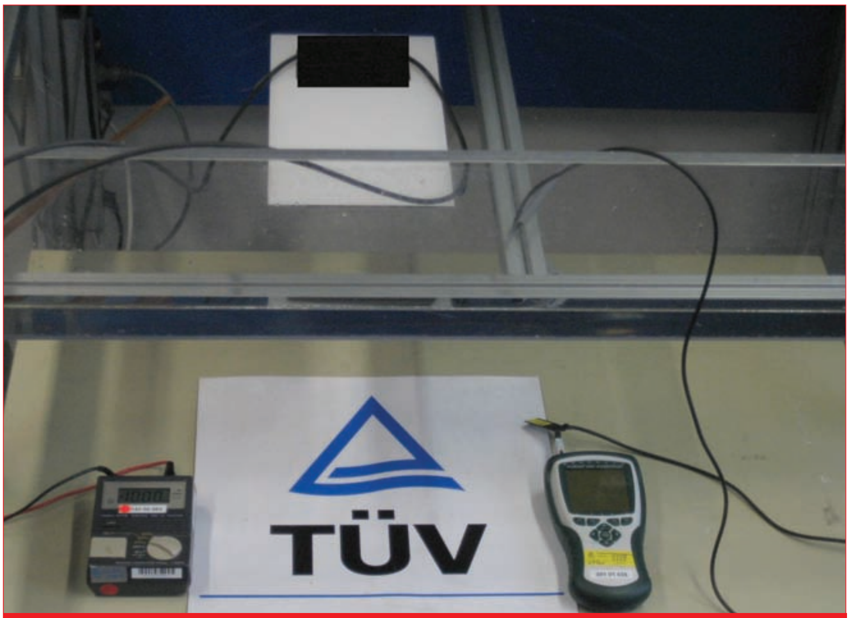

Figure 4. Wet leakage current test: with the junction box lying in the liquid solution, the resistance is measured between the solution and the current-carrying parts.

sectional area. Sometimes cable glands with different inlets are used to cover a wide range of different cable diameters. In this case the cable gland has to be tested with every inlet to consider the worst-case condition. The difference in testing a PV junction box without already mounted or specified cables is the use of a test mandrel, but again all combinations must be considered to check the worst-case scenario.

The cord anchorage is tested by pull and torsion tests. After these tests the cables or mandrels fixed in the PV junction box must not show a displacement exceeding 2mm or a torsion exceeding 45°. In general, potting material must not be considered to be adequate chord anchorage.

To check if the PV junction box is suitable to be mounted or operated at lower temperatures, a cold impact test has to be performed. After storing the PV junction box for a minimum of 5 hours in a test chamber having a temperature of –40°C, four impacts, each having an energy of 1J, will be administered to the box in different positions. No damage that may impair safety or function of the PV junction box should be evident.

The other tests of test group D must be performed on pre-aged specimens of groups E and F, so they will be described in the corresponding test groups. The following test sequences E–H and test group I refer to tests according to module standards and is the reason why they are very similar.

Figure 5. Bypass diode test stand: test equipment for measuring temperatures at bypass diodes of junction boxes mounted on PV modules.

Test group E: Test sequence I – thermal cycle test (tc200)

For this test sequence a specimen will be used that has been prepared as described in paragraph 5.2.5 of EN 50548. The specimen must be mounted on the mounting surface and completely assembled according to the instructions of the manufacturer. At the beginning of the manufacturer's guidelines there will be a description of which mounting surfaces, adhesives, etc. should be used, especially for the case of a PV junction box that is intended to be installed on several backsheet foils. Additionally, the tests must be carried out with the maximum specified number of bypass diodes in an arrangement that covers the worst-case condition.

The cell connections must be bent down and fixed so that they have a conductive connection to the mounting surface. For the thermal cycle test sequence, cell connections will be electrically connected in order to find out if the adhesive material used to fix the PV junction box to the mounting surface meets the requirements of both the IP protection test and the wet leakage current test before and after the thermal cycles.

The first part of the sequence is the IP protection test. According to the specification of the applicant, the tests have to be carried out as described in EN 60529. The IP code consists of two characteristic numerals: the first describes protection against solid objects (5 or 6 in the case of dust); the second describes protection against the ingress of water.

For the first numeral, 5 or 6, the test of tightness against the ingress of dust will be carried out with a low-pressure method in a special dust chamber. No dust must enter the PV junction box for numeral 6. For numeral 5, however, a small amount of dust entering the PV junction box is allowed, but it must be ensured that the dust does not decrease creepage distances or come into contact with live parts.

For the second numeral, a water test, depending on the degree of protection, must be performed. The specimen can be splattered with water from a hose having specified nozzles (IPX5 or IPX6), or it can be submersed in water at a specified pressure and under other conditions (IPX7 or higher). Due to the fact that every IP degree higher than IPX6 does not cover any lower degree, and that minimum IPX5 is required, two different tests have to be performed in the case of IPX7 or higher.

No water must enter the PV junction box. This requirement will be checked by the r.m.s. withstand voltage test using a voltage of 2000V + 4 × rated voltage, applied between a metal foil covering the enclosure and the connected cables of both polarities.

After the IP test, a wet leakage current test has to be performed. This test is very similar to the one described in IEC 61215, with the difference that the connectors must not be immersed in the water/wetting agent solution but must be sprayed instead. This difference is also under discussion by the IEC TC82 Working Group 2 for the next edition of IEC 61215.

The specimen is immersed in the solution to a depth sufficient to cover all surfaces between the mounting surface and the box, but not the cable entries. The cable entries, along with the connectors and the other surfaces of the PV junction box, are sprayed with the solution. A test voltage having a value equal to the rated voltage (but at least 500V) is applied between the connected output cables and the liquid test solution. The measured insulation resistance should not be less than 400MΩ.

Next, the thermal cycle test for 200 cycles (also referred to as the tc200 test) has to be performed with temperatures of –40°C (or lower, if specified by the manufacturer) and +85°C (or higher, if specified by the manufacturer). The rate of change of the temperature must not exceed 100°C/hour. This is followed once again by the r.m.s. withstand voltage test as described above and the impulse voltage withstand test, depending on rated voltage.

As indicated in test group D, the pre-aged specimen of test sequence E must be checked by a mechanical test in which the retention of the PV junction box on the mounting surface is considered. To do this, a force of 40N will be applied for 30 minutes in each direction parallel to the mounting surface and after that for 30 minutes (without jerks) in a direction perpendicular to the mounting surface. During the tests no displacement of the PV junction box must occur, and the subsequent wet leakage current test as described earlier must be passed.

The fixing of the lid must also be checked: a test probe 11 according to IEC 61032 has to be applied with a force of 75N for 1 minute to all areas where this could cause a loosening of the lid. During the test, the lid must not come off.

Test group F: Test sequence II – damp heat test

This sequence is very similar to test sequence I and the specimen must be prepared in the same way. If several combinations are used, this sequence must also be performed for each of them. Test sequence II starts with the wet leakage current test, followed by the damp heat ageing test, using a test temperature of +85°C (or higher, if specified by the manufacturer), a relative humidity of 85% ± 5% and a test duration of 1000 hours.

After the damp heat conditioning, the r.m.s. withstand voltage test as described earlier must be performed. This is followed by the test sequence of test group D, to check retention of the PV junction box on the mounting surface, and then the wet leakage current test. The fixing of the lid is also tested after the damp heat pre-treatment.

Test group G: Test sequence III – thermal cycle test (tc50) and humidity freeze test

The specimen has to be prepared in the same manner as in test sequences I and II. Test sequence III begins with the thermal cycle test as described in test sequence E, but only for 50 cycles (thus referred to as the tc50 test).

Immediately after the tc50 test, the humidity freeze test must be performed. For this test, temperatures of –40°C (or lower, if specified by the manufacturer) and +85°C (or higher, if specified by the manufacturer) also have to be applied, but each dwell time is different from that in the thermal cycle. In addition, a relative humidity of 85% ± 5% (controlled at the dwell time of the highest temperature, not at the cooling and heating phases and dwell time of the lowest temperature) has to be applied. Ten such cycles are to be carried out on the specimen. After this, the r.m.s. withstand voltage test as described above must be performed, followed by the wet leakage current test.

Test group H: Test sequence IV – bypass diode thermal test

The specimen has to be prepared in the same manner as in test sequences I, II and III, but the cell connections must not be short-circuited. If the PV junction box is intended to be used with several types and/or combinations of bypass diode and/or with several rated currents of the PV junction box, the tests must be performed in all possible combinations with the relevant number of specimens.

Another consideration is whether or not the PV junction box is potted. If the PV junction box is intended to be potted so that the bypass diodes are not accessible, the thermal couples must be fixed before potting upon consultation with the testing lab. It is important to read the data sheet of the diode supplier since the placement of the thermal couple depends on the value of the related junction temperature. Some diode suppliers specify the junction temperature with reference to the case temperature, while others specify it with reference to the lead temperature.

Additionally, thermal couples must be fixed near the bypass diode on the insulation materials serving as support for live parts and the enclosure. In the current official edition of EN 50548, the evaluated temperatures of the insulation material are reference temperatures for the ball pressure test (see the important note in test group B).

The specimen must be installed in a heating chamber which has been pre-heated to a temperature of 75°C ± 5°C. It is recommended to store the specimen for a dwell time of 30 minutes before starting the test. After this resting period a current equal to the rated current ± 2% has to be applied for 1 hour, and the temperatures of each bypass diode are then measured. These temperature values are then used in the formula given in paragraph 5.3.18.3 of EN 50548 to calculate the junction temperature. The value obtained must not exceed the specified limit temperature.

The current is then increased to 1.25 × rated current and maintained for 1 hour. Temperatures should be measured, but this is not necessary. The diodes must still be operational and a visual inspection must show no major defects such as:

- current-carrying parts not being kept in position;

- deformation of insulation parts that serve as protection against electric shock;
- other deformation of insulation parts that may pose a safety issue or impair the function of the junction box.

Finally, the specimen must meet the requirements of a wet leakage current test.

Test group I: Reverse current test

The specimen has to be prepared as described in test sequences I to III, but for the reverse current test the cell connection is specified. The connection must have the maximum cross-section as specified by the manufacturer and must be installed in such a way that the test current can flow through all current-carrying parts of the PV junction box. Additionally, it is required that all blocking diodes be short-circuited.

The specimen must be placed with its back on a pinewood board in a horizontal position, covered by a single layer of cheesecloth specified in the relevant part of IEC 60695. A single layer of cheesecloth is laid on the surface of the junction box so that the outer surface of the junction box is completely covered. The specimen is then heated to the upper rated ambient temperature. Once this temperature has been reached, a current equal to the reverse current of the junction ± 2% must be applied to the specimen for 2 hours. The PV junction box passes the test if there is no flaming of the junction box, and no flaming or charring of the cheesecloth in contact with the junction box.

Tests during production

An important part of the procedure for type approval certification is ensuring the quality and compliance of the PV components. To achieve this, a frequent factory surveillance of PV components by TÜV Rheinland experts is necessary. Of even greater importance are the type and frequency of the quality measures performed in the production process. Routine tests need to be carried out, but also a product verification test (PVT) which is frequently performed by the manufacturer must be approved. A list of required routine and product verification tests is available from the relevant department of TÜV Rheinland. Hopefully these measures will someday be standardized.

> "If a manufacturer changes materials, construction, rated values, etc. then the conformance of a PV junction box to a standard must be reassessed."

Retesting guideline

If a manufacturer changes materials, construction, rated values, etc. then the conformance of a PV junction box to a standard must be reassessed. Although a retest does not always have to be carried out, most modifications will require it. To avoid having the PV junction box undergo all type approval tests, only partial tests, depending on the kind of modification, have to be performed. Since TÜV Rheinland has many laboratories worldwide, it is important that the requirements for the type tests as well as for the retests be precisely the same. In order to achieve this, retesting guidelines for all PV components have been issued, but have not yet been standardized.

About the Author

Guido Volberg is the director of the Technical Competence Center PV Components at Cologne-based TÜV Rheinland. He began work at TÜV Rheinland in 1995 as an engineer in electrical components and created the first TÜV internal standards for PV components in 2001. Today, collaborating internationally with the other TÜV Rheinland laboratories, he coordinates a team for testing PV components. Guido is also responsible for developing test programmes for innovative products within the PV business sector. He is currently participating in standardization work through the IEC working groups for flat-plate photovoltaic modules (IEC TC 82 WG2) and balance of systems (IEC TC 82 WG3/WG6).

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Current status and future potential of back-contact (BC) module technology

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ABSTRACT
This paper describes the technical concepts and current status of back-contact module technology. A back-contact module has the advantage of a higher conversion efficiency because of less shading of the front of the cell, fewer inactive areas in the module and lower series resistance in the interconnection. Aesthetically, back-contact modules are more attractive than standard modules. Furthermore, module manufacturing is gentler due to there being less cell handling during the process. The two main technical concepts related to back-contact modules – interconnector technology and printed circuit backsheet technology – are discussed in this paper. An overview is given of the production status of current back-contact module manufacturers to also show the significant potential of this technology in economic terms.

Why back-contact technology?

Module efficiency

The most efficient modules available on the market use back-contact (BC) technology. Sunpower has recently displayed modules reaching 20.4% efficiency powered by their current generation of 22.9% efficient Maxeon IBC (interdigitated back-contact) or BC-BJ (back-contact back-junction) cells.

What makes back-contact modules more efficient? Module efficiency is determined to a large extent by cell efficiency. By turning to BC technology, relative efficiency gains of 2–4% can be reached at the cell level, depending on the specific BC technology. This gain is mostly due to the fact that BC cells partially or totally avoid optical shading by front metallization: all contact pads for cell interconnection have been moved to the rear of the cell. However, up to 20% of relative module efficiency is determined by module technology, meaning cell interconnection, encapsulation and module design aspects. Overall, these effects lead to an efficiency loss of 10–15% from cell to module for conventional FBC (front-back contact) cells.

BC module technology can do better. Because of the rear contacts, cell interconnectors do not shade the cells and can be optimized to strongly reduce serial resistance losses in the string. They can also be optimized to use conductive material (copper) more efficiently than the conventional flat ribbons for FBC cells. By adjusting local conductive cross-section to the varying local current, leading to tapered cross-sections, 25% of the copper can be saved without losing power. This adapted increase of conductive cross-section can result in a 2–4% relative efficiency gain, attributable to the switch to BC technology.

Since the cells have all their contacts on the back side, the interconnection of strings can be moved more easily behind the cells, and the cell distance can be reduced by 1–2mm. This reduction of the inactive module area provides a relative efficiency gain of around 3–4% at the module level, since efficiency takes into account total module area.

Adding up all these effects – cell efficiency gain, reduced inactive area and reduced stringing serial resistance loss – leads to a relative module efficiency gain of approximately 10% in favour of BC technology. The relative module power gain only amounts to approximately 6%, since it does not profit from the reduction in inactive module area.

Module cost

At the cell level, switching to BC technology requires 2–3 additional process steps, for example laser drilling for MWT (metal wrap through) and EWT (emitter wrap through) technology or contact isolation. The related additional costs seem low enough to be almost matched by the gain in efficiency at the cell level. Consequently, the specific price in €/W remains relatively constant.

BC technology is seen as a means of introducing very thin solar cells into module production. BC module samples have been successfully produced using 120µm cell and conductive adhesives [1]. Because of the SMD (surface mounted device)-type process flow, the cells only need to be handled once or twice to get to their final position in the module. The use of special interconnectors and joining materials, again made possible by the rear-contact design, can reduce thermo-mechanical stress in the cell.

As soon as it becomes possible to manufacture very thin solar wafers and cells with satisfactory production yield, the associated cost saving can then be attributed to BC technology. Approximately 60–65% of conventional module cost is associated with the solar cell. At the module level, BC technology is not yet evident as a cost saver in terms of material costs, which are the largest share of the module manufacturing costs. Structured interconnectors are more expensive than flat wires, and in the PC approach (printed circuit on backsheet) it is not yet clear to what extent cost savings can be achieved by high volume production.

In module production, cost savings appear to be possible by introducing a high-throughput manufacturing line with a low footprint compared to conventional lines. A very important factor will be the production yield compared to conventional lines. The reduced cell handling in a BC module production line may help to reduce cell breakage and thus improve the yield.

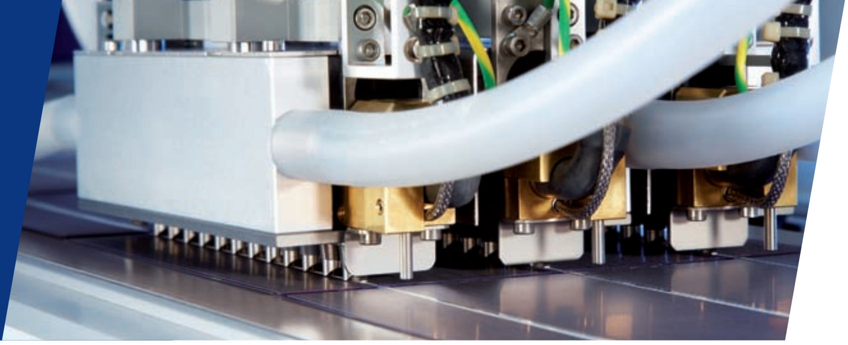
Module aesthetics

BC technology has been recognized as a candidate with a high potential for use in building-integrated PV (BIPV) [2]. The reasons for this are the strong reduction (or total lack) of metallic reflections on the cell, the strong reduction of inactive (white) area throughout the module and even the possibility of designing customer-specific metallization patterns on MWT cells that also consider aesthetic aspects. Maximizing efficiency has the side effect of minimizing visual interference.

Cell types and interconnection challenges

For the process of string production, the contact layout of the BC cell is critical [3]. IBC cells typically have their contacts located on two opposite cell edges (Fig. 1). The cell metallization itself has to carry an increasing amount of cell current over the whole cell length; this can limit feasible cell formats. An MWT cell only collects current locally at the cell level by contact pads, which are distributed evenly over the total cell area.

IBC interconnectors only have to bridge a small distance (approximately 5mm) in between cells (Fig. 2). They need to provide



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mechanical stress relief in between cells against loads originating from temperature changes and module deflection. On cells with distributed contacts, the interconnector is supposed to collect the current from the contact pads and carry it towards the cell edge. The interconnector cross-section is critical for serial resistance losses. The interconnector design has to provide stress relief not only in between cells, but also in between contact pads on one cell. A tapered design adapts the cross-section to local current.

Power losses due to stringing series resistance can be significantly reduced by increasing the amount of copper per cell and optimizing the interconnector design (Fig. 3). In current MWT cell designs the interconnector that contacts the emitter pads needs to cross over the base metallization of the same cell, requiring an isolating layer. This layer may be either an isolating coating that is selectively applied to the solar cell by screen printing or an adapted encapsulant material.

> "Power losses due to stringing series resistance can be significantly reduced by increasing the amount of copper per cell and optimizing the interconnector design."

Different designs of single and multiple bows have been proposed for stress relief [4]. Optimal design ensures a compromise between ohmic resistance due to bow length and mechanical stiffness. If MWT cells are interconnected with conventional flat ribbon wires and conventional soldering tools, the mismatch in thermal expansion between copper and silicon leads to cell bow. Additionally it is difficult to reduce serial resistance losses by increasing or optimizing the conductive cross-section. The metal foil can be structured to provide local stress relief and adapted cross-sections by using a punching tool. Masking and etching PC (printed circuit) strips or PC backsheets allows very flexible configurations [5,6,7].

Different strategies have been suggested for the interconnection process itself (Fig. 4). A pre-lamination joint formation has the advantage of enabling string quality control before irreversible lamination takes place. It requires a dedicated tool, as is the case with post-lamination joint formation. For the latter, laser soldering through the front glass has been proposed. In-lamination joint formation has the appeal of using the laminator additionally as a soldering or curing tool, but this usually requires a preliminary fixation of cell position with respect to the interconnector material and careful tuning of the simultaneous processes.

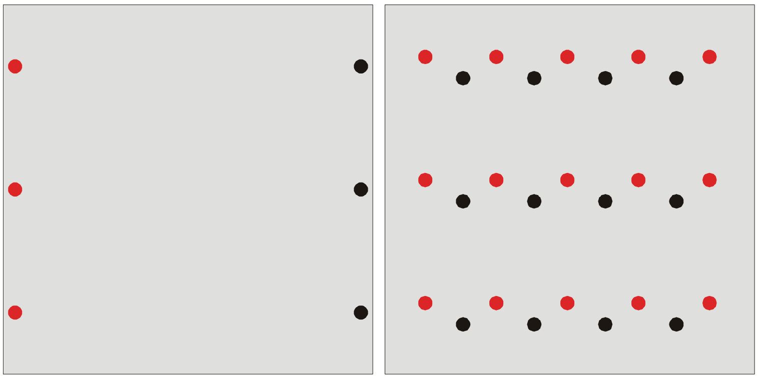


Figure 1. Schematic view of BC cells with edge contacts (left) and distributed contacts (right).

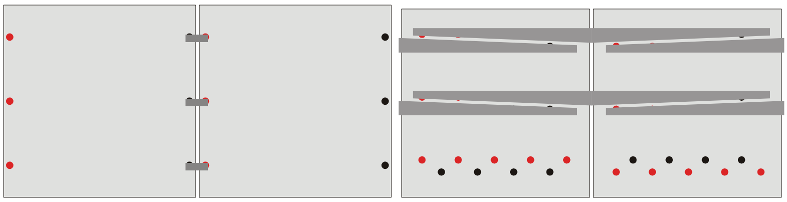


Figure 2. Interconnection schematic for cells with edge contacts (left) and distributed contacts (right).

For joining, solder paste and conductive adhesives have been proposed. Adhesives are filled with silver particles, work out more expensive and provide a less satisfactory conductivity than solder joints. Their advantages include lower process temperature and lower stiffness, both of these properties helping to reduce mechanical stress on the joints and cells.

Reliability

Extensive research has been carried out to assess the reliability of BC modules. At the cell level, the laser-drilled holes and MWT laser contact separation may reduce cell mechanical stability if not properly executed. The mechanical stability of the contact pads also requires special attention.

At the module level, certification according to IEC 61215 and IEC 61730 is effectively mandatory for reliability and safety conformance. In practice, module manufacturers do not rely on these basic tests for new products; they use accelerated-ageing and outdoor-exposure tests that are more robust than those defined by the standard. Thorough testing will increase confidence in module

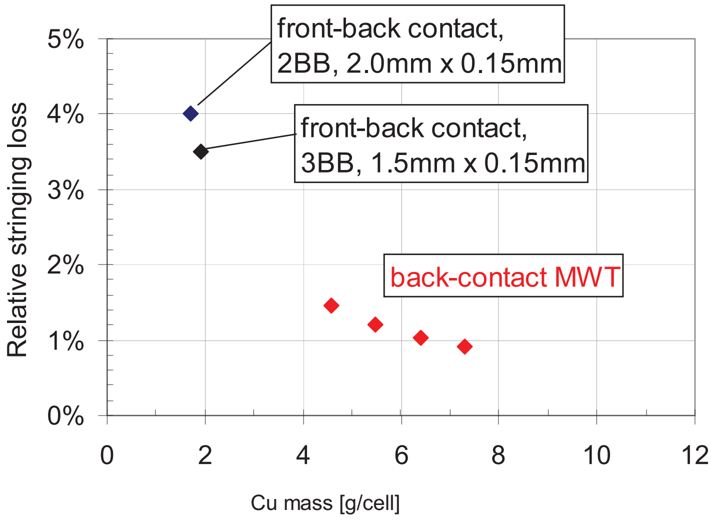


Figure 3. Calculated serial resistance power losses due to cell stringing, I_{mpp} = 8.3A.

Interconnector material	Interconnection process	Joining material
■ structured interconnector	■ pre-lamination	■ solder paste
■ PC strips	■ in-lamination	■ conductive adhesive
■ PC backsheet	■ post-lamination	

Figure 4. Technology choices for BC cell interconnection.

reliability, but it is generally not possible to guarantee a module service lifetime from accelerated-test findings.

BC module technology introduces new interconnector designs, where mechanical and thermomechanical stresses require special attention. Critical tests include mechanical load and temperature cycling. If new materials are additionally introduced, the interaction needs to be studied especially under a damp-heat accelerated-ageing environment. Since there is as yet no long-term reliability evidence regarding any specific BC module technology apart from Sunpower, BC modules have experienced some difficulties on the path to commercialization.

> “BC module technology introduces new interconnector designs, where mechanical and thermomechanical stresses require special attention.”

Manufacturing concepts

In principle, traditional pick-and-place assembly steps handling single cells and single interconnectors are feasible for producing BC modules. This is especially true for cells with edge contacts, where only one, relatively small, interconnector per cell is required. The vision behind BC module technology foresees a more elegant process, taking advantage of the SMD character of BC cells to speed up manufacturing. Eurotron proposes a system where the module is assembled sunny side up on a vacuum carrier and then flipped, together with the front glass, into a sunny-side-down position. This stack is then introduced into the laminator for adhesive curing and lamination. The following steps are included (Fig. 5), following layup and fixation of the PC backsheet on a vacuum carrier:

1. Screen printing of joining material (solder paste or adhesive)
2. Layup of a perforated encapsulant (2)
3. Cell layup
4. Layup of a front encapsulant (1)
5. Layup of front glass
6. Flip of entire stack

After the entire stack has been flipped to sunny side down, further processing, including joint formation and lamination, can take place.

Recently a process flow was proposed that requires only a single cell-handling step [4]. The module layup starts with the front glass and a specially structured encapsulant foil is placed on the glass. When vacuum is applied laterally, the structures allow the fixation of the entire cell matrix on the layup (sunny side down). The interconnector material is prepared on a separate vacuum tray and then flipped on the cell matrix. The process sequence of the one layup assembly (OLA) technology is shown in Fig. 6. It consists of the following steps, following layup and fixation of the PC backsheet on a vacuum carrier:

1. Layup of a structured front encapsulant (1) on the front glass
2. Cell layup and vacuum fixation
3. Layup of a perforated encapsulant (2)
4. Screen printing of joining material (solder paste or adhesive)
5. Flip of PC backsheet onto the cell matrix

After the stack has been completed, further processing, including joint formation and lamination, can take place. This sequence may be modified for the use of structured interconnectors not initially fixed to the backsheet. These interconnectors may be preassembled on a vacuum carrier, screen printed with the joining material and then flipped onto the cell matrix. After joint formation, the backsheet can be applied.

Current state of the technology

Interconnector technology

Achieving a module efficiency higher than 20% in production, Sunpower manufactures the most efficient modules available on the market. Their back-contact E20 modules use back-junction back-contact (BC-BJ) cells that have an efficiency of 22.4% and point contacts at the cell edges (Fig. 1). NREL confirmed a record module efficiency of 20.8%, with a fill factor of 77.9%. According to recent publications [8,9], a lot of effort has been taken to lower the power loss from cell to module (18.7% module efficiency in 2007)

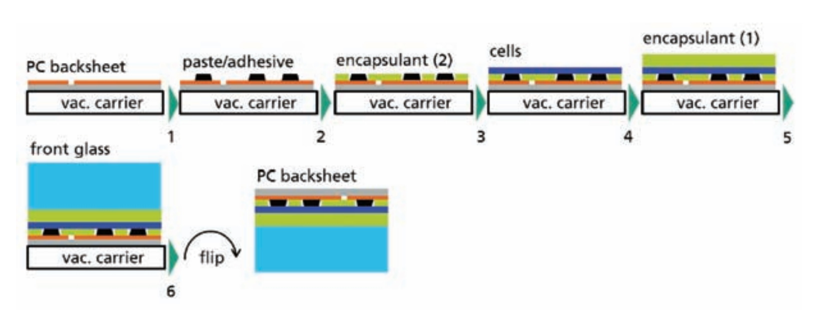


Figure 5. Eurotron layup concept.

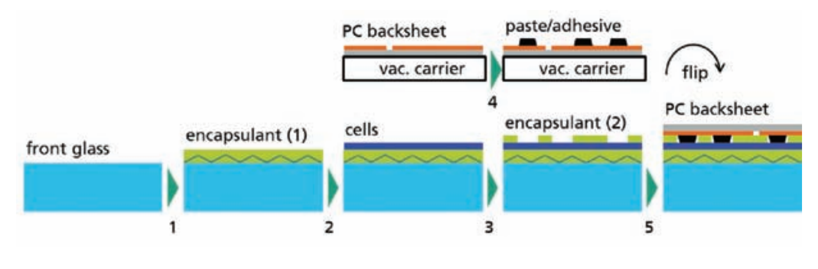
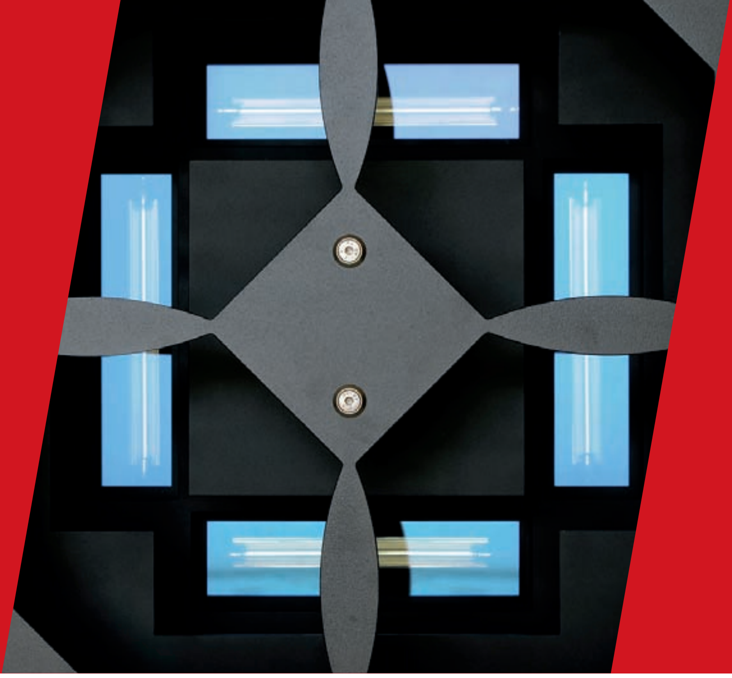
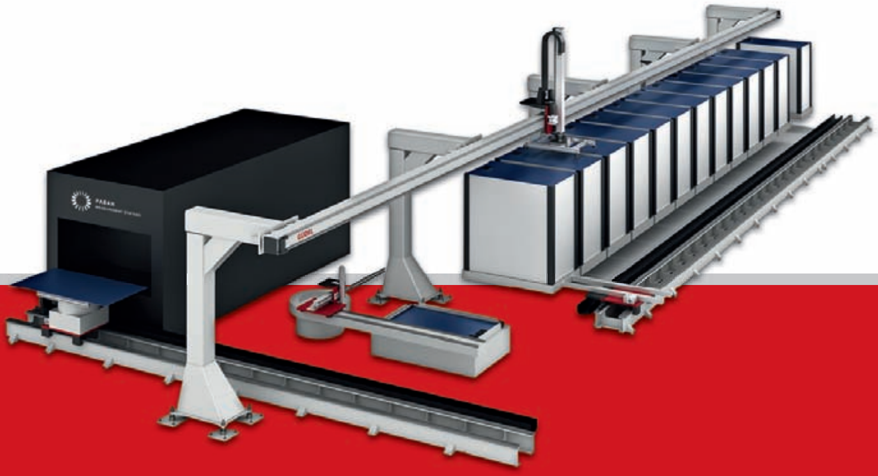


Figure 6. OLA concept.





and investigate the module reliability. Sunpower claims their modules to be long-term stable, showing no degradation in the field and under extended IEC testing. No PID (potential-induced degradation) has been observed. To date, 20MW of E20 modules have been installed, and the current production capacity is planned to reach 116MW in Q4 2011.

The ELPS technology of Canadian Solar is based on MWT cells and a stringing technique with ribbons [10]. For monocrystalline cells, efficiencies of up to 19.2% are reached, leading to module efficiencies in production of 16.2%. Their multicrystalline MWT modules are 15.5% efficient. Canadian Solar deems the concept of back-contact foils to be as yet unproven, while their approach is said to rely on proven materials. However, an easy switch to the conductive backsheet is possible and this manufacturer claims to have passed module certification successfully. Field tests are in progress and a target production capacity of 50MW has been set for the second half of 2011.

Fraunhofer ISE recently reported efficiencies above 18% for multicrystalline MWT cells and above 20% for multicrystalline Cz MWT cells [11]. With optimized structured interconnectors, fill factor losses from cell to module of the order of 1% (relative) have been measured on small modules. For demonstration purposes, MWT cells of 120µm thickness have been connected with lead-free SnAg solder. On account of the special interconnector material, the strings do not show any bow related to thermal expansion mismatches after soldering.

Printed circuit backsheet technology

In a joint development project with Schott Solar, Solland is about to commercialize MWT modules using the conductive backsheet approach. The cells are electrically connected to the conductive backsheet in a laser-soldering step after lamination. Module efficiencies of 16.4% (multi) and fill factor losses of 0.2–0.5% from cell to module have recently been published. Both companies see the potential for transferring the recent success of Schott with monocrystalline material to the MWT technique to achieve higher efficiencies. Regarding long-term stability, 60 modules have been deployed in the field since 2008, yielding results similar to standard crystalline modules: 1% degradation has been observed after IEC testing and 5% degradation after doubling the basic standard test sequences [12]. The pilot line has a capacity of 20MW and pilot production is currently being ramped up. In order to reach cost effectiveness fast enough, Solland is willing to license its technology. As a result, the generated economies of scale will primarily lower the cost of the conductive backsheet.

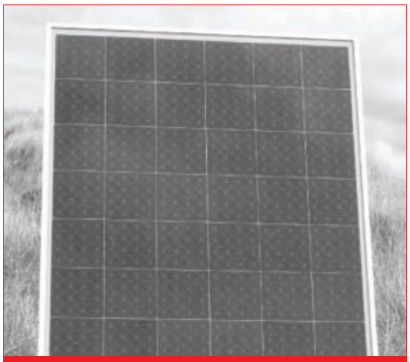


Figure 8. Module sample with MWT cells on a PC backsheet [1].

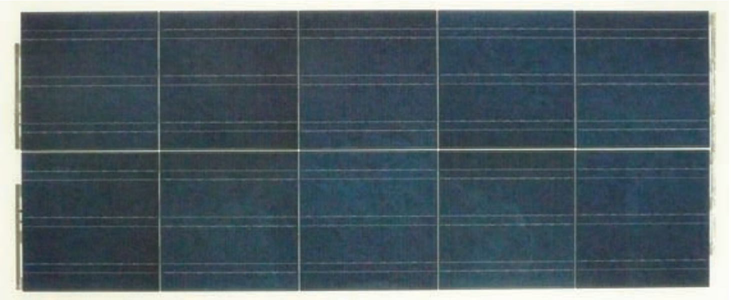


Figure 7. Module sample with MWT cells from Photovoltech and structured interconnectors, manufactured at Fraunhofer ISE.

> “Reliability engineering focuses on the use of new materials and the adaptation of certification tests to better reflect degradation mechanisms seen for BC modules with conductive foils.”

Current research activities at ECN focus on the module integration of cells with efficiencies above 20%, leading to a module efficiency above 19% (Fig. 8). Other issues are the use heterojunction modules and the transfer of microelectronic interconnection techniques to PV modules. The conductive backsheet concept is promoted in conjunction with conductive adhesives that cure during lamination. Reliability engineering focuses on the use of new materials and the adaptation of certification tests to better reflect degradation mechanisms seen for BC modules with conductive foils. The problem of a higher cost of the backsheet is expected to be solved as more suppliers enter the market. In 2010 ECN first reported the IEC-61215 certification of a type of MWT module manufactured with conductive adhesives and PC backsheets on a semi-automated Eurotron line.

Eurotron, the manufacturer of back-contact module production lines using the conductive backsheet technique, expects the backsheet cost to come down to 10–12€/m^2 in time. In Eurotron’s cost scenario, standard FBC modules with a production cost of 1.18€/Wp are still more expensive today than the BC module concept at 1.10€/Wp. A production capacity of 300MW is expected to be operational by January 2012 and Eurotron plans to sell a cumulated production capacity of 1GW by the end of 2012.

Outlook

The potential of BC technology is impressive: a considerably higher module efficiency paired with thin-cell compatibility. Not surprisingly, cell and module manufacturers expect a market share of 40% BC technology by the year 2020 [13]. To facilitate this growth, material costs for BC cell interconnection need to come down or remain low. In the PC backsheet approach, cost reduction is expected to occur with market volume growth. In the structured interconnector approach, the punching step inevitably adds some cost to the simple coated copper foil.

A second factor that will promote growth relates to the expanding pool of experience and comprehensive data from modules exposed to outdoor conditions and accelerated ageing. An important step for proving module reliability has already been taken in the certification of the first types of BC module.

References

[1] Lamers, M. et al. 2011, “17.9% metal-wrap-through mc-Si cells resulting in module efficiency of 17.0%”, *Prog. Photovolt: Res. Appl.*, DOI 10.1002/pip.1110.

[2] Schönecker, A. et al. 2002, “ACE designs: The beauty of rear contact solar cells”, *Proc. 29th IEEE PVSC*, New Orleans, Louisiana, USA, pp. 106–109.

[3] van Kerschaver, E. and Beaucarne, G. 2005, “Back-contact solar cells: A review”, *Prog. Photovolt: Res. Appl.*, Vol. 14, No. 2, pp. 107–123.

[4] Wirth, H. et al. 2010, “New technologies for back contact module assembly”, *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 3846–3849.

[5] Bennett, I.J. et al. 2009, "World record module efficiency for large and thin mc-Si MWT cells", *Proc. 24th EU PVSEC*, Hamburg, Germany, pp. 3258–3261.

[6] de Jong, P. 2010, "Achievements and challenges in crystalline silicon back-contact module technology", *Photovoltaics International*, 7th Edn, pp. 138–144.

[7] Bennett, I.J. et al. 2007, "Low-stress interconnection of solar cells", *Proc. 22nd EU PVSEC*, Milan, Italy, pp. 2674–2678.

[8] Bunea, G. et al. 2011, "High volume production of 20% efficient polarization free modules", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3165–3168.

[9] Kim, D. et al. 2011, "High reliability of Sunpower modules with >20% efficiency", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3103–3106.

[10] Wu, J. et al. 2011, "19.2% efficient H-patterned mono silicon metal wrap through solar cells", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 1004–1007.

[11] Thaidigsmann, B. et al. 2011, "HIP-MWT – A new cell concept for industrial processing of high-performance metal wrap through silicon solar cells", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 817–820.

[12] Augustin, L.M. et al. 2011, "Mass production and field performance of durable metal-wrap-through integrated back contact foil based 'Sunweb' modules", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3113–3116.

[13] SEMI PV Group Europe 2011, "International technology roadmap for photovoltaic (ITRVP.net): Results 2010", March [available online at http://www.itrvp.net].

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Harry Wirth received a diploma degree in physics from the University of Freiburg, Germany, in 1995. He subsequently earned his Ph.D. from the École Polytechnique Fédérale de Lausanne (EPFL), and from 1999 he was in charge of the R&D group of a specialized insulating glazing manufacturer. In 2005 he returned to Fraunhofer ISE to set up the Photovoltaic Modules group and was also responsible for the installation of the PV Module Technology Center at Fraunhofer ISE. Since October 2010, Dr. Wirth has headed the new division of Photovoltaic Modules, Systems and Reliability, which is mainly engaged in the development, testing and monitoring of photovoltaic modules.

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A new DSC method for the quality control of PV modules: Simple and quick determination of the degree of crosslinking of EVA encapsulants

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ABSTRACT

This paper presents a new differential scanning calorimetry (DSC) method that allows the determination of the degree, or level, of crosslinking of ethylene-vinyl acetate (EVA) copolymers, including EVA films used as encapsulants for photovoltaic (PV) applications. This method can also determine additional characteristics of EVA, such as its weight per cent (wt %) vinyl acetate (VA) content and its fluidity. The paper describes the procedure and its application to EVA film samples laminated at 145°C, for different lengths of time in an industrial-type laminator for PV modules, as well as to EVA uncrosslinked samples of different composition and fluidity. The scope of the method compared to other characterization methods for the degree of crosslinking of EVA is discussed. An experimental comparison is also made to rheological and gel content methods.

Introduction

A large majority of PV modules need a support or back sheet, a front cover or front sheet, and, in between, a layer of encapsulated, conveniently interconnected, PV cells which must be protected against environmental exposure, including mechanical loading, impacts, moisture, oxidation and other possible causes of damage or deterioration [1,2]. The most common way of creating this multi-layered structure is a lamination process, during which all the layers are stacked and thermally sealed in a laminator.

The encapsulant is a transparent polymeric material responsible for the protection of the strings of interconnected PV cells. Most module manufacturers still prefer a crosslinkable ethylene-vinyl acetate (EVA) copolymer. A typical EVA film for cell encapsulation is 300 to 500 microns thick and comprises a VA-rich EVA base (e.g. a 33 wt % VA content), a crosslinking system (mainly a peroxide or a peroxide mixture), an adhesion promoter (e.g. silanes), and a cocktail of conveniently chosen UV-stabilizers and antioxidants [2]. In the case of EVA encapsulants, good processability in the lamination step is achieved by regulating the flow properties of uncrosslinked EVA and adjusting its crosslinking kinetics, so that the material presents an optimized rheological behaviour, i.e. becoming liquid enough during the first stages of the lamination for a complete encapsulation of the cells to take place, and crosslinking fast enough during the last stages for the encapsulant to become a thermoset solid.

> “The actual properties of the EVA encapsulant after the lamination step depend, to an important extent, on its degree (or level) of crosslinking.”

The actual properties of the EVA encapsulant after the lamination step depend, to an important extent, on its degree (or level) of crosslinking. This paper introduces a new characterization method for this property, which retains the simplicity of the most popular industrial quality control techniques while extending the range of potential applications.

Determination of the degree of crosslinking of EVA encapsulants

Swelling experiments and mechanical measurements are two possible techniques for directly determining the crosslinking densities of polymer networks. However, they are seldom used in quality control, because of the complex underlying physics, the need for careful sample preparation and measurement, and the long time required to obtain reliable data.

Industrial companies use indirect, simpler techniques, among which the so-called ‘gel content’ technique is by far the most widely used. Measuring the gel content implies carrying out the solvent extraction of the soluble fraction of the crosslinked polymer. The remaining insoluble fraction of the original dry sample is considered to be composed of the crosslinked polymer network. The results are expressed either in terms of per cent ‘insolubles’ (% gel content) or in terms of the complementary per cent ‘solubles’ (% extracted material). High gel contents correspond to densely crosslinked networks. The method is fairly simple and easy to perform. On the other hand, the extraction experiments must be carried out at relatively high temperatures (over 70°C) for 12 to 24 hours. Another important drawback is the need to handle (and dispose of) organic solvents. There is certainly a need for efficient ventilation systems, good management of fire and explosion hazards, and responsible disposal of used solvents.

Recently a new indirect method for determining the degree of crosslinking for EVA-based encapsulants was proposed [3]. It is based on the fact that the crosslinking reaction of EVA, initiated by peroxides, is an exothermic process. This method uses differential scanning calorimetry (DSC) on small samples of EVA, whether uncrosslinked or crosslinked. DSC is a well-known technique for the thermal characterization of polymers [4]. It is

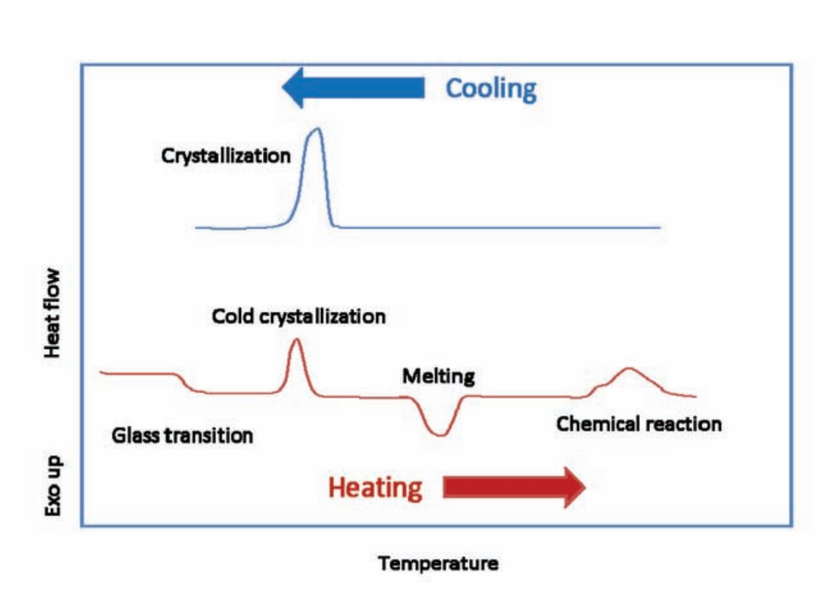


Figure 1. Schematic DSC thermogram showing a heating scan and a cooling scan. The main possible thermal transitions expected for polymers are indicated.

based upon a controlled heating or cooling (temperature scan) of two metallic closed crucibles containing, respectively, a small sample (usually a few milligrams) of the material to be analyzed and air (closed crucible with no sample). During the scan, the temperatures of the crucible containing the sample and the empty (containing only air) crucible (reference) are compared; if a difference arises, the calorimeter compensates immediately so that the temperatures remain equal. The amount of heat required to compensate is measured and recorded. Whenever the analyzed sample undergoes a thermal transition (understood to be any process giving rise to heat absorption or release), this event will appear in the thermogram as an upward or downward deviation of the baseline (peak or jump). With the 'Exo up' convention (meaning released heat is represented as an upward deviation of the base line, and, correspondingly, absorbed heat as a downward one), the most common thermal transitions that polymers may undergo are schematically shown in Fig. 1.

The recently proposed DSC method, hereafter referred to as the 'residual peroxide method' [3], measures the heat released by the exothermic crosslinking of EVA encapsulant film samples. When the encapsulant is uncrosslinked, a heating scan up to the temperature zone where the reaction takes place (> 100°C) will produce an exothermic signal similar to the one shown in Fig. 1 labelled 'chemical reaction'. The integral of the heat flow signal will correspond to the total maximum enthalpy that the crosslinking reaction, carried out in its entirety, will release. The residual peroxide method is based on the assumption that an already laminated EVA sample still has some heat to release when submitted to a DSC scan. By comparing it to the heat released by the uncrosslinked (no lamination) sample, a relative degree of crosslinking of the laminated sample may be determined. The method correlates well with gel content measurements [3]. On the basis of this good agreement, the new calorimetric measurement could be used for determining the degree of crosslinking of EVA encapsulants, and subsequently the crosslinking kinetics, namely the evolution of the crosslinking degree for different lamination times. The use of DSC has some important advantages over the gel content technique: it does not need any solvents, and the DSC equipment can easily be operated by the manufacturing teams. The sample needed for a measurement is very small (only a few milligrams), and the measuring time is very short (typically less than one hour) compared to the solvent extraction time. On the other hand, the residual peroxide DSC method relies on the presence of this residual additive, and is therefore not applicable to samples with complex or unknown thermal history (since, for the method to be accurate, all of the peroxide decomposition must have taken place either during the manufacturing process or during the post-lamination DSC measurement). Obviously, the method cannot be applied, or needs to be adapted, to samples being crosslinked by methods other than pure peroxide-initiated crosslinking.

Introducing a new, improved calorimetric method

This paper introduces a new DSC method which maintains the advantages of the use of DSC over other techniques such as rheology, swelling experiments or gel content measurements. Moreover, it is based upon more direct principles than the residual peroxide method (structural changes in EVA), and thus considerably improves the range of potential applications.

Materials and methods

The EVA copolymers for lamination experiments were provided either by STR Spain or by Etimex (now Solutia): the STR film reference was 15420P/UF, and the Etimex film reference was Vistasolar 486.00. All other EVA copolymers in pellet form were provided by Arkema under the references Evatane 18-150, 18-500, 24-03, 28-05, 28-150, 40-55 and 42-60.

The lamination of EVA encapsulant films was carried out by stacking, downside-up, a 16×16cm, 3.2mm-thick glass plate, a thin Teflon non-adherent sheet to prevent the EVA/glass adhesion, two EVA sheets to be crosslinked, one more Teflon non-adherent sheet, and two more EVA sheets which served as damping layers. In this stack, the two EVA sheets to be crosslinked were placed in the position that they would normally occupy in the lamination stack of a typical glass/EVA/cells/EVA/back sheet PV module.

The stack was laminated at 145°C in an industrial-type 3S laminator (model S1815E), following a standard lamination procedure including degassing and crosslinking stages. In this procedure, the actual lamination time (after 5 minutes' degassing) was varied between 3 and 15 minutes (in the standard procedure the lamination time is usually 10 minutes). All DSC measurements were carried out in a TA Instruments DSC calorimeter (model Q 10) equipped with an RCS 90 cooling device. All samples weighed between 5 and 12mg, and the measurements were conducted under a continuous nitrogen flow of 50ml/min. No sample conditioning was applied before the DSC measurements.

Three heating scans covering a temperature range from −70°C to 100°C were carried out with a heating rate of 10°C/min. After each heating scan, a cooling scan was applied from 100°C to −70°C, except for the third cooling scan, for which the lower temperature limit was −20°C. Before each heating scan the temperature was equilibrated at −70°C for 5 minutes; no equilibration time was applied at 100°C before the cooling scans. The upper temperature limit (100°C) was designed to prevent the samples from continuing to crosslink during the DSC experiment, in contrast to the residual peroxide method.

The rheological measurements were carried out using an Anton Paar Physica MCR 301 rheometer under a parallel-plates configuration, in the shear (oscillatory) mode. After a period of testing, the experimental temperature was set to 100°C,

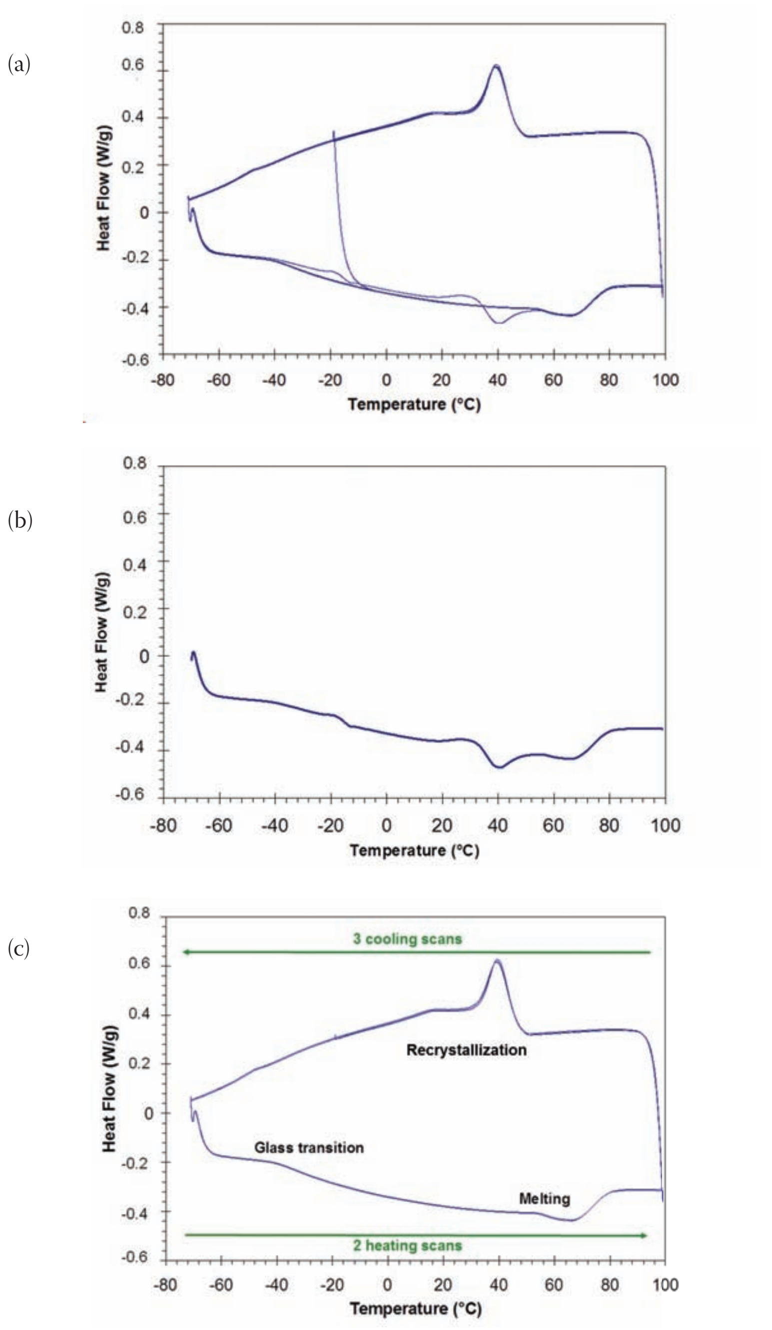


Figure 2. (a) Typical DSC thermogram obtained by applying the procedure described in this paper. (b) First heating scan (from –70°C to 100°C) of this specific DSC experiment. (c) DSC thermogram in (a) without the first heating scan in (b), and without the final return from –20°C to room temperature.

and frequency sweeps from 0.01 to 10Hz were conducted. The elastic, G', and viscous, G'', components of the complex shear modulus were measured, and their ratio, tan δ = G''/G', was determined (the lower this ratio, the more elastic the material, i.e. the better the crosslinking).

The gel content measurements were carried out through solvent extraction in xylene (Rectapur, three isomers mixture) at reflux temperature for 12 hours, by adapting ASTM D-2765-95 standard. The gel content was calculated by (% gel content) = 100 – (% extracted).

Results and discussion

Reproducible thermal transitions of EVA by DSC analysis

The sample crucibles were weighed before and after the DSC characterization, in order to check for any possible weight loss. No weight losses were detected when using the DSC procedure (three heating–cooling scans) described above. A typical heat flow vs. temperature plot is shown in Fig. 2(a); the first heating scan from –70°C to 100°C at 10°C/min is shown in Fig. 2(b). Fig. 2(c) shows the same plot as in Fig. 2(a), but without the first heating scan, and without the last return to room temperature. By comparing Figs. 2(a)–(c), it is clear that only the first heating scan is not reproducible. Indeed, the plot in Fig. 2(c) shows three neat, very reproducible thermal transitions for the EVA copolymer, corresponding to: the glass transition region (at around –40°C), the melting region (with a single endothermic peak at around 70°C of peak minimum), and the recrystallization region (with a maximum peak at around 40°C during cooling).

Several authors have shown and sometimes discussed [3,5–8] the double endotherm in the melting region from the first heating scan in DSC of EVA copolymers. Imperfect crystalline regions of different sizes and metastable states may explain this kind of melting behaviour, leading to a first DSC scan of EVA copolymers which is dependent on the thermal history of the sample. Fig. 2(c) shows that, after the first scan, subsequent heating scans lead to a very reproducible melting behaviour for EVA; the same is true for the glass transition. One important aspect of this characteristic behaviour of EVA copolymers, when using DSC to follow crosslinking evolutions (according to the method proposed herein), is that the elimination of the very first heating scan allows the non-reproducible component of the thermal history of the samples to be erased, and this, in turn, allows the characterization measurements by DSC to be performed without any requirement concerning previous conditioning of the samples.

> “We believe that quality control measurements could be carried out in about 30 to 45 minutes per sample.”

Regarding the recrystallization behaviour, it is clear from Fig. 2(c) that all three cooling scans superimpose very well. This means that, if only the recrystallization region is to be analyzed for the EVA characterization (discussed later), the experiment can be stopped after only the first or, at most, the second cooling scan, making it possible to reduce the measurement time per sample considerably. If, again, only the recrystallization region is used for data analysis, further optimization is possible by using a lower temperature limit much higher than –70°C. We believe that quality control measurements could be carried out in about 30 to 45 minutes per sample.

Analysis of the glass transition and melting regions

It is well known that the glass transition temperature, T_g, of polymers may increase

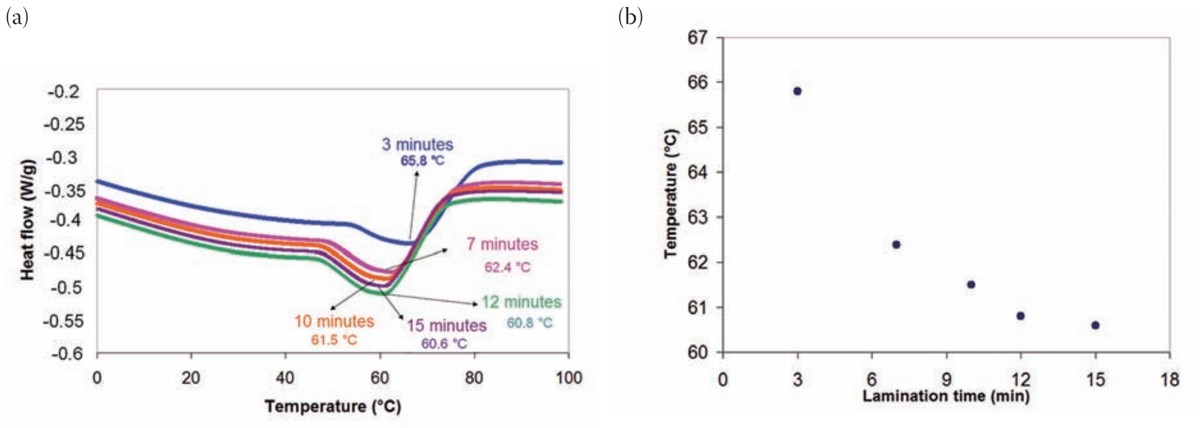


Figure 3. (a) Zoom-in on the melting zone for EVA encapsulating films after lamination times of 3 to 15 minutes. The melting temperatures corresponding to the minimum heat flow are also shown. (b) Melting temperature as a function of lamination time.

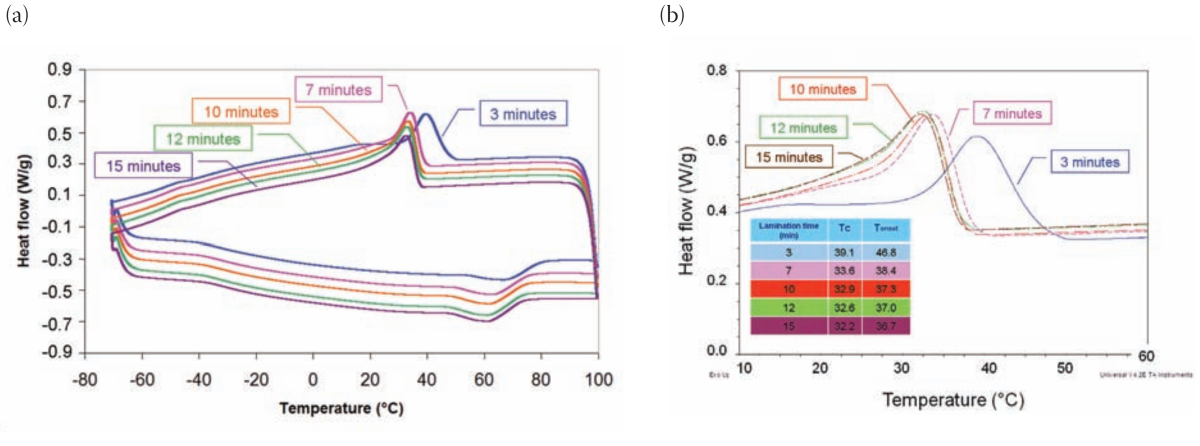
when they are crosslinked [9]. Although we did verify this effect in our work, the shift appears too small for T_g measurements to be used to follow crosslinking kinetics, and the results will not be discussed here.

EVA copolymers present a broad melting region, possibly due to the imperfect crystallization of ethylene-derived moieties caused by the insertion of VA-derived groups into the polymer chains [4,7,8], as may be concluded from the fact that increasing the vinyl acetate content reduces the total crystallinity of EVA copolymers. As shown in Fig. 2, the first heating scan in DSC produces multiple (at least two) melting peaks related to the thermal history of the sample. From the second heating scan onwards, the melting transition appears as a very reproducible, broad endothermic deviation from the DSC baseline, with a part of the melting taking place in the form of a large endothermic peak. Fig. 3(a) shows a zoom-in on the melting region from the second heating scan, for samples undergoing different lamination times; a clear shift towards lower temperatures of the large peak can be observed. Fig. 3(b) shows the variation of the melting temperature, taken at the lowest value of the heat flow signal, *q*, of Fig. 3(a), as a function of the lamination time. The melting temperature initially decreases very sharply with lamination time, and then tends towards a stable value at high degrees of crosslinking. By following the evolution of the melting temperature, obtained as described above (second or subsequent heating scans), it is possible to differentiate samples with different degrees of crosslinking, up to reasonably high crosslinking levels.

Analysis of the recrystallization region

Fig. 4(a) shows the plots of the first cooling scan and the second heating scan, for the five samples at different lamination times described earlier. For clarity, the curves were shifted downwards with respect to the sample of 3 minutes' lamination time (blue curve). The recrystallization region is, by a large margin, the transition region which undergoes the biggest change with crosslinking: not only does the recrystallization peak shift to lower temperatures, as for the melting region, but also the shape or form of the peak is significantly changed. Fig. 4(b) shows a zoom-in on the recrystallization region, corresponding to the three cooling scans carried out on each sample. It can be seen from this figure that the DSC scans lead to extremely reproducible results. Indeed, only the less crosslinked sample (3 minutes' lamination time) reveals the fact that three cooling scans have been plotted; for all the other lamination times, the results are so reproducible that the three scans superimpose very well, as if only one curve were plotted. It is also apparent from Fig. 4(b) that the shape of the peak changes with crosslinking (increasing lamination time), mostly at the lower temperature side of the peak.

In order to characterize the temperature shift of the recrystallization peak, we have selected two parameters, as illustrated in Fig. 5(a): the temperature of the recrystallization peak's maximum, T_c, and the extrapolated temperature of the onset of crystallization, T_{onset}. In order to characterize the change of the peak's shape, different parameters may



Lamination time (min)	Tc	T_{onset}
3	39.1	46.8
7	33.6	38.4
10	32.9	37.3
12	32.6	37.0
15	32.2	36.7

Figure 4. (a) DSC plots for all the samples at different lamination times. A downward shift of 0.05W/g has been applied to the curves for lamination times of 7 to 15 minutes. (b) Zoom-in on the recrystallization region of the DSC plots for all the different samples.

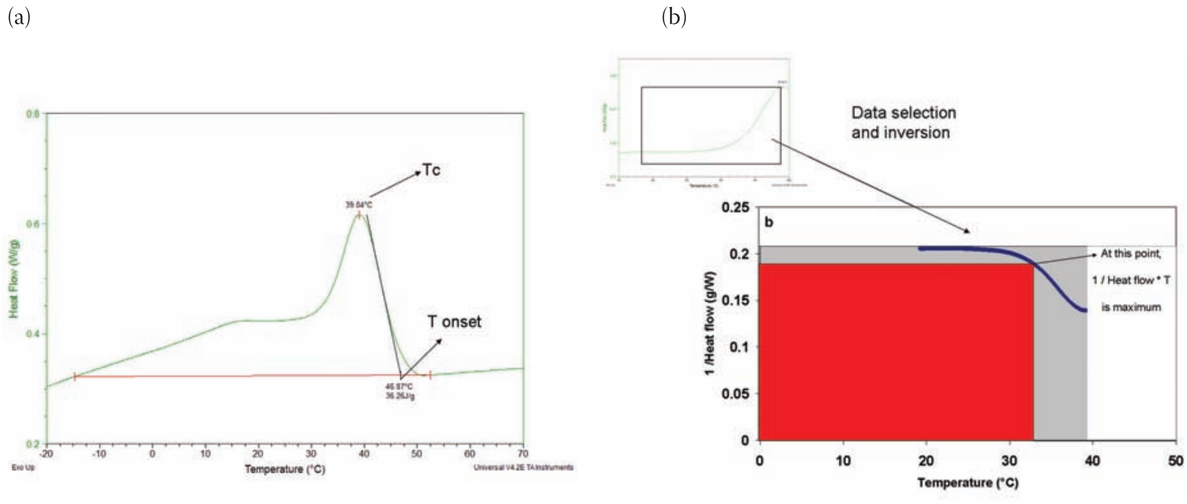
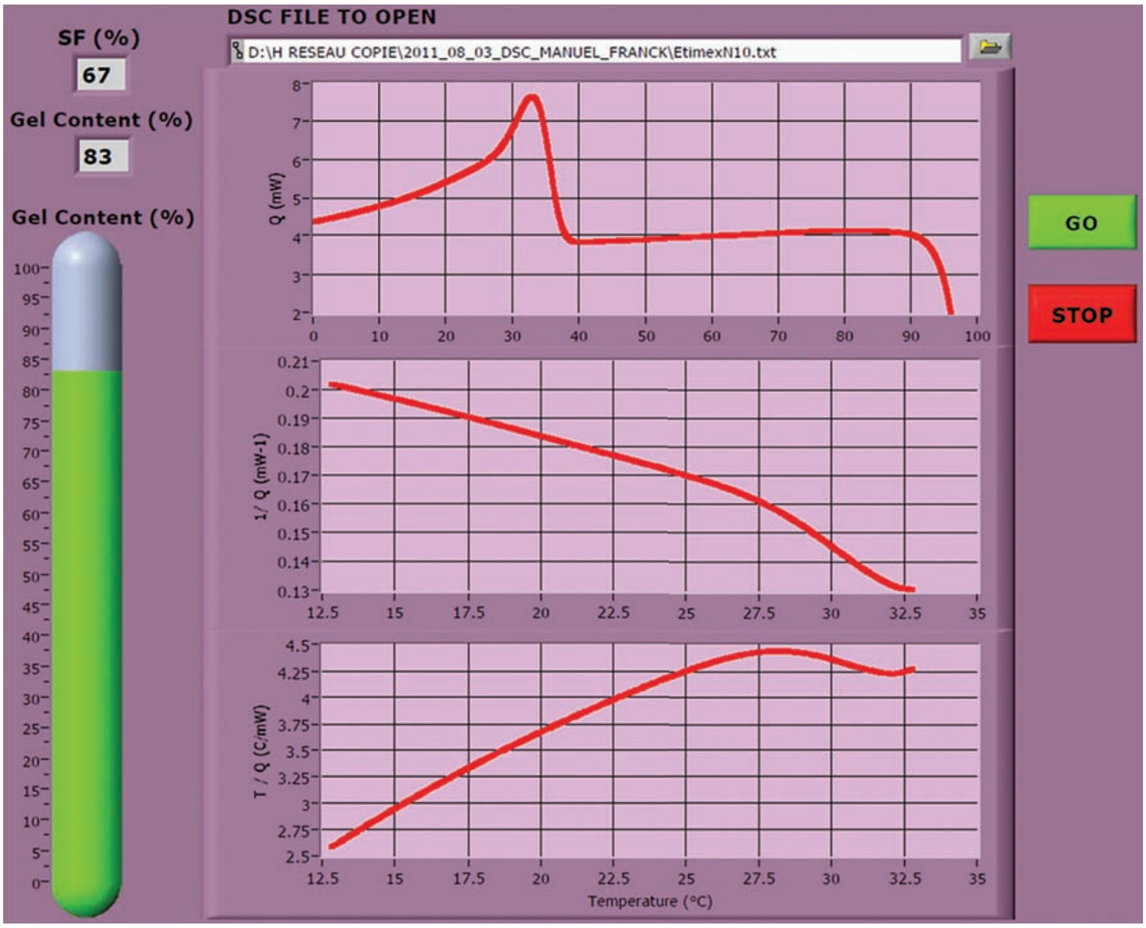


Figure 5. (a) Determination of the temperature shift parameters T_c and T_{onset}. (b) Calculation of the shape factor *SF* = 100 × red area / (red + grey area).

be used. After trying several possibilities, we chose a graphical method, related to the concavity of the lower temperature side of the crystallization peak, specifically the temperature region contained between T_c and T_c–20°C. In fact, the graphical method is similar to the calculation of fill factors from characteristic plots of current (*I*) vs. voltage (*V*), well known in the PV community. In order to do this, the steps below are followed:

1. Selection of heat flow (*q*) data between T_c and T_c–20°C.
2. Inversion of the *q* values by taking their inverse function, 1/*q* (the plot of 1/*q* vs. *T* between the limits T_c–20°C and T_c then looks much like a plot of *I* vs. *V*).
3. Determination of the maximum value of the product 1/*q* × *T* (in the


SF (%) 67

Gel Content (%) 83

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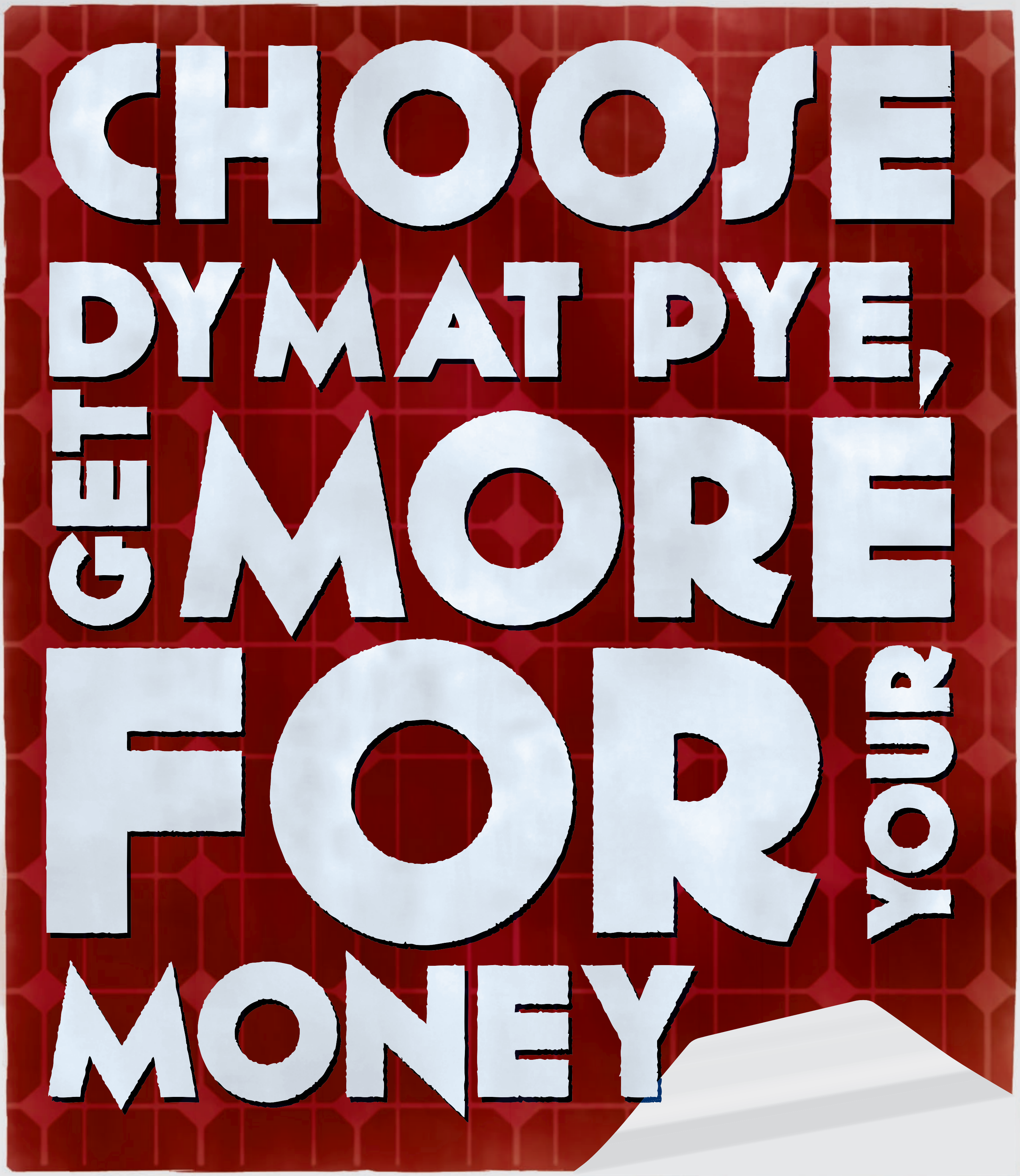
Figure 6. Labview graphical display of the plots needed to calculate the shape factor. The computed value of the shape factor and its correlated gel content (see text) are also indicated (top left). The green bar on the left reflects the final result: the sample with 12 minutes' lamination time is well crosslinked (> 80%).


CHOOSE
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same way that a maximum power is obtained from I vs. V plots).

4. Calculation of the area of the rectangle defined by the coordinates of this maximum, i.e. T and $1/q$ at which the product ($T \times 1/q$) reaches a maximum.

5. Calculation of the area of the rectangle defined by the limits of data, i.e. T_c on the one hand, and ($1/q$) at T_c–20°C on the other.

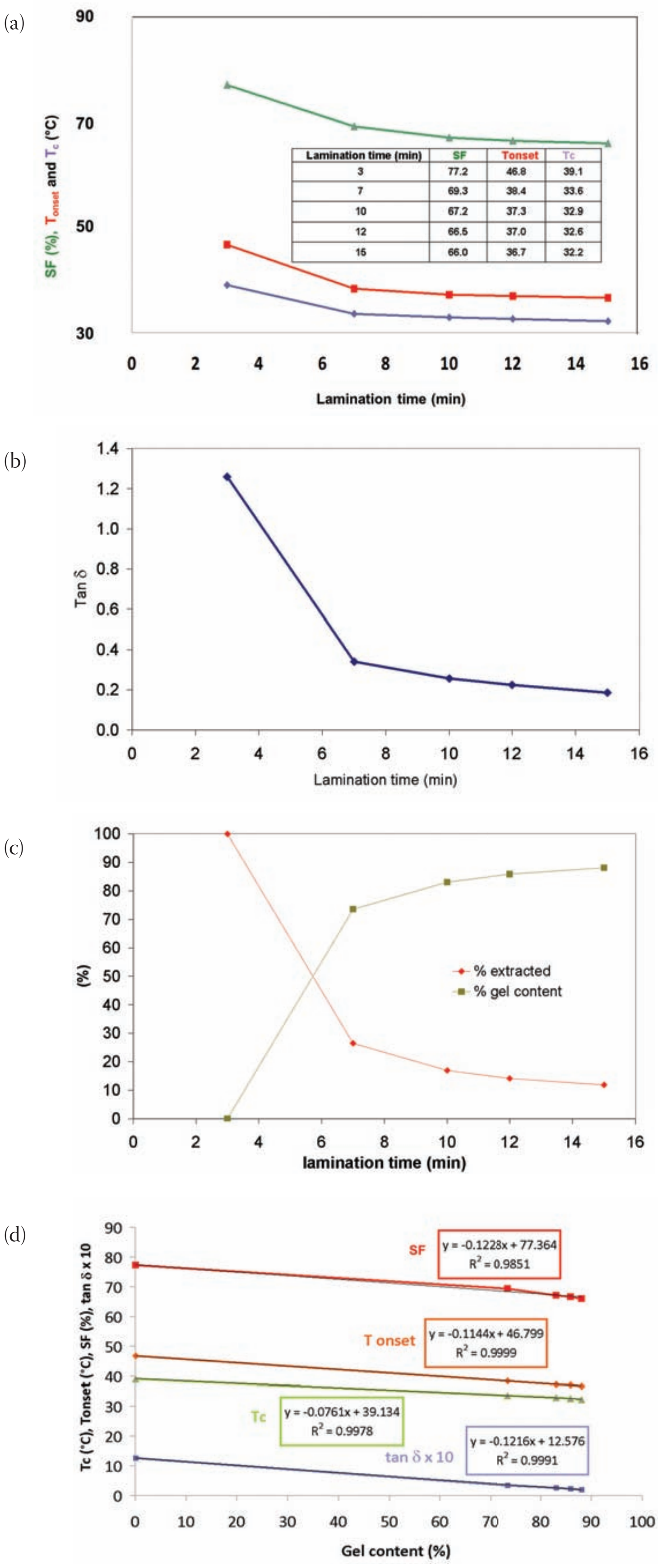
The shape factor is then obtained as the ratio given by the first rectangle area (step 4) divided by the second rectangle area (step 5); a more practical form can be used by multiplying this ratio by 100, in order to use it as a per cent scale.

Fig. 5(b) illustrates the shape factor (*SF*) calculation. Although more complicated to obtain than the parameters which describe the shift towards lower temperatures of the crystallization peak (i.e. T_c and T_{onset}), the shape factor may be easily programmed for automatic calculation from the DSC data between the temperature limits of T_c and a lower limit, defined here as T_c–20°C. This single numerical parameter represents a modification of the shape of the crystallization peak, and could be particularly useful as a graphical method that is less dependent than the temperature shift parameters on quality of the baseline and calibration issues.

A Labview program displaying the calculation of the shape factor is shown in Fig. 6. The plots in the main window correspond to: the raw DSC data at the crystallization region, q vs. T (top); the inverse function of the selected data, $1/q$ vs. T in the T_c–20°C to T_c interval (centre); and the product $1/q \times T$ vs. T in the same interval (bottom). The maximum in the last plot ($1/q \times T$ vs. T) defines the coordinates needed to calculate the red rectangular area in Fig. 5(b). The current criterion for what the gel content should be for an EVA encapsulant to be acceptably crosslinked is roughly > 75–80% [2]. Fig. 6 considers the sample for 12 minutes of lamination time. The green bar on the left is a graphical expression of the final result: according to the method described here, using the shape factor of the recrystallization peak and its correlation with gel content measurements (see below), the sample is well crosslinked (correlated gel content > 80%).

Fig. 7(a) shows the evolution of the three parameters – T_c, T_{onset} and *SF* – which characterize the crystallization region as a function of the lamination time for the EVA encapsulant films considered in this work. It can be seen from this figure that the trend is the same as for the melting temperature in Fig. 3(b).

Two other methods – rheology and solvent extraction – have been used for



Lamination time (min)	SF	Tonset	Tc
3	77.2	46.8	39.1
7	69.3	38.4	33.6
10	67.2	37.3	32.9
12	66.5	37.0	32.6
15	66.0	36.7	32.2

Figure 7. (a) Characteristic parameters *SF*, T_c and T_{onset} as a function of the lamination time. (b) Values of tan δ at 1Hz and 100°C for the film samples at different lamination times. (c) Per cent extracted material and gel content for the EVA film samples at different lamination times. (d) Correlations between the different characteristic parameters and the gel content.

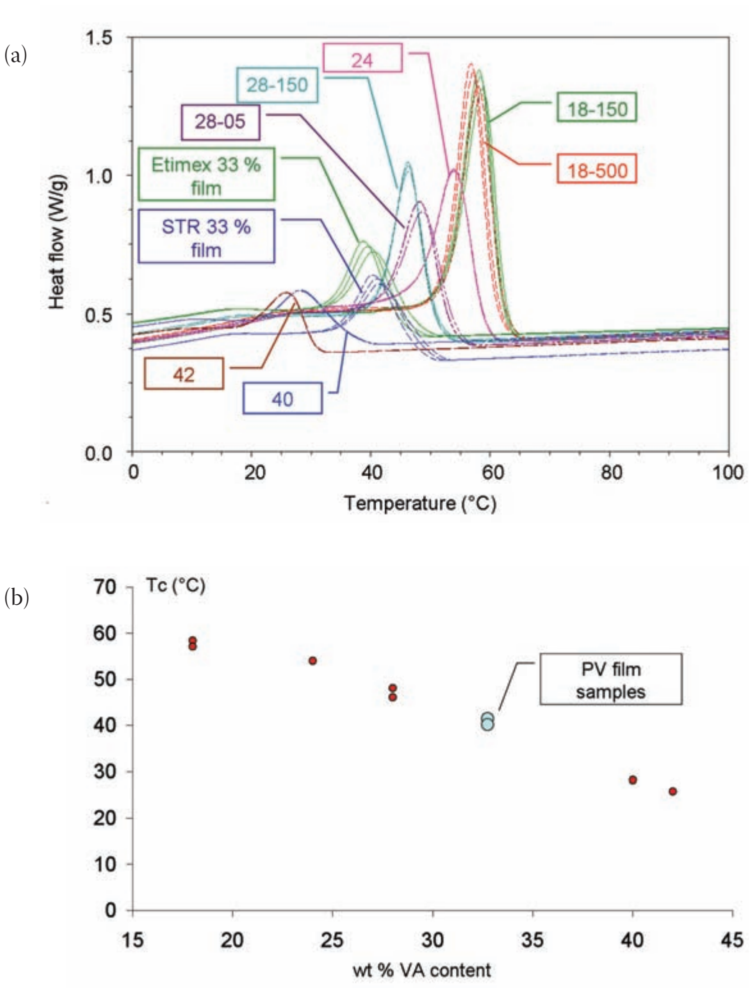


Figure 8. (a) Recrystallization DSC plots for the pellet samples (the numbers correspond to the wt % VA content of each EVA sample). Two PV encapsulant-grade films are also shown (33%). (b) Recrystallization peak temperature, T_c, as a function of wt % VA content for the corresponding samples in (a).

comparison with the new DSC method described in this paper. The experimental details for both are given in the materials and methods section. Fig. 7(b) shows the values of tan δ at 1Hz and 100°C, from rheological measurements as a function of the lamination time; the trend is very similar to that for the DSC characteristic parameters (melting temperature, T_c, T_{onset}, SF).

Solvent extraction experiments were carried out on the same EVA samples as before, laminated at different times. Fig. 7(c) shows the results in the form of both the % extracted material and, its counterpart, the % gel content (see materials and methods section). The same type of trend as for the DSC parameters and the rheological measurements is found for the % extracted material. Moreover, the solvent extraction measurements confirm that the sample at 3 minutes is not crosslinked. As can be seen from Fig. 7(d), the DSC parameters (obtained from the recrystallization region) and the rheological data correlate very well with gel content measurements. The correlation between the melting temperature (not shown) and the gel content is less satisfactory.

> “This new DSC method offers the advantages of DSC over rheology or gel content measurements, while avoiding the drawbacks of the recently reported residual peroxide DSC method.”

We can conclude that, with the use of this new DSC method (referred to hereafter as the ‘Sollia method’), the degree of crosslinking of EVA encapsulant films can be determined from DSC parameters obtained from the melting, and, even better, from the recrystallization zones of thermograms conducted under conditions where the samples do not crosslink in the DSC calorimeter. This new DSC method offers the advantages of DSC over rheology or gel content measurements, while avoiding the drawbacks of the recently reported residual peroxide DSC method. Indeed, the Sollia method could be considered to be an upgraded DSC method because:

- it relies on structural changes in EVA copolymers, caused by crosslinking, rather than on the residual peroxide content of the EVA formulation;
- being independent of residual peroxide, it may be applied to EVA samples with any thermal history, including return-from-the-field samples;
- it does not require any sample conditioning;
- it can be applied to EVA samples crosslinked by processes other than peroxide reactions;
- besides the degree of crosslinking, it yields other types of valuable information about EVA, as will be shown in the following sections.

Vinyl acetate (VA) content

Fig. 8(a) shows a zoom-in on the recrystallization region of different EVA copolymer samples (pellets and PV encapsulant films: see materials and methods). All the samples are uncrosslinked, and three cooling scans are shown in each case. It can be seen from this figure that the recrystallization peaks shift to lower temperatures with increasing VA content. This trend is also evident in Fig. 8(b), where the selected DSC parameter T_c has been plotted against the wt % VA content of the EVA copolymer samples. The values of the characteristic parameter T_c for two EVA encapsulant films from two different manufacturers, with a stated wt % VA content of 33%, are also plotted. The EVA encapsulant films fit quite well between the peaks of the curves corresponding to 28 and 40 wt % VA content in Fig. 8(a) (or between the T_c values in Fig. 8b). Moreover, the plot in Fig. 8(b) is linear in the zone defined between 24 and 42 wt % VA. Thus, by using the DSC method described here, it should be possible to accurately predict the wt % VA content of an unknown EVA sample.

Fluidity (molecular weight distribution)

Fig. 9 shows the recrystallization peaks of the 18 and 28% VA content samples in Fig. 8. For each of these, two different samples were analyzed: EVA 18-150 and EVA 18-500 for 18%; EVA 28-05 and EVA 28-150 for 28%. The number after the wt % VA content represents the fluidity of the material, as measured by its melt flow index; the higher the number, the more fluid the sample. (The melt flow index is

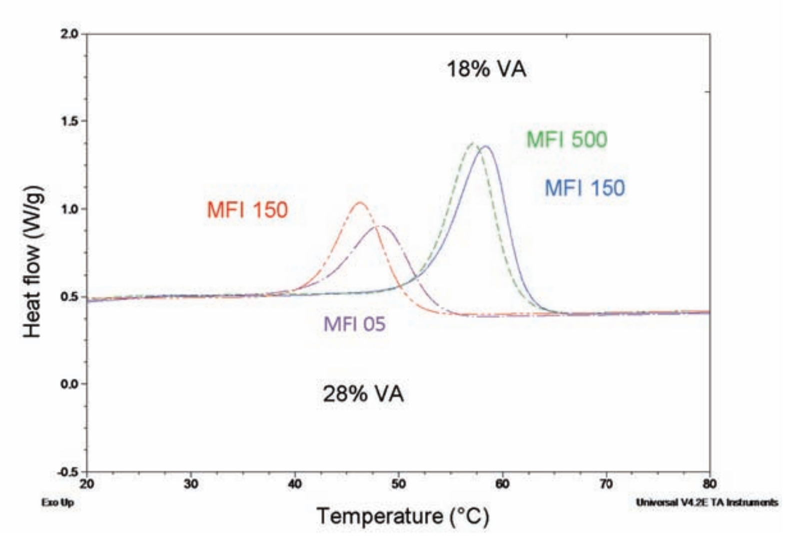


Figure 9. Recrystallization DSC plots for the pellet samples of 18 and 28 wt % VA content. Samples with the same wt % VA content but different melt flow indexes (MFI) are shown.

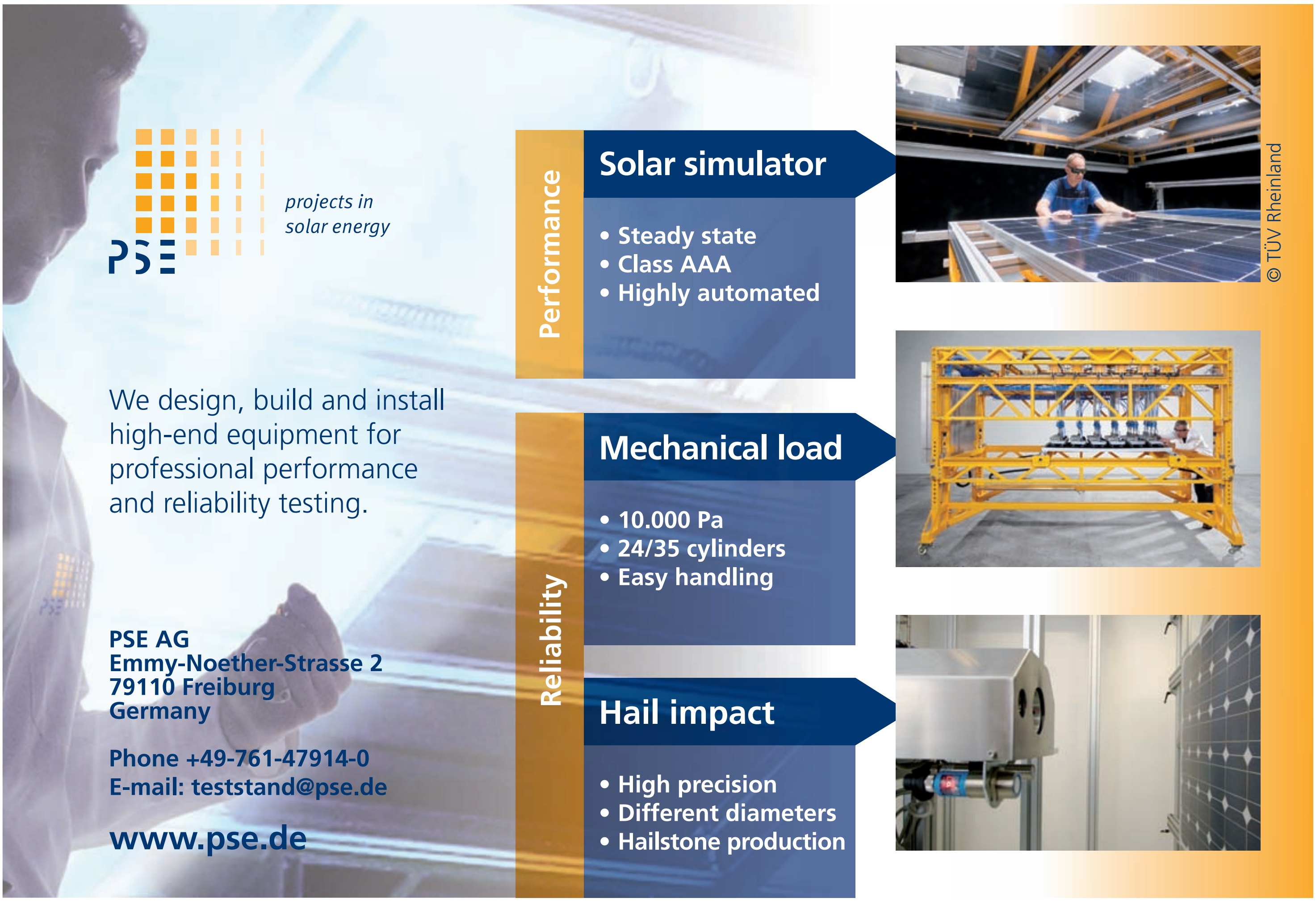
a standardized method of expressing the forced flow of a heated polymer sample through a hole; the temperature, and the pressure applied to the sample to push it through the hole, are constant. The melt flow index value corresponds to the weight of polymer that passes through the hole during a fixed time interval.)

It can be seen from Fig. 9 that higher melt flow indexes, corresponding to more fluid polymers, present recrystallization peaks at lower temperatures. This temperature shift can easily be characterized by the parameters T_c and T_{onset}, as indicated in the recrystallization section analysis. The width and form of the peaks may also be considered. Given that the fluidity of the polymers is related to their molecular weight distribution, the DSC method proposed here (Sollia method) can also give an insight into this important molecular characteristic of the copolymers.

> "Given that the fluidity of the polymers is related to their molecular weight distribution, the DSC method proposed here (Sollia method) can also give an insight into this important molecular characteristic of the copolymers."

Conclusions and perspectives

This paper has presented a new DSC method that can be used to determine the degree of crosslinking of EVA copolymers, which, particularly in relation to PV encapsulant applications, offers an alternative to a recently reported DSC method based upon the residual peroxide content of laminated encapsulant films. The new method is based upon changes in the microstructure of EVA copolymers. The effect of crosslinking on the thermal transitions of EVA has been discussed, and a method has been outlined for obtaining reliable, reproducible characteristic parameters, allowing the degree of



crosslinking of EVA film encapsulants to be determined. The preferred parameters for the method are those extracted from the recrystallization region of the DSC plots, such as the temperature at the peak maximum, T_c, the temperature of the onset of recrystallization, T_{onset}, and the shape factor, *SF*, reflecting the form of the lower temperature part of the recrystallization peak. The last of these is a single number which reflects a significant shape change, and should be independent of calibration or uncontrolled temperature shifts.

The Sollia method, described here, allows the determination of the degree of crosslinking of EVA copolymers independently of their thermal history (return-from-the-field analysis becomes possible by DSC), and should be applicable to complex crosslinking mechanisms, including those without peroxides. The fact that the method proposed here is based upon intrinsic properties of EVA copolymers allows us to explore other potential applications. Two of these have been identified: 1) determination of the wt % content of VA in unknown EVA copolymer samples; and 2) characterization of the fluidity of EVA samples. In all cases, the method may be used either in a comparison to known references, or, in a relative way, in a comparison of unknown samples. However, future work is still necessary to determine the full potential of this new DSC method.

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References

[1] Cuddihy, E.F. et al. 1983, "Applications of ethylene vinyl acetate as an encapsulation material for terrestrial photovoltaic modules", Jet Propulsion Laboratory, Pasadena, CA. Rep. 83-35.

[2] Czanderna, A.W. and Pern, F.J. 1996, "Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: A critical review", *Solar Energy Mater. & Solar Cells*, Vol. 43, pp. 101–181.

[3] Xia, Z., Cunningham, D.W. and Wohlgemuth, J.H. 2009, "A new method for measuring cross-link density in ethylene vinyl acetate-based encapsulant", PV-tech [available online at http://www.photovoltaicsinternational.com/technical_papers/a_new_method_for_measuring_cross_link_density_in_ethylene_vinyl_acetate_bas].

[4] Billmeyer Jr., F.W. 1971, *Textbook of Polymer Science*. New York: John Wiley & Sons, Inc.

[5] Huskic, M. and Sebenik, A. 1993, "Characterization of crosslinked ethylene-vinyl acetate copolymers", *Polymer International*, Vol. 31, pp. 41–44.

[6] Agroui, K. et al. 2006, "Thermal stability of slow and fast cure EVA encapsulant material for photovoltaic module manufacturing process", *Solar Energy Mater. & Solar Cells*, Vol. 90, pp. 2509–2514.

[7] Bistac, S., Kunemann, P. and Schultz, J. 1998, "Crystalline modifications of ethylene-vinyl acetate copolymers induced by a tensile drawing: Effect of the molecular weight", *Polymer*, Vol. 39, No. 20, pp. 4875–4881.

[8] Stark, W. and Jaunich, M. 2011, "Investigation of ethylene/vinyl acetate copolymer (EVA) by thermal analysis DSC and DMA", *Polymer Testing*, Vol. 30, pp. 236–242.

[9] van Krevelen, D.W. and te Nijenhuis, K. 2009, *Properties of Polymers*. Amsterdam: Elsevier.

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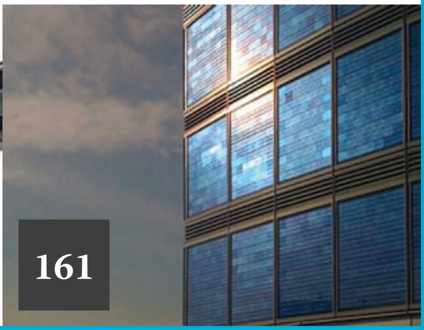

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Tonopah Solar secures US$737 million loan guarantee from US DOE for its Crescent Dunes CSP project

The US Department of Energy (DOE) advised that it had awarded a US$737 million loan guarantee to Tonopah Solar Energy for its 110MW Crescent Dunes Solar Energy Project. Sponsored by SolarReserve, the 100MW CSP solar power tower is said to be the first of its kind in the US and the tallest molten salt tower in the world. The project will be built on land leased from the Bureau of Land Management in Tonopah, Nevada.

The CSP project will generate power with molten salt as the main heat transfer and storage medium for the system. It plans to use 17,500 heliostats to collect the sun's thermal energy, which will heat the molten salt flowing through the 640-foot tall solar power tower. Solar power produced by the Crescent Dunes project will be sold to the Nevada Power Company, a utility subsidiary of NV Energy.

In addition to the DOE loan guarantee, SolarReserve and ACS Cobra both invested in the CSP project. ACS Cobra's Nevada-based affiliate, Cobra Thermosolar Plants will serve as the project's general contractor. The project is anticipated to generate over 500,000MWh per year of solar electricity.

It is hoped 600 jobs will be created over the 30-month construction period, with more than 4,300 direct, indirect and induced jobs at companies throughout the US.

Source: Tonopah Solar Energy

The Crescent Dunes Solar Energy Project has secured a US$737 million US DOE loan guarantee.

Asia News Focus

Astronergy modules to equip 6MW system in South Korea

China-based Astronergy will supply modules and inverters for a new 6MW PV project in South Korea. Work is expected to begin on the project by the end of the year and when completed, it will be one of the largest utility-scale developments in the country.

Astronergy, a subsidiary of Chint Group, will supply half of the inverters and all of the monocrystalline modules on the unique system, which is being connected to the national grid by a series of underwater cables.

China's project pipeline passes 16GW

Commercial PV capacity in China has now passed the 16GW milestone, according to a new report from Solarbuzz. The China Deal Tracker report also claims that the country is on course to match the US in terms of 2011 installations, with 195 systems, accounting for 1.8GW, scheduled to be grid connected by the year's end.

Falling module and BOS prices have considerably improved internal rates of return (IRR) for projects, alongside a recently-launched FiT policy leading to an upsurge of development across China. Solarbuzz estimates that 1,104 non-residential projects are either completed or close to completion.

The leading developers include China Power Investment, China Guodian and China Huadian amongst others, which have accounted for nearly 1GW of total installations in 2011.

At present ground-mounted systems dominate the PV landscape. Building-mounted systems represent just 10% of the national pipeline.

Singapore to take solar to the water with US$8.6 million floating solar system

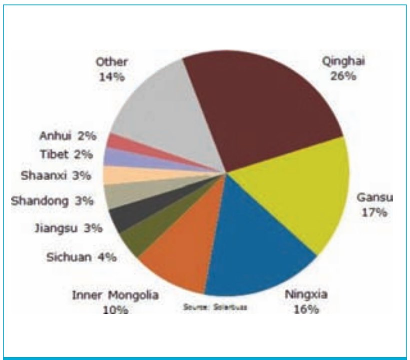
Singapore's Economic Development Board (EDB) and national water agency PUB are literally launching solar into the water with a new US$8.6 million floating solar system in the Tengeh Reservoir. According to The Straits Times, the pilot project is a way for the country to look beyond its land constraints and expand its solar development beyond rooftops.

The 2MW Tengeh Reservoir project will be connected to the national grid and will be a public and private partnership with the government agencies working with private companies to develop the system. EDB and PUB will also be taking the opportunity to examine other effects from the project, including the cooling effect of the water on body on the solar panels.

Development banks to withdraw support for India's PV sector

The US Government-sponsored banks that have helped fund the takeoff of India's fledgling solar industry may soon move to withdraw their support, according to an official at the Overseas Private Investment Corporation (OPIC).

Peter Ballinger, OPIC's director, has said that the agency is rapidly approaching its lending limit for PV projects in India and opined that multilateral lenders like the Asian Development Bank (ADB) and the World Bank (WB) could shortly be forced



Source: Solarbuzz

China's non-residential PV project pipeline by province.

Image: Flickr/ Antuan Goodwin

The floating solar array at Far Niente winery in the Napa Valley. One of the PV systems that inspired Singapore's EDB and PUB's new floating solar project.

Source: Edouard Stenger

Multilateral lenders like OPIC, the ADB and the WB could shortly be forced to reassess their aid packages to India.

to reassess their aid packages. Projects in India now account for 8.5% of OPIC's total loan book, nearing its 10% limit for any one country.

India hopes to complete its first round of large-scale PV installations by January, and was planning to hold an auction for a further 350MW of projects in late November.

Africa News Focus

Nigeria's NASENI to develop 7.5MW solar panel manufacturing plant in Karshi, Abuja

Nigeria's National Agency for Science and Engineering Infrastructure (NASENI) recently revealed plans to develop a 7.5MW solar panel manufacturing plant in Karshi, Abuja, so that Nigeria can begin to cut its dependency on the importation of solar panels.


Source: nairaland

NASENI plans 7.5MW solar panel manufacturing plant in Nigeria.

NASENI advised the manufacturing facility would lead to solar street lighting, water pumping for irrigation, powering repeater and telecommuting stations, powering traffic lights and the small scale processing of farm products.

First phase of 500MW Moroccan project to begin in 2012

Work will begin next year on the first phase of the 500MW Desertec concentrated solar power (CSP) plant in Morocco, according to German newspaper Süddeutschen Zeitung. The initial development stage will cost around €600 million and add 150MW of capacity to the yet-to-be-named site.

Total investment in the Desertec Industrial Initiative (DII), which is a joint venture between 12 predominantly German developers, is estimated at €2 billion and it could come online as early as 2014. The CSP plant will be one of the largest in the world when completed, and further details regarding its location, financing and technology are due to be released in early 2012.


Source: GENI

The Desertec project is part of an ambitious plan to help eventually cater for 15% of Europe's energy requirements through solar installations in North Africa.

Middle East News Focus

Saudis activate Solar Frontier CIS thin film-powered 500kW PV plant on Farasan Island

Although better known as one of the world's largest suppliers of oil, Saudi Arabia continues to join the solar age with the inauguration of one of its first larger-scale photovoltaic power plants on October 1. The facility, a 500kW system comprised of Solar Frontier CI(G)S thin-film modules, is located on Farasan Island and was installed by the Saudi Electricity Co. and Solar Frontier's parent company, Showa Shell Sekiyu (which is partially owned by the Saudi Arabian Oil Co.).

The PV power plant, expected to generate 864,000kWh per annum, will save the equivalent of transferring 28,000 barrels of diesel fuel to the island annually, the companies said.

SEC will be responsible for the operations and maintenance of the site, while Solar Frontier will provide continuous technical support through its office in the kingdom.

Middle East set for solar boom over next decade

Solar power is poised to become an important part of the Middle East's energy mix over the next decade, according to a leading expert on solar within the Gulf Cooperation Council (GCC).

Dr. Khalid Klefeekh Al Hajri, Qatar Solar Technologies' (QSTec) CEO, made the claim at the recent GCC-France Economic Forum and believes that to maximise the potential of this solar boom, the region needs to facilitate an influx of skilled PV professionals.

There is a growing demand within the GCC and North Africa for solar power and several countries, including Qatar, the UAE and Saudi Arabia, are already embracing the technology and researching how it can be applied to desalination, solar cooling and oil and gas refining.

Source: Qatar Solar Technologies

Ravindra Kansal, president and CEO, Middle East, Africa & CIS Punj Lloyd & Dr Khalid Klefeekh Al Hajri, QSTec's CEO, at the signing ceremony for the Ras Laffan plant.

QSTec is one of the leading names in driving solar in the Middle East and in October unveiled plans to build a US$1 billion solar-grade polysilicon manufacturing facility in Qatar. The 8,000 MTPY (metric tonnes per year) plant is being built on 1.2 million square metres of land in Ras Laffan Industrial City and has a scheduled completion date of late 2013.

North America News Focus

BYD opens US headquarters and unveils electric bus

Mayor Xu Qin and his delegation from the Shenzhen province headquarters in China of Build Your Dreams (BYD) arrived in style in the company's new electric bus, the eBUS, to the opening ceremony of its North American headquarters in Los Angeles, California, in October. The eBUS was created in partnership with Hertz for use at Los Angeles International Airport.

Source: ESN

BYD's all-electric eBUS shuttle bus fleet at Los Angeles International Airport.

"The BYD all-electric bus not only knocks down emissions dramatically, but it also results in an estimated saving of up to US$500,000 over the lifetime of each vehicle," said Richard Broome, senior VP of corporate affairs and communications for the Hertz Corporation.

A manufacturer of electric/hybrid vehicles and solar power systems, BYD's

Source: EDTA

Richard Broome, senior VP of corporate affairs and communications for the Hertz Corporation.

launch of its North American operations will bring up to 150 green-collar engineering and management jobs focused on research and development, and will serve as the focal point for privately owned BYD dealerships across the continent. BYD employs over 200,000 people worldwide.

First Solar modules to power solarhybrid's 1.5GW pipeline

The CEO of solarhybrid said it is enlisting the help of First Solar to help equip a 1.5GW project pipeline it is on the verge of buying from Solar Millennium. First Solar would not confirm the existence of the supposed deal.

At a press conference in Berlin, solarhybrid CEO Tom Schröder said the company was planning to enter into a joint venture with First Solar to equip the Californian project locations of Blythe (1000MW) and Palen (500MW) with its CdTe modules, if the transaction with Solar Millennium is realized. He made no mention of whether the partnership with First Solar would include the solar company's EPC and O&M services or was just a module supply deal.

Schröder added that he expects to finalize negotiations with Solar Millennium around the end of November.

Until a few months ago, both Blythe and Palen were due to be flagship installations for concentrating solar power (CSP) technology. However, in August, Solar Millennium chose to switch the latter to PV and solarhybrid now plans to do the same at Blythe when it completes the purchase at the end of the month.

Source: First Solar

Although groundbreaking at Blythe began in June, Solarhybrid has only now switched from CSP to PV.

Fonroche to install 44MW system in Puerto Rico

French renewable energy company Fonroche is investing US$115 million in a new 44MW solar farm in Puerto Rico. The farm will cover 65 hectares and be fitted with panels from Fonroche's manufacturing facility in Agen, France. Fonroche is building the system for the Puerto Rico Energy and Power Authority, which has signed a 20-year power purchase agreement, worth US$240 million, for the electricity produced by the solar farm.

Puerto Rico is currently experiencing something of a boom in terms of downstream installations; two months ago AEG closed financing on a 24MW project in Guayama, while other major developments are planned for Lapas (63MW) and Yabucoa (30MW).

Residential PV sales company Solmentum opens eighth sales office

San Francisco-based Solmentum has opened its latest sales office in Walnut Creek, California, adding to its seven other sales offices located throughout California and New Jersey. Solmentum sells metered electricity to homeowners and gives them the chance to "go solar" without paying the upfront costs of an entire PV system.

The company noted that since many homes do not qualify, it complements traditional market methods with specific strategies that allow Solmentum to find the right homeowners and begin a long-term relationship with them.

Building work begins on 250MW California Valley Solar Ranch

More than three years after announcing the project, construction work is finally set to begin on NRG Energy and SunPower's record-breaking 250MW (AC) California Valley Solar Ranch in San Luis Obispo county.

A groundbreaking ceremony for the project, which will be one of the largest in the world when completed, took place November 10, with company management from NRG and SunPower, as well as several local dignitaries, attending. The first phase of development is scheduled to go online next spring and will add 25MW.

The remaining 225MW will be added over the following two years, creating 350 construction jobs and injecting US$315 million in the local economy.

Europe News Focus

GE Energy Financial Services, KGAL invest €111.1M in 50MW CSP, molten salt storage project in Spain

GE Energy Financial Services, a unit of GE and KGAL, announced that they are jointly investing €111.1 million in a 50MW parabolic trough concentrated solar power plant that uses molten salt energy storage in Torre de Miguel Sesmero, Badajoz, Spain. The two companies will invest structured equity in Extresol II, which was developed by Spain's ACS. Further financial details surrounding the investment were not disclosed.

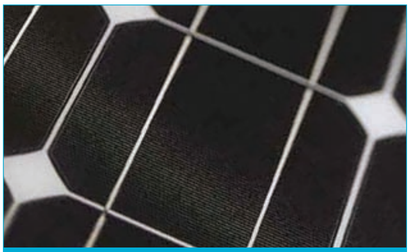
Extresol II was completed by ACS's subsidiary Cobra in December 2010. The investment represents GE Energy Financial Services' first in a CPV power plant using molten salt storage.

Source: Business Wire

GE Energy Financial Services is investing with German fund KGAL in a 50MW parabolic trough concentrated solar power plant using molten salt energy storage, shown here, in Badajoz, Spain.

aleo solar supplies modules for PV project in north Italy

aleo solar has helped finance and equip a new 1MW PV system in Vittorio Veneto, Italy. The Germany-based module manufacturer joined forces with Ailita Engineering and Italian bank BIIS on the project, which was connected to the grid in May.



Source: ArchiExpo

aleo's modules will power the 1MW system in Vittorio Veneto.

In its first year of operation the aleo-powered array is expected to generate more than 1.2 million kWh of electricity. Building work on the project took less than two months and was carried out by Ailita.

JinkoSolar modules chosen for 5MW UK project

AEE Renewables and EPC Graess Solartechnik have chosen JinkoSolar as module provider for a new 5MW PV project in the UK. The location of the system is yet to be disclosed, but when completed next year it will be one of the largest in the country.

Jinko modules are already powering AEE and EPC's systems in Hawkchurch (4MW) and Swindon (5MW) and the decision to build a new plant, despite the recent tariff cuts, is a boon to large-scale solar in the UK.

Conergy to install 9.4MW in Germany

Conergy is set to expand its European project portfolio by installing two new PV power systems in Germany. In addition to taking on engineering, procurement and construction responsibilities for Grimmen's 8.2MW and Thalham's 1.2MW solar parks, Conergy will also fully equip and operate both sites.

The first installation phase at Grimmen park, located in the Mecklenburg-Vorpommern town's industrial district, is due to be completed by the end of the year. Once at full capacity in 2012, it will be providing electricity for around 60% of Grimmen's population.

Nine hundred kilometres away in southern Bavaria, Conergy is carrying out final preparations before building work begins on its second turnkey installation in Thalham in December. The park, which is the first solar venture in the Hintz family's investment portfolio, will span 2.4 hectares and feed 1,300MW of electricity into the south German grid with the help of 5,000 Conergy PowerPlus modules and 70 Conergy IPG 15 T inverters.

Source: Conergy

Conergy's Power Plus modules will be used on the 1.2MW Thalham project.

OPDE sells 7.93MW Italian solar power plants to ForVEI for €33 million

ForVEI investment company has revealed that it had bought two solar PV facilities developed by the OPDE Group amounting to a total of 7.93MW. The €33 million (US$45 million) project was financed by Intesa Sanpaolo with the power plants located in the Italian Piedmont region. Both solar farms are fully operational with the 6.19MW Tortona project and the 1.74MW Predosa installation utilizing Trina Solar and Canadian Solar modules, SMA inverters and Mecasolar single-axis solar trackers.

Source: OPDE

The 6.18MW Tortona solar project was recently acquired by ForVEI.

Moser Baer completes 23.8MW solar project in Lauta, Germany

Moser Baer Clean Energy Limited (MBCEL) has commissioned a 23.8MW solar power plant in Lauta, Germany, said to be the company's largest to date. Funded with approximately €50 million long-term debt financing from DKB bank in Germany – the same financier for the company's Thuringen and Meissens projects, the farm uses c-Si technology, SMA central inverters and was built with Conecon as the construction partner.

The month of October alone saw MBCEL commission 70MWp of solar energy across various projects, and the company's COO, Lalit Jain, said the company plans to commission in the region of 200MWp by next year.

Product Reviews

Ametek

Ametek's fully automated EN50530 test solution reduces PV inverter time to market

Product Outline: Ametek Programmable Power is offering a fully automated EN50530 test solution that utilizes three core 'Surround the Inverter' elements: the TerraSAS Solar Array Simulator, MX/RS Grid-Simulator and CTS Compliance Test System. The programmable power products and systems simulate the output of solar arrays, the loads applied to the output of the inverter, and the interface with the grid, providing a comprehensive and energy efficient means of testing PV inverters.

Problem: Testing to the EN50530 standard for efficiency of grid-connected PV inverters normally requires an engineer or technician to be present to manually progress through each curve set.

Solution: The automated test system is configured and controlled via Ametek's Windows-based software that enables users to select the EN50530 Test regime, connect the inverter under test, start the test, walk away and return to collect the report. The system provides a turnkey approach to testing the maximum peak power tracking (MPPT) characteristics for grid-tied inverters and DC charge controllers. The ability to simulate virtually any fill factor or solar cell material allows validation of the MPPT algorithm with a power source. Hardware control is accomplished by an application that communicates directly to the PV simulator using RS422, which operates as a dedicated IV curve generation processor.

Applications: PV inverter manufacturers and testing houses.

Platform: TerraSAS Solar Array Simulators are available as single- or multi-channel systems from 5kW–1MW (80V–1500V). Single/Three-Phase MX/RS Series Grid Simulators are available from 15kVA–1MVA.

Availability: Shipment of the EN50530 solution is expected to begin in early Q2 of 2012.

Kipp & Zonen

Smart SMP Pyranometers from Kipp & Zonen correct for temperature variance inaccuracies

Product Outline: Kipp & Zonen has introduced a new and intelligent generation of pyranometers that are equipped with an extremely low power Smart Interface. The new Smart SMP Pyranometers offer industry-standard digital and amplified analog outputs within the well-known CMP series housings.

Problem: Thermopile pyranometers suffer from inherent inaccuracy due to temperature variance. Eliminating measurement inaccuracy or correction capabilities would improve measurement sensitivity. Monitoring the solar radiation plays an important role in analyzing both the efficiency of the cells and evaluating optimal locations for solar farms.

Solution: The active use of a built-in digital temperature sensor is one of the biggest breakthroughs in the development of the SMP Smart Pyranometer. The integrated 'Modbus' enables communication with the pyranometer allowing connection to digital equipment such as programmable logic controllers (PLCs). Moreover, all SMP pyranometers are programmed to have identical sensitivity and output levels, making them easily interchangeable for re-calibration or service.

Applications: Wide range of PV cell and module irradiance monitoring on commercial-scale solar power plants and larger utility-scale solar farms.

Platform: The output range is programmed so that all SMP pyranometers have identical sensitivities, allowing easy installation and exchange for recalibration. Serial communication allows access to measurement data, instrument status, operating parameters and calibration history. The Smart Interface also corrects for sources of inaccuracy.

Availability: Currently available.

Locus Energy

Locus Energy releases irradiance modeling software service

Product Outline: Locus Energy is preparing to launch 'Virtual Irradiance,' a patent-pending software service providing accurate estimates of historical and real-time solar irradiance across North America as an add-on to the company's web-based residential and commercial monitoring platform.

Problem: The methodology produces solar irradiance estimates that are claimed to provide greater accuracy than previously published academic models, which can feature large margins of error.

Solution: The Locus Energy model establishes baseline irradiance levels derived from government satellite imagery and weather feeds and then iteratively refines the estimates by cross-referencing performance data collected by the company's network of several thousand monitoring sites across the US. The Virtual Irradiance model produces solar irradiance data that enables the user to mitigate risk by improving project location selection and more accurately modelling and analyzing system production at an individual site or across an entire fleet.

Applications: Continental North America coverage (some limitations in Canada and Mexico). Individual site or fleet-wide data capability, including real-time and historical estimates.

Platform: Virtual Irradiance is fully integrated with the Locus Energy monitoring platform, improving existing analytics. Additionally, the model will be leveraged throughout Locus Energy's future products, such as the SolarNOC, planned for release in Q1 2012.

Availability: Since October 2011.

Molex

Molex's panel-mount DC connectors prevent accidental and unauthorized decoupling

Product Outline: Molex has further expanded its range of SolarSpec products with the development of pin (male) and socket (female) panel-mount DC connectors. Its internal locking and touch-proof design feature an innovative nut mechanism for simple assembly and a durable connection for cable attachment to solar inverters.

Problem: The NEC 2008 (690.33) and NFPA 70 US code-compliant solution developed by Molex is an interlocking mechanism that prevents accidental and unauthorized decoupling of the connector during service in the field and provides for reliable connection and safe handling.

Solution: SolarSpec panel-mount DC connectors offer contact resistance of below 0.5mΩ. The contact can handle as much as 30.0A and accommodates 2.50mm^2 and 4.00 to 6.00mm^2 (14 AWG and 12 to 10 AWG) cable to meet a wide range of customer requirements. The connectors are IP67-sealed to protect against the ingress of dust and water while the housing body is resistant to UV and ozone damage. The touch-proof safety design protects installers and maintenance engineers from electrical currents with molded surface ribs to allow secure gripping, especially while wearing work gloves. For added security, a Molex field service tool is required to disengage the latch when unplugging.

Applications: Panel-mount DC connectors.

Platform: The DC connector for solar inverters complements the SolarSpec portfolio, which now encompasses the junction box for silicon PV panels, crimp terminal DC connectors for direct attachment to solar junction boxes, field installation and PV grid wiring and DC cable assemblies.

Availability: Since October 2011.

American Electric Technologies

American Electric Technologies' central inverters reduce BOS costs

Product Outline: American Electric Technologies has introduced two new models in its 1000V Integrated Solar Inversion Station (ISIS) product line designed for utility-grade solar projects 1 MW and above. The ISIS line is said to be capable of capturing up to 15% more watts per string, while operating with the widest ambient temperature range from -40°C to 60°C.

Problem: Utility-scale solar developers, owners, operators and financers have realized significant project cost/watt reductions through lower PV panel price drops. The next step towards reducing solar LCOE is reducing BOS costs.

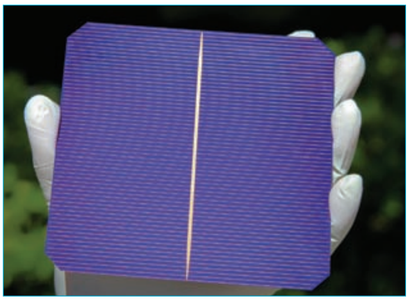
Solution: The ability to run solar farms at 1000V versus traditional 600V farm designs enables utility-scale project developers to implement DC and AC designs at the highest voltage levels, thus reducing BOS cabling costs and power losses from the PV panel through the grid connection point. The new 1.5MW UL 1741 platform and 38kV interconnect system also reduce field installation labour costs by incorporating all key solar inverter elements into a skidded, pre-commissioned, factory-built, NEMA 3R outdoor platform. ISIS claims using the world's widest power factor compensation capabilities for on-demand FERC 661A voltage regulation and the highest UL 1741 witness-tested PV open circuit voltage and input current levels.

Applications: Utility-scale PV power plants.

Platform: AETI's ISIS 1000V product line now includes both 1.0MW and 1.5MW solar inversion platforms as inverter-only solutions, or as integrated solutions with a medium voltage of 15kV or 38kV class step-up transformer and utility interconnect systems. All ISIS inverters incorporate a master combiner, a DC and AC disconnect switching system, and the inverter system in a NEMA 3R enclosure.

Availability: Since September 2011.

Silevo



Silevo launches tunneling junction cell architecture in new high-efficiency module

Product Outline: Silevo has launched a new type of PV module that claims the industry's best performance-to-cost ratio. This is said to be achieved by combining high-performance crystalline silicon N-type substrates, thin-film passivation layers and a unique tunneling oxide layer in a single solar module.

Problem: Until now, the solar industry has not had a module that optimizes both performance and cost at a ratio that creates optimal LCOE, according to Silevo. While thin-film modules offer good cost and energy harvest, their low efficiency leads to a high BOS cost.

Solution: Powered by 'tunneling junction' architecture, Silevo's proprietary 'Triex' technology is said to deliver high efficiency, competitive module costs as well as optimal energy harvest, according to the company. Triex's 'silver-free' technology also eliminates the use of costly silver pastes that traditional c-Si device manufacturers rely on for electrodes. By utilizing a low resistivity copper-based metallization scheme instead, Silevo is immune to silver's increasing cost issue in the marketplace, while capturing the performance advantages of copper.

Applications: A wide range of installations form residential to utility-scale.

Platform: Silevo is currently producing modules in pilot production, manufacturing Triex cells that demonstrate 20–21% conversion efficiency on full-size substrates. The Triex technology roadmap shows headroom for up to 24% conversion efficiency in commercial products. The company claims that the Triex technology yields cell temperature coefficients of -0.22%/°C.

Availability: Customer qualification samples are currently shipping from the pilot production facility in Fremont, CA, with high-volume commercial production to begin the first half of 2012.

Product Reviews

SunPower

SunPower's CPV C7 Tracker claims the lowest utility-scale solar power plant LCOE

Product Outline: SunPower has launched the SunPower C7 Tracker, a solar PV tracking system that concentrates the sun's power seven times to achieve what is claimed to be the lowest LCOE for utility-scale solar power plants available today.

Problem: BOS cost reductions have included modular racking and electrical connection systems. However, reducing overall components' usage can assist in reducing installation times and project development costs. Combined with CPV technology, it could provide the lowest LCOE in the industry.

Solution: The C7 Tracker combines single-axis tracking technology with rows of parabolic mirrors, reflecting light onto 22.8%-efficient SunPower 'Maxeon' solar cells, which are the world's most efficient commercially available solar cells. Using mirrors to reduce the number of solar cells required to generate electricity is claimed to lower the LCOE by up to 20% compared to competing technologies. For example, a 400MW C7 Tracker power plant requires less than 70MW of SunPower solar cells.

Applications: The C7 Tracker is designed for regions with high solar irradiance through direct sunlight, including the US Southwest and areas of the Middle East, Africa, Europe, Asia and Australia.

Platform: The C7 Tracker includes modular solar cell receivers allowing for future performance upgrades. Additionally, the SunPower advanced Tracker Monitoring and Control System (TMAC) provides wireless control of the power plant for increased operating efficiency and reduced maintenance cost.

Availability: Currently available.

Suntech

Suntech's HiPerforma module series uses Pluto cell technology

Product Outline: Suntech has launched its new generation of high-efficiency HiPerforma product line with the introduction of HiPerforma Pluto Vdm-295 and HiPerforma Wdm-245. Both products use Suntech's advanced Pluto cell processing technology.

Problem: Continued cell technology advances are required to provide lowest cost per watt. High reliability also enables longer warranty periods and better, more consistent performance warranties, leading to positive power tolerance figures.

Solution: HiPerforma modules are claimed to feature higher efficiency than industry standard cells, lower temperature coefficients and higher power output per watt installed due to an improved spectral response. This results in up to 12% higher power output based on same nameplate power. The new HiPerforma Pluto Vdm-295, a 295W panel utilizing 72 six-inch multicrystalline cells, is ideal for both commercial rooftop and utility-scale electricity generation, having a conversion efficiency of up to 15.2%. The new HiPerforma Pluto Wdm-245, a 245W panel using 60 six-inch polycrystalline cells has a conversion efficiency of up to 14.8%. Its universal format combined with optimum temperature behaviour makes it suitable for a wide variety of applications.

Applications: Commercial rooftop and utility-scale electricity generation.

Platform: The HiPerforma Pluto Ade-200 is designed for small residential roofs. The new modules extend the product portfolio with polycrystalline products and have a 25-year power output. In addition, the panels feature 0+/-5% positive power tolerance and have been built to withstand all weather conditions.

Availability: Currently available.

Unirac

Unirac's ISYS Single Access Tracker requires fewer foundation installations for faster construction

Product Outline: Unirac has launched the ISYS Single Axis Tracker which is claimed to be the most robust and versatile ground -mounted tracker system on the market today. The system is able to work with any space or module system. Unirac backs the ISYS Tracker with a 20-year structural performance warranty.

Problem: EPCs, utilities and solar integrators have identified a distinct need for a higher-load capacity tracker requiring fewer foundation installations and offering quick assembly and reduced maintenance.

Solution: Designed for large-scale solar installations, the pre-assembly ISYS Single Access Tracker works with any standard solar modules, providing a flexible, highly versatile tracking solution for solar arrays. Optimized for quick construction, there is no field fabrication required and minimal foundation installations. Unirac claims that 20 modules can be fitted on each foundation, four times that of competing solutions, which reduces construction time and materials requirements, according to the company.

Applications: Commercial and utility-scale solar arrays.

Platform: The ISYS Tracker is made with highly durable structural tubes that reduce material costs and enhance structural integrity enabling the ISYS Tracker to withstand up to 25 psf of snow and 120mph winds while GPS and tilt sensors ensure a precise and unparalleled tracking system. It is also resistant to corrosive environments. Standard bearings have been replaced by a no-maintenance, long-life sleeve/bushing to ensure parts performance over the long haul.

Availability: Since October 2011.

Utility-scale PV power plants – investment costs and electricity price

Denis Lenardič, pvresources, Jesenice, Slovenia

ABSTRACT

It is essential to understand the investment and operating costs of photovoltaic power plants in terms of economic parameter calculations such as levelized cost of electricity (LCoE). The dynamic behaviour of national and international markets requires a precise and detailed estimation of costs, and this knowledge is especially important to investors and policymakers. Only if the investment and operating costs of PV power plants are known can the price of electricity and the more detailed levelized cost of electricity be precisely calculated. High investment costs also require reliable investment policies and close cooperation between financial institutions (such as banks and investment funds) and power plant investors. Investment in large-scale PV power plants requires a detailed evaluation of solar radiation potential and grid availability, as well as a load analysis and a precise economic evaluation. When the investment cost based on the above-mentioned parameters is known, an estimation of the operating costs should be the next step. When all the costs of a PV power plant have been estimated, the price of electricity, or even a more detailed LCoE, can be calculated. This paper presents the trend of investment costs and some typical maintenance costs, and calculations of electricity price based on recent real data for large-scale PV power plants.

Investment costs

The average investment cost of large-scale photovoltaic power plants has decreased from about €6 million per MWp in 2008 to about €2 million per MWp in 2011. Data for recent years is presented in Figs. 1 and 2. Considering PV power plant size and investment costs over a short period of time (for example 1 year), investment costs increase fairly linearly, regardless of the installed PV power capacity.

> “The average investment cost of large-scale photovoltaic power plants has decreased from about €6 million per MWp in 2008 to about €2 million per MWp in 2011.”

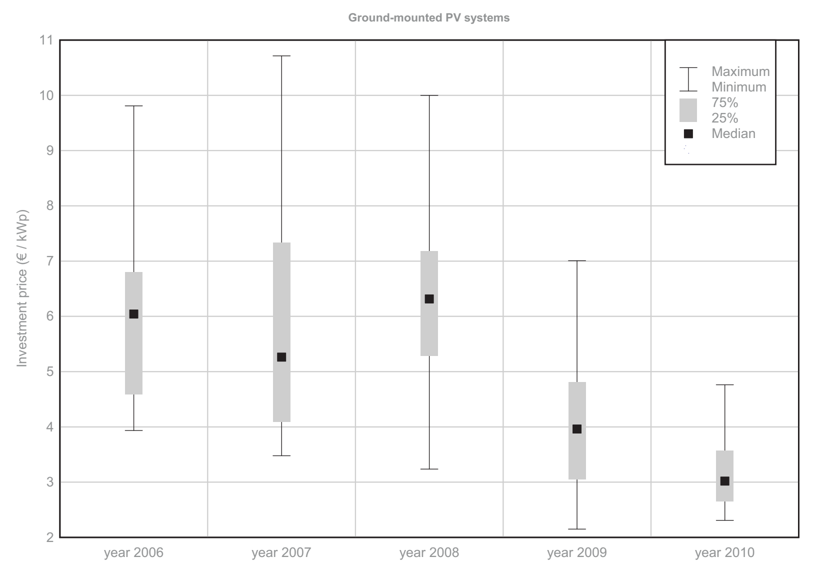


Figure 1. Investment costs (€/MWp) for ground-mounted PV power plants > 200kWp capacity during the period 2006–2010. After reaching a peak in 2008, prices have decreased significantly in subsequent years [1].

The analysis of investment costs presented in this paper is based on detailed investment-related data collected in recent years by the author’s research [1] and taken from approximately 500 PV power plants that were commissioned between 2006 and 2011.

Only the average investment costs are considered, but overall investment cost for tracking PV power plants is slightly higher than for fixed-mounting ones. To express the calculations in €, US$ or other currencies, the mean exchange rates based on OECD Main Economic Indicators (MEI) can be used [2]. Note that the amount of data available varies each year.

As will be shown later, the investment cost is not the only criterion that should be considered during the planning phase of a PV power plant. Different technologies could have a significant impact on power plant investment costs, but they could have a significant impact on yield per area as well. It should be noted once again that only a detailed yield analysis can provide guidelines for making decisions regarding investment in new PV power plants. Detailed investment data is available for approximately 100 roof-mounted PV power plants: Fig. 2 presents the mean investment cost (€/MWp) for 2007–2010.

Based on the data from power plants commissioned in Italy, investment costs are estimated to lie within a similar range to that in Germany and Spain, with an average value of between €2.5 million and €3.5 million per MWp in 2010. A large amount of investment data are available for other countries, but Italy and the Czech Republic, in particular, are worth mentioning. In Europe the Czech Republic has offered some quite interesting financial conditions. The average investment value for crystalline PV power plants was at a similar level to the thin-film power plants in Germany in recent years. Basically, no significant difference between investment price (per kWp) for utility-scale and smaller PV power plants has been observed lately.

The largest part of the investment cost relates to the price of solar modules. For small-scale PV power plants, the proportion is slightly more than 50% of total investment costs; however, it is much higher for utility-scale PV power plants. The trend of solar module prices for PV power plants less than 100kWp power capacity in Germany [3] is shown in Fig. 3; further information on market prices can be found in the literature [4].

> “The largest part of the investment cost relates to the price of solar modules.”

Additional costs that need to be considered in the investment calculation are those of the land required for PV power plants; these costs may be either for leasing or for purchasing the land. Some data is available in the literature, but no detailed land rental cost correlation regarding soil quality, GDP or population density has been found as yet [5]. Therefore, the global average land rental cost of US$100/hectare per year might help to calculate the land rental cost as proposed in the literature [5].

Maintenance and operating costs

Only a few systematic studies of maintenance and operating costs have been published in the last few years. Some data based on maintenance cost analysis in the USA [6,7], Germany [8] and Italy [9] are available, for example. Total operating and maintenance costs (excluding land or roof rental cost) might vary from 1 to 5% of the total annual cost as reported in literature [6,7]. A selection of data from a report issued by the Electric Power Research Institute (EPRI) [6] is given in Table 1.

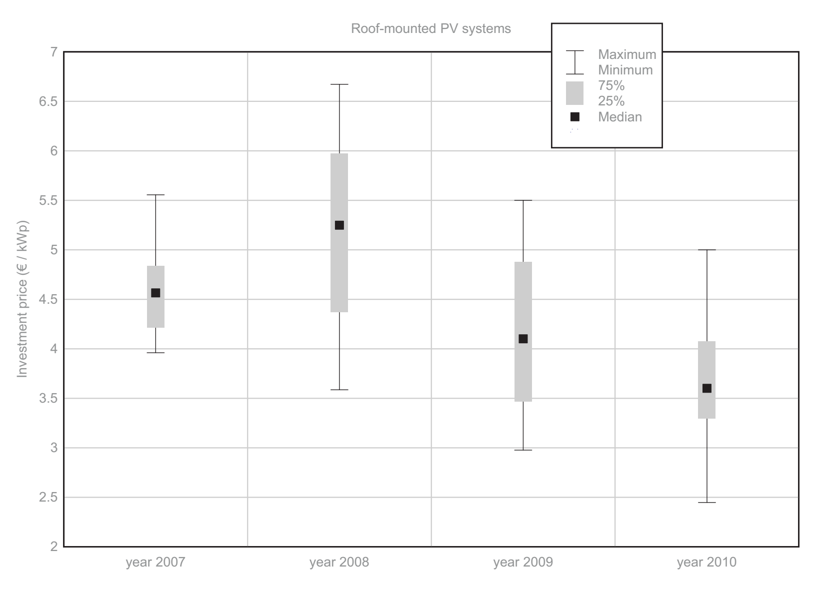


Figure 2. Investment costs (€/MWp) for roof-mounted PV power plants > 200kWp capacity during the period 2007–2010, sorted by year of construction [1].

Breakdown of cost	sc-Si fixed tilt [US$/kW year]	c-Si single-axis tracking [US$/kW year]
Scheduled maintenance/cleaning	20	30
Unscheduled maintenance	2	5
Inverter replacement reserve	10	10
Insurance, property taxes, owner’s costs	15	15
Total operating and maintenance costs	47	60

Table 1. Utility-scale PV power plants: estimates of operating and maintenance costs (US$/kW year). (Additional, more detailed data may be found in EPRI’s report [6].)

Source: Electric Power Research Institute (EPRI) [5]

Levelized cost of electricity (LCoE)

Electricity price is based on the investment data of PV power plants as presented in this paper and on the predicted yield as announced by plant owners or plant planning/construction companies. Because simulation data of only limited precision is available, it should be emphasized that there will be some degree of uncertainty associated with these values and they should be used for information purposes only. The long-term value of the price of electricity is based on investment data and on different discount rates (see Table 2). Annual maintenance costs of 1% of investment costs are also taken into account. The present value (PV) can be

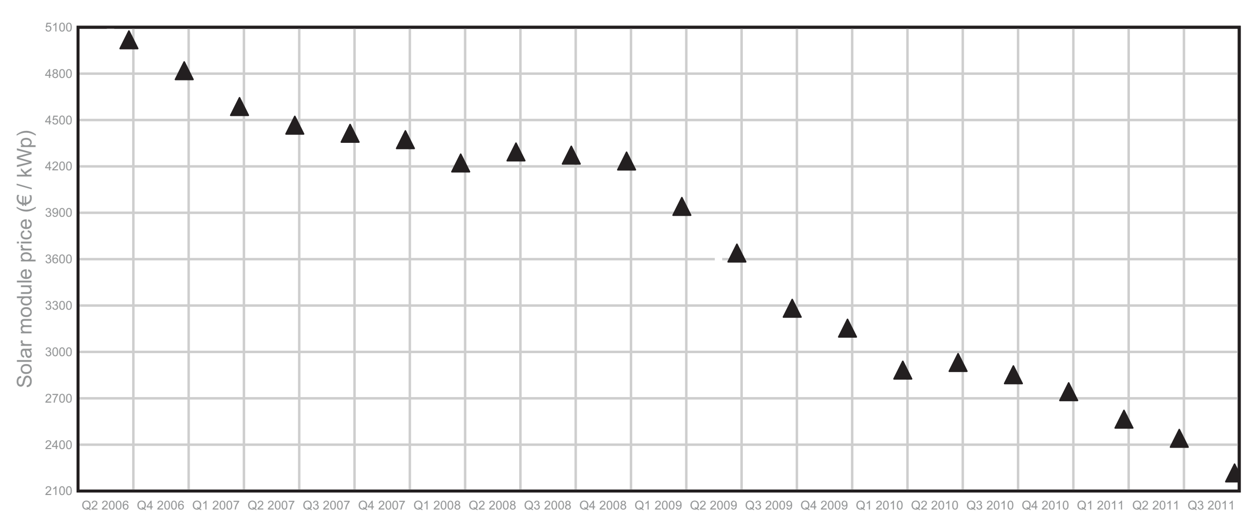


Figure 3. Solar module prices (€/kWp) for PV power plants < 100kWp capacity in Germany (prices exclude VAT).

Source: BSW-Solar Photovoltaik-Preisindex, BSW-Solar 10/2011 [3]

Discount rate (WACC)	Lifetime [years]				
	10	15	20	25	30
0.05	0.1295	0.0963	0.0802	0.0710	0.0651
0.06	0.1359	0.1030	0.0872	0.0782	0.0726
0.07	0.1424	0.1098	0.0944	0.0858	0.0806
0.08	0.1490	0.1168	0.1019	0.0937	0.0888

Table 2. Capital recovery factors for the most commonly used discount rates and lifetimes related to photovoltaic systems. Additionally, a 10% discount rate is often used, though only for off-grid systems and not for those connected to the grid.

calculated using the formula

$$PV = a\frac{(1+i)^n - 1}{i \cdot (1+i)^n} \qquad (1)$$

where *PV* = present value, *a* = annuity, *n* = time period and *i* = discount rate.

The discount rate *i* can be calculated by applying the weighted average cost of capital (WACC) given by the equation (see Breyer et al. [11])

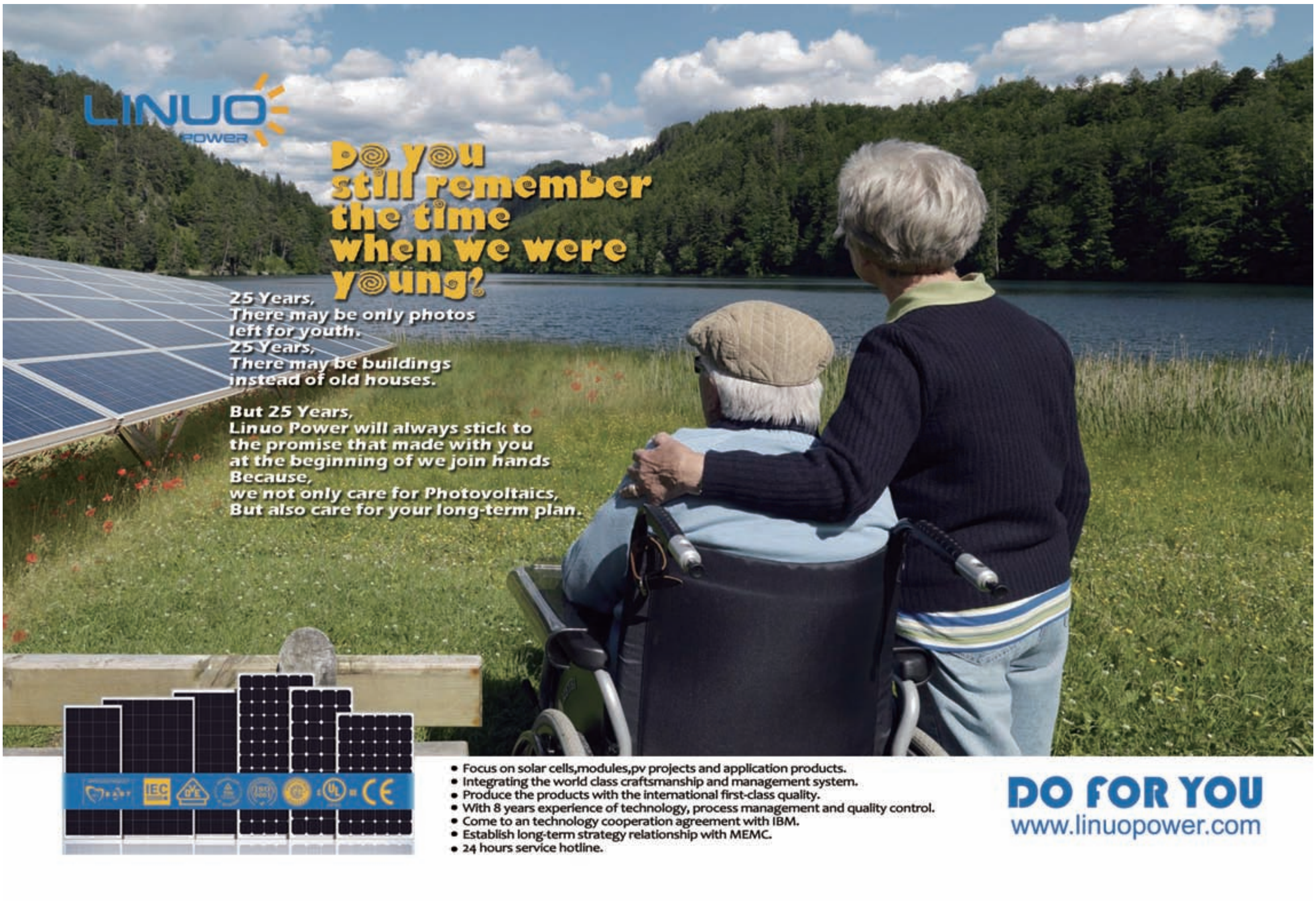
$$i = WACC = \frac{E}{E+D} \cdot R_e + \frac{E}{E+D} \cdot R_d \cdot (1 - T_c) \qquad (2)$$

where *E* = market value of the firm's equity, *D* = market value of the firm's debt, R_e = cost of equity, R_d = cost of debt and T_c = corporate tax rate.

The costs of depreciation and interest are often expressed in terms of the capital recovery factor (CRF). The CRF is a ratio of the constant annuity to the present value

Figure 4. Electricity price for 5% discount rate and 20-year system lifetime for different yield rates.

$$CRF = \frac{a}{PW} \qquad (3)$$



where a = annuity and PV = present value.

Substituting the expression for PV from Equation 1 into Equation 3 yields the equation for the CRF

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{4}$$

which may be evaluated using the values for different lifetimes and discount rates given in Table 2. (For a more detailed explanation of economic evaluation see Short et al. [10].)

The levelized cost of energy (LCoE) or levelized energy cost (LEC) is the constant unit cost (per unit of energy produced) of a payment stream that has the same present value as the

total life-cycle cost of a power plant. It is most relevant to energy providers such as electric utilities or PV power plant investors. The calculation methodology is explained in detail in the literature [12,13], as is the practical application of the LCoE method in terms of grid-parity calculations [11,14]. LCoE is given by the expression

$$LCoE = \frac{Total\ Life\ Cycle\ Cost}{Total\ Lifetime\ Electricity\ Production} \tag{5}$$

where the total life-cycle cost includes all costs, not just those of investment. Other costs – for example those associated with operation and maintenance, insurance, land rental and so on – should be taken into account as well. If a system is financed for a shorter period than a lifetime then residual value should also be considered. Costs can be calculated by

$$costs = \sum_{n=1}^{N} \frac{c^n_{annual}}{(1+i)^n} \cdot (1 - T_c) \tag{6}$$

where c_{annual} = total annual costs, N = lifetime (years), i = discount rate and T_c = corporate tax rate. (For details see Campbell [12].)

The weighted yield over the total lifetime (kWh/kWp) of the system is calculated by the equation (see Jordan et al. [15])

$$Yield_w = \sum_{n=1}^{N} \frac{Yield_i \cdot (1 - R_D)^n}{(1+i)^n} \tag{7}$$

where $Yield_w$ = weighted yield over the lifetime (kWh/kWp), $Yield_i$ = initial yield in the first year (kWh/kWp), N = lifetime (years), R_D = system degradation rate (% per year) and i = discount rate. It is important to note that the system degradation rate should be considered in order to obtain reliable estimates of the yield in the long term [15,16]. An average value of 0.7% per year has been reported in the literature [15] and can be used for detailed calculations for estimating costs.

Figure 5. Electricity price for 6% discount rate and 20-year system lifetime for different yield rates.

Figure 6. Electricity price for 7% discount rate and 20-year system lifetime for different yield rates.

Figure 7. Electricity price for 8% discount rate and 20-year system lifetime for different yield rates.

Based on calculated values, the LCoE can be determined by using the equation (see Breyer et al. [11])

$$LCoE = \frac{CRF \cdot CAPEX + costs}{E_{total}} \tag{8}$$

where CRF = capital recovery factor, $costs$ = total costs calculated using Equation 6, $CAPEX$ = capital expenditure (investment costs) and E_{total} = total lifetime electricity production. In Equation 8, the value of the investment costs (CAPEX) is considered in the calculation of LCoE; alternatively, LCoE can be calculated using different equations, including (for example) a detailed calculation of the net present value (NPV) or depreciation [12,13,14].

> “It is important to note that the system degradation rate should be considered in order to obtain reliable estimates of the yield in the long term.”

Electricity prices

Electricity prices for systems with a planned 20-year lifetime, discount rates ranging from 5 to 8%, and typical annual yields of 900kWh/kWp, 1000kWh/kWp, 1500kWh/kWp and 2000kWh/kWp are shown in Figs. 4–7. (Additional information may be found in Baumgartner [17].) The yield range presented in these figures covers the typical annual yield (rough estimate) achievable in European countries. A yield of 900kWh/kWp can be achieved in northern Germany using fixed-mounting systems; up to 1500kWh/kWp is possible in Italy, Greece and Spain and around 2000kWh/kWp in these countries when using two-axis tracking systems. The range of investment costs covers typical investment costs in the period 2008–2011. Note that the values shown are based on rough estimates – for a detailed economic evaluation more accurate data is necessary. For these calculations, annual maintenance costs representing 1% of the investment are considered [6].

More detailed equations for electricity price calculations are also available in the literature [5,13]. Using these equations, more accurate calculations are possible, such as the calculation of electricity price as a function of solar module or balance of system (BoS) costs.

References

[1] pvresources.com, “PV power plants put into service till end of 2010”, database [partially available online at www.sunenergysite.eu/en/top50pv.php].

[2] OECD, “Financial Indicators (MEI): Exchange rates (USD monthly averages)” [available online at http://stats.oecd.org].

[3] Bundesverband Solarwirtschaft e.V. 2011, “Statistische Zahlen der Deutschen Solarstrombranche (Photovoltaik)”, October [available online at http://www.solarwirtschaft.de/fileadmin/content_files/BSW_Solar_Fakten_PV_1110.pdf].

[4] Solarbuzz, “Module pricing” [available online at http://solarbuzz.com/facts-and-figures/retail-price-environment/module-prices].

[5] Hoogwijk, M.M. 2004, “On the global and regional potential of renewable energy”, Ph.D. dissertation, Utrecht University, The Netherlands.

[6] Electric Power Research Institute (EPRI) 2010, “Addressing solar photovoltaic operations and maintenance challenges: A survey of current knowledge and practices”, White Paper, July.

[7] Orlandi, B., Zakaria, R. and Carraretto, C. 2011, “Large scale PV in Italy: Technical, financial and contractual challenges”, *Proc. Renew. Energy World Europe 2011 Conf.*, Milan, Italy.

[8] Kost, C. and Schlegl, T. 2010, “Stromgestehungskosten Erneuerbare Energien”, Studie, Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg, December.

[9] Hansen, T. et al. 2005, “Photovoltaic power plant experience at Tucson electric power”, *Proc. ASME Internat. Mech. Eng. Congr.*, Orlando, Florida, USA.

[10] Short, W., Packey, D.J. and Holt, T. 1995, “A manual for the economic evaluation of energy efficiency and renewable energy technologies”, NREL/TP-462-5173, National Renewable Energy Laboratory.

[11] Breyer, C. et al. 2009, “Grid-parity analysis for EU and US regions and market segments – dynamics of grid-parity and dependence on solar irradiance, local electricity prices and progress ratio”, *Proc 24th EU PVSEC*, Hamburg, Germany.

[12] Campbell, M. 2009, “Minimizing utility-scale PV power plant levelized cost of energy using high capacity factor configurations”, *Photovoltaics International*, 4th Edn.

[13] Whisnant, R.A. et al. 2006, “Economic analysis and environmental aspects of photovoltaic systems”, in Luque, A. and Hegedus, S., Eds., *Handbook of Photovoltaic Science and Engineering*, New York: John Wiley & Sons, Inc.

[14] EPIA 2011, “Solar photovoltaics competing in the energy sector (2011): On a road to competitivness” [available online at http://www.epia.org/publications/].

[15] Jordan, D. et al. 2010, “Outdoor PV degradation comparison”, *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA.

[16] Jordan, D. 2010, “Degradation rates”, NREL, February [available online at http://www1.eere.energy.gov/solar/pdfs/pvrw2010_jordan.pdf].

[17] Baumgartner, F. 2008, “Was kann der Solarstrom leisten?”, Vortragsreihe ZHAW Energie Apero, June, Winterthur, Switzerland [available online at https://home.zhaw.ch/~bauf/pv/talks/080612_energie_apero_zhaw_baumgartner.pdf].

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The road to PV competitiveness – PV generation cost in Europe

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ABSTRACT

In recent years solar photovoltaic electricity has shown a steady decrease in cost, thanks to technological improvements and economies of scale. Over the last 20 years the price of PV modules has dropped by more than 20% each time the cumulative volume of PV modules sold has doubled. System prices have fallen accordingly: during the last 5 years a price decrease of 50% has been seen in Europe. This trend will continue in the foreseeable future. System prices are expected to fall in the next 10 years by 36–51%, depending on the segment. Importantly, there is a huge potential for further reductions in generation costs: around 50% by 2020. The cost of PV electricity generation in Europe could decrease from 0.16–0.35€/kWh in 2010 to 0.08–0.18€/kWh in 2020, depending on system size and irradiance level. That decline in cost will continue in the coming years as the PV industry progresses towards becoming competitive with conventional energy sources. Under the right policy and market conditions, PV competitiveness can be achieved in some markets as early as 2013, and then spread across Europe in the different market segments by 2020. This paper summarizes the first part of a newly published EPIA report about PV competing in the energy sector. The report illustrates why PV can become a mainstream player in the energy field before 2020. The study, carried out with the support of the strategic consulting firm A.T. Kearney, shines new light on the evolution of Europe's future energy mix and PV's role in it.

Introduction

The coverage of the study in the EPIA report [1] concerning solar competitiveness is as follows:

- Technologies: the two major categories of commercial PV technologies available on the market are
  - Crystalline silicon
  - Thin film
- Market segments: four categories, out of many, cover a large part of the market, from small-scale residential systems to large ground-mounted installations. The typical installed capacities for these segments are
  - Residential households: 3kW
  - Commercial buildings: 100kW
  - Industrial plants: 500kW
  - Utility-scale plants (ground-mounted): 2.5MW
- Countries: the countries targeted are potentially the five largest electricity markets in Europe, with various combinations of solar irradiance and different country risk and financing conditions. Representing 82% of the European PV market in 2010 [2], they are France, Germany, Italy, Spain and the UK.

Assessing PV's full generation cost

To measure the growing competitiveness of PV, the new study considers the full generation cost of PV electricity generation by using the concept of levelized cost of electricity (LCOE). LCOE represents the cost per kWh and covers all investment and operational costs over the system lifetime, including the fuels consumed and the replacement of equipment. It therefore allows a comparison of the cost of producing a kWh of electricity between various generation technologies.

The LCOE formula used is one that has been developed by the International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development (OECD). This formula, shown in Fig. 1, is widely accepted in the energy domain. For each system the LCOE calculation takes into account:

- The lifetime of the plant
- Capital cost (CAPEX)
- Operational and maintenance costs (OPEX)
- The discount factor, expressed as the weighted average cost of capital (WACC)
- The location of the plant, which for PV is essential for considering differences in solar exposure

PV system price: capital expenditure (CAPEX) as the starting point

The starting base for the LCOE calculation is the total installed PV system price (also referred to as capital expenditure/cost or CAPEX). In practice, the capital cost is usually paid upfront. This represents a significant part of the total investment (around 80–90% depending on the market segment). The CAPEX includes margins taken over the entire value chain and is split into the following elements:

$$\text{LCOE} = \frac{\text{CAPEX} + \text{NPV of total OPEX}}{\text{NPV of total EP}}$$

CAPEX: capital expenditure (investment costs)
OPEX: operations and maintenance costs
EP: electricity production (in kWh)
NPV: not present value

Source: IEA/CECO-NEA

Figure 1. The LCOE formula.

- PV modules
- Inverter (allows connection of the system to the electricity grid)
- Structural components (for mounting and connecting the modules)
- The cost of installation (including the costs relating to project development, administrative processes, grid connection, construction and installation, and all profit margins)

Fig. 2 shows the relative share of the different components in the total PV system price. In 2010 the module price reflected on average around 45–60% of the total installed system price, depending on the segment and the technology. Installation costs were the second most important driver (21–26%), followed by the cost of structural components (10–20%) and the inverter cost (6–14%). The figure additionally provides an insight into how the relative importance of the different cost components will evolve

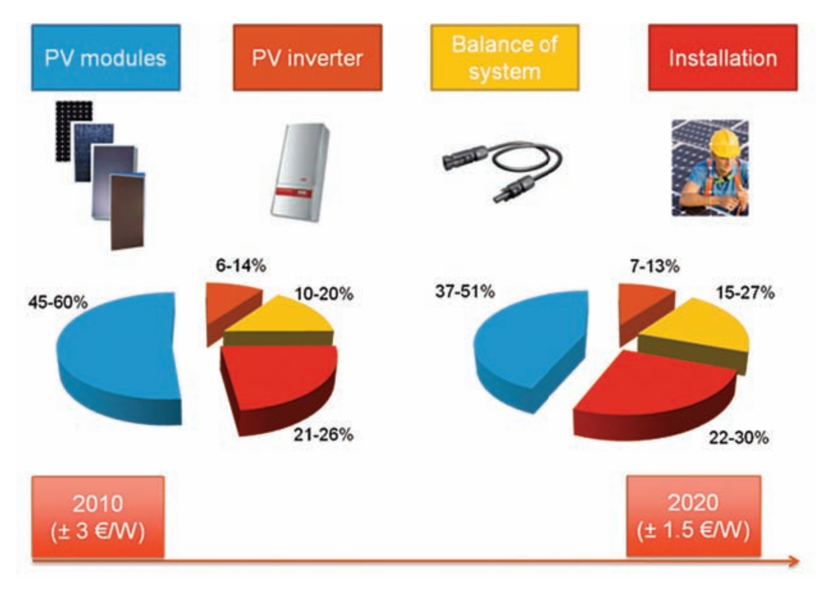


Figure 2. Evolution of the drivers behind the PV system price or CAPEX (industry averages).

through to 2020. The relative share of PV modules in the total system price has already fallen significantly over the years: in 2005 the module price reflected around 51–73% of the total system cost for large ground-mounted installations. Nevertheless, the cost of the modules is expected to remain the most important cost driver during the next decade and could still represent 37–51% of the total installed system price in 2020. The inverter price is expected to follow (more or less) the evolution of the total PV system price.

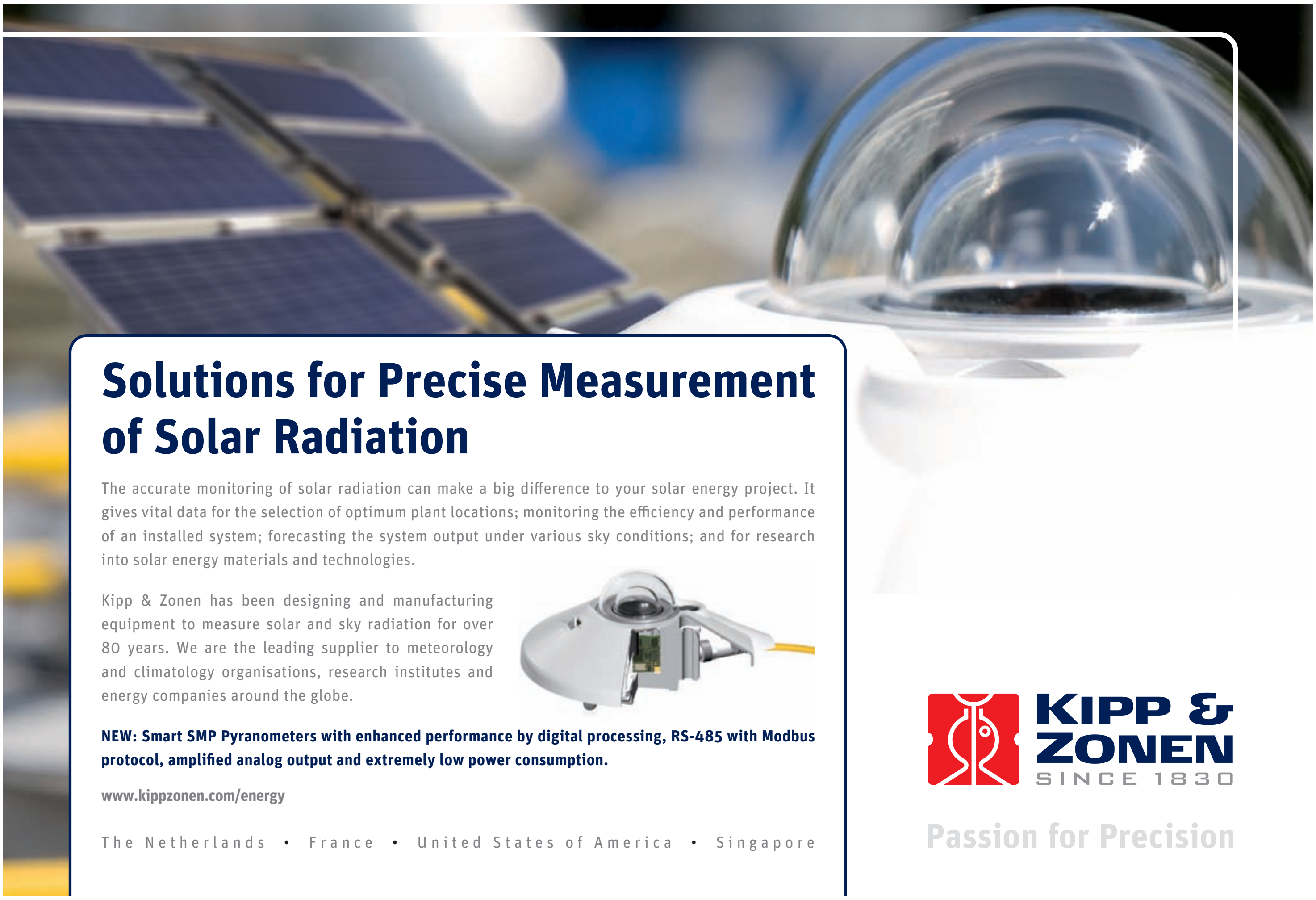
On the other hand, due to expected higher prices for commodity materials (steel, aluminium, copper, etc.) used in the cables and mounting structures, combined with an increase in labour costs, the relative share of the structural components as well as the installation is expected to increase. However, both the cost of structural components and the cost of the installation are subject to the evolution of module efficiency. Therefore, even though their relative shares will most likely increase, technological innovation in the field of PV module efficiency is an important driver for further system price falls in absolute terms.

> “The cost of the modules is expected to remain the most important cost driver during the next decade.”

PV system life cycle cost, including the operational expenses (OPEX)

When calculating the generation cost, the total system life cycle cost has to be considered, including all costs incurred over the entire life cycle of the PV system. Therefore, some additional cost drivers need to be taken into account:

- Costs of operation and maintenance services (includes margins)
- Price of one replacement of each inverter (because the lifetime of inverters is shorter than that of PV modules)



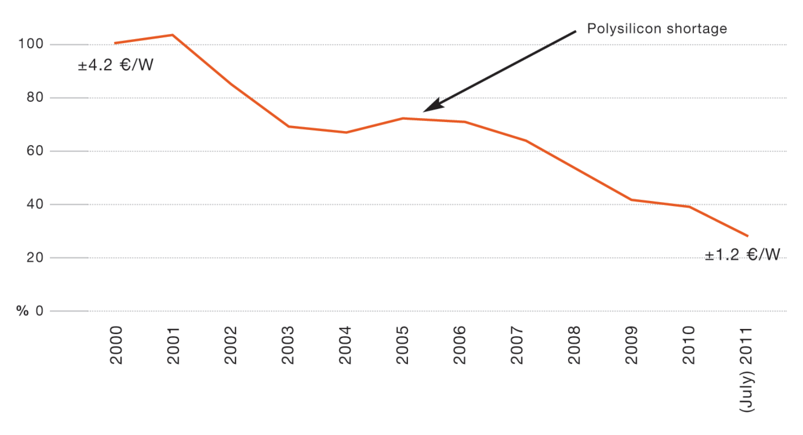


Figure 3. Evolution of the average price of a PV module in Europe.

- Land cost (for large-scale ground-mounted systems only)
- Cost of take-back and recycling of the PV system at the end of its lifetime

As mentioned earlier, the capital cost (between 80 and 90% of the total investment) is usually paid upfront. All other costs highlighted above, however, are paid over the lifetime of the system.

Energy output of a PV system

To calculate the cost per kWh of electricity produced, the total energy output of the PV system has to be determined. This includes the following parameters:

- Solar irradiance: the data on solar irradiance are based on the PV-GIS database of the Joint Research Centre of the European Commission and the SolarGIS database of Geomodel Solar. Extreme values (falling outside of a ±5% band) for each of the countries have been discarded.
- PV module degradation: this affects the performance of the PV system over its lifetime. The assumption is based on the generally accepted guaranteed performance of the PV modules – namely 80% of the initial performance after 25 years. For the purposes of this report, the assumption on the degradation of PV modules is directly tied to the assumption on the lifetime of the PV modules for which the guaranteed lifetime has been used. An increase in lifetime then reflects the improvements in degradation ratios over the years, resulting in a guaranteed lifetime of 80% of the initial performance after 35 years for modules produced in 2020 (see the assumptions on lifetime below).

Critical assumptions

Harmonized cross-European hardware costs

In order to assess the evolution of PV system prices correctly, a harmonized cross-European hardware cost is assumed (modules, inverters, structural components) as well as standard margins for installers. These are based on the German example and therefore reflect the prices in a 'mature market.' The reasoning behind this mature market assumption is that, with further growth of other European and international markets, prices and margins will globally converge.

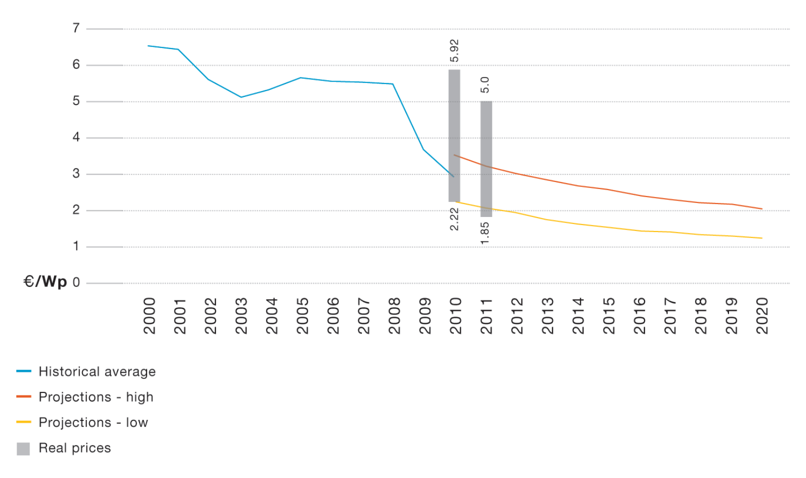


Figure 4. Evolution of the PV system price in Europe.

Lifetime

In order to calculate the generation cost, based on continuous technology developments, a gradual increase in the technical guaranteed lifetime of the PV modules, starting at 25 years and increasing to 35 years in 2020, is assumed. The same reasoning is used for inverters (15 years in 2010 to 25 years in 2020). The technical guaranteed lifetime of the components does not necessarily coincide with the time horizon considered by investors in PV.

Discount rate

All cost and revenue transactions that are not made upfront have to be discounted in order to come up with a present value. The discount factor used is differentiated by market segment and by country. A country-specific risk has been taken into account based on the differences in long-term government bond yields between the five countries assessed. Moreover, a distinction has been made between private PV owners (residential systems) and business investors (all other market segments).

The assessed capital cost in each of the countries does not necessarily reflect the full cost of financing PV systems. While the figures take into account the stability of the financial climate in the different countries, they do not reflect how financing institutions perceive PV technology today and how they will do so in the future: therefore, the current discount factors used by individual and institutional investors are most likely higher. Given that the awareness of financing institutions is rising and that PV is increasingly being perceived as a low-risk investment, the current return demanded by investors in PV could start to decline. From the current levels of 6–8% in the residential segment, the requested return could go down to 4.4–6.1%; in the other segments, a similar decrease from the current 8–12% to 6.5–8.2% could be achieved in the target countries of this study once awareness of the real (technological) risk has widely spread and risks related to the political environment are lifted. If this were to fail to happen, the result would be the LCOE of PV remaining higher than it should be, delaying the competitiveness of PV by on average one year.

Market scenario

Determining PV's generation cost in 2, 5 or 10 years' time requires an assessment of how PV system component prices could go down in the future. Since this depends heavily on market evolution,

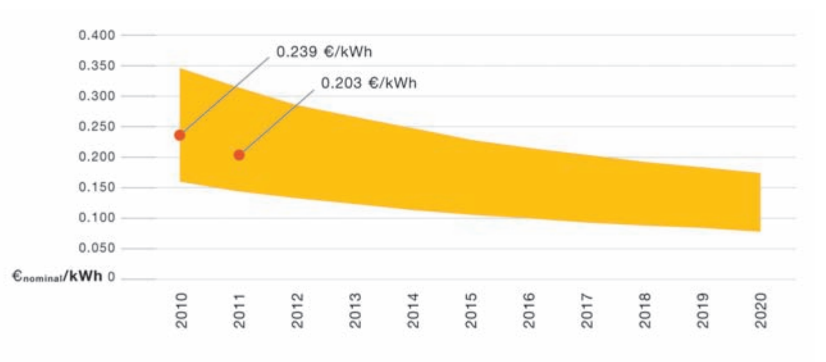


Figure 5. LCOE range projection of European PV for 2010–2020.

an intermediate scenario is chosen: from 2010 to 2015, EPIA's Policy-Driven scenario [2] is taken into consideration. After 2015, EPIA's Accelerated Growth scenario, based on Greenpeace and EPIA's Solar Generation 6 PV market development scenarios [3], is considered. The technology split is based on the Solar Generation 6 report.

Learning rates

All learning factors considered are based on the realized price reductions in the PV industry since the 1980s–1990s:

- PV modules: an initial learning factor of 20% is assumed. For every doubling of the cumulative volume sold, the price will decrease by 20%. Although for thin-film PV modules the learning rate is assumed to remain at 20% until 2020, this rate could decrease to 15% for crystalline silicon modules by 2020.

- Inverters: a learning factor of 20% is assumed for small-scale inverters (used in residential systems) and 10% for large centralized inverters (used in all other market segments).

PV module efficiency roadmap

The evolution of the cost of some components, for example cables and mounting structures, depends on a number of factors, such as the evolution of raw material prices and scale and learning effects. In the evolution of the installation cost, the scale and learning effects are highly relevant as well as the expected increase in labour costs.

In contrast, a significant part of the costs related to the structural components and the installation are influenced by PV module efficiency: the higher the efficiency, the fewer the structural components required. The efficiency evolution of the modules has therefore been taken into account, based on the roadmaps developed by EPIA and the European Photovoltaic Technology Platform [4,5].

Results: a huge potential for cost reduction

The PV module price follows a steady learning curve

The cost of PV systems has been falling for decades and is now approaching competitiveness. Fig. 3 illustrates this remarkable price decline for PV modules: the average price of a PV module in Europe in July 2011 reached around 1.2€/W, which is about 70% lower than 10 years ago. At the time of writing, PV module prices below 1€/W can be found on the market.

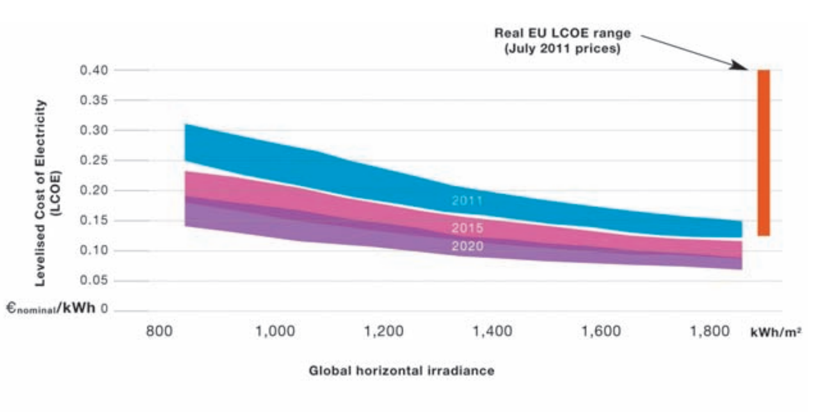


Figure 6. LCOE range projection of European PV for 2011–2020 in relation to irradiance levels.

> "The cost of PV systems has been falling for decades and is now approaching competitiveness."

The PV system price could decrease by 36–51% by 2020

Fig. 4 indicates that PV system prices (CAPEX) have also declined rapidly: during the last 5 years a price decrease of 50% has occurred in Europe. Moreover, over the next 10 years, system prices could decline by about 0.83–1.59€/Wp – a price decrease of 36–51%, depending on the segment. It is important to acknowledge that significant reductions in the total installed system prices are feasible in all countries and over all market segments.

PV system prices went down sharply during the first half of 2011 – a consequence of a slow market start and a growing global production capacity. However, the observed real market prices in several countries are noticeably different from those in Germany, where the prices are the lowest and the market is more mature. But that gap is narrowing quickly. The lack of maturity of several PV markets in Europe has kept prices in most EU countries higher than in Germany. There is no single, easily remediable reason why PV system prices are higher in some countries than in others. There are many factors that explain the current price variations, such as the lack of competition in smaller markets, political choices that favour only the most expensive PV systems, and administrative rules and grid connection procedures that increase the time to market. All these could have a significant impact on the price level. Moreover, unsustainable support schemes could also artificially slow down the price decrease.

A 50% lower generation cost in 2020 is possible

The study finds a huge potential for the decline in generation cost: a fall of 50% by 2020 (see Fig. 5). Moreover, whereas the spread of the current results for PV's generation cost in Europe is fairly wide, this range will decrease in the future to almost half the width of that in 2010. The wide range reflects the large set of different parameters considered:

- Two different sets of technologies

- National differences among the five countries studied with respect to irradiance levels, financial conditions (including VAT for the residential segment), total installed PV system prices and operation and maintenance costs

- Four different market segments

As mentioned above, the study assumes competitive cross-European hardware prices (modules, inverters, structural components) as well as competitive development prices (including the margins for installers). The range therefore reflects the generation cost assuming mature market prices. Accordingly, the average European LCOEs for 2010 (0.239€/kWh) and for the first half of 2011 (0.203€/kWh) are shown in Fig. 5. This calculation considers the real market volumes and market segmentation in Europe.

> "In each of the countries studied, attractive generation costs can be reached within the next 10 years in all market segments considered."

Moreover, the decline in generation cost is relatively stable across all market segments. In each of the countries studied, attractive generation costs can be reached within the next 10 years in all market segments considered.

Fig. 6 indicates the potential range of PV's generation cost in Europe from 2011 to 2020 in relation to the different irradiance levels. Higher irradiance levels are of course a driving factor for lower generation costs. The figure however demonstrates that attractive levels of generation cost could be achieved even in less sunny Northern European regions.

Assessing competitiveness

Finally, PV competitiveness can be assessed. Competitiveness is analysed by comparing PV's generation cost with the PV revenues (dynamic grid parity) and/or directly with the generation cost of other electricity sources (generation value competitiveness).

Competitiveness of PV electricity for final consumers is defined as 'dynamic grid parity' – the moment at which, in a particular market segment in a specific country, the present value of the long-term net earnings (considering revenues, savings, cost and depreciation) of the electricity supply from a PV installation is equal to the long-term cost of receiving traditionally produced and supplied power over the grid.

For large-scale PV installation, 'generation value competitiveness' is assessed: this is the moment at which, in a specific country, adding PV to the generation portfolio becomes equally attractive, from an investor's point of view, to investing in a traditional technology, normally based on fossil fuel.

The EPIA study [1] indicates that competitiveness can be achieved in some markets as early as 2013, and then spread across Europe in the different market segments by 2020.

References

[1] EPIA 2011, "Solar photovoltaics competing in the energy sector – On the road to competitiveness" [available online at http://www.epia.org/publications/].

[2] EPIA 2011, "Global market outlook for photovoltaics until 2015" [available online at http://www.epia.org/publications/].

[3] EPIA and Greenpeace International 2011, "Solar generation 6: Solar photovoltaic electricity empowering the world" [available online at http://www.epia.org/publications/].

[4] European Commission Joint Research Centre – Strategic Energy Technologies Information System (SETIS) 2011, "Solar Europe industry initiative – Key performance indicators" [available online at http://setis.ec.europa.eu/activities/eii-key-performance-indicators/SEIIKeyPerformanceIndicators.pdf/view].

[5] European Photovoltaic Technology Platform 2011, "A strategic research agenda for photovoltaic solar energy technology" [available online at http://www.epia.org/publications/other-publications.html].

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The next eight years in building-integrated photovoltaics (BIPV)

Lawrence Gasman, Principal Analyst, NanoMarkets LC

ABSTRACT

The solar industry suddenly finds itself in an altered business climate in which construction markets seem permanently damaged and government subsidies are under challenge. This paper outlines how BIPV provides a strategy for expanding the market for PV and creating value-added products in a radically changed political, economic and financial environment.

	2011	2015	2018
Tiles and floating panels	691.9	2,015.5	6,628.1
Flexible BIPV products	153.8	1,071.3	4,339.2
Glass	1,171.6	4,357.5	12,668.8
Total	2,017.3	7,444.3	23,636.1

Table 1. Summary of BIPV markets (US$ million).

Introduction

NanoMarkets' latest analysis [1] suggests that building-integrated photovoltaics (BIPV) presents some important opportunities in what we consider will continue to be a challenging business climate for the solar industry for years to come.

- Despite the occasional encouraging monthly statistic, we think it is unlikely that the construction boom (which was fuelled by public policy mistakes in many developed nations) will happen again in the foreseeable future. But without a rapidly growing construction industry, the solar business is robbed of part of an important addressable market on which it has counted for many years.

- We also think that the governmental subsidies on which the solar industry has relied for a couple of decades are likely to experience declining political support. This trend may be counteracted to some extent by both policy makers and electorates who favour 'green energy' over nuclear energy in the light of the Japanese nuclear disasters. However, it is unlikely that this factor will be sufficient to keep some of the most important subsidies in place for solar. And anyone who believes that the solar industry can do well in the absence of subsidies should take a look at the recent history of the Spanish solar industry.

These issues should not be treated lightly. Inevitably they are factors that produce slower growth for the solar industry compared to what that growth might once have been. Moreover, in a market climate in which slow economic growth is endemic, one should expect choices to be made in favour of options with low initial cost. Such an environment cannot be good for the solar industry, which intrinsically is all about high upfront costs, followed by low operating costs.

A new business case for solar is needed

What all this adds up to is this: the traditional business case for solar has been badly mauled in today's business environment. If we are not to go backwards in time to the 1980s, when the solar industry existed primarily to serve the needs of a small circle of enthusiasts, something radically new is required. More specifically, what is needed here is a new kind of solar – one that provides a transformed price/performance offering to the marketplace. This 'new kind' of solar could emerge in different ways:

- The most obvious perhaps would be through entirely new technology. For example, one can easily imagine micro- or nano-concentrators or some entirely new absorber material based on quantum dots or metamaterials, say, ramping up conversion efficiencies (and ultimately making significant reductions in $/W) to a point where photovoltaics would be much more competitive with other sources of electrical power. Such developments may be highly likely in the long term. But the operative words here are 'long term.' And one might add to any description of such technologies the word 'risky.'

- NanoMarkets believes that BIPV offers a route to an entirely new way of thinking about solar costs and also to teasing out new addressable markets, even in difficult times. As this paper explains, BIPV represents a technology that can spread the costs of PV across multiple functionalities, thereby reducing the need for subsidies. And BIPV also seems to imply the potential for an entirely new aesthetic – one that will be market expanding for the solar firms that adopt it. However, taking the BIPV road is not without its risks too, nor is it an entirely immediate prospect. But it is less risky and nearer term than any strategy that involves a fundamental shift in the materials used for solar panels.

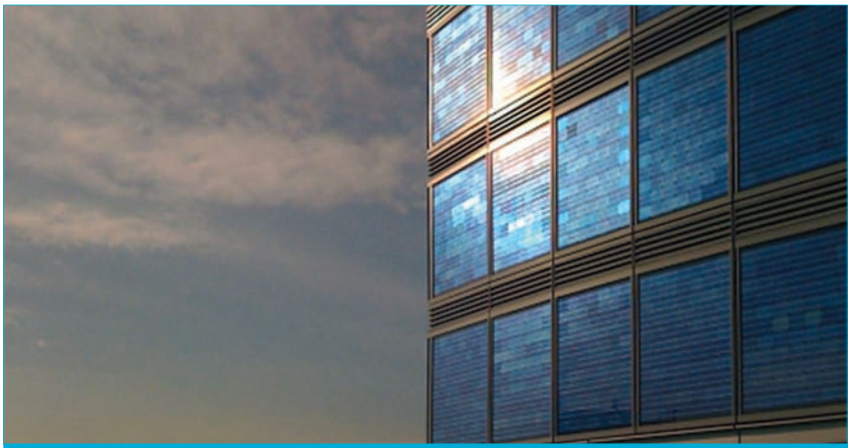
> "If we are not to go backwards in time to the 1980s, when the solar industry existed primarily to serve the needs of a small circle of enthusiasts, something radically new is required."

As Table 1 shows, we believe that the aggregate revenues from BIPV will be quite large; these revenues will be established in part by taking custom away from traditional solar business, but also by tapping into new markets that are difficult to reach using conventional solar panels.

BIPV: aesthetics and opportunities

Throughout the several decades of the existence of solar, its aesthetic has been one that might reasonably be said to be propagandistic or 'in your face,' to the extent, that is, that solar energy had an aesthetic at all. In its earliest days, purchasers of solar power systems typically did not care that much about how the solar panels on their roofs looked; the point was to be part of a movement. To the extent that there was an aesthetic it was a political one.

Of course, this kind of aesthetic does not come close to being universally acceptable; the markets to which it can appeal are inherently small. Large roof- or wall-



Source: RELAB

Figure 1. The Visionaire, a high-rise residential tower in the Battery Park City area of south-western Manhattan, shows how aesthetics can be easily addressed in BIPV installations.

mounted solar panels are not generally considered aesthetically pleasing any more than satellite dishes are; at best, people get used to seeing these installations as they become more common.

In some cases conventional PV installations can even run foul of local building ordinances. To put it in blunter terms, not only are significant segments of the building owner/building manager market not being turned on to using photovoltaics as a way of providing electricity to the buildings they control, but they are also quite definitely being put off the whole idea. This is not something the solar industry can afford to let happen at a time when its political support and markets are both under strain.

The first-generation BIPV products – building-attached PV (BAPV), as they are sometimes called – went some way towards addressing the issues mentioned above. BAPV could, for example, be installed flush with roofs and was therefore less objectionable. Second-generation BIPV products take this trend to a dramatic new level:

- By integrating PV absorber layers and electrodes into roofing, siding and glass, second-generation BIPV products become something entirely new, or at least they create a major strategic shift. That is, the old-style PV industry produced something called a 'solar panel.' Under the second-generation product paradigm, the solar industry is merging into the building product business, while at the same time preserving the best performance characteristics of solar panels. More specifically, second-generation BIPV products are generally made to provide 10–14% PV efficiency, while also meeting all the codes and standards of traditional high-end building products.

- BIPV in its second-generation form is just another kind of roofing product – it is no longer a radical form of energy system. This is a good thing from the perspective of marketability: PV industry insiders often have a hard time understanding how novel PV systems seem to most building owners and managers. We believe a shift of this kind will open up many new markets for PV.

- Second-generation BIPV also brings a new familiarity to the purchasing of PV panels; with this kind of BIPV, buying a panel could become just another option in the purchasing of roofing or siding, for example. Moreover, the latest BIPV products are designed to be delivered through standard building industry supply chains and installed by the usual building industry professionals. These new BIPV products, we expect, will start 'bootstrapping' themselves into the market as ease of installation and attractive functionality trigger ever more demand.

- The final goal is that BIPV will be seen as part of the standard portfolio of high-end 'green' building products used by architects and builders.

> “BIPV in its second-generation form is just another kind of roofing product – it is no longer a radical form of energy system.”

As we have already noted, we think that this 'normalization' of PV is certain to open up new markets for BIPV. However, one should not underestimate the difficulties in such a transformation.

Getting BIPV panels accepted by the roofing and siding industries will be a challenging business development issue in particular. It may mean even taking some steps backwards before we can move forwards. Thus, for example, Ascent Solar has demonstrated a flexible laminate product called WaveSol Light. This product is claimed to be 8–9% efficient, and claims improved aesthetics on curved building surfaces. However, Ascent has retreated from the BIPV markets. Instead, the company is focusing on niche markets such as the military and defence; off-grid charging solutions in developing countries; power for portable electronics; and custom and standard products for rooftop integration on buses, heavy goods vehicles and trains. It is only once these markets are established that Ascent will return to the BIPV sector.

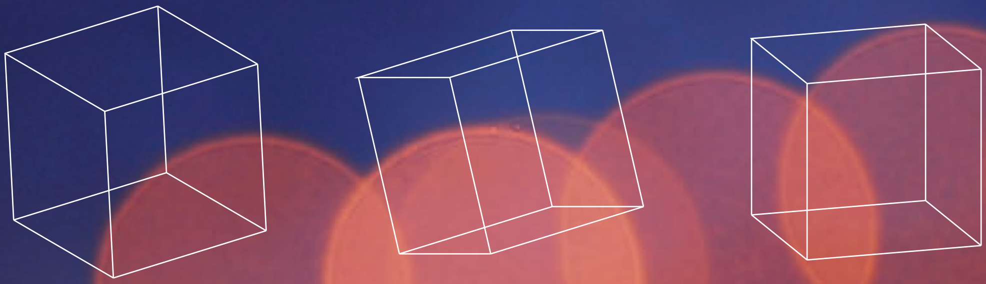
And the aesthetic questions at the beginning of this section also raise issues:

- It is one thing to use second-generation BIPV concepts to cover up the PV; it is quite another to use BIPV to actually enhance the aesthetics of the building. Some of the earliest examples of BIPV have emphasized aesthetics quite explicitly, but they have done so only by employing architects. Architecture is a lot more than simply going for the lowest-cost building. That is why using an architect rather than simply a builder/draughtsman is almost always the most expensive option in constructing a building. Bringing a specifically BIPV aesthetic to moderate-budget buildings – where BIPV aesthetic is defined as something that shows off the PV in a beautiful way – is an issue that has barely been talked about yet. However, in the long run, creating a BIPV aesthetic is not just a challenge, but also another part of making PV fit into a post-subsidy world.

- Crystalline silicon still provides the highest PV conversion efficiency and – with clever understanding of optics, mechanics and industrial engineering – can be incorporated into new second-generation BIPV products. Pythagoras Solar is noteworthy for using arrays of prisms to hide crystalline silicon cells on their sides in double-pane insulated glass units (IGU) that appear almost completely transparent when looking straight at them.

- Thin-film PV-based BIPV glass is another approach to creating a new PV aesthetic using the BIPV concept. These panels replace the squareish silicon cell space pattern with tighter, more precise pinstripe or other patterns and eliminate the tabbing that spans the spaces between cells. Uniform thin-film semi-transparent and opaque panels also exist for side-wall spandrels, shade screens and canopies.

The bottom line here is that second-generation BIPV holds open the possibility of expanding the market for PV by normalizing it as part of the building products market. That being so, it enables designers to come up with something quite new: a BIPV aesthetic that follows its own rules and goes well beyond just hiding ugly silicon panels!



	Advantages	Disadvantages
Crystalline silicon		
Rigid BIPV	Cells fit well into tile-shaped packages Suitable for flush mounting Cell appearance can be attractive	Cell appearance can be considered unattractive Limited sizes and shapes of cells Silver tabbing usually required
Flexible BIPV	Would offer a classic PV appearance if it could be made affordably in volume	Standard cells too rigid and fragile for flexible BIPV Ultra-thin silicon only shown in labs with no commercial product plans known
'Transparent' BIPV	Custom shapes can be handled with attractive cell layouts Cell appearance can be attractive	Cell misalignment produces irregular reflections, and tabbing may look unattractive Even use of prism/mirrors limits off-axis transparency
Thin-film/organic-based PV		
Rigid BIPV	Clean, uniform appearance Suitable for flush mounting	More or larger panels required for same power
Flexible BIPV	Clean, uniform appearance Curved installations possible Versatile for use on many surfaces	Additional framing needed for some installations Versatility can lead to some undesirable installations
'Transparent' BIPV	Clean, factory precision appearance Some may produce transparent BIPV glass with no visible pattern	Very low efficiency limits economic appeal Custom/irregular panel shapes may have unattractive patterns or be impossible

Table 2. Aesthetic advantages and disadvantages of BIPV.

> "The bottom line here is that second-generation BIPV holds open the possibility of expanding the market for PV by normalizing it as part of the building products market."

This new aesthetic has yet to be fully defined, although as a practical issue the degree to which factors other than cost matter is highly dependent on the particular building, the particular architect, etc. Architects, we believe, might help promote BIPV as an aspect of 'green/LEED' building design. But as the BIPV market evolves, the content of some future BIPV aesthetic will become clearer. What is relatively clear at the present time are the dimensions in terms of which such an aesthetic will be defined. These are shown in Table 2, which also illustrates some of the aesthetics-related advantages and disadvantages of crystalline silicon thin-film and organic-based BIPV.

BIPV and its new economics

Also of critical importance to the future of BIPV is the fact that BIPV products exhibit an economics which is fundamentally different from that of standard PV products. With regular PV we are looking at a large upfront cost – high enough that, outside of a few small market niches, PV makes little sense without government subsidies. With BIPV the cost of the PV is added to the cost of a roofing shingle, a sheet of wall cladding or even a window. But at the same time, the functionality is increased: the product is now a roofing tile and a PV panel.

In much the same way that an integrated fax/copier offers good economics for both fax and copying functionalities, because it shares a common electronic and electrical infrastructure, a BIPV product becomes a good deal because the PV functionality and the building product share a common substrate. Quite how good a deal is ultimately technology dependent, because we expect the level of integration, and therefore improvements in BIPV economics, to increase over time:

- Today we are probably talking about a PV laminate on an otherwise fairly conventional roofing product.
- Another new approach to BIPV is the manufacture of BIPV tiles that interlace with conventional high-end roofing tiles. This approach has been used for a few years with crystalline silicon PV, but only to a small extent with thin-film PV. Now, however, there is increasing development of interlacing products with slightly different approaches. New CIGS-based flexible roofing products such as Dow Chemical Company's shingle product make additional markets more accessible to PV and BIPV firms.

In the future we are talking about something closer to a more monolithic type of integration, with the integration being created at the layer of the materials themselves. What this might mean is the introduction of some kind of composite material that could genuinely be claimed to be both a PV absorber layer and an attractive and highly functional roofing material.

Nothing like this exists yet, but when it does, it would present the possibility of a BIPV roofing product that would cost only slightly more than the equivalent roofing product without PV functionality. This could be a very attractive offering, potentially reducing the cost of PV panels by orders of magnitude.

Of course, while the adoption of a BIPV strategy improves the economics of BIPV, it does not eliminate the inverter or other peripherals from the cost equation. But our belief is that the integration aspect of BIPV will still be sufficient to lower costs not just to a point where the addressable markets for PV would expand significantly, but also to the point where PV could become inexpensive enough to exist without government subsidies. So BIPV could be a key technology strategy for the survival of the PV industry in a world in which economic growth will be severely curtailed for the next few years.

> "The possibility of a three-year ROI for grid-connected BIPV is certainly possible with government incentives and grid electricity costs greater than US$0.20/kW."

A large cost breakthrough still lies in the future for BIPV, although many second-generation BIPV products can already offer payback periods of seven to ten years without incentives, which at current low interest rates may be acceptable in some markets. And, of course, in most markets in which it competes at the moment, BIPV can

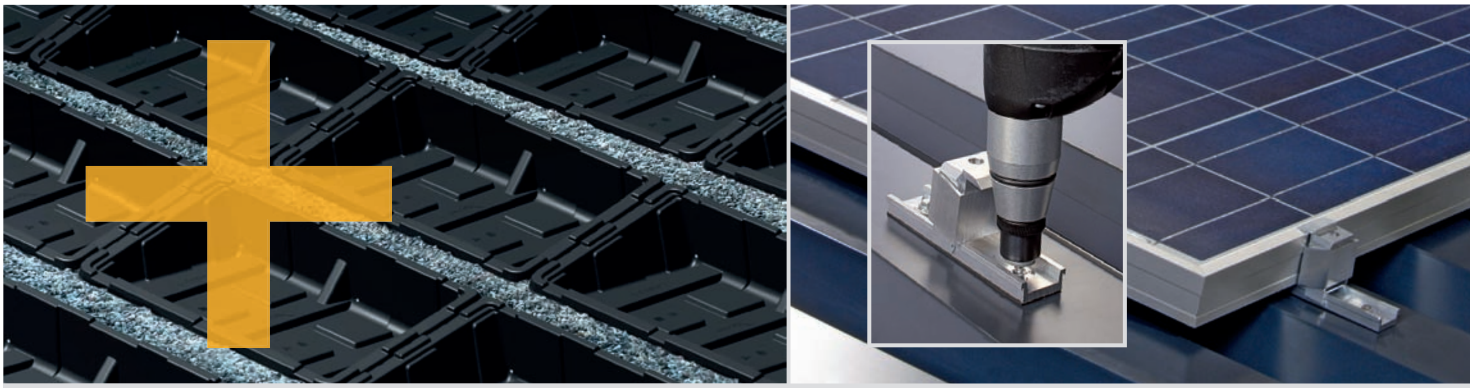
Source: Romag

Figure 2. Romag's BIPV installation in the London Borough of Hackney, UK, covers the glazed roof of the local Council's 'Customer First Centre.'

still tap into government subsidies. In a few places there are even incentives specifically aimed at BIPV, based on the idea that BIPV (as opposed to regular PV) may have added value from a communitarian as well as an individual point of view.

Given the benefits of BIPV and various potential market scenarios, NanoMarkets sees several thresholds for BIPV payback time consideration, specifically three, five, ten and twenty years. The possibility of a three-year ROI for grid-connected BIPV is certainly possible with government incentives and grid electricity costs greater than US$0.20/kW. Even a 20-year ROI, while probably not of interest to most residential and commercial owners, could be acceptable for schools or other government buildings (see Table 3).

The BIPV approach is easiest to justify when the conventional building materials



BIPV ROI (years)	Residential	Commercial	Government	Off-Grid/Special
3	Strong	Strong	Strong	Strong
5	Some	Strong	Strong	Strong
10	Some	Some	Strong	Strong
20	None	None	Some	Some

Table 3. Level of interest in BIPV for end-user segments as determined by ROI term.

that BIPV is designed to match or replace are high-end, high-cost ones. If the building material costs are already comparable to, or higher than, the cost of PV by itself, there is much more ability to absorb a significant part of the PV cost into the cost of the building materials used or replaced. This situation already exists for some expensive building materials such as certain architectural glass and high-end roofing slate. Declining PV prices will also eventually allow significant portions of PV costs to be absorbed by mid-range and lower-end building materials, enhancing BIPV's market position in those categories.

BIPV has some big backers

Just a few years ago, BIPV meant little more than using completely conventional panels and hiding them with architectural features. Currently, a lot of what passes for BIPV is actually flush-mounted panels and little more. Still, there is reason to hope that a next generation of BIPV products is emerging in which: 1) fully integrated BIPV products will come from a factory with the PV devices already incorporated; and/or 2) building materials do not function well without the PV devices, or vice versa.

When this happens, the distinction between the architectural and building material costs of a BIPV product and the PV costs is much fuzzier. BIPV suppliers can then more easily maximize the perceived value of the architectural aspects of their BIPV products, leaving a smaller portion of the BIPV costs to be assigned as PV system costs and increasing their opportunity to improve profitability. In this environment, it becomes far less clear that subsidies will be needed to keep the solar business in business, as it were.

No doubt we are still a long way off from achieving such goals, but there are signs of progress. It is particularly encouraging, we think, that BIPV is being treated seriously enough that large companies are getting into this business. The participation of such companies would, it seems, be essential for the development of BIPV for at least two reasons:

- First, in today's financial climate, strategic investment by a large multinational may be the best hope for an innovative start-up to secure funding for its BIPV business.
- Second, an alliance between such a BIPV start-up and a larger firm seems to be essential in order to provide access to a sophisticated marketing channel for the smaller company. It is clear that not all marketing channels are created equal, and we think that BIPV firms which can build alliances that get them into the conventional professional building materials and do-it-yourself supply chains will be substantially advantaged.

We have already mentioned Dow as a major firm that already sees opportunities in the BIPV space. Dow is constructing a facility in Michigan capable of producing up to 200MW of its BIPV shingles by 2015. But there are other big firms entering the BIPV market too. For example, both Tata Steel and Pilkington Glass (now part of Japan's NSG group) are collaborating with Dyesol to develop DSC technology for BIPV applications. The collaboration with Pilkington Glass covers commercial architectural canopies, side walls and shade structures. Tata Steel is looking at the potential for DSC-based BIPV-on-steel roofing, with plans for a multi-million square-metre pilot line being discussed.

There are also, of course, many medium-sized firms in this BIPV space that we expect to thrive. And what all of the firms in the BIPV business appear to share are strategies focused on creating value-added products that effectively distinguish them in the marketplace from the sector of the PV industry that specializes in plain vanilla and rapidly commoditizing solar panels of the kind that Chinese companies have proved so good at supplying.

Conclusion

While the underlying technology of BIPV products that are likely to appear on the market is just the same as for the ones that have been touted by the PV industry for (more or less) the past decade, the BIPV perspective on product strategy is the only one that seems to us to offer a relatively short-term fix to a market environment in which subsidies may eventually become a thing of the past and in which the potential for price wars is frighteningly real. In addition, the arrival of genuinely integrated BIPV products will also lead to a new architectural aesthetic for them, which could, when translated into business strategy terms, mean the opening-up of entirely new markets for PV in the not too distant future.

Reference

[1] NanoMarkets 2011, "Building integrated photovoltaics markets, 2011" [available online at http://www.nanomarkets.net/index.php/market_reports/report/building_integrated_photovoltaics_markets_2011].

About the Author

Lawrence Gasman co-founded NanoMarkets, where he is currently principal analyst and his consulting clients include both multinationals and start-ups. Lawrence was educated at the London School of Economics and London Business School; his latest book is on the commercialization of nanotechnology.

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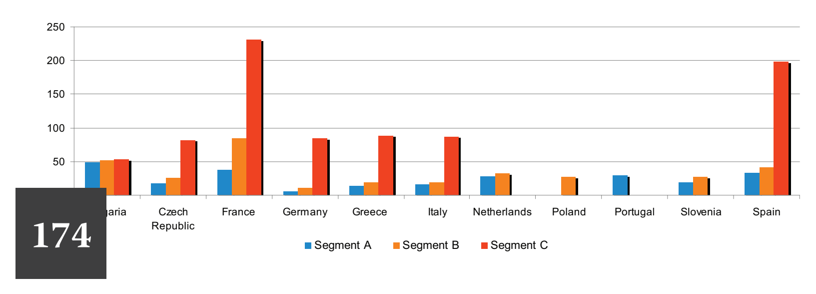

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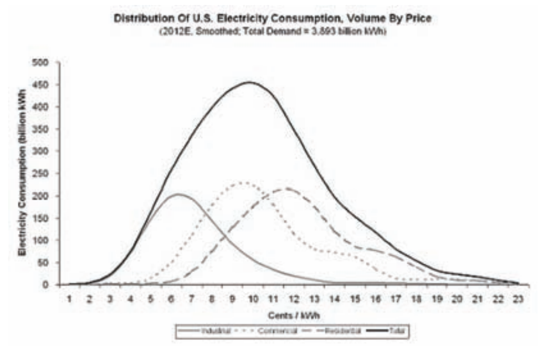
News

Solar demand in US near inflection point for massive growth, says Keiser Analytics

A unique bottom-up analysis of retail electricity prices across the US by Keiser Analytics paints an incredible picture of the potential adoption of solar power at the residential and commercial level as installation costs fall to reach retail grid parity and below. Should the inflection point be released, US solar module demand could top 100GW over the next five years, compared to the expected 2011 demand of approximately 2GW.



Source: Keiser Analytics

"While the recent price declines of solar PV equipment are well known, what is less appreciated is the size and distribution of U.S. electricity consumption," noted Richard Keiser, former analyst at Sanford Bernstein and now President of Keiser Analytics.

The report highlights that most residential and commercial PV installations in US between 2010 and 2011 have cost between US$5 and US$8 per watt, while remaining above the retail price of electricity paid by most consumers across a diverse number of electricity providers and irradiance levels.

The new report looked at the retail price of electricity across all US States from US Energy Information Association (EIA). The data were analyzed segment by segment, state by state, to determine the points at which the NPV of a solar PV investment becomes positive relative to the NPV of electricity purchases from the utility.

So far the US market demand for PV has the ability to support installations of between 2–5GW of capacity, based on installation costs in the US$5–$6 per watt range, less than 1% of electricity generation in the country.

However, as the installed cost decreases to US$4 per watt, 2% of US electricity needs could be economically viable. But the key cost level is at US$3 per watt, when approximately 17% of US electricity could be economically served by solar PV, according to the report. This is equivalent to over 300GW of solar PV capacity, according to the analysis by Keiser.

Market Trends & Developments

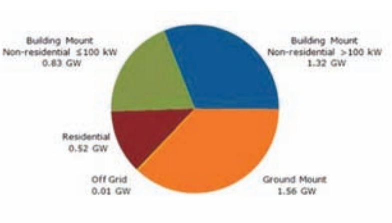
European PV market demand to pick up in Q4, but tough 2012 ahead, says Solarbuzz report

Solarbuzz's new European PV Markets Quarterly predicts that 2011's fourth quarter will see a quarter-over-quarter rise of 22% in the EU PV market, but 2012 will still be a tough year to navigate. Solarbuzz noted that downstream companies would need to be able to manage a new pricing environment in the midst of flailing incentives and grid parity economics.

While quarter-over-quarter results are anticipated to be up 22%, year-over-year growth, per the report, is expected to drop 25% due to a combination of solar incentive cuts, feeble project financing and module price's dropping so much that, according to Solarbuzz, companies will need to get rid of their inventories or be faced with substantial write-downs.

The report found that ground-mounted solar installations took over one-third of the EU market in the second half of 2011 despite falling 27%, while non-residential building-mounted installations will take a 55% share in 2011. Solarbuzz advised that European markets are feeling the effects of narrowing PV incentive policies, bank lending restrictions, policy changes and utility concerns due to electricity grid stability.

Solarbuzz acknowledged that 2012's first quarter, expected to be down 72% quarter-over-quarter, would see the ground-mounted sector hit the hardest and falling 81%.



Source: Solarbuzz

Solarbuzz's Q3'11 European market segmentation forecast (total quarterly market 4.24GW).

Residential lease is predicted to decrease by 41% while the German market as a whole is likely to plunge by 11% year-over-year. The report additionally concluded that installed system prices are calculated to wane by an average of 17% throughout 2012.

The EU report found that Austria, Belgium, Bulgaria, Greece, Romania, Spain, Ukraine and the UK are set to offer the most stable volumes or growth over the next one to five years in the smaller market segment.

IMS Research raises global PV installation forecast for 2011

IMS Research last raised its global PV installations forecast for 2011 to over 22GW back in August. However, emerging markets such as North America and Asia are driving installations, especially in the second half of the year, leading the market research firm to raise its forecast further to 24GW, a 24% increase over 2010's installation figures that IMS says reached 19GW.

IMS's recently released Q4'11 PV Demand Database shows that installations exceeded 8GW in the first half of 2011 and would reach 15GW in the second half, supporting its previous projection that installations would rise dramatically in the latter half of the year.

IMS noted that confusion over Italian installation figures prevailed and stated

Source: IMS Research

"Despite installing just 45MW last year, the UK is set to install more than 500MW in 2011 and become the 8th largest PV market," explained Sharma.

that Italy would – for the first time – become the world's largest market in 2011, installing 6.8GW of new capacity.

However, Europe is only expected to see installations increase by 3% this year; Italy cannot compensate for falls in Germany and the Czech Republic and slowdowns elsewhere.

North America and Asian markets are performing well, according to the market research firm. The two regions are expected to generate 85% of the global growth in installations in 2011.

"The PV market continues to diversify in 2011; this will create short-term pain for suppliers that can no longer solely rely on one market to fuel their growth, but creates long-term stability for the industry by helping to balance the effects of a single country's incentive policy and reduce large swings in supply and demand," commented Ash Sharma, senior research director for PV.

Module shipments up, revenues flat in Q3, as China Sunergy warns of weak Q4

Upon the disclosure of its third quarter 2011 financial results, China Sunergy noted that its results were direct reflections of lacklustre market demand, coupled with faster than expected average selling price (ASP) declines and inventory write-downs. The Q3 2011 revenues saw no significant change with revenues being finalized at US$145.8 million, a 1.3% increase over Q2 2011 results and a 15.9% year-over-year surge.

China Sunergy advised that the slight 1.3% increase quarter-over-quarter in its revenues was mainly due to an increase in quarterly shipments, but went on to note that corresponding revenues were offset by falling ASPs.

Shipments for the third quarter totalled 116.2MW, of which module shipments accounted for 115.6MW, the highest quarterly shipment volume for the company to date.

Although the shipment results showed a 30.1% increase over Q2 2011 shipments, actual shipments fell below the company's previously stated guidance of 140MW to 160MW. The company also stated that sales decreased in Q3 from the European market, but increased in new market segments. Revenue from module sales was US$145.5 million, making up 99.7% of the quarter's total revenue.

In the outlook for the fourth quarter and full year guidance, China Sunergy acknowledged that a continuously weak demand in the market and an industry oversupply would continue to affect its results. The company is expecting shipments in Q4 2011 to reach between 95MW and 110MW. Gross margin levels are anticipated to break even in the quarter while a net loss is projected during Q4. The full 2011 year has China Sunergy predicting total shipments to be between 395MW and 410MW.

Applied Materials suffering from steep decline in orders and revenue from solar sector

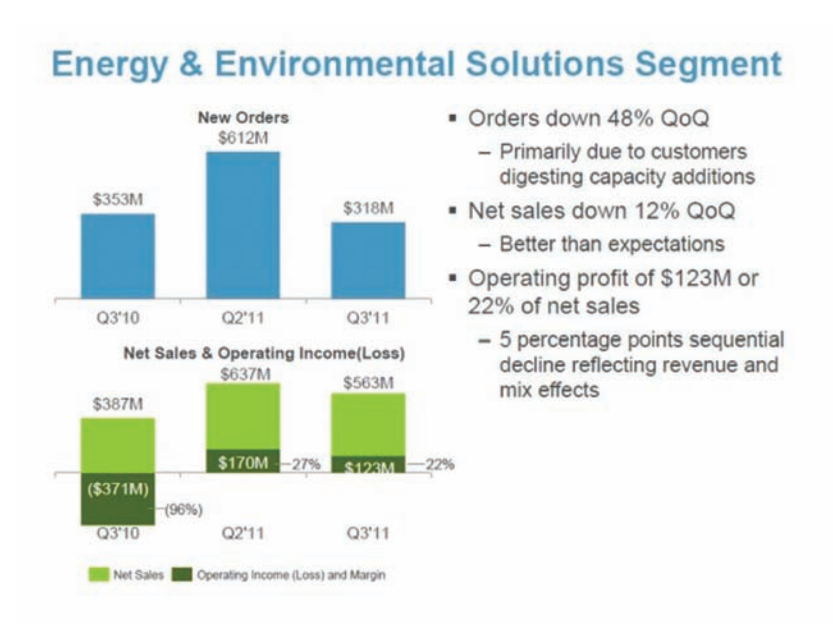
After a record revenue financial year, Applied Materials is experiencing a significant reduction in equipment orders and revenue from PV manufacturing customers.

Though cancellations were minimal, backlog decreased by 26% to US$2.4 billion, of which 14% is within its EES division, which includes PV equipment. Management expects PV related global CapEx to at fall by at least 50% in 2012 as manufacturers combat massive overcapacity and focus on cell efficiency improvements and technology buys.

Applied Materials noted Q4 and full-year financial results that EES division orders declined 73% to US$86 million with net EES sales of US$315 million, down 44% on the previous quarter. Operating income decreased to US$17 million – 5% of net sales – reflecting the net sales decline.

However, the rapid drop in revenue and new orders is set to get worse. Applied's management noted that it expected EES sales to decline between 40–60% in the next quarter as a direct result of the steep order decline and the business segment operating close to but below break-even position.

Based on the rapid fall in new orders and projected low levels over the next two quarters, the worst spending period looks likely to be the first half of 2012, with the hope that a recovery in equipment spending occurs in the second half.



Energy & Environmental Solutions Segment

- Orders down 48% QoQ
  - Primarily due to customers digesting capacity additions
- Net sales down 12% QoQ
  - Better than expectations
- Operating profit of $123M or 22% of net sales
  - 5 percentage points sequential decline reflecting revenue and mix effects

Source: Applied Materials

After a record revenue financial year, Applied Materials is experiencing a significant reduction in equipment orders and revenue from PV manufacturing customers.

Source: China Daily

The World Bank loan will help the Moroccan Government achieve its goal of increasing solar capacity to 2000MW by 2020.

Morocco's 500MW CSP plant receives US$297 million World Bank loan

The World Bank has approved a US$297 million loan to help finance the 500MW Desertec concentrated solar power (CSP) plant in Ouarzazate, Morocco.

The World Bank's International Bank for Reconstruction and Development arm will contribute US$200 million towards the loan, with the remaining US$97 million coming from its Clean Technology Fund. All US$297 million is going towards completing the first phase of development and adding 160MW of capacity by 2014.

By securing the loan, Desertec is one step closer to starting work on Ouarzazate, which, when completed, will be the largest in the world. The record-breaking project is also set to play a central role in Morocco's solar roadmap – by 2020 the Moroccan Government aims to increase its solar capacity to 2000MW – while also boosting the economy by creating jobs and improving energy security and exports.

Germany set for 15% FiT cut in 2012

The Bundesnetzagentur, Germany's Federal Network Agency, will cut the country's solar feed-in tariff (FiT) by 15% in 2012. The subsidy reduction is more severe than the 12% forecasted by many industry insiders and was triggered by the 5.2GW of new capacity installed between October 2010 and September 2011.

Source: Enchanted Learning

A Q4 installation rush could lead to further cuts in mid-2012.

Under the German Government's Renewables Act, the FiT adheres to a degression regime, where cuts are dependent on the previous year's installation figure. Although the figure is well below the 7.8GW installed the previous year, the collapse is not as dramatic as had been expected when the German Government initially announced its FiT cut. Indeed, between July and September 1.6GW was installed, just 100MW shy of the corresponding year-on-year number.

UK looks set for 50% feed-in tariff cuts

The UK's Department of Energy and Climate Change (DECC) has published its consultation document for the comprehensive review of solar feed-in tariffs. After weeks of speculation surrounding the UK government's support for solar power, the new proposed rates and the timeline within which they will be implemented have finally been outlined.

As was widely expected, DECC has proposed to cut the FiT rate for solar PV by more than 50%. The proposals, which are subject to consultation, would introduce a new tariff for schemes up to 4kW in size of 21p/kWh – down from the current 43.3p/kWh. Reduced rates are also proposed for schemes between 4kW and 250kW.

Source: Protect Britain

The DECC's review consultation is due to close on December 23, 2011.

DECC reiterates that consumers who already receive FiT payments will not be subject to change and those with an eligibility date on or before December 12 will receive the current, higher rates for 25 years.

The proposed FiT cuts follow the reduction of larger-scale solar incentives, which were implemented on August 1 this year. The comprehensive review consultation is due to close on December 23, 2011.

First incentive scheme for large-scale solar launched in Australia

Australian Capital Territory (ACT) is launching a new incentive scheme to promote large-scale solar in the state. It is Australia's first scheme targeted at utility systems and aims to help install projects totalling up to 210MW.

Under the ACT legislative assembly's proposal, a reverse auction process will be introduced, inviting companies to demonstrate how they can provide the greatest amount of power for the lowest cost.

The first stage of the bill will see 40MW of solar capacity auctioned off. This auction is due to get underway before the end of the year and after a summer filled with subsidy cuts, closures and adjustments, the news is a boost to the country's flagging PV industry.

Source: Gunaxin

Australia is launching a new incentive scheme to promote large-scale solar installations.

Gujarat proposes new feed-in tariff rates

The Gujarat Electricity Regulatory Commission (GERC) has proposed the new FiT rates for PV projects commissioned from January 29, 2012 until March 31, 2015.

These new rates range from INR10.27 (US$0.21) to INR13.14 per kWh (US$0.268) and are applicable for ground-mounted, rooftop and concentrating solar power (CSP) systems.

Should the proposed rates be confirmed, CSP projects will be eligible to receive levelized tariff payments between INR12.45 (US$0.252) and INR13.14 (US$0.266) per kWh, while systems over 100kW are in line for tariffs from INR10.37 (US$0.21) to INR10.92 (US$0.221) per kWh. Rooftop projects under 100kW will still receive the greatest assistance, with subsidies ranging from INR12.6 (US$0.255) to INR13.24 (US$0.268) per kWh. The deadline for feedback on the new FiT is December 1.

Source: flagartist

The GERC has proposed the new FiT rates for PV projects commissioned from January 29, 2012 until March 31, 2015.

Gujarat's solar industry is booming at present and this is reflected in the GERC's change of approach in terms of subsidies; previously PV had been eligible for higher tariffs than CSP, but with PV module and inverter prices continuing to fall, the commission is believed to feel project developers are deserving of less generous handouts.

Since 2009, more than 80 companies have signed power purchase agreements worth an estimated 965MW in Gujarat. At first, progress was slow, with red tape and financial difficulties holding up developers. However, the state is finally beginning to deliver on some of its early promise – in October, a 30MW system was completed in Banaskantha – and GERC expects many more to be commissioned by the year's end.

Rough trade: US takes steps to release China's grip on solar markets

By **Nilima Choudhury**

The United States and China are embroiled in what the New York Times has dubbed "the most politically charged trade case in many years".

Seven US-based crystalline silicon solar cell manufacturers have formed The Coalition for American Solar Manufacturing (CASM), led by SolarWorld and First Solar (the identities of the five remaining members are yet to be disclosed). The CASM has accused Chinese manufacturers of violating global trade laws with its "anti-competitive trade aggression".

In October, CASM filed petitions with the International Trade Commission (ITC) and the US Department of Commerce (DoC) calling on the government to apply high tariffs on Chinese solar cell manufacturers, claiming China is using the antidumping and countervailing trade laws to "protect" its own industries.

COALITION for AMERICAN SOLAR MANUFACTURING

CASE

The CASM has also accused the Chinese government of deliberately keeping the Yuan low to gain a trade surplus. Part of SolarWorld's complaint is that the Chinese government has not been forthcoming about the extent of its subsidies. As a member of the World Trade Organization, China is expected to disclose its subsidies regularly so that other countries can decide how to respond and determine whether those subsidies unfairly enable certain companies to grab market shares.

China has rejected these claims and blames US restrictions on high-tech exports for fuelling the imbalance.

But the CASM also has its critics. The Coalition for Affordable Solar Energy (CASE), a group of 25 solar organizations, was formed a few weeks after the CASM's petition was filed to defend China's involvement with US trade, believing it to be important in order to continue competition and growth on an international level.

It has been difficult to identify official figures to deduce the extent of support for the CASM's actions. Recent polls have presented extreme results. A poll by PV Magazine showed that 76% of respondents opposed the filing of the petition, whereas a survey published by the Solar Energy Industries Association (SEIA) implies that 82% of the American public agree with CASM. The number of participants taking part in the surveys was not disclosed.

According to the SEIA, in the last 12 months, the US solar industry has grown by 69%. The solar industry is one of the fastest-growing industries in the US with more than 100,000 jobs across more than 5,000 companies. The US was also a net exporter of solar products in 2010 to the tune of US$2 billion, one of the recipients being China, which spent more than US$200 million.

According to the CASM, between 2008 and 2010, there has been a 310% 'surge' in Chinese exports to the US. They have brought neither technological nor cost advantage, says the coalition, which goes on to blame the Chinese for the 40 to 50% price drop in modules seen this year.

Below is a timeline of the events taking place in the dispute.

October 19

Petition written to the Department of Commerce and International Trade Commission by the Coalition for American Solar Manufacturing fronted by SolarWorld America, a subsidiary of Germany's SolarWorld, accusing the Chinese government of providing "massive" illegal subsidies to advance the exports of domestic Chinese crystalline silicon solar wafer, cell and module manufacturers, and dumping crystalline silicon solar cells into the US market.

October 20

US-based SEIA, which represents 1,000 members working in the PV industry, published a statement in part to offer their support to CASM but also to advise caution.

SEIA president Rhone Resch said, "As long as the US is able to compete on an even playing field, the combination of policy certainty, private investment and continued technological advances will keep the solar industry as one of the fastest-growing economic sectors in the country."

October 24

An unnamed official from China's Ministry of Commerce was quoted on Chinese national news site, Sohu, as saying that global economic recovery could be greatly hampered by the CASM's allegations: "The Chinese government hopes the United States will scrupulously abide by its promise to oppose trade protectionism, avoid adopting protectionist measures on Chinese solar cell products, jointly protect a free, open and fair international trade environment, and adopt more rational means of handling trade frictions." According to the official, China's policies do meet World Trade Organization rules.

In response, CASM spokesman Gordon Brinser, president of SolarWorld, produced a statement: "The Chinese government's claims that our actions are improper and protectionist and that its illegal subsidies and massive dumping of solar product are helping the global economy and the environment, are absurd. China is one of the biggest trade protectionists in the world. In the solar industry, China is gutting manufacturing and jobs here in America and abroad while China's solar industry pollutes its own people.

"China is a heavy user of the antidumping and countervailing trade laws to protect its own industries. It is no coincidence that China has been named in the most antidumping and countervailing duty cases from countries all around the world: it is the worst violator of global trade laws.

"It is widely known that China's economic growth model is causing huge disruptions in the global economy.

"Worst of all, China's manipulation of its currency severely distorts global markets. China's predatory and illegal aggression is crippling the US industry. CASM is holding China accountable for its disregard of the very trade rules it has agreed to follow."

November 2

CNPV Solar Power became the next target of accusations levied at it from the CASM. A CNPV spokesman said: "We are currently reviewing the petition with our legal counsel and will be prepared to respond vigorously if an investigation is initiated. We reject any allegations in the petition with regard to CNPV's business conduct."

This followed CNPV's recent entering into an agreement with a US manufacturer in September, whereby CNPV signed a contract with Solar Solutions and Distribution for residential and commercial installations. However, at present, CNPV is in the process of reviewing the antidumping and countervailing duties petition in the US against Chinese competitors.

Other China-based exporters of PV products include JinkoSolar Holding and Suntech. Jinko was implicated due to a recent fluoride wastewater leak at its Haining, China plant. The company responded to the claims stating that the company intends to carry on its

Gordon Brinser, president of SolarWorld and CASM spokesman.

manufacturing practices as normal while the ITC and DoC decide how to respond.

A spokesman from Suntech said that it will continue to build on its existing relationships with US companies but pointed out that: "[a]nyone can file one of these actions; having filed an action is in no way a validation from the US government as to the merits of the action."

November 2

The Chinese Renewable Energy Industries Association, China Photovoltaic Society, Industrial Commission of China Renewable Energy Academy and the China Photovoltaic Industry Alliance issued a joint statement regarding the CASM's petition.

Junfeng Li, Deputy Director General/ Professor, Energy Research Institute, National Development and Reform Commission of the People's Republic of China (PRC) and secretary general of Chinese Renewable Energy Industries Association (CREIA) published a statement, the main points of which were as follows:

I. To actively expand the PV energy market is still the universal understanding, and the PV energy market is continuing its growth.

II. It is a law of market economy that certain companies and technologies will lag behind and be eliminated from the market.

III. Chinese PV companies are globalized, making great contributions to the development of the global PV industry.

IV. The development of the Chinese PV industry has driven the development of the US PV industry and promoted employment in the US

V. Launching the Investigations will harm US public interest and global welfare.

VI. We hope the Chinese and US companies could be open with each other and cooperate; we request the US Government consider not to initiate the Investigation petition.

November 8

The CASM advised that it had welcomed 75 additional employers, who had officially registered their support for the group. Additionally, CASM announced that it has gained the support of the largest union in the US – the United Steelworkers (USW), which boasts over 850,000 active members.

Leo Gerard, international president of the United Steelworkers, said, "Unfortunately, China continues to operate in a manner that is utterly inconsistent with its WTO obligations, which comes at the expense of developing our nation's clean energy sector and creating and sustaining clean energy jobs for American workers. We urge you to vigorously apply and enforce our trade laws in these solar cases so that American workers and domestic industries can have a fair chance to compete in the US market."

"Manufacturing is the fuel that drives our economic engine," said Gordon Brinser, US president of SolarWorld, the spokesman of CASM and the named petitioner in the case. "Members of the Steelworkers Union understand that the key to American economic growth is healthy competition. Their support for US trade actions that keep quality, high-paying jobs in America and allow American companies to compete fairly in the global marketplace is greatly appreciated."

November 8

In response to the petitions by CASM, a competing group was set up. Representing 25 organizations and more than 9,200 jobs in the US solar industry, Jigar Shah, head of the Carbon War Room and founder of Sun Edison, created the Coalition for Affordable Solar Energy (CASE) to defend the solar industry competition and growth in the US and globally.

According to CASE, "Global competition is making affordable solar energy a reality in America and around the world. SolarWorld's action to block or dramatically curtail solar cell imports from China places that goal at risk. Protectionism harms the future of solar energy in America and negatively impacts consumers, ratepayers and over 100,000 American solar jobs. The coalition is committed to growing a domestic solar industry, promoting innovation, and making solar an affordable option for all Americans."

Shah added, "There's been overwhelming opposition throughout the US solar industry to SolarWorld's short-sighted trade petition."

November 9

The US DoC announced it would initiate an intensive, year-long investigation into whether Chinese imports are threatening the American solar industry and plans to release its preliminary findings early next year.

Gordon Brinser commented, "We are pleased that the facts have begun to speak for themselves. China's plans for the US market have been clear from its excessive and illegal subsidization of its export-heavy industry, its ever-escalating drive to dump product at artificially low prices on the US marketplace and its contrived public-affairs tactics, including a new coalition for Chinese importers that purports to serve the interests of American consumers."

November 12-13

APEC Leaders' Meeting – Hawaii

President Barack Obama hosted this year's Asia-Pacific Economic Cooperation in Hawaii, and told reporters, "We're going to continue to be firm that China operates by the same rules as everyone else. We don't want them taking advantage of the United States."

Chinese President Hu Jintao responded, "China's foreign exchange policy is a responsible one." He said China will "continue reforming its exchange rate mechanism", stating that America's trade deficit and unemployment are not caused by the Yuan exchange rate and that a large appreciation in the currency would not solve US problems.

November 16

The CASE calls for peace. Founder Jigar Shah said, "Let's put an end to this. There are no winners in a trade war. Every day we fight amongst ourselves, we lose credibility. The only people slapping hands right now are solar industry critics.

"A US – China solar trade war could obstruct global solar trade and negatively impact many US exporters of solar products," added Shah.

In reply, the CASM has asked the CASE why it is "defending China's anti-competitive, unsustainable trade aggression?" The CASE is yet to offer an official response.

And now we wait for the International Trade Commission to reach its decision next year.

All information contained within this feature is taken from the PV-Tech.org website and is correct at time of press.

Nilima Choudhury is web and publications editor for *Photovoltaics International* journal and PV-Tech.org.

PV LEGAL: Reducing bureaucratic barriers is key to successful deployment of PV in the EU

Marie Latour, European Photovoltaic Industry Association (EPIA), Brussels, Belgium

ABSTRACT
The benefits of solar photovoltaic (PV) power are well known, and, as this awareness rises and the cost of generating PV electricity declines, the technology is becoming more competitive with conventional electricity sources in market segments all across Europe. But bureaucratic hurdles remain a persistent threat to the widespread installation and integration of PV, often making it difficult to take advantage of the technology. In many countries, administrative processes and permitting procedures still require significant improvement. As a result, planning and connecting a solar photovoltaic system to the grid can still take several years in Europe.

Introduction

PV LEGAL is a European project that aims to identify and reduce administrative obstacles to the planning and installation of photovoltaic (PV) systems. Supported by the European Commission in the Intelligent Energy Europe programme, PV LEGAL involves 13 national PV industry associations, the European Photovoltaic Industry Association (EPIA) and the consultancy eclareon GmbH. The project is being coordinated by the German Solar Industry Association, BSW-Solar.

The project's first phase created an extensive database in order to identify bureaucratic barriers for project developers in the selected countries, with information for the three main market segments: small PV systems on residential buildings (Segment A), medium-sized PV systems on commercial buildings (Segment B) and ground-mounted PV systems (Segment C). For each of these segments, the steps leading to the commissioning of PV systems have been identified and described in detail [1], with information pertaining to duration, waiting periods and legal/administrative costs of the processes (Fig. 2).

There are many examples of administrative delays at the national level. For example, in France the average time between the start of a project and the first kWh injected into the grid ranges from 39 weeks for residential installations to 220 weeks for ground installations (Fig. 3). A European comparison conducted by the PV LEGAL consortium reveals that France is one of the countries in which the time required to fulfil administrative obligations is longest. And in the UK, for certain large-scale projects, planning permission enquiries and grid connection permits can involve a total waiting time of up to 22 weeks, i.e. 5½ months.

Recommendations

As a next step the project partners have developed recommendations for cutting red tape that are tailor-made for each participating country. For countries not participating in the project, a new PV LEGAL publication [2] clusters the main barriers identified and presents solutions to overcome them. Those recommendations are grouped into four main categories: 1) permitting procedures; 2) grid connection rules and technical standards; 3) grid connection procedures; and 4) grid capacity issues.

1. Permitting procedures

Administrative permitting procedures are often the most difficult obstacles to be overcome by a PV developer. These procedures may involve obtaining building permits, grid connection licences, environmental impact assessments, electricity production licences, and the like. The recommendations below aim at streamlining and harmonizing the PV permitting procedures in the spirit of article 13 of the European renewable energy sources (RES) directive.

> "Administrative permitting procedures are often the most difficult obstacles to be overcome by a PV developer."

a) Lean and appropriate permitting procedures: permitting procedures should reflect the decentralized nature of PV.

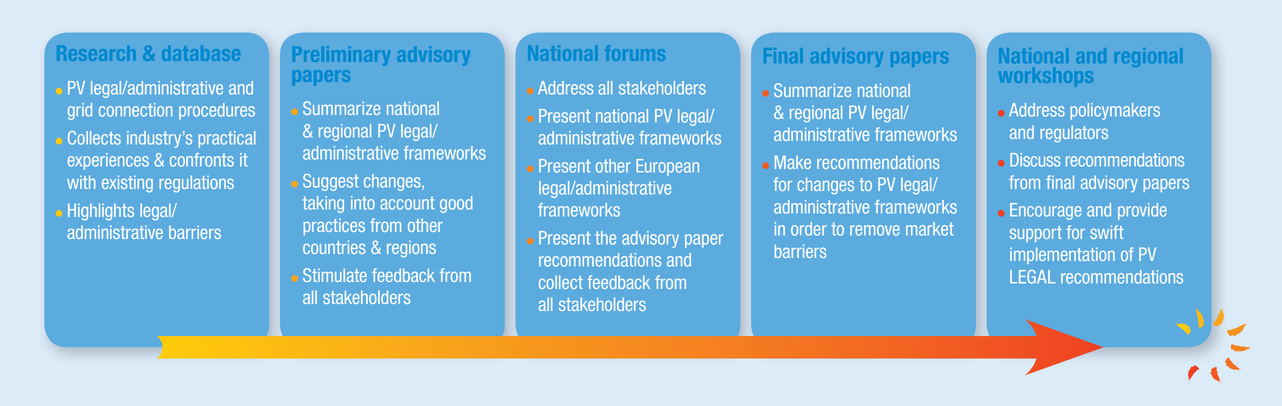


Figure 1. PV LEGAL steps towards removing bureaucratic barriers for PV system installations.

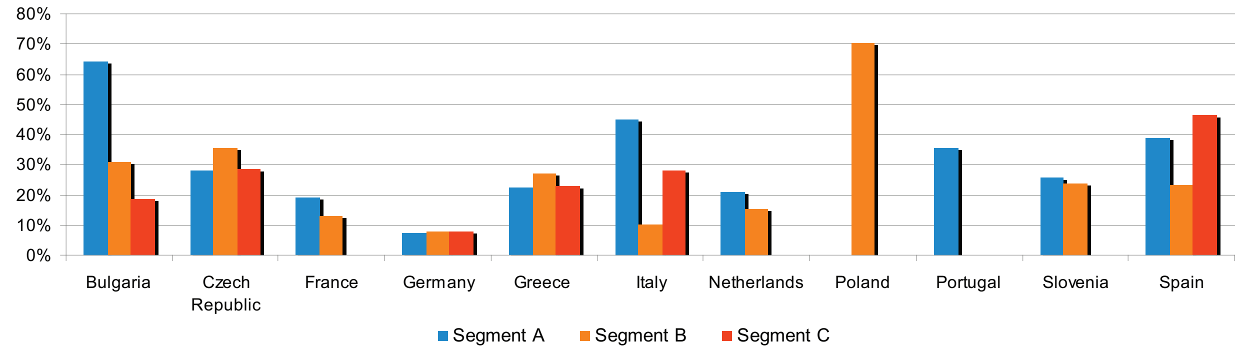


Figure 2. Legal/administrative costs as a share of overall project development costs (excluding PV equipment).

That means setting streamlined and lean procedures that reduce the burden on planners and administrations. Permitting procedures applicable to large conventional power plants do not reflect the simple, decentralized nature of PV technology and should therefore be altered. In addition, permitting authorities should not be allowed too much discretionary authority in the administrative process, since otherwise procedures become less clear and the outcome less predictable. An example of good practice in this field is the introduction of so-called 'bound decisions' in Germany: in the authorization process the administration has no discretionary power. If the requirements for the permission defined by law are fulfilled, the permit authority has no choice but to grant the permission. In case of rejection, the German judicial system provides for a broad range of legal remedies and independent courts.

b) One-stop shop for all permission procedures: the number of public departments/staff involved in PV permitting should be kept to a minimum. With a one-stop shop approach – such as the one that has been implemented in Greece for residential PV – administrative burdens can be lifted from the project planner as well as from the administration. In Portugal all permitting procedures are handled online and taken care of by one authority.

c) Definition of deadlines: deadlines should be defined for authorities to deal with permitting requests. Whenever deadlines are not met, a legal entitlement for PV system operators should be enforced that allows for the reimbursement of potential damages suffered due to the delay. The penalties should be more than symbolic: they should be strong enough to compensate for a missed feed-in tariff degression step, for example.

d) Guidance for planning authorities: clear and consistent guidance for planning officers should be made available to enforce a uniform approach to permitting. Planning authorities should clearly and uniformly define the permits needed. Training/workshops should be organized for local authorities, and support should be granted for municipal agents in charge of permitting. This could avoid diverging interpretations of building regulations by regional authorities, as installers of domestic solar PV systems are experiencing in the UK.

e) Waive building permits for rooftop PV systems: rooftop PV systems, at the least, should be exempted from building permissions, to allow for a burden-free development of this market segment. The exemption should be defined by the law and should cover all types of rooftop PV systems. A simple notification of the system to the planning authority (as required by the RES directive) should be sufficient. In Germany, for example, even this requirement is waived – only a notification to the Federal Network Agency for statistical purposes is requested.

f) Spatial planning should not prevent PV development: in some countries spatial planning provisions can prevent PV systems from being built. Spatial planning provisions should therefore not discriminate explicitly against PV. Instead, spatial planning should foresee the priority of RES over conventional energy sources.

g) Permitting fees: fees should not be charged by authorities for permitting procedures since permitting procedures can be tailored to the needs of PV and administrative efforts can be significantly reduced. However, if fees need to be collected (e.g. for larger projects), they must be transparent and proportionate. Regional differences should be avoided, as is the case in Spain, to allow for more planning certainty, and the fee structure should be published and accessible on the Internet.

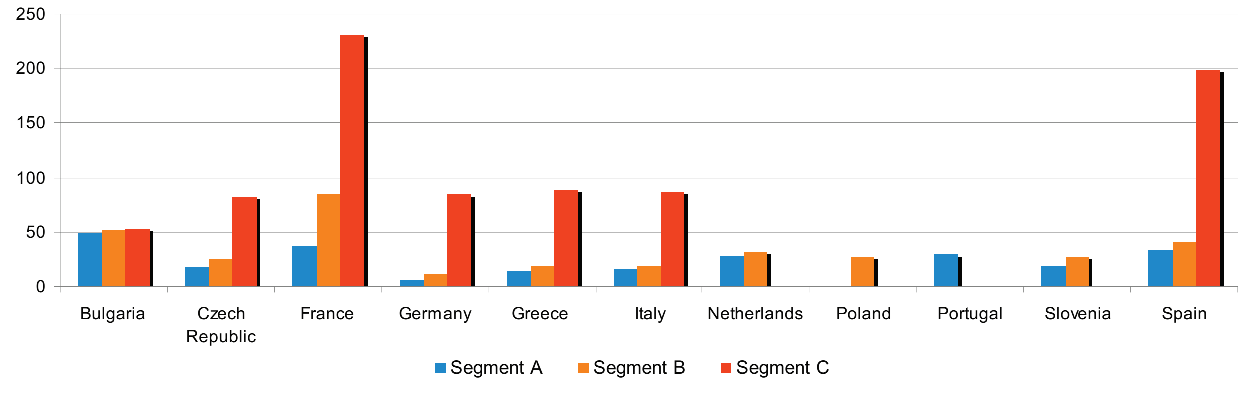


Figure 3. PV project development process: overall duration in weeks.

2. Grid connection rules and technical standards

In order to be allowed to connect to the electricity distribution or transmission grid, PV systems must meet certain criteria defined by grid operators and electricity market regulators. Often these criteria do not take into account the characteristics of PV systems and thus represent a barrier to their penetration. The recommendations below aim at involving the PV sector in the discussion on technical standards and at harmonizing rules at national levels.

a) Involve the PV industry in defining technical standards: as PV technology becomes a significant factor in the energy supply system, it will be crucial to involve the PV industry in defining technical standards. Industry know-how is necessary when revising grid codes or setting up grid connection rules to accommodate the needs of distributed energy generation technologies. This input will ensure the safe operation of the grid and should be required by national energy law. The case of Portugal, where the PV industry was not consulted when the regulation for the connection of production and consumption meters changed, reflects the kind of barrier that can occur when there is no consultation with involved parties prior to the decision. This adaptation of the technical scheme resulted in higher costs for system owners.

b) Define clear technical standards and grid connection rules at the national level: technical standards and grid connection rules should reflect the features and requirements of PV technology. Standards and rules should be clear, specific and uniform, and ideally be developed at a national level to avoid regional peculiarities that hinder broad PV penetration. Distribution system operators (DSOs) should be involved as well as all energy generation stakeholders. Further, all steps needed for the connection of a PV system to the grid should be clearly described. Ideally, PV system planners should be legally entitled to a connection study and all relevant information needed to plan for connecting the PV system to the grid.

c) Technical standards and grid connection rules defined at the national level should be binding and exclusive: to ensure transparency, good grid access and low PV system installation costs, grid connection rules defined at the national level should be binding and not subject to stricter definition by individual DSOs. Guidelines for DSOs on how to harmonize procedures – such as the ones used in Slovenia – should be created. A uniform template grid connection application form should be used by all DSOs, as is done in the UK.

> "Standards and rules should be clear, specific and uniform, and ideally be developed at a national level to avoid regional peculiarities that hinder broad PV penetration."

d) Set up an independent mediation office to efficiently resolve conflicts between parties: an independent mediation office (based on the example of the Clearingstelle EEG in Germany) could be helpful in resolving conflicts between parties without bureaucratic delays. The independence of such a body must be ensured.

3. Grid connection procedures

Connection to the grid is often the last and decisive step in the development of a PV system. While some Member States do not yet even recognize the need for RES systems to have priority grid access, in most countries these processes are often plagued by severe delays that have a significant impact on the economic returns of PV systems. The recommendations below aim at enhancing the transparency and efficiency of grid connection procedures in the spirit of article 16 of the European RES directive.

a) Member States should provide for priority access of renewable energy systems to the grid: in the spirit of the EU directive for the promotion of RES it is crucial to ensure that PV systems are connected to the grid as a priority. This is foreseen in Italy, for example, while in some other countries the lack of provisions hampers PV grid connection procedures.

b) Streamline grid connection procedures: lengthy and complicated grid connection procedures can significantly slow down or even prevent the installation of PV systems. The following recommendations should be adopted:

- Limit paperwork so that the DSO's requirements on the PV system operator are proportionate. In some of the researched countries, up to seven communication steps with the DSO are necessary in order to connect a PV system.

- Implement simpler procedures for small systems to allow for swift and non-bureaucratic installations in the residential rooftop segment (e.g. by defining the connection point of the house by default as the appropriate connection point for the PV system).

- Introduce one-stop shop procedures that reduce the number of people involved in the grid connection process (only one interlocutor on the DSO side).

- Introduce online procedures that have proved to be effective in some countries and allow for swift processes when dealing with the DSO. For instance, in France the main DSO (ERDF) has set up a website via which the system developer can follow the status of the grid connection process for projects under 36kVA.

c) Define deadlines for the allocation of the grid connection point: the allocation of a grid connection point (alternatively: the connection of the PV system) should be undertaken by the DSO as soon as possible, but not later than six weeks after a connection request has been made.

d) Define legal penalties for not respecting deadlines: in cases where time limits for the allocation of a connection point are not kept, a legal entitlement for PV system operators should be enforced, allowing for the reimbursement of the potential expenses incurred as a result of the delay. The penalties should be appropriate to compensate for missed feed-in tariff revenues and not just be of a symbolic nature.

e) Grid connection costs should be appropriate: grid connection costs charged to the PV system operator must be proportionate, transparent, standardized and regulated. Information about the costs should be made publicly available and monitored by an independent body (e.g. the electricity market regulator).

> "Grid connection costs charged to the PV system operator must be proportionate, transparent, standardized and regulated."

f) PV grid connection training and connection by installers: the RES directive foresees the implementation by Member States of training schemes for renewable energy installers. Such training schemes should include PV grid connection modules. As is the case in Germany, installers trained in these national schemes, if listed by the DSO, could then be allowed to connect PV systems. In some countries, only the DSOs are allowed to connect PV systems to the grid. At least for residential rooftop systems the PV installer should be empowered to make the connection.

4. Grid capacity issues

The exceptional growth of PV installations in several European countries in recent years represents a challenge to Europe's distribution and transmission grid infrastructure. Unfortunately, in some cases this challenge has become a reason to curtail or totally block the installation of further PV and RES capacity. The recommendations below aim at addressing, in a reasonable manner, the issues deriving from increased penetration of the grid infrastructure by PV and RES generators.

a) Grid analysis and regional grid concepts: an independent body (e.g. the electricity market regulator) should evaluate the grid infrastructure status, especially in the case of grid operators refusing to connect further PV and RES capacity because of grid saturation. This is the only way to allow for an unbiased and objective assessment of the state of the grid. Such a study should evaluate costs, benefits and the potential for grid extension and improvements. At the same time (and building on ambitious RES targets for regions), strategic grid concepts taking into account the future load curves and other regional specifics should be developed by the DSOs in cooperation with the RES sector. The current moratorium in the Czech Republic and in some regions of Greece reflects a lack of thorough analysis of the grid potential. In these areas no more PV is being connected because of apparent hosting capacity limits.

b) No generic limits for PV: in all cases, fixed limits imposed on the connection of PV in certain areas or to a connection point should be avoided. For instance, in Spain it is not possible to install a PV capacity in excess of 50% of the transmission line's thermal capacity. Instead, capacity issues eventually should be evaluated on a case-by-case basis.

c) Public availability of grid data: information should be publicly available (e.g. on the websites of the grid operators) on the grid status, grid capacity availability, generation capacity, PV installations connected to the grid, and grid permits granted. This will give PV developers adequate planning information. In France grid information is published quarterly by the DSO; however, this information is not detailed enough. Since March 2011 the DSO must communicate to the government a detailed list of new projects on the waiting list during each quarter.

d) Legal provision on grid extension and cost: in order to avoid PV system grid connection refusals, the energy law should clearly define the conditions under which grid operators must extend the grid to accommodate more RES generation capacity. At the same time, the law should specify who must bear the grid extension and improvement costs. One way would be to require that the grid be extended if reasonable from a macroeconomic perspective. The cost for the development of the grid could be collected by the DSO via grid charges and passed on to the electricity consumers.

e) Clear deadlines for grid extension: deadlines for grid extension should be set so that grids can generally accommodate large amounts of PV and renewable generation capacity. In the case of Slovenia, this obligation for extending the grid exists but can significantly delay the procedure since 5 to 10 years' planning is necessary.

> "Sufficient grid capacity to connect PV systems should be ensured so that licences are not a scarce commodity traded for profit on a secondary market."

f) Prevent grid connection speculation: sufficient grid capacity to connect PV systems should be ensured so that licences are not a scarce commodity traded for profit on a secondary market. In countries with regulatory frameworks that provide for the reservation of grid capacities when developing PV systems, those reservations should be issued only for specific projects. Milestones should be established according to which a continuous development process can be tracked. Reservations should be issued for a limited time – with a validity period sufficient to realize the PV system but not overly long. France, for example, has recently set up a mechanism that requires PV developers to prove the seriousness of their intentions; however, this process is sometimes so complex that it becomes impossible for small installers to develop a system.

Conclusion

The European Union's directive for the promotion of renewable energies (Directive 2009/28/EC) sets binding renewable energy targets to be achieved by 2020 for each Member State; it includes stronger provisions for the reduction and simplification of administrative barriers and access to the grid for renewable energy systems. That means, among other things, that Member States should take steps to simplify rules and authorization procedures for setting up PV systems, and encourage distribution system operators to remove barriers to PV grid connection. Only by removing these barriers and reducing administrative burdens can Europe achieve its renewable energy goals.

References

[1] PV LEGAL database [available online at http://www.pvlegal.eu/database.html].

[2] PV LEGAL 2011, "Key recommendations for reduction of bureaucratic barriers for successful PV deployment in the EU" [available online at http://www.pvlegal.eu/en/results/key-recommendations.html].

About the Author

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100GW of commodity PV

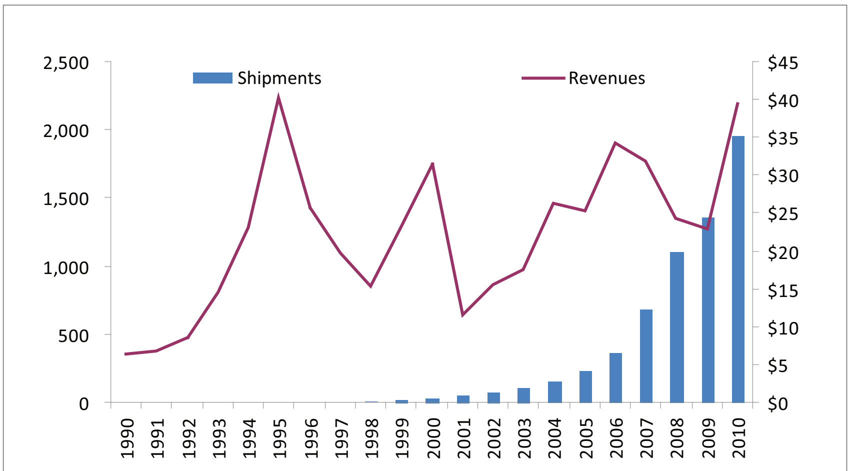
Alfonso Velosa, Gartner, Tucson, Arizona, USA

ABSTRACT

The PV industry stands on the verge of an enormous achievement – an installed base of PV plants with 100GW of energy generation capability. This milestone has come about because of the contributions of a fully global industry that has blossomed in the past decade. Yet even though the PV industry traces its heritage to before the space programme, as with any dynamically growing industry most industry members have joined in the past five years. And each generation often makes the same mistakes that a previous generation made. Sometimes the same people move from one industry to another and repeat the same mistakes there. The PV industry is rediscovering ultra-competitive market dynamics that have previously been seen in other high-technology commodity markets. This paper begins with a discussion of one such market – the dynamic random access memory (DRAM) industry – and then looks at the current PV market and the industry outlook.

Volatility and consolidation in the DRAM market

The DRAM market serves as a history lesson whose key points apply very well to the PV market. A large number of companies invested in the development of a technologically complex memory chip that was a core contributor to the computer industry. Yet despite that core contribution, the DRAM industry has suffered severe volatility. Fig. 1 shows the revenue and shipments on a megabyte basis for the past 20 years.



Source: Gartner (November 2011)

Figure 1. Global DRAM shipments (megabyte billion) and revenues (US$ billion).

> "The PV industry is rediscovering ultra-competitive market dynamics that have previously been seen in other high-technology commodity markets."

The DRAM industry experienced several major periods of volatility and turmoil. Prices have been severely affected by this turmoil (sound familiar in the PV market?) as well as by continued technology development. The list of firms exiting the market was a 'who's who' of the technology arena, ranging from Intel and IBM to NEC and Mitsubishi. The characteristics of the winners may be familiar – they have the ability to invest in manufacturing capacity and market development in a downturn, possess a good technology base and excel at high-volume manufacturing.

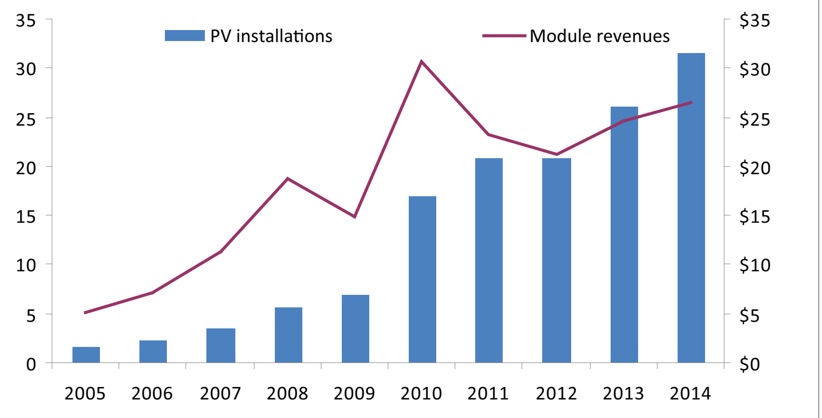
These elements are useful in considering the dynamics of the current PV market, starting with demand, pricing, the competitive landscape and the implications for the market.

100GW of installed PV by 2013

Fig. 2 highlights the amazing run that the industry has had so far. Worldwide, installations are approaching a cumulative installed base of 60GW of energy generation capability by the end of 2011, facilitated by huge step functions in demand in 2008 and 2010.

What is even more impressive is that there is the potential to reach 100GW of installed systems by 2013. Even in the exuberant 2008 market, a high probability would not have been assigned to reaching this milestone so soon, given pricing and financing trends.

As a caveat to any discussion on a PV industry forecast, it should be remembered that 12 months in the PV industry often resembles 3 to 5 years in other industries, so PV forecasts have bigger error bars than other markets. Looking at global



Source: Gartner (November 2011)

Figure 2. Global PV installations (GW) and module revenues (US$ billion).

PV markets, Gartner forecasts PV panel installations will reach 34GW in 2014, in the most likely scenario. This represents a compound annual growth rate (CAGR) of 16% from 2010 to 2014. This growth rate reflects the scale reached by the market, particularly the widespread adoption of PV around the world. But like all good things, as adoption has grown, growth rate has slowed down, particularly given the historic CAGR of 66% from 2006 to 2010.

Fig. 2 also highlights the fact that the PV market has had one of the shortest industry cycles possible. Its revenue recovered from the down cycle of late 2008 and early 2009 to reach another record high in 2010, and then got hit by demand and price uncertainty again in 2011. Revenue for the PV panels from installations is forecast to contract by a compound annual rate of 4% through 2014 to $26 billion.

Yet given the steep fluctuations seen in demand, it is worth discussing this forecast from the perspective of two sets of core building-block assumption areas. The insights that these provide will help in understanding the numbers in the most likely scenario.

Shift of PV demand's centre of gravity

PV demand remains dependent on government incentives. While European economies were strong and the PV market relatively small, governments provided generous incentives to meet their altruistic commitments. Investors funded these PV plants to reap attractive rates of return, creating a boom in the market.

> "PV demand remains dependent on government incentives."

But the macroeconomic uncertainty of the past 3 years has taken a strong toll on these incentives, with some governments, such as Spain, gutting their incentive programmes. Fortunately, other governments limited their reductions or set more predictable schedules. This, combined with falling PV project costs, enabled investors to find attractive returns, even as risk premiums fluctuated during the most recent set of macroeconomic crises. Fig. 3 illustrates Gartner's view of the attractive national markets.

Germany remains an attractive market for PV and has established streamlined processes and procedures for PV project construction, permitting and interconnection. The country has a strong commitment to renewable energy resources: with its stated goal of reducing nuclear energy plants, PV is an attractive option. The German government has instituted stepped reductions in its incentives programme, including its most recent announcement of a 15% reduction in January 2012. Gartner's view of PV price points (see the next section) indicates PV will remain an attractive market for investors and developers. Note that, given its large installed base of PV systems, time of use and time of supply are increasingly important factors in Germany, especially given weather-based fluctuations. The incentive programmes there will increasingly take account of either back-up fossil fuel generation plants or storage technologies.

Data about installations in Italy indicate it will be the largest market in 2011 for PV plant activations and connections to the electric grid, although almost half of these may have been built last year but not connected until this year. However, this magnitude of installations is not expected to be sustainable given development complexity in Italy and uncertainty about its incentives.

Finally, the US, Japan and China form very attractive growth markets, driven by government incentives and/or price considerations. Japan's energy crisis after the tsunami led the government to institute increased support for PV systems. This favours domestic Japanese PV firms in an extremely competitive market. The US continues to have a mix of incentives for PV systems, although the tax grant programme is unlikely to be renewed in this political environment. However, US

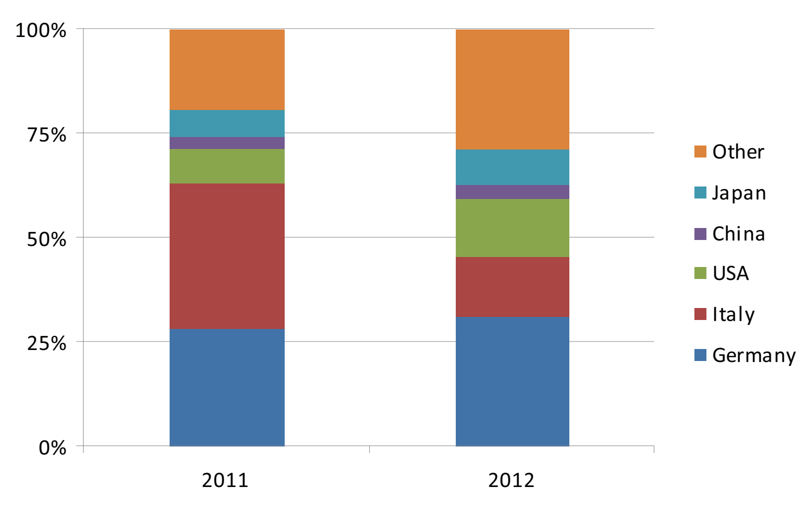


Figure 3. PV installations by country (% based on GW forecast).

Source: Gartner (November 2011)

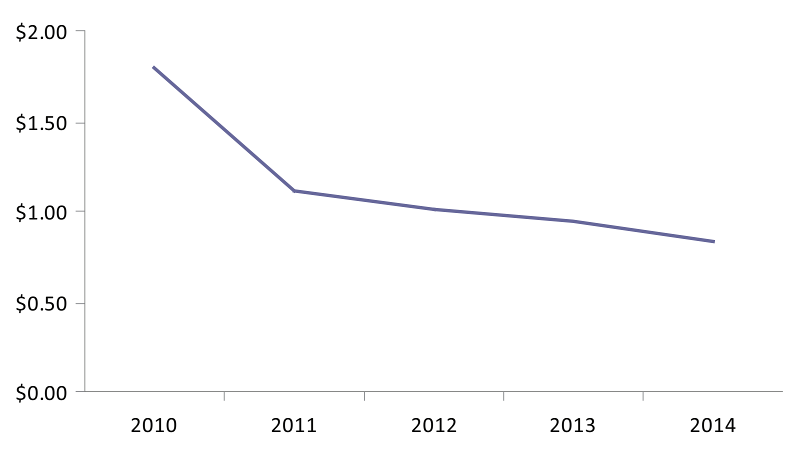


Figure 4. Average selling price of PV modules (US$/W).

Source: Gartner (November 2011)

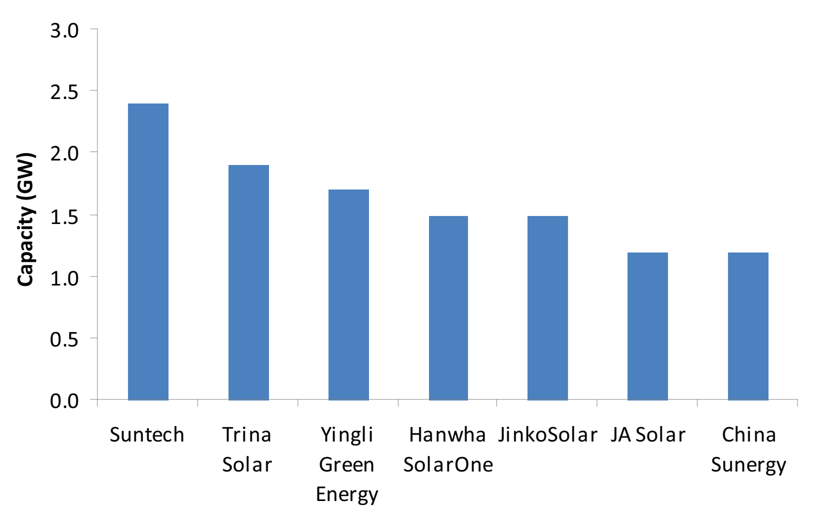


Figure 5. Planned module manufacturing capacity of key Chinese PV firms to end of 2011.

Source: Company reports (September 2011)

utilities are increasingly commissioning PV power plants or signing power purchase agreements (PPA) from PV plants, driven by their public utility commission requirements. Note that the prices for these PPA contracts are extremely aggressive, with 1–2MW projects at $120 per MWh plus an additional time of use price supplement and large projects at much less.

China rounds out the list of attractive markets. As part of China's 12th Five-Year Plan, support for PV was announced, with a target of 20GW by 2020. China will need to invest the next couple of years in developing the processes and procedures for site identification, financing, permitting and grid interconnection. Therefore Chinese domestic demand will continue to ramp up for the next two years as it develops its processes. However, its long-term potential does make China a very attractive opportunity for PV value-chain members.

The fundamental assumption here then remains that the price relationship to existing or stepped-down government incentives is good enough to incentivize investors to build more power plants. This leads to the next topic – price.

Downward pressure on PV system prices

The dynamics of the revenue contraction presented in Fig. 2 are reflected in the price trends for PV modules as shown in Fig. 4. The 2011 revenue contraction in particular reflects the hangover in current module pricing, with current lows of $1.00 to $0.85 per watt for very large utility-scale installations. These October pricing levels are spurring demand as investors work to ensure that they lock in 2011 incentives, either from FiTs in Europe or from the US tax grants. Unfortunately, the market volatility that has driven price cuts will remain in 2012, with continued uncertainty in government incentives and inventory levels, and macroeconomic levels still being a factor in investor confidence.

Yet just like the bankruptcies and consolidation in the DRAM industry, the bankruptcies of Solyndra, SpectraWatt and Evergreen highlight the fact that pricing is affecting PV companies that are unable to reduce their price structures. And note that there are an unknown number of tier 3 Chinese PV firms that either have gone bankrupt or are desperately searching for financing. The good news is that it is unlikely that the 2011 price decline rates will be replicated in 2012, given current industry cost structures, but competition and lower government incentives will continue to have an impact on pricing.

The top-tier companies can be expected to maintain their price competitiveness by increasing their investments and focusing on:

- Economies of scale
- Technological R&D
- Flexible cost models
- Access to capital

A crowded, competitive PV module field

Yet given these statements on price competitiveness, there continues to be an excess of manufacturing capacity relative to projected demand. The difference covers the entire spectrum of the PV value chain, starting on the silicon side and going through the module side. This reflects the nature of business investments that have been made during the recent market peaks and partly reflects the industry's use of low-cost government funding or incentives for manufacturing capacity.

It is particularly instructive to look at the Chinese volume leaders. Fig. 5 highlights the scale of the manufacturing capacity of key Chinese firms. Few other firms apart from Sharp and First Solar can match the scale of the Chinese firms or have the ability to access low-cost financing sources. This will be a critical influencing factor in making the scale, R&D and cost control investments that will determine competitiveness in the industry.

With a large number of smaller firms competing in this market, the previously discussed characteristics of the winners remain critical. They have the ability to invest in manufacturing capacity and market development in a downturn; they have access to low-cost capital; they have a good technology base; and they excel at high-volume manufacturing. In particular, the larger players will be able to invest in the necessary R&D to improve their products at price points beyond what the competition can match.

Conclusion - a stabilizing commodity module market

The PV module market has reached enormous heights, with 100GW of installed systems just around the corner. However, it also appears to be entering a low-price, low-margin phase, where few of the module vendors will have significant profitability under current business models and pricing. The large vendors who have the capacity and technology will consolidate their power in this market, as has been the case in other markets. A wave of consolidation will probably be seen as the normal slow seasonality of the first half of 2012 combines with these low-price points and margins to hit the weakest players in the market.

This does mean, however, that a market in which there will be attractive work with and around PV is on the horizon. Project development will be a growth market, as electricity from large PV generation plants is reaching a price point that brings them close to being competitive with other generation plants. First Solar, SunPower and Sharp have made aggressive moves in this direction, and traditional energy firms, from EDF to NextEra Resources, are making more and more aggressive investments in this arena.

The excitement of the module industry's growth phase has waned a bit, but continued investments are expected in technology that improves module efficiency and lifetime quality. Nevertheless, just as PCs, servers and other markets innovated and leveraged DRAM price trends, a significant energy and excitement exists in the end markets that use PV modules. Project development, consulting and financing will be poised to grow significantly, as will complementary markets such as energy storage.

About the Author

Alfonso Velosa is a research director with the semiconductor team at Gartner. In this role, he focuses on sustainability topics such as photovoltaic systems and smart cities.

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By **Tom Cheyney**

Solar PV progress shows there's more to BYD than battery storage, electric cars, as company hits 1GW capacity, dials in selective emitter technology

While BYD's Solar Power International exhibit-hall booth might have been modest in size and the company's reputation may not be as well-established as its Chinese PV industry counterparts, there are few enterprises that can match the scope of its vertically integrated and potentially synergistic business platform in the renewable and cleantech space. Building around what it calls "three green dreams" – solar power, energy storage, and electric vehicles (with some solid state lighting thrown in for good measure) – the Shenzhen-based, Berkshire Hathaway-backed, US$7 billion company recently opened its new North American HQ near downtown Los Angeles and signed a deal to provide EV shuttle buses and cars to rental giant Hertz.

At SPI though, the emphasis was on BYD's solar division, a group that has quietly built up more than a gigawatt in crystalline-silicon wafer and cell production capacity and 800MW of module manufacturing capability since 2008.

Like many other c-Si cellmakers, BYD is working diligently on a selective emitter solution, in an effort to drive efficiencies higher without adding cost. The acronym for its own SE technology flavor is NES, which stands for "narrow finger and busbar electroplated selective emitter," according to the company's solar unit general manager, Tom Zhao.

The former Motorola man said during BYD's press conference that median efficiencies on 156mm polycrystalline production cells had reached 17.4%, close to the midway point on a tight distribution curve between 16.9% and 18%. By next year, the roadmap calls for the average numbers to reach 17.6% and 18% in Q2 and Q4, respectively.

A check of the product specs on the firm's Series-3BB modules, which incorporate the NES cells, shows top panel efficiencies of 15.6% on the P6-30 255Wp models and 15.46% on the higher-rated, P6-36 300Wp devices.

Zhao noted that the aforementioned "narrow finger and busbar" reduce shading area on surface of the cell, allowing more active area and absorption of incident light and thus increased current. Stating that the finger width on a standard cell would be in the 70–110µm range, the NES process shrinks that down to 40–80µm while also reducing the distance between the fingers. The normally 1.8–2.0mm-wide busbar gets trimmed down to 1.0–1.5mm via the enhanced processing procedures.

He described how the locally deep phosphorus doping level under the fingers and busbar facilitates lower Rs, and shallow phosphorus doping levels in the active emitter area produces lower surface recombination and higher IQE. There's also better short wavelength response in the cells (in the 300–400nm blue range of the spectrum).

The key process in the NES process, electroplating, reduces series resistance and improves finger conductivity. Unlike the Suntech EP approach, which uses copper, BYD's employs silver as the plating metal. When I asked Zhao if there was any thought to transitioning to a less expensive, more abundant element than silver, he said there were no plans to do so, noting the potential risk of peel-off with copper and general robustness of the material of choice.

He also pointed out another difference between the Suntech and BYD process schemes: his company uses a high-precision silk-screening step rather than the laser etch employed by the Wuxi firm, followed by a coating step to add the seed layer to the cell, which is then fired, resulting in a "conjunction" that is very strong.

Photo: Tom Cheyney

This produces "good narrowness" and shows fewer issues with shunting, the GM said.

Zhao said the production operations were highly automated, putting the percentage level at 90% for the module manufacturing lines. Among the process and quality control measures in place, he cited pervasive optical and inline inspection steps and microcrack control resulting in <2–3% damage in production and "zero cracks seen by customers." Electroluminescence tests are done in three locations on the module lines: postsolder, postlamination, and preflash test.

Although the wafer and cell capacity – including some newly added lines – exceeds a gigawatt and the moduling nameplate is close behind at 800MW, global module oversupply and the resulting demand hit have reached BYD's factory floors as well. Current run rates (mostly poly c-Si-based) are in the 40–50% range, he said, with efforts "to secure more demand" ongoing in China and elsewhere. A countervailing cost reduction point in BYD's favour: no long-term polysilicon contracts, allowing the company to benefit from record low spot-market prices.

One customer adding to the order books was announced at the SPI press event. Samba Energy, a US project development company, will soon deploy 1.2MW of BYD modules and inverters on school and commercial rooftops in the Northeast and Pacific regions, with another 10MW of product in the pipeline for Q1 2012 and more on the way in the future.

Zhao also briefly described an intriguing plan that BYD is working on with a Chinese utility, a hybrid power plant that would incorporate solar and possibly wind power generation coupled with large-scale energy storage, something he said would help make the output from the system "more predictable."

Given BYD's broad green product portfolio, such a project seems tailor-made for the company, with the initials standing for "build your dreams."

This column is a revised version of a blog that originally appeared on PV-Tech.org.

Tom Cheyney is senior editor, North America, for the *Photovoltaics International* journal and PV-Tech.