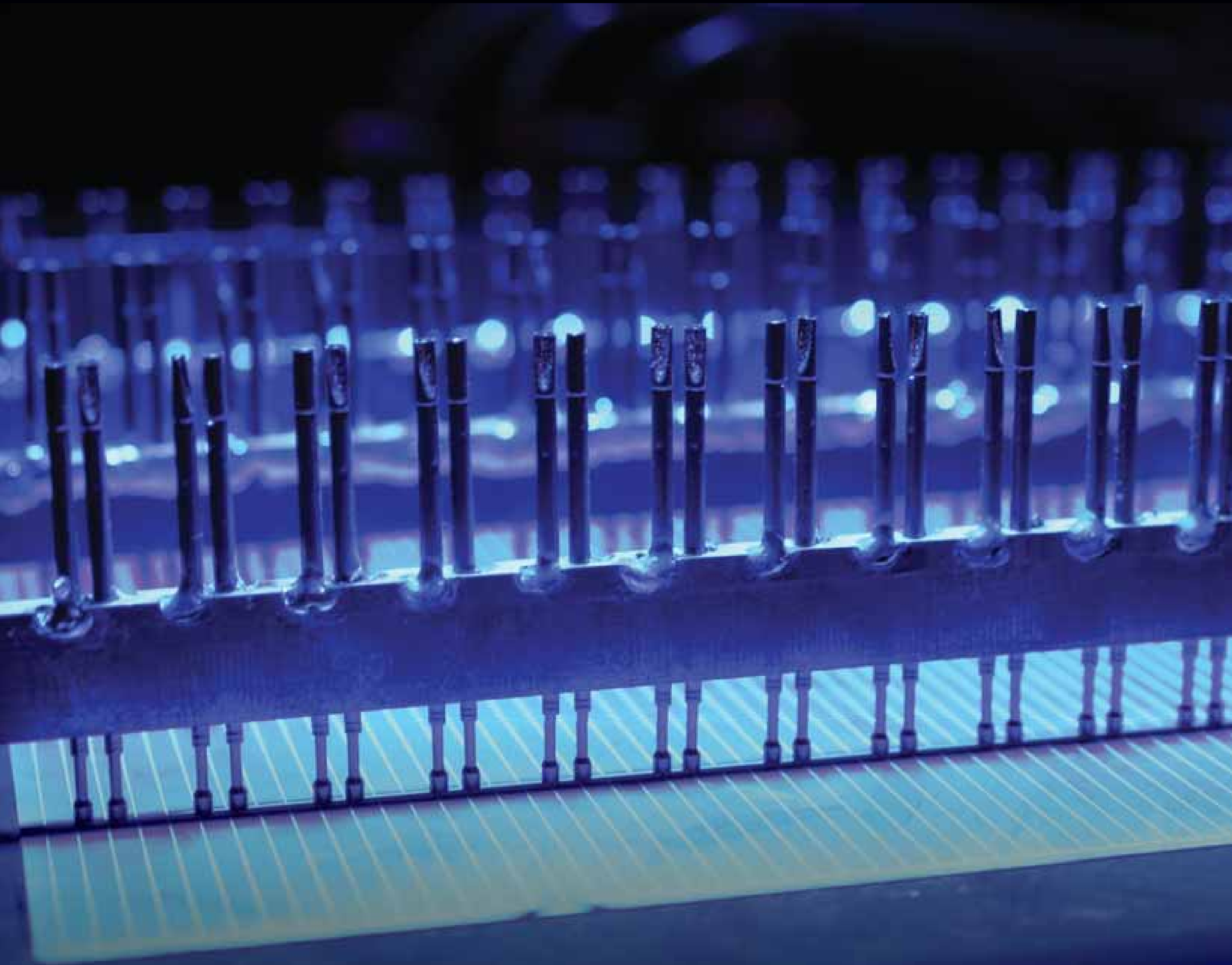
Thirty Second Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS



Fraunhofer CSP Multicrystalline PERC solar cells: Is light-induced degradation challenging the efficiency gain of rear passivation?

ISC Konstanz Back-contact technology: Will we need it in the future?

ECN LPCVD polysilicon passivating contacts for crystalline silicon solar cells

Fraunhofer ISE n-type multicrystalline silicon for high-efficiency solar cells

Solar Intelligence Solar PV technology trends for 2016

Second Quarter, May 2016

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Cover image: Fraunhofer CSP's rapid quantum efficiency measurement setup using a WAVELABS LED solar simulator.

Image courtesy of Fraunhofer CSP, Halle (Saale), Germany

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Foreword

Arguably the defining PV technology trend of the past year or so has been the steady adoption of PERC (passivated emitter rear cell) architecture. PERC's promise of higher efficiencies through upgraded – rather than entirely replaced – production lines has assured its position as the technology of choice for providing a quick boost to cell performances.

That trend was much in evidence at the inaugural PV CellTech event hosted by Solar Media in Kuala Lumpur in March. The conference was a first for the industry, bringing together leading figures from the worlds of PV research and manufacturing to discuss the technology trends shaping the industry both now and looking ahead to the next few years.

Inevitably, the impact of PERC was a key talking point. As our chief analyst, Finlay Colville, reports on p.104, with PERC on course to account for over 10% of all p-type c-Si production globally in 2016, the technology is now one of main drivers for the internal technology roadmaps of all silicon cell providers and is indirectly influencing the development of other technologies in competing n-type and thin-film segments.

Nevertheless, PERC is not without its drawbacks, and one of these is its increased susceptibility to light-induced degradation, particularly in the multi c-Si variant and at higher temperatures. On p.37, researchers from the Fraunhofer Center for Silicon Photovoltaics describe the process by which PERC cells can degrade under certain conditions. Their paper explores the science behind the degradation that multi-PERC cells can suffer and possible remedies to the issue, including advanced testing regimes to screen cells for LID.

Meanwhile, continuing the PERC theme in this issue, researchers from Fraunhofer ISE look at a new metallization technique for PERC cells (p.57). Their so-called 'FolMet' procedure uses regular aluminium foil as a metallization layer behind a PERC cell. Although at relatively early stages of development, the process has already been shown to offer significant cost-of-ownership advantages, potentially promising a new phase in the evolution of PERC technology.

Elsewhere in this issue we look to analyse the latest technology announcements from the First Solar stable (p.71). In recent years, First Solar has been supplying modules largely to its own projects – a model that has served it well during the recent downturn for module suppliers. But the company is now poised to reposition itself as a module supplier once again, and has announced a swathe of new products off the back of which to launch this campaign.

Other highlights from this issue include ISC Konstanz on the future of back-contact technology (p.79) and ECN on the development of a new technique for minimising recombination losses in silicon solar cells (p.45). And as always, we also bring you our regular report on the latest manufacturing capacity expansion plans being outlined across the industry (p.15).

The team from *Photovoltaics International* will be at the EU PVSEC and Intersolar Europe events in Munich in June. We hope to see you there.

John Parnell
Head of Content
Solar Media Ltd

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:

Prof Armin Aberle, CEO, Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS)

Prof Aberle's research focus is on photovoltaic materials, devices and modules. In the 1990s he established the Silicon Photovoltaics Department at the Institute for Solar Energy Research (ISFH) in Hamelin, Germany. He then worked for 10 years in Sydney, Australia as a professor of photovoltaics at the University of New South Wales (UNSW). In 2008 he joined NUS to establish SERIS (as Deputy CEO), with particular responsibility for the creation of a Silicon PV Department.

Dr. Markus Fischer, Director R&D Processes, Hanwha Q Cells

Dr. Fischer has more than 15 years' experience in the semiconductor and crystalline silicon photovoltaic industry. He joined Q Cells in 2007 after working in different engineering and management positions with Siemens, Infineon, Philips, and NXP. As Director R&D Processes he is responsible for the process and production equipment development of current and future c-Si solar cell concepts. Dr. Fischer received his Ph.D. in Electrical Engineering in 1997 from the University of Stuttgart. Since 2010 he has been a co-chairman of the SEMI International Technology Roadmap for Photovoltaic.

Dr. Thorsten Dullweber, R&D Group Leader at the Institute for Solar Energy Research Hamelin (ISFH)

Dr. Dullweber's research focuses on high efficiency industrial-type PERC silicon solar cells and ultra-fineline screen-printed Ag front contacts. His group has contributed many journal and conference publications as well as industry-wide recognized research results. Before joining ISFH in 2009, Dr. Dullweber worked for nine years in the microelectronics industry at Siemens AG and later Infineon Technologies AG. He received his Ph. D. in 2002 for research on Cu(In,Ga)Se2 thin-film solar cells.

Dr. Wei Shan, Chief Scientist, JA Solar

Dr. Wei Shan has been with JA Solar since 2008 and is currently the Chief Scientist and head of R&D. With more than 30 years' experience in R&D in a wider variety of semiconductor material systems and devices, he has published over 150 peer-reviewed journal articles and prestigious conference papers, as well as six book chapters.

Jim Zhu, Chief Scientist, Wuxi Suntech

Jim Zhu has bachelor and master's degrees from Fundan University and a Ph.D. from the Shanghai Institute of Technical Physics of the Chinese Academy of Sciences. In 2007 he joined Suntech as group VP with responsibility for customer service, quality management and R&D. He has been the company's Chief Scientist since 2013.

Florian Clement, Head of Group, MWT solar cells/printing technology, Fraunhofer ISE

Dr. Clement received his Ph.D in 2009 from the University of Freiburg. He studied physics at the Ludwigs-Maximilian-University of Munich and the University of Freiburg and obtained his diploma degree in 2005. His research is focused on the development, analysis and characterization of highly efficient, industrially feasible MWT solar cells with rear side passivation, so called HIP-MWT devices, and on new printing technologies for silicon solar cell processing.

Sam Hong, Chief Executive, Neo Solar Power

Dr. Hong has more than 30 years' experience in solar photovoltaic energy. He has served as the Research Division Director of Photovoltaic Solar Energy Division at the Industry Technology Research Institute (ITRI), and Vice President and Plant Director of Sinonar Amorphous Silicon Solar Cell Co., the first amorphous silicon manufacturer in Taiwan. Dr. Hong has published three books and 38 journal and international conference papers, and is a holder of seven patents. In 2011 he took office as Chairman of Taiwan Photovoltaic Industry Association.

Matt Campbell, Senior Director, Power Plant Products, SunPower

Matt Campbell has held a variety of business development and product management roles since joining the SunPower, including the development of the 1.5MW AC Oasis power plant platform, organized SunPower's power plant LCOE reduction programmes, and the acquisition of three power plant technology companies. Campbell helped form a joint venture in Inner Mongolia, China for power plant project development and manufacturing. He holds an MBA from the University of California at Berkeley and a BBA in Marketing, Finance, and Real Estate from the University of Wisconsin at Madison.

Ru Zhong Hou, Director of Product Center, ReneSola

Ru Zhong Hou joined ReneSola as R&D Senior Manager in 2010 before being appointed Director of R&D in 2012. Before joining ReneSola he was a researcher for Microvast Power Systems, a battery manufacturer. His work has been published in numerous scientific journals. He has a Ph.D. from the Institute of Materials Physics & Microstructures, Zhejiang University, China.

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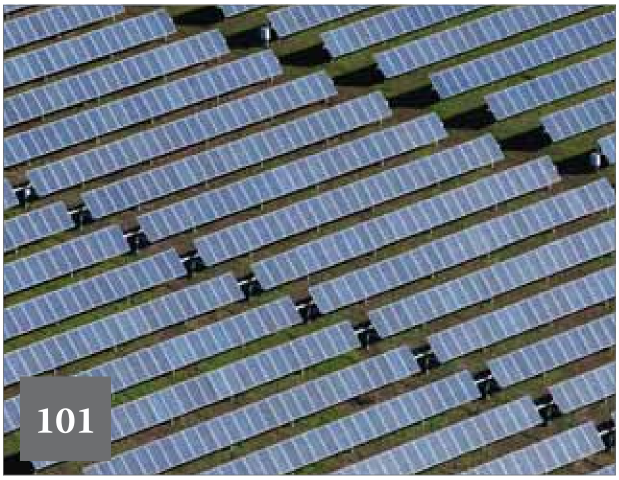


Product Reviews

Kyoshin Electric

Kyoshin Electric offers accurate high-efficiency solar cell IV measurements for production lines

Problem Outline: Kyoshin Electric Co (KOPEL) has introduced the KSX-3000H, a solar cell IV measurement system that can be used for a wide variety of high-efficiency solar cell architectures including PERC and heterojunction.

Problem: High-efficiency solar cells tend to have higher voltage (capacitance) than conventional cells, which can result in an extended time for the solar cell to respond to light and voltage at MPP (maximum power point), potentially leading to incorrect measurements. Cell testing in volume production is also increasing, requiring fast and accurate measurements inline.

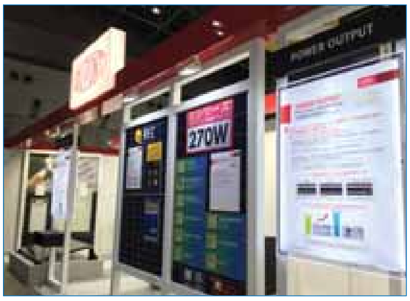
Solution: The KSX-3000H system consists of Class AAA+ solar simulator with better than 0.2% temporal instability, 10% spectral match and 1.5% spatial non-uniformity. It operates at high speed with accurate measurement and without any compensation. The system can keep the IV measurement time within one second including the data transmission. The throughput for measurement and selection can be as high as 3,600 cells/h (if the sorter speed allows).

Applications: The KSX-3000H can be used in R&D and volume production solar cell lines.

Platform: The KSX-3000H shares the same light source as the KSX-1000 but uses an improved IV measuring unit and software. It provides all the benefits of the KSX-1000, such as high measurement accuracy, low maintenance cost, and high throughput. A chiller unit and a vacuum pump are provided as options for more accurate measurement. The KSX-1000 can also be upgraded to the KSX-3000H simply by replacing the IV measuring unit and software.

Availability: Currently available.

DuPont



DuPont's 'Solamet' PV19B metallization paste uses proprietary tellurium technology

Product Outline: DuPont Photovoltaic Solutions' new 'Solamet' PV19B front-side metallization paste is claimed to offer superior efficiency gains over rivals and high print speeds for greater throughput.

Problem: To gain improved solar cell conversion efficiencies from front-sided cells, producers need to focus on the fabrication of higher contact aspect ratios with narrower lines with better edge definition and smoother morphology to increase surface area light absorption. However, improved productivity and throughput remain key concerns to lower production costs, requiring better printability and yield.

Solution: DuPont Solamet PV19B is claimed to enable more than 0.1% solar cell efficiency improvement over other products currently used in the industry. Based on DuPont's proprietary tellurium technology, Solamet PV19B PV metallization paste combines excellent contact performance with the ability to achieve very fine line, high aspect ratio, and smooth finger lines, according to DuPont. Moreover PV19B is claimed to possess excellent paste transfer, allowing higher print speeds to be deployed such that industry average throughputs can be improved by up to 26%.

Applications: Standard screen print process.

Platform: DuPont Solamet PV19B paste is able to be co-fired with back-side (p-type) aluminum conductors such as 'DuPont Solamet PV3xx' and 'DuPont Solamet PV5xx' tabbing silvers. It is also designed for rapid dry and fast (spike) firing, with the thermal budget above 600°C kept to a minimum, ideally <8 seconds to ensure optimum electrical contact to the wafer.

Availability: February 2016 onwards.

Heraeus

Heraeus' new SOL500 series low-temperature silver pastes support HJ and organic cells

Product Outline: Heraeus Photovoltaics has announced the introduction of a new family of low-temperature Ag-pastes that are designed for emerging third-generation solar cell architectures such as heterojunction or organic solar cells.

Problem: As new materials are tried and developed for third-generation front-junction n-type solar cells, new metallization processes are susceptible to high-temperature treatment or simply do not require high-temperature processes, which can potentially lower overall processing costs.

Solution: The new SOL500 series is formulated for the processing of solar cell types which cannot withstand high firing temperatures. The SOL560 is designed for the curing temperature range of heterojunction solar cells of less than 200 degrees Celsius. The SOL530 accommodates the 125-135°C range required in the production of organic solar cells. Heraeus' new SOL540 is a fast-curing, screen-printable, low-temperature processing paste that has the added benefit of high adhesion for busbar applications. Heraeus' new SOL550 has been optimized to provide low resistivity. This product is designed for applications such as HIT cells.

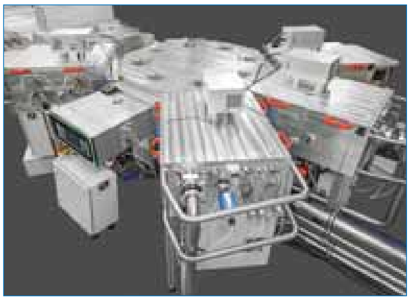
Applications: Third-generation PV cells such as heterojunction or organic solar cells.

Platform: Designed for a variety of applications, Heraeus' SOL530, SOL540 and SOL550 all offer faster cure times, higher efficiencies and greater adhesion than commercially available materials, according to the company. The SOL560 can be stored and processed at room temperature, which relieves PV cell manufacturers from time-consuming freeze and unfreeze processes.

Availability: Currently available.

Product Reviews

INDEOtec



INDEOtec's Octopus II PECVD system provides superior film thickness uniformity and passivation

Product Outline: INDEOtec's Octopus II PECVD system has proven capabilities in the formation of heterojunction solar cells that enables top and bottom side thin film substrate deposition without the need of substrate flipping and vacuum breakage.

Problem: The ability to provide double-sided plasma-enhanced chemical vapor deposition (PECVD) deposition of intrinsic and p/n doped a-Si:H layers for heterojunction PV cell devices has the potential to both lower processing costs and provide superior film thickness uniformity and passivation levels.

Solution: The OCTOPUS II system generation deploys several new PECVD reactor elements for RF and VHF plasma deposition such as the Mirror reactor concept, which enables the top and bottom side thin film substrate deposition to be carried out without the need of substrate flipping and vacuum breakage. The proprietary reactor design and a unique electrode arrangement allow low plasma ignition levels and low ion bombardments, which result in superior film thickness uniformity and excellent passivation levels, according to INDEOtec.

Applications: With PECVD deposition the system can deposit semi-conducting layers including a-Si:H, µc-Si:H, nc-Si:H, SiGe:H. Multiple layers (layer stacks) may also be deposited in one reactor without any interruption of the vacuum.

Platform: The OCTOPUS platform offers a modular and fully automated cluster deposition system for the deposition of various singular or multiple stacks of thin films by means of PECVD or PVD. The OCTOPUS system significantly reduces the substrate handling and avoids vacuum breakage between top and bottom side deposition cycles.

Availability: Currently available.

HIUV

HIUV New Materials develops double-glass EVA for defect-free lamination

Product Outline: Shanghai HIUV New Materials Co has introduced a newly developed 'pre-crosslinking' EVA. The G401W EVA is designed specifically for double-glass PV modules with the aim of eliminating a series of issues encountered with conventional EVA materials in the lamination process.

Problem: Common problems resulting from white EVA encapsulant lamination are typically related to its overflow on the panels' internal components, formation of wrinkles on the EVA surface of the final laminate and a cell shifting effect.

Solution: HIUV New Materials uses 'electron beam' technology to crosslink plastic materials to improve product performance. Polymer chains are cross-linked in the same way they are formed in a common laminator at high temperatures, with the difference that polymer bonds are controlled before the material utilization in a so called 'pre-crosslinking' stage. The specially tuned EVA is therefore ready to be used by the module maker in order to laminate white double-glass panels free of defects, according to the company. The mechanical characteristics of the G401W EVA have been specifically designed to solve the glass bending effect happening in the laminator. The high reflection rate of G401W EVA material is intended to provide an increase in the overall power performance of PV modules with a typical gain against a conventional PV panel with a single backsheet of around 3W.

Applications: Double-glass PV module lamination.

Platform: PV modules adopting the G401W EVA can be laminated in a very fast time and the structure remains simple with a single layer of G401W on the cell back side, making it suitable for all the commercially available laminators.

Availability: Currently available.

Meyer Burger

Meyer Burger's DW288 Series 3 diamond wire cutting tool produces wafers of 145 µm thickness

Product Outline: The DW288 Series 3 diamond wire cutting tool has been designed for use with extremely thin wires.

Problem: As regards kerf loss, the general rule is: the thinner the wire, the better the material yield and the greater the output. However, thinner wires pose new challenges for solar suppliers. They can twist or break all too easily, particularly at high speeds. It is therefore vital that the machine control system and cutting processes are properly coordinated.

Solution: The DW288 Series 3 is said to be already used to manufacture wafers just 145µm thick with a Total Thickness Variation (TTV) of only 10µm, compared to today's standard TTV of up to 30µm, which would be far too high for such thin wafers. The low TTV is said to be due an optimized geometry with narrow axis distance, alongside specially developed cutting processes. With high-efficiency cell-coating technologies such as heterojunction, the trend is increasingly towards the thinnest possible wafers.

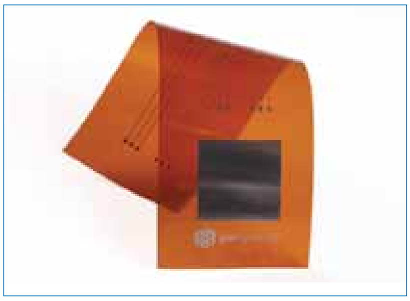
Applications: Next-generation monocrystalline wafers for heterojunction solar cells and other advanced cell architectures.

Platform: DW288 Series 3 is claimed to have an unmatched wire speed of 30 m/s,. Additional output is made possible by a loading length that has been enlarged to 650mm. A special wire tensioning system rapidly regulates any fluctuations, even at the highest speeds and accelerations, while ultra-light pulleys keep fluctuations in the wire tension within narrow limits. On a specially designed working spool, the wire is wound side by side in a single layer. This has enabled Meyer Burger to eliminate any wire-to-wire contact and to boost the performance of the wire by more than 50%.

Availability: Currently available.

Product Reviews

PV Nano Cell



PV Nano Cell's single-crystal, nanometric silver conductive ink enables non-contact digital inkjet printing

Product Outline: PV Nano Cell has commercially developed 'Sicrys,' a single-crystal, nanometric silver conductive ink delivering enhanced performance for digital conductive printing in mass production applications. The inks are also available in copper-based form.

Problem: Solar cell metallization is not yet fully optimized for cost and resource conservation. Cell producers currently endure silicon cell breakage during cell metallization, and higher-than-necessary costs for silver. Traditional screen printing of conductive grid lines involves direct contact with brittle cells, resulting in breakage and silicon waste. Additionally, the current technologies for metallization create lines that are wider and thicker than necessary, inflating silver costs.

Solution: PV Nano Cell's Sicrys inks enable non-contact digital inkjet printing rather than traditional screen (or stencil) printing. A transition to inkjet printing will allow a reduction in silver consumption per watt by printing narrower lines, controlling accurately the pattern thicknesses and increasing the cell efficiency. Moreover a reduction in cell breakage rate is expected which will in the future allow the reduction of the wafer thickness.

Applications: Sicrys inks can be used for 2D and 3D applications including metallization of PV as well as printed circuit boards, sensors, RFID, smart cards, antennas, advanced packaging, and touchscreens.

Platform: Sicrys inks enable metallization of solar cells with inkjet printing. The silver loading is said to be higher than that of other inks on the market, and offers high conductivity and low viscosity. PV Nano Cell also offers copper conductive inks as low-cost alternative to silver ink.

Availability: Currently available.

LayTec

LayTec's 'LID Scope' system targets expected performance losses from LID effect

Product Outline: LayTec has introduced the first commercially available system for simulation and monitoring of light-induced degradation (LID). The tool performs accelerated or real-life degradation tests fully automatically. It is claimed to deliver highly reproducible results and a permanent monitoring of Voc changes by integrated metrology.

Problem: The performance of c-Si solar cells drops significantly when exposed to light. After a short time of employment in the field, the efficiency of the solar cells degrades by up to 10% until a stable level of performance is reached. This effect is called light-induced degradation and has been known for about 30 years.

Solution: LID Scope degrades cells in a well-controlled procedure with electrical current and high temperatures by applying novel physical models developed by Fraunhofer Center for Silicon Photovoltaics (CSP) in Germany (patent pending). For the first time, cells can be degraded in a repeatable way, which means that LID Scope offers identical LID performance control from line to line and from lab to lab. This means that cell producers can now exactly quantify the loss, thus eliminating costly safety margins on the price-per-watt.

Applications: LID testing of c-Si solar cells including PERC.

Platform: LID Scope is a table-top system that uses electrical current and controlled heating to achieve an automated and repeatable degradation and to predict the efficiency loss in the field. These features make the tool an inevitable part of quality control and production optimization in PV industry. The manufacturer can choose between the Quick Test for fast production control or the Real-life Test to simulate exposure close to in the field conditions.

Availability: May 2016 onwards.

S'Tile

S'Tile licensing 'i-Cell' technology for low-cost high-efficiency modules

Product Outline: S'Tile is introducing a new solar cell technology for high-efficiency modules for commercial and utility-scale applications and customized modules.

Problem: The main constraint on providing high-efficiency modules is the power losses within the module because of the very high current delivered by the cells and flowing along the strings of the modules. These high currents also mean a limitation for reducing the production costs mainly driven by the high amounts of material consumption.

Solution: S'Tile has developed the 'i-Cell,' a cell without busbars, delivering a high voltage and a current much lower than that of typical c-Si solar cells. An i-Cell consists of several small-area sub-cells connected in series using standard cell processes. This i-Cell concept combines both advantages of low cost of thin-film technology with the high efficiency of crystalline technology. By using two times less silver on the cell and two times fewer tin/copper ribbons in the strings compared to traditional technology, S'Tile is able to produce modules with a very high power to cost ratio. The module has a very high power per surface area due to the absence of shading by busbars and to a very short space between the cells.

Applications: Small and medium PV plants and roofs, PV systems in association with energy storage.

Platform: Owing to its flexibility to adapt dimensions and electrical parameters outputs, the technology is particularly suitable for the production of high-efficiency modules and of customized modules. The company is installing a 15MW pilot line for the production of specially designed i-Cells and for the assembling of modules.

Availability: The technology will be available for licensing in the US, Central and South America and Asia with pilot production starting in June 2016.

Fab & Facilities

News

SolarCity's 1GW Buffalo fab using technology from Japan, Germany and Taiwan

The 1GW Buffalo fab has experienced some minor delays with the delivery of equipment.

SolarCity's 1GW factory in Buffalo, New York, will likely be equipped with tools from suppliers in Japan, Germany and Taiwan.

In February 2016, SolarCity, the largest residential solar PV installer in the US said in its fourth quarter 2015 earnings call that its ambitious 1GW Buffalo Riverbend manufacturing facility had been impacted by longer than expected equipment lead times, pushing some equipment installs into the second half of 2016.

However, much of the equipment set to produce its hybrid heterojunction cell and module technology from its acquisition of start-up Silevo remained a mystery.

According to PV Tech's analysis, German equipment specialist Singulus Technologies is one of the key front-end suppliers to the Buffalo fab, possibly supplying its modular SILEX II wet processing batch system for n-type monocrystalline wafer texturing and its HISTARIS inline sputtering system for anti-reflection, barrier, buffer and precursor layers.

A stumbling block did exist in identifying the a-Si (PECVD) deposition tool supplier, until by accident we stumbled across Taiwan-based firm, Archers Systems.

In a February 2016 press release, believed to be related to a new order from Taiwan-based solar cell producer, Neo Solar Power (NSP), Archers makes clear reference to the "US largest rooftop solar PV provider" and its "1GW HJT solar cell production capacity", which noted that it had "successfully delivered and received the final acceptance for the equipment ordered by this client in 2015".

There still remains some uncertainty over whether we have got these supplier selections right as on purpose they were not contacted as they would surely be under NDA agreements. There also remains some uncertainty in regards to some other tool selections but the picture is emerging.

Market

Global PV manufacturing capacity expansion announcements in March increase to 7.3GW

Preliminary analysis of global PV manufacturing capacity expansion announcements for March 2016 have revealed over 7.3GW of planned future expansions of solar cell and module production.

The planned expansions are primarily due to several companies – including JinkoSolar, Trina Solar and Canadian Solar – adding meaningful capacity to meet expected global demand in 2016.

Dedicated solar cell capacity expansions announcements reached 3.1GW in March, compared to 1.26GW in the previous month. The increase was primarily driven by JinkoSolar, Trina Solar and Tainergy Tech.

Overall capacity expansion announcements in 2016 are continuing to track significantly higher than in 2014 and 2015.

However, dedicated solar cell and integrated cell and module plant expansions are running almost at the same levels since the second half of 2015, indicating that after a two-year period of mainly dedicated module assembly expansions carrying low capital expenditure, PV manufacturers are having to correct major cell to module imbalances or add cell capacity to retain established imbalances as further module assembly expansions are also planned in 2016.

JA Solar matching production capacity to shipment guidance for 2016

JA Solar has said it expects full-year 2016 shipments to be in the range of 5.2GW to 5.5GW, including 250MW to 300MW of module shipments to its downstream projects.

The company is increasing its manufacturing capacity to match expected demand, which will include expanding in-house wafer capacity to 2.0GW, solar cell capacity to 5.5GW and module capacity to 5.5GW by the end of 2016.

Management noted in the earnings call that the majority of the capacity expansions would take place at its existing facilities in China. However, its integrated cell/module plant in Malaysia could ramp to 600MW to 800MW in 2016, dependent on overseas demand.

The company said that capital expenditure in 2016 could reach around US$350 million to meet wafer, cell and module planned expansions.

Baofang Jin, chairman and CEO of JA Solar said: "Our outlook for 2016 is bright. We expect growth of over 30%, as countries around the world continue to encourage the growth of clean, renewable energy.

"We are able to capture this market growth due to our industry-leading reputation for quality and value. We intend to aggressively protect that reputation through our ongoing investment in research and marketing."

Europe

Trina Solar takes over Solland Solar's Dutch cell plant

Leading 'Silicon Module Super League' (SMSL) member Trina Solar has acquired the solar cell manufacturing assets of bankrupt producer, Solland Solar, in the Netherlands. No financial details were disclosed.

PV Tech had previously reported that just before Solland Solar's parent company Pufin Group filed for insolvency, Trina Solar had secured a supply deal from the Dutch firm for over 200MW of solar cells.

Trina noted that its wholly owned subsidiary, Trina Solar Netherlands, had made the purchase of the plant and planned to re-start production in the coming weeks.

Jifan Gao, chairman and CEO of Trina Solar, said: "This investment will be one of the components of our ongoing global expansion strategy. In particular, this new cell facility in Europe, along with our in-house manufacturing capacity in Thailand and other overseas capacities allows us to leverage our global resources so that we can further expand our presence and enhance our competitive edge in overseas markets, especially the US and Europe."

Former Centrosolar module assembly plant in Germany back in production

CS Wismar GmbH with a team of former Centrosolar staff have restarted PV module assembly operations at the former

Sonnenstromfabrik facility in Wismar, Germany

Centrosolar Group AG went bankrupt in 2014, which led to rival module manufacturer, Solar-Fabrik, acquiring the facility in July, 2014. However, Solar-Fabrik itself went bankrupt in February 2015.

CS Wismar said the manufacturing facility had a capacity of around 525MWp and would primarily offer OEM services for companies focused on the fast growing US market.

Dr Bernhard Weilharter, sales director at CS Wismar said: "The demand is there. The market will recall good experiences with modules from Wismar – over our 20-year production history at Wismar we had a complaint rate of less than 0.02% p.a. – such quality rates are unequalled in the industry. Even before the production start people were asking us when superior-quality modules made in Wismar would finally go on sale again."

Credit: Centrosolar

Centrosolar's Wismar fab is back in production, with a capacity of around 525MW.

Polysilicon

REC Silicon restarts FBR production at Moses Lake

REC Silicon will restart FBR polysilicon production at its Moses Lake facility in the US during May, with full production planned to be resumed in June 2016, the company has confirmed.

The company had previously said the shutdown was due to high polysilicon inventory levels and its cash position, on the back of the ongoing anti-dumping duties placed on US-based polysilicon into China as part of the wider solar trade war.

Tore Torvund, REC Silicon, CEO said: "We have reduced our inventories and market conditions have improved to the point to enable us to restart production in Moses Lake, with FBR cash costs near US$10/kg. Further, the maintenance work that has been completed during the curtailment period should allow us to run the FBR unit as well as Silane III and IV for two years without an extended outage."

On a global basis, polysilicon had been in oversupply for several years but tight supply exists in China, due to the limited access polysilicon producers in the US (Hemlock, REC Silicon and SunEdison) have to the largest market after high anti-dumping duties were imposed and shipment loopholes closed.

REC Silicon noted in its first quarter 2016 financial report that it expected around an extra 17,000MT of polysilicon to come on stream in 2016, compared to 72,000MT claimed in 2015, which has primarily been absorbed by global downstream PV installation growth.

Wacker opens 20,000MT Tennessee poly plant

Wacker Chemie has officially opened its 20,000MT polysilicon plant in Tennessee with production now ramping up. The company expects to be at full capacity in the third quarter of 2016.

Wacker CEO Rudolf Staudigl said the company expected between 60 and 70GW of installed PV capacity this year.

"Cost for electricity produced by photovoltaic systems has declined markedly in recent years. Consequently, this way of generating energy has become even more competitive, which is opening up new markets," explained Staudigl.

In particular, he said he expects India to join the US, China and Japan among the largest sources of end demand in 2016.

"This will spur demand for high-grade material of the best quality, as supplied by WACKER," emphasised Staudigl. In the photovoltaic sector, silicon technology has clearly beaten other technologies, he said.

According to the company, the site in Charleston, Tennessee is the company's single largest investment having been built over five years at a cost of US$2.5 billion. It will employ around 650 people once it reaches full capacity.

Credit: Wacker Chemie

Wacker's new poly plant in Charleston, Tennessee, will employ 650 people once it reaches full capacity.

Cells

REC Solar to switch all production capacity to half-cut PERC cell technology

Integrated PV module manufacturer REC Solar will migrate all production at its manufacturing facility in Tuas, Singapore to its half-cut PERC cell technology, used for its 'TwinPeak' series modules.

The recently announced capacity conversion (automation, technology upgrades) (1.3GW) and R&D investment in collaboration with Singapore-based R&D centre, SERIS (Solar Energy Research Institute of Singapore) includes SG$200 million (US$182.3 million) capacity conversion and SG$50 million R&D spending over the next three and five years respectively.

The R&D spending with SERIS will be used for development of a novel 350W PV module over the next five years. REC Solar claims the new module is expected to generate 1.35 times more energy while at a comparable cost and size to standard multicrystalline modules.

Capacity expansions are therefore coming from higher cell and module conversion efficiencies rather than added new capacity.

According to PV Tech's assessment, REC Solar would become the first PV manufacturer to switch all production capacity to half-cut and PERC cell technology. Other companies such as SolarWorld are also planning to migrate all production to PERC cell technology.

Neo Solar Power adding 50MW heterojunction solar cell line

Taiwan-based major solar cell producer Neo Solar Power (NSP) is installing a 50MW N-type heterojunction (HJ) solar cell line, according to reports.

Taiwan-based PV equipment specialist Archers Systems said in a statement that it had secured the repeat order from Neo Solar Power, it had previously only said that it had made a deal with a leading Asia-based solar cell manufacturer which was developing bifacial cells. Digitimes, which covers tech news in Taiwan and China said on Friday that the line will have an annual production capacity of 50MWp.

The latest order included its PECVD tool for coating high uniform thin-film layer's and a new type of PVD system using reactive plasma technology to provide higher uniformity Transparent Conductive Oxide (TCO) layer with higher conductivity and higher transparency, claimed to provide a 1% efficiency gain, leading to cell conversion efficiencies over 23%.

Emerging markets

Saudi energy minister wants investors for PV export industry

Saudi Arabia's energy minister has said he believes it will be impossible to keep fossil fuel resources "in the ground" even in the next 50 years but nonetheless sees his country as an ideal potential manufacturer-exporter of PV panels.

Ali bin Ibrahim Al-Naimi, minister of petroleum and mineral resources for the Kingdom of Saudi Arabia, who is also the head of OPEC, said at an international event in Berlin in March that instead of trying to eliminate fossil fuel use and emissions should instead be "controlled". He also reiterated recent comments he has made about wanting to establish the kingdom as a PV manufacturing base and invited investors to consider Saudi Arabia as a potential hub of the renewables industry.

Al-Naimi was speaking at the Berlin Energy Transition Dialogue, a German federal government-backed event which sought to share lessons from Germany's own 'Energiewende' ('energy transition') with international stakeholders including utilities and policymakers and provoke discussion on the topic and its relevance to the rest of the world.

"I hope I can interest investors, worldwide, especially in Germany," the minister said.

"Come to Saudi Arabia, join hands with our business community and develop an industry integrated from the sand, the pure sand, to the factories. Then generate power from photovoltaics."

India plans support scheme for large-scale domestic solar equipment manufacturing

The Indian government is planning a policy to support the development of large-scale solar manufacturing facilities in India, according to energy minister Piyush Goyal.

Goyal's comments at the Surya Kranti Summit Organised by Bharat Solar-Power Development Forum in New Delhi were widely reported by the local press.

He said: "We are working on a policy to promote large-scale domestic manufacturing of solar equipment for making it more competitive."

Aiming for a "quantum jump" in domestic production of solar equipment and potentially including silicon wafers, Goyal said the new policy will soon be sent to India's Union Cabinet for approval.

Meanwhile, a committee headed by Department of Industrial Policy and Promotion (DIPP) secretary Amitabh Kant has already provided contours of the policy to be evaluated.

PV manufacturing capacity expansion announcement plans and analysis for 1Q 2016

Mark Osborne, Senior News Editor, Photovoltaics International

ABSTRACT
In this quarterly report on global PV manufacturing capacity expansion announcements in the first quarter of 2016, key analysis is devoted to the continued high level of intensity, which is continuing to track significantly higher than in the prior-year periods of 2014 and 2015. The report will also provide insight into the specific capacity expansion plans of the largest PV manufacturers, known as the 'Silicon Module Super League' (SMSL).

January 2016

PV manufacturing capacity expansion announcements for January 2016 revealed over 9.5GW of planned future expansions.

At 9.5GW of total expansions, which include dedicated crystalline silicon solar cell, integrated solar cell and module assembly and dedicated module assembly but no thin-film expansions, the January figure was the second highest monthly figure reported since the beginning of 2014. The record was set in November 2015 when over 25GW of new announcements were made after a regular reappraisal raised the figure from over 19GW, initially.

Around 2.67GW of dedicated c-Si solar cell announcements were made in January, notably with LG Electronics announcing it would expand n-type monocrystalline cell production from 1GW to 3GW by 2020 with capital expenditure of US$435 million. LG also revealed that it would add six cell production lines to its existing eight lines in a phased expansion, taking capacity to 1.8GW by 2018 and reaching 3GW by 2020.

January also delivered 5.35GW of planned module assembly capacity expansions and 1.5GW of integrated cell and module expansions.

The key announcement on c-Si module assembly was made by India-based integrated utility and solar developer Essel Infra and China-based Golden Concord Holdings (GCL), which owns GCL-Poly and GCL Integrated Technology Co. The companies announced a memorandum of understanding with the Andhra Pradesh government to invest US$2 billion in developing 5GW of module assembly capacity by 2020 in the Indian state.

Also announced were plans by Al-Afandi Group to build an integrated c-Si Solar cell and module plant in Saudi Arabia with an initial 120MW capacity and ambitions to expand in phases to 1GW over an undetermined time.

Geographical split

On a geographical basis, January continued the trend set in 2015 for capacity expansions outside China and the broadening of the PV manufacturing footprint around the world. Out of the nine main announcements of new capacity in January, only one was located in China, while plans included India, Malaysia, South Korea, Taiwan, Saudi Arabia and Italy.

Based on a preliminary analysis, conversion to effective capacity from announcements in January could be around 1GW by the end of 2016.

February 2016

Global PV manufacturing capacity expansion announcements for February 2016 revealed over 5.7GW of planned

Credit: Canadian Solar

Canadian Solar was one of the key contributors in another busy quarter for manufacturing capacity expansion announcements.

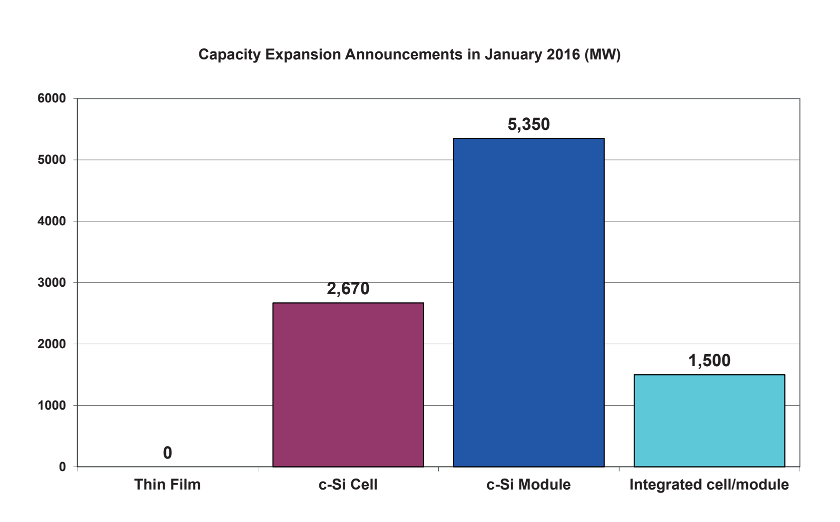


Figure 1. Capacity expansion announcements in January 2016 (MW)

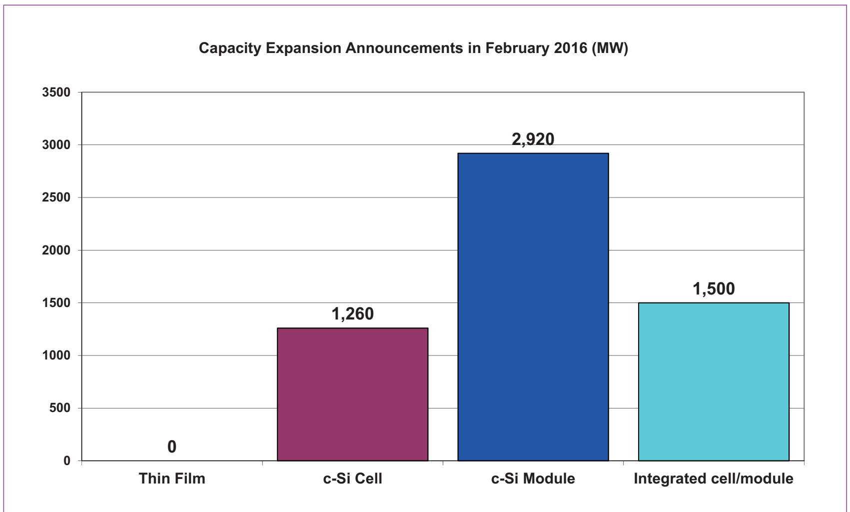


Figure 2. Capacity expansion announcements in February 2016 (MW)

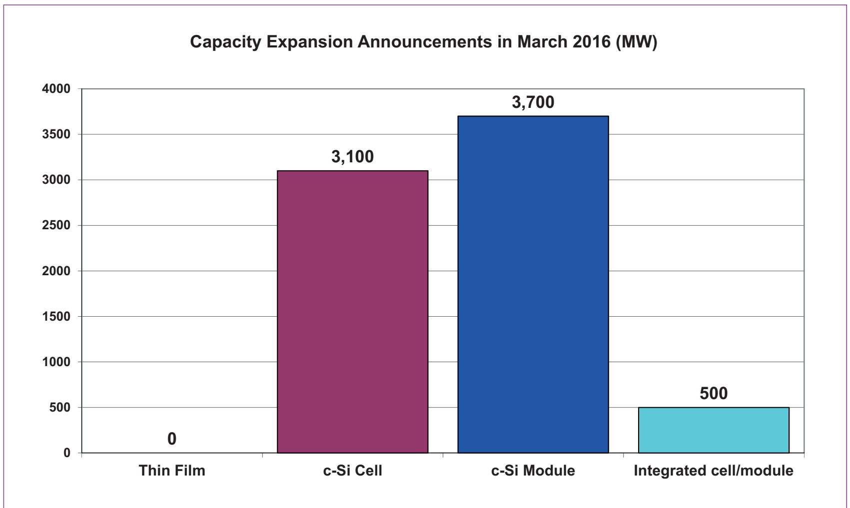


Figure 3. Capacity expansion announcements in March 2016 (MW)

future expansions.

Total expansion announcements included dedicated crystalline silicon solar cell, integrated solar cell and module assembly and dedicated module assembly. However, no thin-film announcements were made in the month, the fourth month in a row.

Total expansion announcements were down from January's 9.52GW), but up from more than 2.7GW in February 2015.

Dedicated solar cell capacity expansions announcements reached 1.26GW in February, less than half the figure in the previous month, while significantly higher than the 300MW announced in February 2015.

Integrated cell and module planned expansions totalled 1.5GW, the same level reached in the previous month. Dedicated module assembly capacity expansions announced in February reached 2.72GW, down from 5.35GW announced in the previous month, yet significantly higher than the 765MW announced in February 2015.

Overall capacity expansion announcements in 2016 are tracking significantly higher than in the prior-year period, driven by several announcements in the multi-gigawatt range. However, these (LG Electronics, Essel Infra/GCL and Jinneng Group/SunEdison) are mainly phased expansions over a number of years.

Geographical split

On a geographical basis, capacity expansion announcements continue to be broadly based. In February 2016 only two announcements (Jinneng Group/SunEdison and GCL Systems) were located in China, though these totalled 3.8GW. This compares with only one announcement in January (500MW) being located in China.

Southeast Asia accounted for just over 1GW of planned expansions, while smaller announcements for smaller projects were made for locations including Brazil (300MW), Algeria (120MW) and Italy (50MW).

Also notable was the planned restart of solar cell production (200MW) at the former Solland Solar facility in the Netherlands by Trina Solar. Asia-based companies have been playing a key role in driving the acquisition of idled capacity in Europe over the last three years.

March 2016

Our preliminary analysis of global PV manufacturing capacity expansion announcements for March 2016 has revealed over 7.3GW of planned future expansions of solar cell and module production.

Total expansion announcements include dedicated crystalline silicon solar cell, integrated solar cell and module assembly and dedicated module assembly, while no thin-film announcements were made in the month, the fifth month in a row.

The 7.3GW of planned future expansions, up from around 5.7GW in the previous month (figure updated from 5.4GW), is primarily due to several 'Silicon Module Super League' (SMSL) members (JinkoSolar, Trina Solar and Canadian Solar) adding meaningful

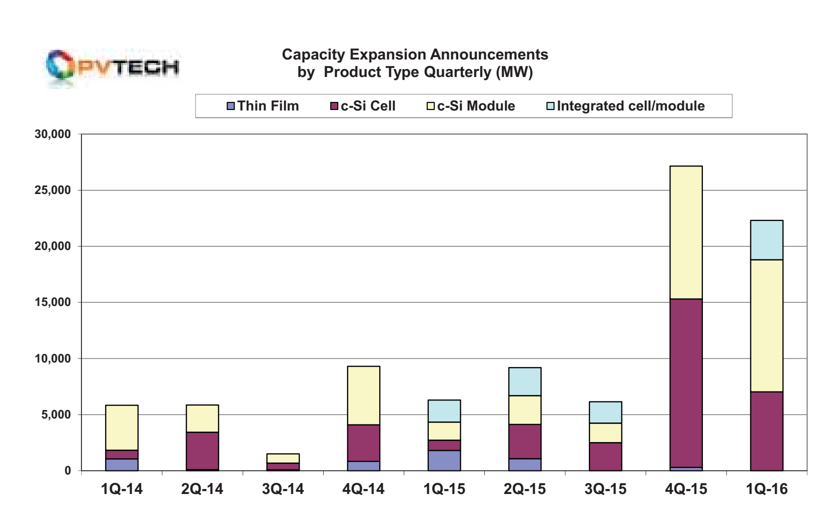


Figure 4. Capacity expansion announcements by product type, quarterly (MW)

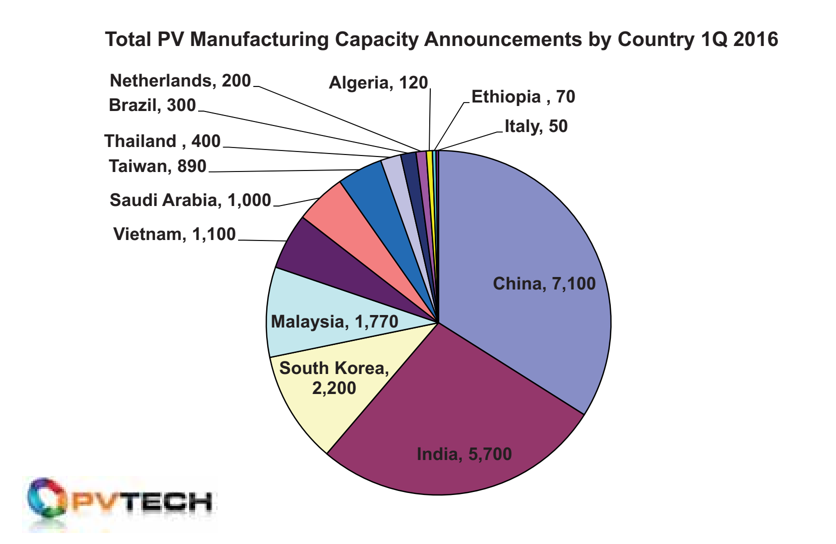


Figure 5. Manufacturing capacity announcements by country Q1 2016 (MW)

capacity to meet expected global demand in 2016.

SMSL members, including JA Solar, Trina Solar and new entrant, GCL Systems, were also behind the strong February figures, as nine companies in February had announced new plans to expand capacity, while the higher March figures include just 10 companies.

Dedicated solar cell capacity expansions announcements reached 3.1GW in March, compared to 1.26GW in the previous month. The increase was primarily driven by JinkoSolar, Trina Solar and Taiwan-based Tainergy Tech.

Although not technically new capacity additions, both SolarWorld and REC Solar are undertaking complete manufacturing line upgrades to PERC (passivated emitter rear cell) technology in 2016, which would boost megawatt nameplate capacity due to efficiency gains.

Integrated cell and module planned expansions in March 2016 totalled 500MW, down from 1.5GW seen in each of the first two months of the year. Dedicated module assembly capacity expansions announced in March reached 3.7GW, up around 1GW from 2.72GW announced in the previous month. Around 3GW of the total in March can be attributed to three SMSL members, JinkoSolar, Trina Solar and Canadian Solar.

Geographical split

In March, expansions were announced for around nine country locations, all in Asia, compared to eight country locations in February, including the Netherlands in Europe, Algeria in North Africa and Saudi Arabia in the Middle East as well as Brazil in South America.

Despite a continued geographical footprint expansion, China continues to be the dominant location for solar cell and module expansions. In March, China accounted for 2.8GW of total announced expansions.

In February 2016 only two announcements (Jinneng Group/ SunEdison and GCL Systems) were located in China, though totalled 3.8GW. This compares with only one announcement in January (500MW) being located in China.

However, Southeast Asia continues to attract further capacity expansion plans. PV Tech has previously highlighted that Malaysia and Thailand have been the dominant locations in the region over the last two years, attracting mainly China and Taiwan-based PV manufacturers.

In the last two years, Malaysia attracted over 2.6GW of new capacity announcements, while Thailand attracted over 2.3GW. Southeast Asia accounted for just over 1GW of planned expansions in February 2016 and over 2.8GW in March.

An interesting trend under development that started in 2015 is the emergence of Vietnam, primarily for dedicated module assembly, driven by low costs and as an alternative location to Malaysia and Thailand. Chinese PV manufacturers have been behind the Vietnam push, initiated by Powerway Group (Boviet Solar) in 2013 and more recently plans from Tainergy Tech, Canadian Solar and Trina Solar.

Overall capacity expansion announcements in 2016 are continuing to track significantly higher than in the prior-year periods of 2014 and 2015.

However, dedicated solar cell and integrated cell and module plant expansions have been running almost at comparable levels since roughly the second half of 2015, indicating that after a two-year period of mainly dedicated module assembly expansions, which require comparatively low capital expenditure, PV manufacturers are having to correct major cell to module imbalances or add cell capacity as further module assembly expansions are also planned in 2016.

Analysis Q1 2016

Total global PV manufacturing capacity expansion announcements in the first quarter of 2016 surpassed 22.3GW, the second highest quarterly figure. The previous quarter (Q4 '15) holds the record at over 27GW. Therefore, the total announcements in back-to-back quarters exceed 49.4GW, completely overshadowing the prior-year period when announcements topped 16GW.

With regards to dedicated solar cell capacity expansion announcements the first quarter exceeded 7GW, compared to 15GW in the previous quarter, yet the second highest on a quarterly run rate since the beginning of 2014.

New announcements of integrated solar cell and module assembly lines reached 3.5GW in the quarter, while the fourth quarter of 2015 did not generate any announcements. Dedicated module assembly announcements in the quarter reached around 12GW, almost identical to the previous quarter.

As with some major announcements made in November 2015 a number of announcements in the first quarter of 2016 were planned phase expansions. In the first quarter (February) for example, the 1.5GW Jinergy Clean Energy Technology Co and SunEdison partnership announcement actually included plans for a first phase expansion of only 500MW in 2016. Another 1GW integrated cell/module plant in January was touted as 1GW but the first phase would be 120MW.

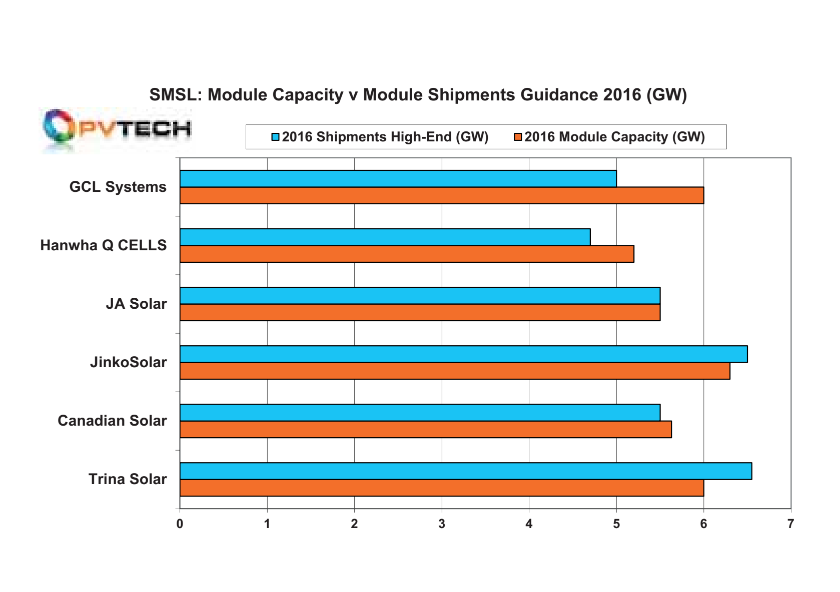


Figure 6. SMSL: Module capacity versus module shipments guidance 2016 (GW)

Geographical split

Month to month and quarter to quarter, the geographical location for new capacity announcements can vary considerably. As already highlighted March 2016 expansions all resided in Asia, compared to eight country locations outside Asia in February. Therefore, it is prudent to look at full-year geographical splits to identify real trends.

As a reference point for the first quarter of 2016, a total of 13 countries were locations for companies to announce planned expansions and new PV manufacturing plants.

Dedicated solar cell and module assembly announcements in the quarter were led by China with 7.1GW of new expansion plans in eight separate announcements. India followed with a total of over 5.7GW with only three announcements. The third leading country was South Korea with 2.2GW of new expansion plans from only two announcements. Malaysia with four announcements was fourth with a total of 2.2GW.

The fifth most popular location with four announcements in the first quarter of 2016 was Vietnam, which attracted 1.1GW of expansions and new plants.

SMSL update

When we first produced the 'Silicon Module Super League' (SMSL) in 2015, members initially included Yingli Green, Trina Solar, Canadian Solar, JinkoSolar, JA Solar and Hanwha Q CELLS. Our analysis showed that significant existing and planned gigawatt levels of nameplate capacity coupled to PV module shipment levels had created a gap of more than 2GW between these players and all other silicon-based PV manufacturers (with the exception of CdTe thin-film leader First Solar).

Through 2014 and 2015, the SMSL members had continued to outpace their rivals in both capacity expansions and shipments and were responsible for turning the most announced expansions into effective capacity during this period.

Since the first quarter of 2016, China-based GCL Systems Integration Technology Co has been added to the SMSL membership, due to its significant capacity additions and shipments in 2015 and planned expansions in 2016. Yingli Green Energy, meanwhile, has been dropped from the SMSL list as its declining shipments in 2015 mean it does not meet the criteria for inclusion in the rankings for 2016.

Trina Solar

First-ranked SMSL member Trina Solar reported full-year 2015 total solar module shipments of 5.74GW, an increase of 56.8% from 3.66GW in 2014.

Trina Solar guided manufacturing nameplate capacity of ingots of 2.3GW by the end of 2016 and wafer capacity of 1.8GW. Solar cell capacity is expected to reach 5GW and module assembly capacity 6GW by the end of the year. Both ingot and wafer capacities will therefore remain unchanged from 2015, while solar cell capacity will increase 2.5GW in 2016 and module capacity by 1GW.

Trina Solar expects total PV module shipments between 6.3GW and 6.55GW in 2016, indicating a continued dependence on third-party modules to meet guided shipment demand.

Canadian Solar

Second-ranked Canadian Solar is finally getting serious about rebalancing its solar cell-to-module in-house capacity as well as dedicating a significant amount of cell capacity to monocrystalline PERC technology.

In November 2015 Canadian Solar announced a major expansion of solar cell capacity after falling to below 50% of in-house module assembly capacity. The driver was to reduce manufacturing costs as OEM prices were on the rise for multicrystalline cells as wafer ASPs increased on tight supply, while monocrystalline wafer and cell prices had been falling on overcapacity issues. The company was more highly dependent on multi c-Si than mono.

To recap, Canadian Solar announced last year that it would increase in-house wafer production from 400MW to 1GW by mid-2016, while solar cell capacity would be expanded from 2.5GW to 3.4GW by the end of 2016, a 900MW increase.

However, the biggest proposed capacity increase was to PV module production, which would be expanded from 4.33GW at the end of 2015, to 5.63GW by the end of 2016, a 1.3GW increase.

Canadian Solar specifically noted that wafer manufacturing capacity at its plant in Luoyang, Henan Province, is expected to reach 1.0GW by June 2016, while cell manufacturing capacity at its plant in Suzhou, Jiangsu Province, is expected to reach 2.0GW by the end of 2016. Cell manufacturing capacity at its Funning plant in Jiangsu Province is expected to reach 1.0GW by July of 2016.

However, new manufacturing plants were also announced that included 300MW in Vietnam, 30MW in Indonesia, 300MW in Brazil and 400MW in Southeast Asia of module assembly capacity.

Canadian Solar also said that a new 400MW cell manufacturing plant, to be located in Southeast Asia, was expected to be commissioned in the second half of 2016.

The capital expenditure budget for all of the capacity expansions planned included an estimated US$104.0 million to be spent in the second half of 2015 and a further US$297.0 million allocated to the expansions in 2016, according to the company.

However, fast forward to the first quarter of 2016 and Canadian Solar made further tweaks to the previously announced plans. Overall, the company expects module assembly capacity to reach 4.63GW by the end of June 2016 and 5.7GW by year-end, compared to previous guidance of 5.63GW, a 1,370MW increase.

On the solar cell side, overall capacity increased 200MW to 2,700MW in the fourth quarter of 2015 and is set to remain unchanged at 2.7GW through to the end of June 2016, but capacity is expected to reach 3.9GW at year-end, compared to previous guidance of 3.4GW by the end of 2016. Total cell capacity expansions between Q3 2015 and the end of 2016 are targeted at 1.4GW.

Digging deeper, the subtle changes include its new solar cell plant in Southeast Asia being ramped to 700MW beginning in the third quarter of 2016, compared to 400MW previously announced. The new module assembly plant in Southeast Asia is also expected to ramp higher in 2016 – to 500MW, rather than the previously planned 400MW. The reality is that the imbalance between cell and module capacity has not been tackled.

Canadian Solar is expecting total module shipments in 2016 to be in the range of approximately 5.4GW to 5.5GW

JinkoSolar

Third-ranked JinkoSolar is adding 1GW of solar module capacity per quarter through to the end of the first half of 2016 to meet the 'minimum' expected demand for its products.

JinkoSolar recently noted that it would add 300MW of wafer capacity in the first quarter of 2016, followed by a further 200MW in the second quarter, taking nameplate in-house wafer capacity from 3GW at the end of 2015 to 3.5GW by the end of the first half of 2016.

Solar cell capacity, JinkoSolar's weakest link with respect to in-house nameplate capacity, is planned to be expanded by 200MW in the first quarter of 2016 and by a further 700MW by the end of the second quarter of 2016. Total nameplate capacity by mid-year is expected to reach 3.5GW, up 900MW from 2.5GW at the end of 2015.

Not surprisingly, the company is expanding module assembly to much higher levels than wafer and cell combined. JinkoSolar is adding 1GW of nameplate module capacity in the first quarter of 2016, and a further 1GW by the end of the second quarter of 2016. The company plans to reach 6.3GW of nameplate module capacity by the end of the first half of the year, up from 4.3GW at the end of 2015.

The initial analysis of these planned expansions and production ramp rates indicates that the company could be purchasing over 3GW of third-party solar cells in 2016 and more than 1GW of third-party modules to meet shipment guidance this year.

In its latest earnings call management were reluctant to provide financial analysts with clear details regarding where the capacity expansions were being undertaken. In its third quarter earnings call, management guided 500MW of solar cell capacity expansions, noting that it would confirm at a later date whether the expansions were planned in China or at its new manufacturing hub in Malaysia. The company said the same in its latest earnings call about the new expansions.

The company guided total module shipments in 2016 to be in the range of 6GW to 6.5GW.

JA Solar

Fourth-ranked JA Solar is increasing its manufacturing capacity to match expected demand, which will include expanding in-house wafer capacity to 2.0GW, solar cell capacity to 5.5GW and module capacity to 5.5GW by the end of 2016.

The majority of the capacity expansions would take place at its existing facilities in China. However, its integrated cell/module plant in Malaysia could ramp to 600MW to 800MW in 2016, dependent on overseas demand.

JA Solar said it expected full-year 2016 shipments to be in the range of 5.2GW to 5.5GW

Hanwha Q CELLS

Fifth-ranked Hanwha Q CELLS has said it expects to reach nameplate capacity of 5.2GW for both solar cells and modules by the middle of 2016 as the company continues major expansions from 2015 announcements. Those expansions would enable in-house production capacities for solar cells and modules to both reach 4.3GW by the end of 2015.

The company reiterated that 600MW of new solar cell capacity expansions come from Hanwha Q CELLS Korea, an affiliate of Hanwha Q CELLS in 2015, while a further 900MW of new cell capacity would also come on stream for the affiliate in 2016. The company also noted that in-house ingot production stood at 1.35GW and wafer production stood at 900MW at the end of the first nine months of 2015.

Hanwha Q CELLS is guiding PV module shipments in 2016 to be in the range of 4.5GW to 4.7GW.

GCL Systems

Sixth and newest SMSL member GCL Systems has undergone an aggressive module capacity expansion drive in 2015, having acquired bankrupt Chinese firms Topoint and Chaori Solar in 2014.

After the acquisition by GCL Systems, the former Chaori Solar facilities were expanded in 2015, including a further 220MW of solar cell capacity, bringing the total to 520MW, and a further 300MW of module assembly capacity to give a total nameplate capacity of 800MW per annum.

At the beginning of 2015, GCL Group, the private parent company to GCL Systems, had separately planned to set up two 1GW module assembly lines in Zhangjiagang and Chenguang, China in 2015. The plants were legally registered entities in January 2015.

Reports indicate that the Zhangjiagang facility officially opened in late May 2015 with the Chenguang facility cited to be operational later in the year. However, GCL Systems had informed us that the Zhangjiagang plant had a planned capacity of 2.35GW, which included the former Topoint nameplate capacity with further expansions in 2015.

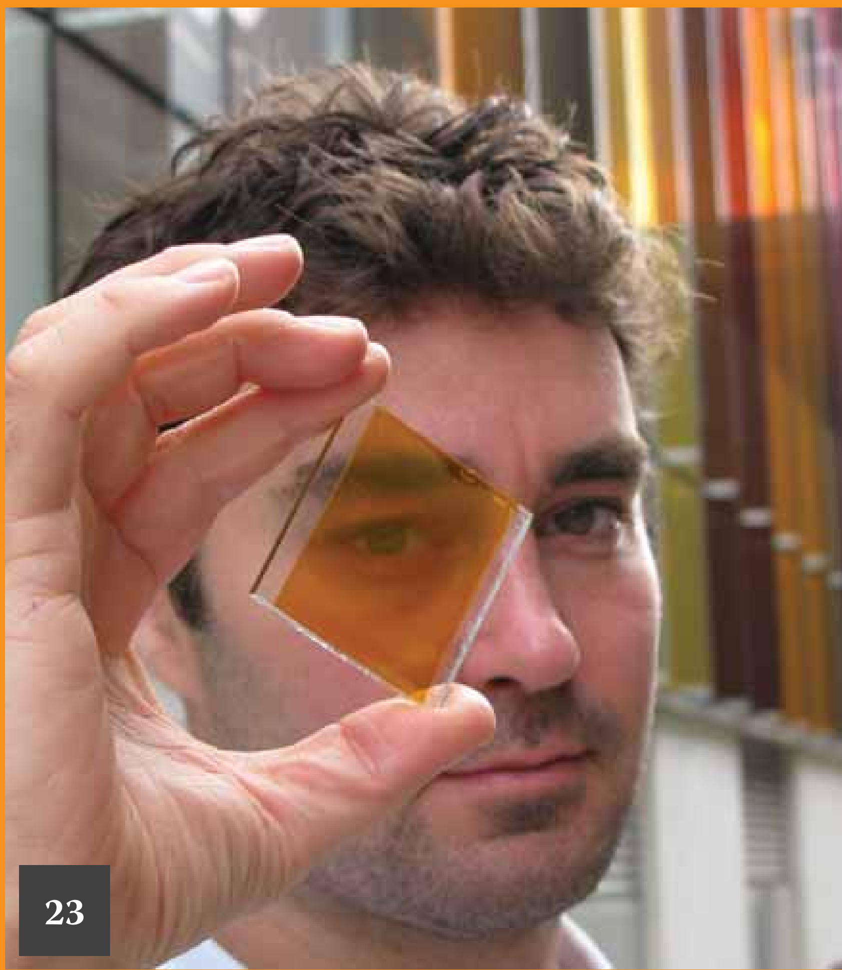
GCL Systems has said that it would be expanding in-house module production beyond 6GW in 2016.

It should be noted that GCL Group and India's Essel Infra announced joint plans to invest US$2 billion in developing 5GW of module manufacturing capacity by 2020 in the Indian state of Andhra Pradesh.

Conclusion

The SMSL members are notable on several levels as not only are they expected to supply almost half of all end-market global PV module demand in 2016, they also demonstrate the most reliable effective capacity expansions. Since our analysis started at the beginning of 2014, SMSL members have consistently taken announced expansions to effective capacity additions within the expected timeframes. Indeed, their expansions of nameplate capacity have not met shipment guidance through the period due to demand.

Materials



News

Polysilicon spot prices in China hit US$20/kg

Polysilicon spot market prices in China surpassed US$20/kg in April and are expected to climb higher in May, according to Taiwan-based market research firm, EnergyTrend.

Polysilicon spot prices had bottomed in January 2016 at just above US$13/kg on overcapacity, notably due to US producers selling excess inventory, because access to the China market had been severely curtailed due to new import duties applied as part of the trade war with the US.

The hike in prices in China was attributed to tighter import controls and checks on polysilicon from overseas to ensure anti-dumping and countervailing duties were being applied properly. Market research firm IHS had already predicted that feed-in tariff (FiT) changes mid-year in China would drive polysilicon demand and price increases in April that could top US$19/kg, up from US$12/kg before Chinese New Year in February.

Karl Melkonyan, solar supply-chain analyst for IHS Technology, said: "Strong demand for polysilicon prices is triggered by the FiT deadline in China. Buyers cannot wait any longer to buy polysilicon for solar modules, if they want them produced and installed before the end of June. It is highly unlikely that polysilicon prices will continue increasing in the second half of the year, but a flat pricing outlook is certainly a possibility, if demand remains as high as previously forecast."

Credit: GT Advanced Technologies

Tighter import controls in China have contributed to a spike in polysilicon prices.

Suppliers

1366 Technologies secures major 'Direct Wafer' supply deal

US-based 'Direct Wafer' producer, 1366 Technologies, has secured a major supply deal with Hanwha Q CELLS that will enable the company to ramp its planned initial 250MW facility in Genesee County, New York state, in 2017.

The deal, based on 1366 Technologies having to meet certain terms and conditions related to its wafer qualification and timing of wafer deliveries with the ramp of the new production facility, would result in Hanwha Q CELLS purchasing up to 700MW of wafers over a five-year period.

Hanwha Q CELLS entered into an earlier development partnership with 1366 Technologies that achieved a solar cell efficiency of 19.1%, independently verified by Fraunhofer ISE. The company had previously announced longer-term plans to expand production in phases that would take the capacity to 3GW, equivalent to 600 million wafers per annum and create around 1,000 jobs.

Linde key materials supplier to new solar cell plants in Southeast Asia

Major electronics, gasses and chemicals supplier Linde Group has been awarded a number of gas and chemical supply contracts for new solar cell plants being established in Southeast Asia by leading PV manufacturers.

Many PV manufacturers are building greenfield cell factories for the first time in key countries in the region such as Malaysia, Thailand and India, and need to navigate permitting and licensing in a new country, enabling Linde to offer its turnkey services.

Andreas Weisheit, head of Linde Electronics said: "Project windows are very short and customers need a materials supplier who can successfully execute sourcing, logistics and engineering solutions on aggressive timelines."

Linde is providing bulk gases such as nitrogen, hydrogen, oxygen, argon and in some cases helium for solar cell production. Specialty gases used in PV manufacture such as silane, ammonia, nitrous oxide, carbon dioxide, methane, hydrogen fluoride, phosphine and diborane were also being supplied through the subsidiary Asia Union Electronic Chemical Corporation (AUECC), which has manufacturing sites in mainland China and Taiwan.

Wacker confident on China future as trade deal nears expiry

German polysilicon firm Wacker Chemie hopes to continue selling to Chinese manufacturers beyond the expiration of its

Credit: Hanwha Q CELLS

Hanwha Q CELLS has made a major order of 1366 Technologies wafers for its planned US capacity ramp.


Credit: Hemlock Semiconductor

Hemlock Semiconductor is suing JA Solar for alleged breaches of a polysilicon supply contract.

existing trade agreement with Beijing.

China closed a loophole that permitted imports of materials to avoid duties if the end product, solar panels, were to be exported. A number of polysilicon firms from the US and Europe imported large volumes prior to the closure of the loophole and now face punitive duties.

South Korea's OCI was given a low tariff rate and Wacker was exempted until the end of April 2016 after a price undertaking was negotiated between China's ministry of commerce and the company.

With that expiration date now passed, the firm is confident that it will continue to be able to sell into China. Wacker and OCI both increased their market share in China as US firms were penalised. The move was interpreted by some as a retaliation for US duties placed on Chinese module manufacturers.

Shipments

Daqo hits record polysilicon shipments and lowest production costs

China-based polysilicon and wafer producer Daqo New Energy has reported that external sales volume and cost structure exceeded prior guidance as demand remained strong in the fourth quarter and full-year 2015.

Daqo reached a record-high quarterly polysilicon production volume of 3,547MT, an increase of 31.9% from 2,689MT in the third quarter of 2015 and 12% above its nameplate capacity, which had been expanded in 2015.Polysilicon production costs also reached a new benchmark for the modified Siemens process.

Daqo had reduced polysilicon average total production cost to US$9.74/kg and cash cost to US$7.69/kg in the fourth quarter, with plants running ahead of nameplate capacity. Daqo reported fourth-quarter revenues from polysilicon sales to external customers of US$42.9 million, compared to US$34.1 million in the third quarter of 2015. The company saw wafer sales of US$16.4 million in the quarter, compared to US$12.5 million in the third quarter of 2015.

GET benefiting from higher wafer shipments as sales up 42.6% in March

Taiwan-based multicrystalline wafer producer Green Energy Technology (GET) reported March 2016 sales 42.6% higher than in the same period of 2015.

GET reported March 2016 sales of NT$1,781 million (US$55.02 million), an increase of 0.8% from the previous month as production utilization rates remain above 95%, but 42.6% higher than in the same period of 2015, primarily due to higher shipments and ASPs on tight supply.

However, GET expected wafer prices could vary mildly in the second quarter of 2016, due to seasonality and policy reasons. The company still plans to expand outsourcing of wafer capacity from partners to increase shipments in 2016. First quarter 2016 sales were around NT$5,269 million (US$163 million), compared to US$124.6 million in the first quarter of 2015, around a 31% increase year-on-year.

Comtec reports 14.5% increase in product shipments for 2015

Monocrystalline wafer producer Comtec Solar Systems Group reported a revenue increase of 20.4% in 2015 on product shipments (ingot and wafers) up by 14.5%, year on year.

Total ingot and wafer shipments for the year were approximately 426.8MW, up from 372.7MW in 2014. In its financial results, Comtec also reported 2015 revenue of RMB1,091.2 million (US$168.4 million), an increase of 20.4% from approximately RMB906.6 million in 2014.

Around 39.7% of total revenue (US$66.9 million) for the year was generated from its major customer with manufacturing operations in the Philippines and Malaysia, down from 48.7% in 2014. Remaining sales were mainly generated in China, the US, Japan and South Korea.

The company has previously warned it would report a loss for the year, due to a series of write-downs, advance polysilicon payments and declining wafer ASPs. The firm's gross loss in 2015 was approximately RMB94.4 million (US$14.57 million) for the year, compared to a gross profit of approximately RMB60.0 million in 2014.

Legal

Polysilicon producer Hemlock suing JA Solar for almost US$1 billion

US polysilicon producer Hemlock Semiconductor has filed a lawsuit against JA Solar for allegedly breaching a long-term polysilicon supply agreement.

Filings with the Supreme Court of the State of New York by Hemlock Semiconductor claim that JA Solar made only one (US$10.3 million) instalment of an initial advance payment of US$103 million to secure polysilicon shipments starting in 2011. Subsequently, Hemlock Semiconductor claimed that JA Solar did not order or take delivery of any polysilicon under the 'take or pay' contract.

The polysilicon producer is seeking damages totalling no less than US$921.1 million from JA Solar. JA Solar confirmed the court action, noting that the company was reviewing the claim.

Hemlock Semiconductor has previously filed a similar lawsuit against SolarWorld's former subsidiary, Deutsche Solar, for breaching a 'take or pay' contract as well as against Japanese module producer Kyocera.

Technology

Sol Voltaics claims gallium arsenide nanowire alignment and orientation breakthrough

Materials start-up Sol Voltaics has claimed a breakthrough in the ability to deploy gallium arsenide nanowires in a thin-film format on crystalline silicon solar cells, creating the opportunity for nanowire alignment and orientation repeatability.

By demonstrating the ability to control nanowire orientation and alignment at the centimetre scale on a standard-sized wafer, Sol Voltaics could move the technology closer to commercial production of tandem solar cells and modules.

Erik Smith, chief executive of Sol Voltaics said: "By aligning nanowires within a membrane, we've taken our greatest stride yet toward manufacturing solar nanowire films at the commercial scale."

The company's development of its 'Aerotaxy' production technology to achieve cost-effective III-V nanowire production had also been progressing well. The Aerotaxy process creates the nanowires by suspending active materials in gases in a precisely controlled environment that then bond to form larger, uniform structures.


Credit: Oxford Photovoltaics

The commercial deployment of perovskite solar cells is close, according to Lux Research.

Lux Research bullish on perovskite commercialization timelines

Market research firm Lux Research believes the commercial deployment of perovskite solar cells could just be around the corner.

The firm believes that commercialization could occur between 2019 and 2021 as partnerships between start-ups and academia as well as more research groups consider spinning off work achieved so far into more start-ups.

A Lux Research report, 'The Rise of Perovskites: Identifying the Best Academic Partners to Work With,' highlighted the significant success in a number of labs around the world that have produced remarkable cell conversion efficiency gains in just a few years with highest reported efficiencies of 21%, compounded by the fact that CIGS (copper indium gallium dieselenide) thin-film cells have achieved efficiencies of 21.7%, yet have been in development for decades.

"While the efficiency question has been answered, there remain issues in stability, cost, and the feasibility of real-world efficiencies that must be addressed before commercialization can occur," said Tyler Ogden, Lux Research associate and lead author of the report.

ECN and Tempress reduce cell recombination losses with polysilicon layer

Energy Research Centre of the Netherlands (ECN) and PV equipment supplier Tempress Systems have developed a new process that reduces solar cell recombination losses, boosting cell efficiencies.

Deposition of an ultra-thin polysilicon layer between the silicon wafer and the backside metal contacts on a conventional n-type monocrystalline solar cell significantly reduced recombination of the light-generated electrons, enabling a cell efficiency of 20.7%, with a possible roadmap towards cell efficiencies of 25%.

Bart Geerligs, senior researcher at ECN, said: "An important advantage of the solution is the possibility for integration with existing mass-production processes. Therefore, it is not necessary to introduce much new process equipment. This innovation leads to robust improved results with perspective for lower electricity costs."

Although the technique had already been applied in microelectronics and solar cells in the laboratory, this was the first time it had been implemented with production-scale tools and solar cells.

NexWafe raises €6 million to produce customer test wafers

Novel epitaxial wafer technology start-up NexWafe, a spin-off from Fraunhofer ISE, has raised €6 million (US$6.8 million) in Series A funding from Swiss-based private equity firm Lynwood.

The funds are to be used for the production of monocrystalline-based solar wafers using NexWafe's high-temperature APCVD multi-chamber reactor technology, which is required for customer evaluations ahead of potential wafer orders and commercialization.

The NexWafe epi-wafer is able to achieve 20% plus cell conversion efficiencies at production costs lower than conventional mono wafer production cost levels.

Marina Groenberg, chief executive of Lynwood, said: "NexWafe's technology will be instrumental in the silicon wafer business serving the PV industry, which is continuously searching for new ways to cut overall cost of high-efficiency silicon PV modules. With its EpiWafer technology the NexWafe team will implement a disruptive manufacturing process that will enable to drastically reduce the cost to manufacture high efficiency Silicon wafers."

Heraeus launches low-temp Ag-pastes and new lab in Japan

PV metallization paste producer Heraeus Photovoltaics has launched a new family of low-temperature Ag-pastes.

The firm's new SOL500 series is formulated for cell types that could not withstand high firing temperatures. The SOL560 paste was designed for heterojunction solar cells that require curing temperatures below 200 °C, while the SOL530 accommodates even lower temperatures in the range of 125-135°C for the production of organic solar cells.

The SOL560 can also be stored and processed at room temperature, which relieves PV cell manufacturers from time-consuming freeze and unfreeze processes. The new pastes meet new grid and busbar applications and are claimed to demonstrate excellent adhesion on ITO or other TCO materials that enable improved printability and excellent line conductivity with minimal pinholes.

Fab & Facilities

Materials

Cell Processing

Thin Film

PV Modules

Market Watch

n-type multicrystalline silicon for high-efficiency solar cells

Stephan Riepe, **Patricia Krenckel**, **Florian Schindler**, **Martin C. Schubert** & **Jan Benick**, Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany

ABSTRACT

High-efficiency silicon solar cells require silicon wafers of high electrical quality as the base material. One advantage of n-type compared with p-type doped silicon is the smaller impact of many metal impurities on the electrical material quality. This applies especially to n-type multicrystalline silicon ingots produced by the directional solidification process, with dissolved metal impurities typically introduced by the crucible system. Investigations of the efficiency losses in n-type multicrystalline silicon solar cells showed that recombination-active crystal defects, such as dislocations, are the dominant limitation of quality in terms of electrical properties. By developing a solidification process with silicon granules as the seed material, high-performance multicrystalline silicon with a low number of dislocation networks, and thus a high electrical material quality, was produced. The applicability of a high-efficiency n-type solar cell concept with a full-area tunnel oxide passivated rear contact (TOPCon) on this type of material was investigated. A TOPCon solar cell with a record efficiency of 19.6% on n-type high-performance multicrystalline silicon demonstrated the potential of this class of material. By improving the front-surface texture and adapting the emitter formation process, it is expected that efficiencies of the order of 22% will be possible on n-type multicrystalline silicon in the near future.

Introduction

The increase in solar cell efficiency has been identified as an important aspect for further cost reduction in photovoltaics. To date, the highest efficiencies of solar cells on silicon wafers have been achieved on n-type monocrystalline silicon (mono-Si) substrates, with record efficiencies exceeding 25.0% [1]. This is partly because of the absence of a cell degradation effect which reduces the efficiency in p-type mono-Si and is caused by the metastable boron–oxygen complex. This effect can be avoided by the use of n-type silicon with phosphorus as the dopant material.

The push for higher cell efficiencies is not limited, however, to just mono-Si; solar cells on multicrystalline silicon (mc-Si) will also need to demonstrate high efficiencies in the future. The latest results obtained for large-area p-type mc-Si solar cells show that efficiencies above 21.0% are achievable with cell processes suitable for mass production [1]. This is of great importance for the PV market, since solar cells on multicrystalline silicon wafers actually dominate the market, with a share of about 65%, because of cost-competitive production technologies.

> "The development of n-type mc-Si as a possible material for cost-effective high-efficiency cells has gained new momentum."

The combination of cost-efficient mc-Si wafers with the advantages of n-type doped substrates has been previously investigated in various material studies. The electrical quality of n-type mc-Si, as in the case of n-type mono-Si, is less inhibited by typical impurities, such as transition metals, than p-type material [2]. Because of the specific capture cross sections of electrons and holes for important metal-related defects, such as interstitial iron Fe_i, their detrimental effect on minority-carrier lifetime is greatly reduced in n-type material; this leads to a higher efficiency potential, under the assumption of comparable cell concepts [2]. However, the lack of appropriate cell concepts and production processes for n-type mc-Si has been hindering this research path in the past. With the development of high-efficiency cell processes for n-type substrates employing low-temperature processes or full-area passivated back contacts, such as heterojunction [3] or TOPCon cells [4], the development of n-type mc-Si

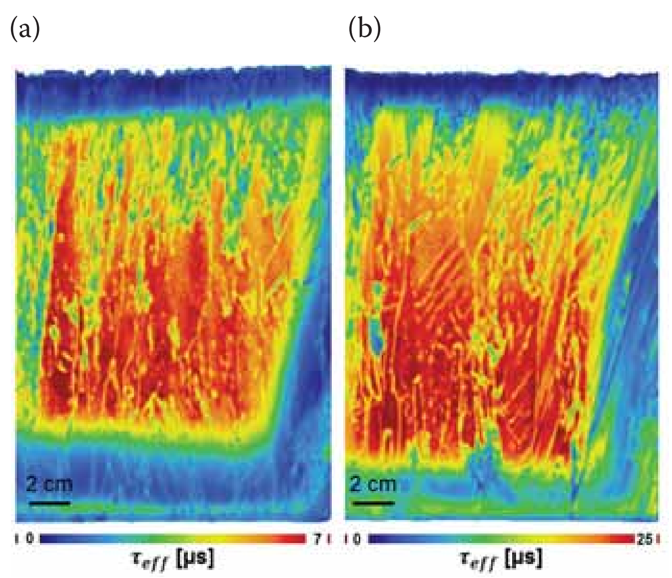


Figure 1. Spatially resolved effective minority-carrier lifetime at the side face of (a) one p-type and (b) one n-type mc-Si edge brick, measured by the MW-PCD technique.

as a possible material for cost-effective high-efficiency cells has gained new momentum.

After a short review of the material-related losses of p- and n-type mc-Si with respect to suitable solar cell concepts, the focus will be on the development of improved ingot-casting processes for n-type mc-Si. The first solar cell results with high-efficiency cell structures on these materials are presented.

Efficiency losses in standard p-type and n-type mc-Si

The production of n-type mc-Si wafers relies on the same basic processes as the ones for p-type material. Ingots can be grown using the same directional solidification techniques as standard material today, but with the use of phosphorus instead of boron as the dopant species. The preparation of bricks out of these ingots, and the subsequent processing steps until the final wafer is created, are identical to the p-type methods. However, a comparison of the material characteristics of p-type and n-type multicrystalline material reveals significant differences.

Fig. 1 shows the distribution of the effective minority-carrier lifetime τ_{eff} measured on the side faces of (a) one p-type and (b) one n-type standard mc-Si edge brick of G2-size ingots grown using the same directional solidification process. The lifetime was measured by a Semilab WT2000D tester using the microwave photoconductance decay (MW-PCD) method at the polished, but otherwise unpassivated, brick sides, with the ingot edge visible on each of the right sides. Despite the strong limitation of the measured effective lifetime by recombination at the brick surfaces, differences in the bulk minority-carrier lifetime between p- and n-type mc-Si are clearly noticeable. The measured lifetime values for the centre part of the n-type ingot are up to a factor of four higher than comparable regions in the p-type ingot (note the different scales for p-type and n-type brick sides); this represents the previously discussed difference in minority-carrier recombination due to introduced impurities. The zone of reduced lifetime at the bottom of the ingot as a result of the in-diffusion of impurities after solidification is smaller for n-type material, albeit the zones near the ingot edge have a comparable width. A closer inspection of these materials reveals that dislocations in the edge region are a significantly limiting factor in the case of the n-type ingot [5].

The resistivity profiles over the ingot height, measured at the ingot centre, show that the resistivity spread for the n-type ingot is greater by a factor of four (Fig. 2). The reason for this is the smaller segregation coefficient of phosphorus (k_0 = 0.35) than that of boron (k_0 = 0.8), which leads to a stronger piling-up of dopants in the liquid phase as the solidification advances from bottom to top.

Whereas lifetime in the as-grown state can yield valuable information (e.g. about the crystallization process), the minority-carrier diffusion length L_D after high-temperature processing [6] is more important for evaluating material quality with respect to final solar cell efficiency. As minority-carrier mobility in p-type silicon is greater than in n-type silicon by a factor of approximately two to three, the minority-carrier lifetime in n-type silicon has to exceed minority-carrier lifetime in p-type silicon by the same factor in order to achieve similar minority-carrier diffusion lengths in both materials. An analysis of the diffusion length images of standard n-type mc-Si wafers after the boron diffusion used for emitter formation on n-type solar cells reveals that very high local diffusion length values of up to 1,400µm can be achieved inside larger grains (Fig. 3). In contrast, large regions of small grains and dislocation

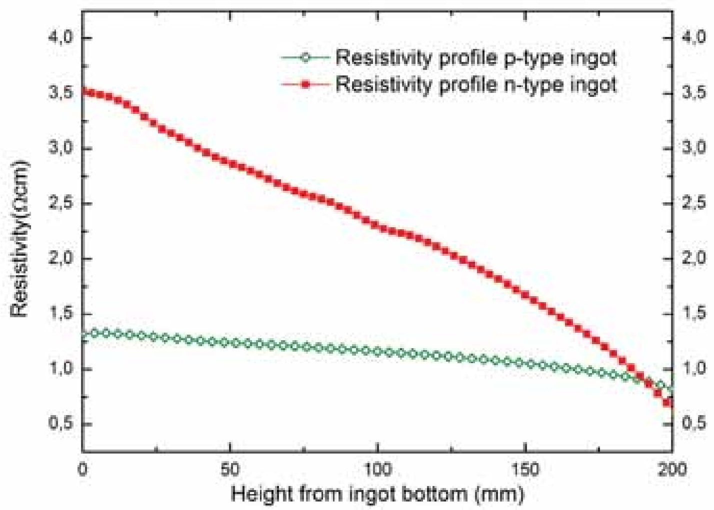


Figure 2. Resistivity profiles of one p-type and one n-type mc-Si brick, measured by the EddyCurrent technique, illustrating the different ranges in resistivity.

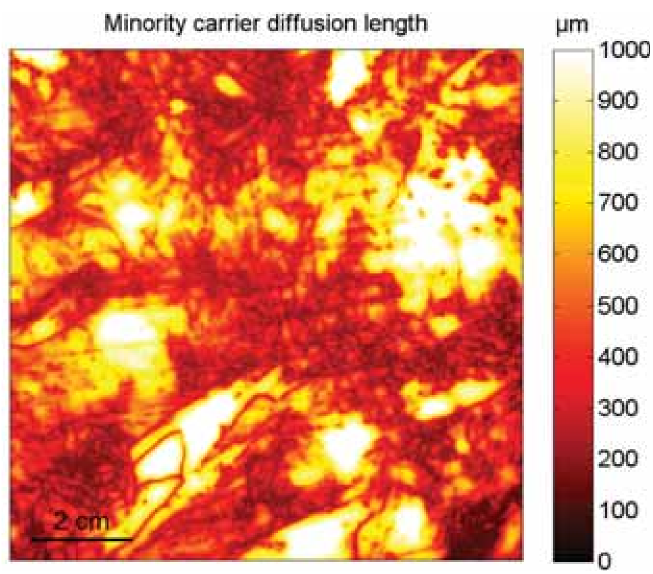


Figure 3. Minority-carrier diffusion length image of a standard n-type mc-Si wafer (10cm × 10cm) after boron diffusion at an irradiation of 0.05 suns, taken by calibrated PL imaging.

networks, visible as dark tangles, show strongly reduced diffusion length values and thus reduced local efficiency in the final solar cell.

A thorough investigation of the efficiency potential of p-type as well as n-type mc-Si materials [2,7] separated the expected material-related losses in high-efficiency cell structures due to homogeneously distributed defects (such as dissolved transition metals) from those due to decorated structural defects (such as dislocation networks and grain boundaries) (Fig. 4). Wafers made from the above-mentioned G2-size p-type and n-type standard mc-Si ingots received typical high-temperature process steps appropriate to the particular cell structure. This treatment ensures that expected changes in material quality during processing due to the gettering effects of impurities during emitter formation and due to impurity dissolution during contact firing are carefully taken into account. The p-type wafers received a phosphorus diffusion by $POCl_3$, as used for emitter formation, with a subsequent firing step; the n-type wafers were treated with a BBr_3 diffusion step without subsequent firing. Further details of the processing and material analysis can be found in Schindler et al. [2,7].

The analysis shows that, in p-type mc-Si material, most of the expected losses in cell efficiency are due to distributed recombination centres, far outweighing the losses due to recombination at decorated structural crystal defects. In the case of the n-type mc-Si wafers analysed, the situation is the opposite, with the recombination at crystal defects being the more pronounced class of defect.

From this investigation it has been concluded that a significant reduction in structural defects should allow the use of n-type mc-Si material for high-efficiency solar cells. Note that the application of a phosphorus diffusion can further reduce the losses in n-type mc-Si [2,7]. A detailed analysis of the limiting material defects, and of the impact of structural defects on carrier lifetime, in n-type multicrystalline silicon can be found in Schön et al. [5].

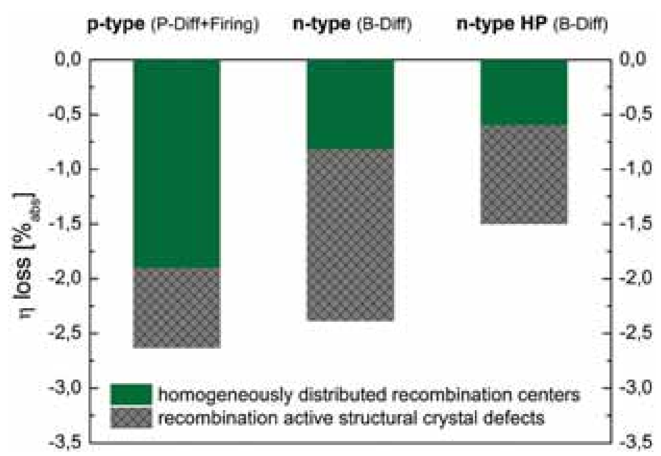


Figure 4. Material-related losses in p- and n-type standard mc-Si wafers from the ingot centre (without edge-region influence) for a high-efficiency cell structure with a cell efficiency limit of 21.8% [2] after typical processing steps. For comparison, the significantly reduced material-related efficiency losses in n-type high-performance (HP) mc-Si for the same cell structure are included in the graph.

Figure 5. Photograph of the cross section of a crystallized G1 ingot with a typical HP mc-Si structure. The unmolten feedstock can be seen at the bottom of the ingot.

> "To reduce the number of structural defects, a crystallization process for high-quality n-type mc-Si was developed using granular silicon as seed material."

Directional solidification of n-type high-performance multicrystalline silicon

In order to reduce the number of structural defects, and especially dislocation networks, a crystallization process for high-quality n-type mc-Si was developed using granular silicon as seed material. For the directional solidification processes, a Multicrystallizer VGF 632 Si furnace by the company PVA Tepla was used. The furnace, initially built for G4-size ingots (equivalent to 250kg of silicon), was retrofitted with a new hot-zone design for the solidification of research ingots of sizes G1 (equivalent to 15kg) and G2 (equivalent to 75kg).

Commercially available high-performance fused silica crucibles of G1 size, with a pre-coated silicon nitride lining, and high-purity polysilicon feedstock were used in all the experiments in this development. In comparison, the standard material discussed in the previous section was solidified in similar fused silica crucibles with a standard quality only. As seed material, silicon granules from a fluidized bed reactor process were placed at the bottom of the crucible prior to filling with polysilicon feedstock. Heavily phosphorus-doped monocrystalline silicon chunks from semiconductor applications served as the dopant material.

During the melting phase, the thermal process is steered in such a way that the feedstock material becomes molten from top to bottom. A small amount of granular material is left unmolten to act as seed material, forming an initial crystal structure with uniformly distributed small grains directly above the seed interface. The grains enlarge with increasing height, as seen in the cross section of a G1 ingot produced by this process (Fig. 5). Multicrystalline silicon material from this type of process has been introduced into the market as high-performance multicrystalline silicon (HP mc-Si) [8].

Because of a mean initial grain size of the order of $1mm^2$, or even less than that, the mechanical stress due to thermal instabilities near the solid–liquid interface can be minimized; the initiation, multiplication and spreading of dislocations is thus diminished. Fig. 6 shows photoluminescence (PL) images of wafers from the upper regions of n-type mc-Si ingots: the image in Fig. 6(a) is of a standard mc-Si edge brick of a G2-size ingot; the one in Fig. 6(b) is of a HP mc-Si centre brick from a G1-size ingot. The grain boundaries are visible as thin black lines against a grey background; dislocation networks or areas with a high density of subgrain boundaries are visible as regions of darker contrast.

In the standard mc-Si wafer (Fig. 6(a)), a large number of dislocations can be found near the ingot edge (left border of the image) as well as in various regions throughout the wafer. A combination of large grains and small grains is typical for this material: the microstructure of the material is therefore very inhomogeneous.

In contrast, the HP material (Fig. 6(b)) has very few regions containing large numbers of subgrain boundaries or dislocation networks. The medium grain size, calculated by image analysis, is enlarged to about $8mm^2$ at this ingot height; thus, the number of structural defects in this material is significantly reduced. The intensity of the background signal inside the grains depends on the intragrain carrier lifetime and on the local dopant density. In order to adjust the target doping concentration, and thus the bulk resistivity, the incorporation of impurities from the crucible system and the furnace atmosphere have to be taken into account.

For n-type material the incorporation of boron, either from the crucible material or via volatile species, could lead to a slight compensation of the free-carrier concentration introduced by the intentional phosphorus doping, thus changing the material resistivity. Variations in the net doping are visible in Fig. 6(b) as larger structures with a slightly higher intensity. This type of structure can be observed in various n-type mc-Si materials, irrespective of the seeding procedure. A spatial analysis of wafers from different ingot heights indicates a connection between this type of structure and the form of the solid–liquid interface. However, the effect of these slight variations on material quality, and thus on solar cell efficiency, seems to be weak.

An evaluation of the efficiency potential of lifetime samples fabricated from this material, analogous to the evaluation of the standard n-type mc-Si samples in the previous section, shows that losses due to recombination-active structural crystal defects could be reduced significantly (see Fig. 4). Thus, reducing the formation of recombination-active structural crystal defects by applying an advanced crystallization process leads to a considerably higher efficiency potential. The use of a higher-purity crucible in this experiment is also reflected in the reduced losses due to homogeneously distributed recombination centres (see Fig. 4). For future development, further optimizations of grain structure and reductions of impurity incorporation should lead to even higher material quality.

Manufacture of high-efficiency TOPCon solar cells

The introduction of the passivated emitter rear cell (PERC) structure to the solar cell market has opened up new efficiency levels for multicrystalline silicon materials. Trina Solar published cell results for their PERC solar cell on p-type HP mc-Si material with a record efficiency of 21.25% [1]. A characteristic feature of this cell architecture is a network of local point contacts at the back side of the solar cell. This poses a possible drawback for multicrystalline material, since the lateral current flow inside the bulk wafer may be hindered by grain boundaries which are typically decorated with impurity atoms and can react as barriers.

In contrast, the structures for high-efficiency cells with a full-area back contact architecture – such as heterojunction cell technology [3] or the recently developed tunnel oxide passivated rear contact (TOPCon) cell [4] – imply a one-dimensional current flow inside the bulk, perpendicular to the wafer surfaces. Since almost all the grain boundaries in HP mc-Si wafers are virtually perpendicular to the wafer surfaces (they have only small angles of tilt), the negative effect of structural bulk defects on the performance of a TOPCon cell should be smaller than in the case of PERC cells. Additionally, the TOPCon cell concept is a suitable candidate for the fabrication of high-efficiency silicon solar cells, as recently shown by Fraunhofer ISE's achieving a record efficiency of 25.1% [1,9].

To investigate the potential of n-type HP mc-Si as a substrate for high-efficiency solar cells, a series of 2cm × 2cm TOPCon cells were processed at Fraunhofer ISE. Wafers with a thickness of 180µm were cut from a G1-size ingot that had been crystallized by the developed HP mc-Si process. After standard wet-chemical texturing, the wafers received a diffused boron emitter on the front side and the TOPCon layer stack on the rear. The metallization scheme included a standard H-shape grid on the front side and a full metallization on the rear. In comparison with the process flow established for monocrystalline silicon, the wet-chemical texturing and the emitter diffusion process via a BBr_3 diffusion were different because of the material characteristics of mc-Si. Finally, the cells received a double-layer anti-reflection coating (DARC) on the front side. (Details can also be found in Schindler et al. [7].)

The cell parameters of the best solar cell are listed in Table 1. An efficiency of 19.6% could be reached, which significantly exceeds previously published values [7,10]. The measured V_{oc} of 663.7mV is suitable for high-efficiency solar cells. The measured J_{sc} of 38.87mA/cm² is of a high level with regard to the standard isotextured front surface. However, because of processing issues during plating, also observed on the float-zone (FZ) reference cells, a low fill factor of only 75.9% limited the overall efficiency.

The map of the short-circuit current density, depicted in Fig. 7, identifies the residual grain boundaries as the principal remaining limitations. The intragrain values for the best solar cell are significantly higher than the average value of $J_{sc,avg}$ = 38.7mA/cm² extracted from a complete cell analysis.

The next development step for adapting the TOPCon approach to n-type HP mc-Si material is an optimization of the boron emitter diffusion in combination with an advanced texturing process; this is expected to significantly increase the overall current density J_{sc}. Additional process steps, such as phosphorus diffusion gettering and adapted hydrogenation for defect passivation, may help to reduce even further the bulk recombination, especially at the grain boundaries, thus reducing the losses directly attributed to the bulk material properties. An optimal implementation of these prospective improvements would result in an overall cell efficiency of the order of 22% [7].

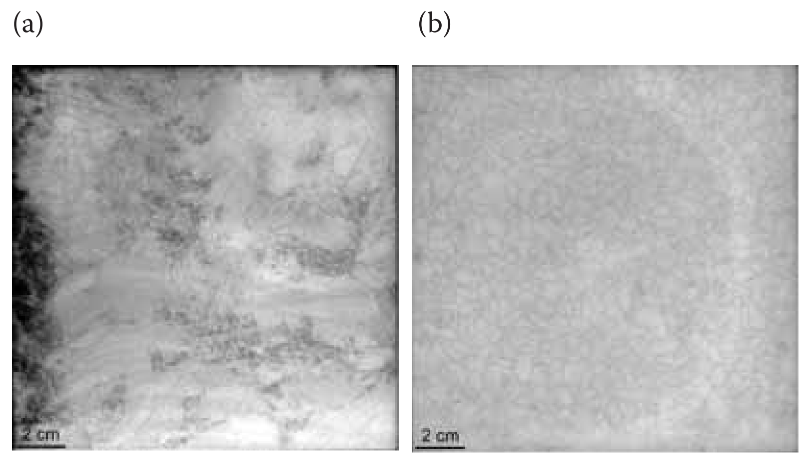


Figure 6. PL image of a wafer from (a) a standard mc-Si edge brick and (b) a HP mc-Si centre brick. The difference in material homogeneity with respect to grain size and the widely differing number of dislocation networks (tangles) are clearly visible.

"The creation of the first solar cells with efficiencies of up to 19.6% corroborates the potential of this new material development for high-efficiency solar cells on multicrystalline silicon wafers."

Conclusion and outlook

On the road to achieving highly efficient solar cells, the development of n-type high-performance multicrystalline silicon has been proved to be a promising option for reducing bulk material limitations for cast silicon ingots. With the use of granular silicon as seed material, n-type multicrystalline wafers with significantly reduced numbers of dislocations and subgrain boundaries can be produced. When an advanced solidification crucible to reduce the incorporation of impurities is employed, high diffusion lengths of up to 1,400µm inside larger grains are achieved. All this, in combination with the discussed TOPCon process, has led to the creation of the first solar cells with efficiencies of up to 19.6%, which corroborates the potential of this new material development for high-efficiency solar cells on multicrystalline silicon wafers.

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Solar cell parameters	Best solar cell (DARC)
V_{oc} [mV]	663.7
J_{sc} [mA/cm^2]	38.87
FF [%]	75.9
η [%]	19.6

Table 1. Solar cell results for the best n-type HP mc-Si TOPCon solar cell [7].

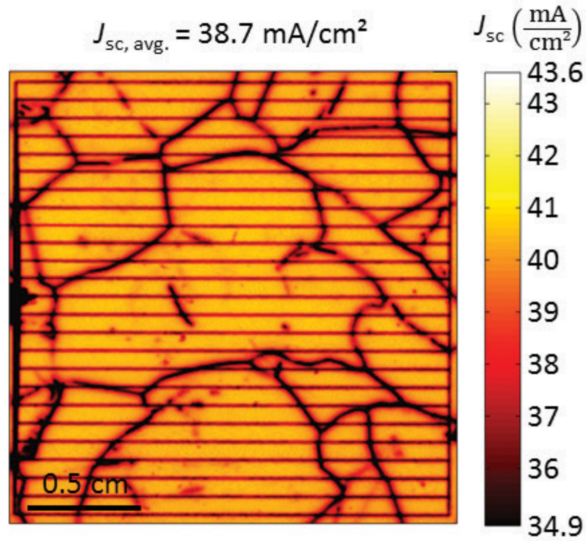

Figure 7. Spatially resolved J_{sc} map of the best solar cell with an average $J_{sc,avg}$ of 38.7mA/cm² [7]. (Source: Schindler et al. [7])

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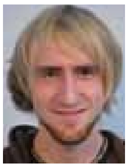
Patricia Krenckel received her Bachelor's and Master's degrees in solid-state and material physics from the University of Göttingen, Germany, in 2010 and 2012 respectively. Currently working on her Ph.D. thesis at Fraunhofer ISE in collaboration with the University of Konstanz, Germany, she is investigating the development of the crystal structure of silicon during ingot casting.



Florian Schindler received his Diploma degree in physics in 2011 from the University of Freiburg, Germany, in collaboration with Fraunhofer ISE. After a period with the Freiburg Materials Research Center FMF, he received his Ph.D. in 2015, again in collaboration with Fraunhofer ISE, from the University of Freiburg. His Ph.D. focused on the electrical material properties and efficiency limits of compensated and multicrystalline silicon. He is currently working as a postdoc in the material and cell analysis group at Fraunhofer ISE.

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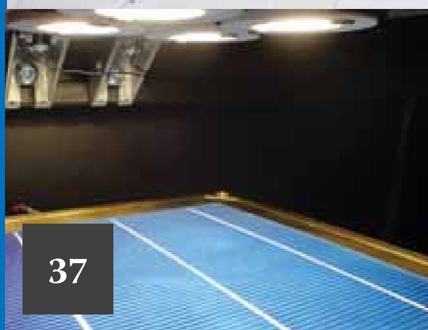
Cell Processing



News

Multi c-Si technology here to stay

Multi c-Si technology has continued to lead volume production in recent years, while providing the lowest cost-per-watt metrics, yet is still able to achieve solar cell conversion efficiencies of 20% plus, according to Pierre Verlinden, CTO of PV module manufacturer, Trina Solar, at the inaugural PV CellTech event in Malaysia in March.

Trina achieved a record maximum cell efficiency (21.25%) for a multi c-Si solar cell in November 2015, adding to a string of records the company made that year and in 2014.

The technology still has a bright future despite some key challenges, Verlinden said. The development and implementation of multi c-Si wafers with significantly reduced dislocations in the substrate would improve conversion efficiency to 21.44%. Reducing iron contamination and deactivation of boron-oxygen (B-O) defects in the wafer (B-O complex), which impact the cell performance, known as light-induced degradation (LID), would boost conversion efficiencies to 21.83%.

Improving the local back surface field of the cell would take efficiencies to 22.33% and passivated contacts could achieve cell efficiencies of more than 22.5%. Coupled to a major reduction in wafer impurities, the solar industry could achieve 0.5% cell efficiency gains for a few more years before saturation occurs.

Credit: Trina Solar

Trina Solar's CTO believes multi c-Si PV technology has a bright future.

Orders

JA Solar places US$18.8 million PERC cell equipment order with Meyer Burger

PV manufacturing equipment supplier Meyer Burger has received a major passivated emitter rear cell (PERC) upgrade order from 'Silicon Module Super League' (SMSL) member JA Solar.

The tool order, valued at over CHF18 million (US$18.8 million), included Meyer Burger's MAiA 2.1 platform for inline PERC cell plasma processes, SiNA PECVD cell coating systems for anti-reflection and passivation layer coating and its DW288 water-based diamond wire cutting technology for monocrystalline wafers.

The JA Solar order equated to total annual output of approximately 1.5GW. Tool delivery and commissioning are expected to occur in the second half of 2016.

JA Solar recently reported that expected full-year 2016 shipments would be in the range of 5.2GW to 5.5GW, including 250MW to 300MW of module shipments to its downstream projects. The company is increasing its manufacturing capacity to match expected demand.

Credit: JA Solar

JA Solar has placed a major order with Meyer Burger for a PERC upgrade.

SoLayTec receives new ALD tool orders for p-type PERC, n-type IBC and bi-facial solar cells

Atomic layer deposition (ALD) equipment specialist SoLayTec has received a number of new tool orders from a range of customers planning p-type PERC, n-type IBC and bi-facial solar cell production in 2016.

Four new customers have placed orders for SoLayTecs's 'InPassion' ALD system, including a new customer based in Taiwan, with shipments expected to start in Q2 2016. Customers of SoLayTec now reside in China, Japan, Europe and Taiwan.

Roger Görtzen, co-founder of SoLayTec and manager of marketing and sales, said: "After several years of having InPassion ALD systems in mass production at multiple customers in China and Japan, SoLayTec is delighted to announce that in the last couple of weeks three orders were received. These machines will be used for production of high efficient solar cell concepts, like p-type PERC, n-type IBC and bi-facial cells."

German PV equipment firms see strong solar cell orders in 2015 - VDMA

Germany-based trade association VDMA Photovoltaic Equipment has said manufacturing equipment orders received by around 100 members increased by 86% in the fourth quarter of 2015, marking a major rebound in purchase orders.

The strong increase in order intake in Q4 2015 followed a 44% increase in the previous quarter driven by planned large-scale capacity expansions not only in Asia but also from the US.

The export quota for German-based PV suppliers was around 85% in 2015, with Southeast Asia accounting for 59% of the exports in fourth quarter of 2015. However, the US accounted for almost 21% of revenue in 2015 for German suppliers, while Europe (excluding Germany) only accounted for 5% of revenue.

Credit: Centrotherm

PV manufacturing equipment orders saw a major rebound at the end of 2015, according to VDMA Photovoltaic Equipment.

Equipment revenue in Germany was said to be around 17% of the total in 2015. Around 52% of revenue came from solar cell related orders, while thin-film accounted for around 21% and module assembly equipment accounted for 14% of sales in 2015.

Cell efficiency

Trina Solar sets 23.5% IBC cell conversion efficiency record for screen printed process

Trina Solar has achieved a new world record for a large-area Interdigitated Back Contact (IBC) solar cell.

Independently confirmed by the Japan Electrical Safety & Environment Technology Laboratories (JET), Trina Solar set the conversion efficiency record at 23.5%, using 156x156mm n-type monocrystalline silicon (c-Si) wafers and a screen-printed process.

Pierre Verlinden, vice-president and chief scientist of Trina Solar, said: "To the best of our knowledge, this is the first time that a mono-crystalline silicon IBC solar cell with an area of 238.6 cm2 exhibits a total-area conversion efficiency of 23.5%."

However, Japan-based Kaneka Corporation is set to present a paper at the 43rd IEEE Photovoltaic Specialists Conference in June, highlighting it has achieved a large-area heterojunction technology-based (HJBC) solar cell with a cell conversion efficiency of 24.5% and a cell of 24.9% that was independently confirmed at AIST.

Imec and Crystal Solar claim milestone in commercialisation of 'Direct Gas to Wafer'

Nano-electronics research center imec and kerfless epitaxial wafer start-up, Crystal Solar, have demonstrated a homojunction solar cell with a record 22.5% conversion efficiency, claimed to pave the way to low-cost solar wafer commercialization.

The potentially disruptive wafer technology was used to fabricate a standard monocrystalline 156x156mm2 cell on 160um to 180um thick grown n-type wafer with built-in rear p+ emitter.

Imec's n-PERT process included a selective front surface field realized by laser doping, advanced emitter surface passivation by Al2O3 and Ni/Cu plated contacts, generating a record high Voc of 700mV, demonstrating the high quality of the 'Direct Gas to Wafer' technology and built-in junction.

The cell efficiency was certified by FhG ISE CalLab. Jozef Szlufcik, PV department director at imec said: "Using these kerfless wafers will be disruptive for the complete solar cell manufacturing value chain."

Copper plated solar cell-to-module reliability tests by imec and BESI exceed expectations

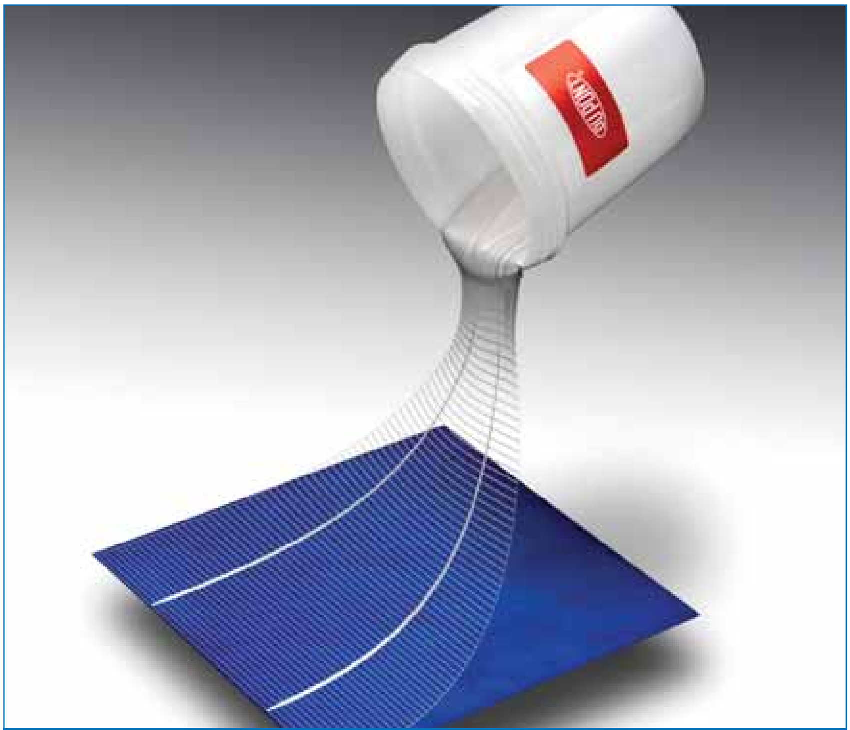
Work carried out by nano-electronic research centre imec and equipment supplier BESI and wholly-owned subsidiary, Meco Equipment Engineers, has shown PV modules featuring copper plated solar cells are highly reliable and outperform IEC61215 life test criteria with only 1% degradation.

The minimal power loss came after a monocrystalline 60-cells Ni/Cu/Ag plated solar module passed 600 thermal cycles (-40°C to +85°C), three times the IEC61215 specification. Specifically, the module consists of 60 front-side laser ablated and Ni-Cu-Ag plated p-type moncrystalline solar cells, using Meco's 'Direct Plating Line' system and annealed in an inline belt furnace.

The copper plated cells were interconnected using a standard solder and lamination process. imec's and Besi's Cu-plated cells and modules outperformed the industrial standard for reliability, which requires less than 5% loss relative to initial power after 200 thermal cycles or 1000 hours of damp-heat testing.

Credit: SolarWorld

SolarWorld is planning to gradually migrate all of its production to PERC and five-busbar technology



Credit: DuPont

DuPont has launched a new metallization paste, Solamet PV19B.

PERC

SolarWorld 'gradually' migrating cell production to PERC and five-busbar technology

High-efficiency products will be the key focus of SolarWorld's expanded manufacturing capacity and technology migrations in 2016.

At the core of SolarWorld's high-tech strategy is migrating all solar cell production to PERC technology and moving from three busbars to five in order to boost conversion efficiencies and limit capital expenditures at the same time.

SolarWorld has upgraded between 800MW to 1GW of conventional Al-BSF production lines to PERC, predominantly monocrystalline, since transferring from its pilot line in 2012.

Migration to PERC on a total nameplate capacity of 1.5GW was in progress, SolarWorld said. Further PERC migration to full production status would be "gradual", notwithstanding that increased production utilization in 2015, due to increased shipments and tight capex control, prevented a more aggressive switch.

SolarWorld's bifacial modules produced for testing in US

PV module manufacturer SolarWorld has started producing its first bifacial Bisun modules at its US manufacturing facility in order to test their capability against standard modules using advanced p-type mono-PERC cell architecture.

The testing will take place on a 205kW solar system at the University of Richmond in Virginia, which will be the first commercial installation of the SolarWorld bifacial Bisun modules.

The Bisun technology is able to generate electricity from direct solar radiation on the front side as well as reflected sunlight on the back side, and these modules can generate up to 25% more energy than standard mono-facial modules. Power generation from bifacial modules also depends on the distance they are installed away from the surface below as well as the reflectivity of that surface. Consequently, the modules will be installed on two roofs – one with gravel and another with a white material thermoplastic olefin (TPO) – to vary conditions in the testing.

Trina Solar starts ramping cell and module production in Thailand

Trina Solar has officially started ramping its solar cell and module assembly plant in Rayong, Thailand, meeting every milestone on schedule, from ground-breaking to production.

Trina's first manufacturing facility outside China was initially announced in May 2015 with 700MW of nameplate solar cell capacity using its 'Honey' multicrystalline PERC solar cell technology and 500MW of PV module capacity.

Financing for the new production plant was facilitated by a consortium of banks led by the Siam Commercial Bank Public Company Limited (SCB), one of the top three domestic banks in Thailand, to the tune of US$143 million, maturing in June 2020.

Jifan Gao, chairman and CEO of Trina Solar said: "The investment in Thailand fits our strategy of prudent capacity expansion in select overseas markets to deliver industry leading products to customers in the US and Europe in particular."

Metallization

DuPont claims cell efficiency benefits from new metallization paste

Materials specialist DuPont Photovoltaic Solutions has launched a new metallization paste.

The company's new 'Solamet PV19B' is claimed to offer a multitude of benefits, including higher PV cell efficiencies and better throughput speeds.

Chuck Xu, global business director, DuPont Photovoltaic Solutions, said: "We are excited to announce the launch of DuPont Solamet PV19B, which can enable more than 0.1% cell efficiency improvement over other products currently used in the industry. We are committed to optimising solar power output and long-term reliability through material science."

As well as higher cell efficiencies, by virtue of its paste transfer attributes, the new product allowed higher print speeds and thus improved average throughput rates – by as much as 26%.

ASM AE wins solar cell metallization business from Risen Energy

PV screen printing equipment supplier ASM Alternative Energy (ASM AE) has secured a repeat order from China-based PV manufacturer Risen Energy.

ASM AE said the order was for its 'Eclipse' metallization tool as part of a solar cell capacity expansion at Risen Energy's Ningbo, Zhejiang Province, China headquarters.

Brian Lau, ASM AE's vice president of business development, said: "Risen has high expectations for ASM AE's platforms, with exceptional throughput capability and extreme accuracy as priorities. Customers like this only serve to make our team and our products better, and our long partnership with Risen is evidence of ASM AE's ability to consistently deliver on their tough requirements."

Risen Energy placed a 950MW automated module assembly line order with Suzhou Horad New Energy Equipment Co last November and plans to take capacity of solar cells and modules to 2.5GW.

Multicrystalline PERC solar cells: Is light-induced degradation challenging the efficiency gain of rear passivation?

Tabea Luka, **Christian Hagendorf** & **Marko Turek**, Fraunhofer Center for Silicon Photovoltaics CSP, Halle (Saale), Germany

ABSTRACT

The passivated emitter and rear cell (PERC) process has been successfully transferred to mass production, with the market share of multicrystalline (mc) silicon being around 50%. This new technology can, however, lead to severe reliability issues despite the higher initial solar cell efficiencies. In particular, light-induced degradation (LID) of mc-PERC solar cells has been reported to cause efficiency losses of up to $10\%_{rel}$. This highlights the importance of understanding different types of LID and of testing the stability of solar cells under actual operating conditions.

Introduction: PERC technology enters mass production

The passivated emitter and rear cell (PERC) is one cell technology upgrade option that has been the focus of many research and development activities during the last few years. Crystalline silicon solar cells with a passivated rear side have successfully entered mass production and are expected to seize a significant share of the different cell technologies in the near future [1]. Cells of this type yield about $5\%_{rel}$ more power than conventional aluminium back-surface field (Al-BSF) cells [1]; this can be attributed to reduced electrical recombination and improved optical properties.

Solar cell efficiencies of more than 22% using PERC technology on monocrystalline Si material were publicly announced by Trina Solar and SolarWorld in December 2015 and January 2016 respectively. The world record for a multicrystalline cell, with an efficiency exceeding 21%, has also been achieved using the PERC technology and was presented by Trina Solar at the recent SiliconPV conference in Chambéry [2].

The upgrading of a solar cell production line to PERC technology is a rather evolutionary step, since a large part of the existing manufacturing equipment can be used for PERC production as well. Major cell producers – such as SolarWorld, Hanwha Q CELLS, Trina Solar, Jinko Solar and JA Solar among others – have already begun to operate PERC production lines, or have made announcements that they will start to do so, leading to a large number of commercially available PV modules based on PERC technology.

The International Technology Roadmap for Photovoltaic [1] predicts that "PERC cells will gain significant market share over BSF cells", reaching a share of about 35% in 2019. Although the share of multicrystalline silicon solar cells is predicted to decrease, this type of material is expected to dominate the market over monocrystalline silicon solar cells for at least the next five to ten years [1].

"mc-PERC solar cells can exhibit significantly stronger power degradations during the first few days of operation than Al-BSF cells."

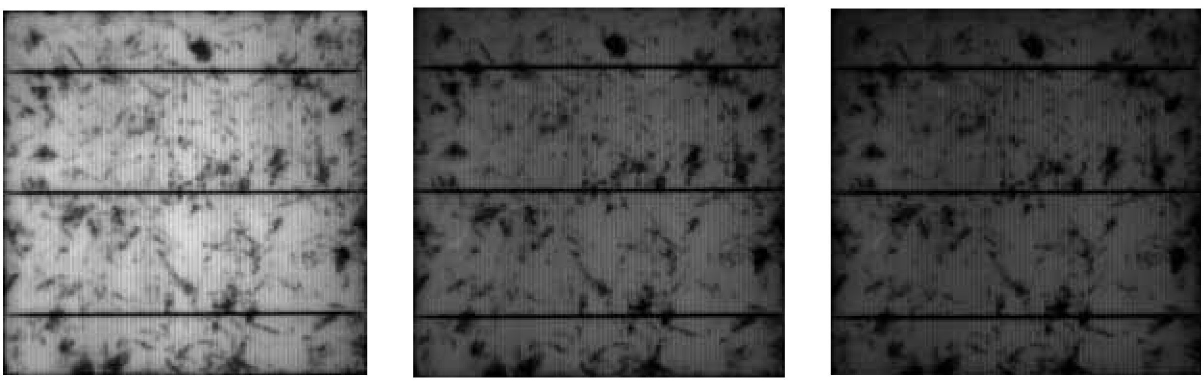


Figure 1. Photoluminescence images (with the same scaling) of an mc-PERC solar cell, initially and after 20 and 30 minutes of a one-sun illumination at an elevated temperature of 95°C.

Degradation of solar cells: PERC technology upgrade brings with it new challenges

While the introduction of the PERC technology leads to a significant increase in cell power, some unexpected challenges concerning cell performance in a normal operational environment have become apparent. Already in 2012 it was reported by Ramspeck et al. [3] that multicrystalline PERC (mc-PERC) solar cells can exhibit significantly stronger power degradations during the first few days of operation than Al-BSF cells produced from the same material.

The phenomenon of illumination leading to the degradation of a solar cell is not a new discovery and has been the topic of investigation for more than 40 years. It was observed that a shift in the Fermi level induced by the increase in excess carrier concentration can cause cell degradation because of the different chemical processes within the solar cell. Since the increase in excess carrier concentration is related to the incident irradiation, this process is generally termed *light-induced degradation (LID)*. However, the same effect is brought about by inducing a current in an unilluminated solar cell, which also causes an increase in excess carrier concentration.

The two best-known mechanisms are the activation of boron–oxygen (B–O) complexes and the dissociation of iron–boron (FeB) pairs. Furthermore, LID has been detected on chromium- and copper-contaminated samples [4–6]. Recently, two additional degradation mechanisms – which differ in their appearance from the well-studied degradation mechanisms – have been described: 1) *mc-PERC LID* [3] (also named *light-and-elevated-temperature-induced degradation LeTID* [7]); and 2) *sponge LID* [8]. The lifetime degradation is reflected by a reduction in the photoluminescence signal, as presented in Fig. 1.

Boron–oxygen complex activation (B–O LID)

The boron–oxygen complex is an extensively studied cause of LID, which in such cases is referred to as *B–O LID*. The efficiency loss depends on the oxygen and boron concentration in the wafer; thus, monocrystalline Czochralski silicon is the worst affected, because of the high oxygen concentration (up to 10^{18} atoms/cm^3). Multicrystalline silicon, on the other hand, is much less affected, because lower oxygen concentrations can be achieved. The defect can be avoided altogether by using an alternative dopant, such as gallium, or by using n-type material.

The activation of boron–oxygen complexes occurs within the first few hours of illumination. The activated defects can be transformed into a stable and recombination-inactive state by illuminating the samples at an elevated temperature; this process is called *regeneration* [9–11]. A quantitative model describing the physical and chemical processes during the degradation and regeneration was recently published [12]. Further, it was shown systematically, by comparing light- and electrical-induced degradation, that B–O LID can be traced back to the carrier injection induced by light rather than to other light-induced effects [13]. The first industrial tools, namely regeneration furnaces, are available for performing the regeneration.

Iron–boron pair dissociation (FeB LID)

Another degradation mechanism is related to the iron–boron dissociation, namely *FeB LID.* In the dark, positively charged iron atoms link to the negatively charged boron atoms as a result of Coulomb interaction. These complexes have shallow energy levels and do not reduce the cell efficiency. The shift in the Fermi level under illumination causes a neutralization of the iron ions, which consequently separate from the boron atoms. Interstitial iron causes a much higher charge carrier recombination under solar cell operating conditions. As a consequence, the dissociation of iron–boron pairs results in a severe efficiency loss in cells with a high iron concentration. As in the case of B–O LID, this degradation effect is well understood [14,15].

mc-PERC LID

In 2012 a new LID mechanism – *mc-PERC LID* – was described by Ramspeck et al. [3]. This type of degradation occurs on p-type mc-Si solar cells, though it is more pronounced on PERC cells than on standard Al-BSF cells. The degradation can lead to an efficiency loss of more than 10%$_{rel}$, as seen in Fig. 2; however, in contrast to the other mechanisms described above, it occurs only at elevated temperatures, in particular above 50°C. Hanwha Q CELLS has therefore suggested a new name for this – *light-and-elevated-temperature-induced degradation (LeTID)* [7].

mc-PERC LID differs from B–O LID and FeB LID by the higher temperature that is necessary for inducing the degradation and the much longer timescales over which the degradation occurs. Compared with B–O LID and FeB LID, a complete degradation of mc-PERC cells is observed only after several hundred hours, even at elevated temperatures of between 50 and 95°C [7]. Furthermore, it has been shown that this degradation demonstrates no correlation with the concentration

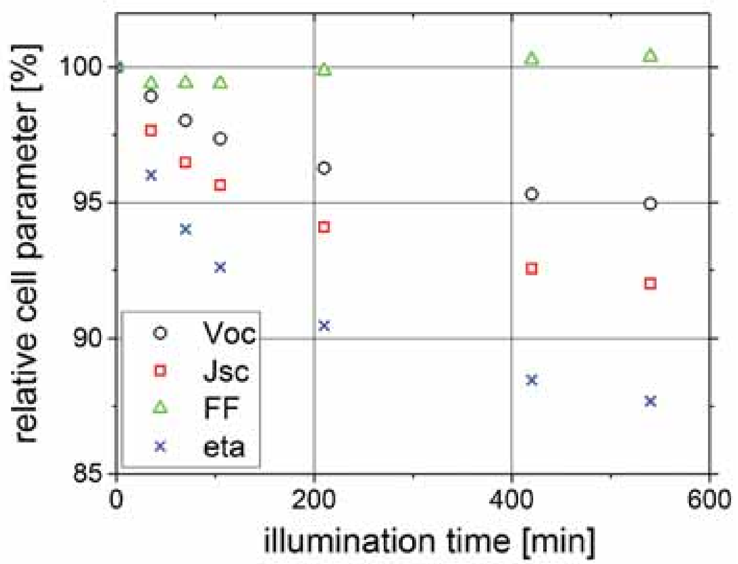


Figure 2. Typical degradation of mc-PERC solar cell parameters under a one-sun illumination and a temperature of 75°C.

of oxygen [7], and that Ga-doped Si degrades in a similar manner [3].

Following a complete mc-PERC LID cycle, the efficiency increases again, an effect referred to as *regeneration* [7]. This is similar to what is known in the case of B–O LID, since the regeneration occurs by carrier injection at elevated temperatures and thus at the same operating conditions as for mc-PERC LID [7]. Similarly to the degradation, the timescale for the regeneration is much longer than that of B–O regeneration, which makes an industrial implementation that matches the process times more challenging. A better understanding of the physical processes involved would support such an industrial implementation. What causes this mc-PERC LID and the corresponding regeneration, however, is still an open question.

Sponge LID

Sponge LID is a new form of light-induced degradation recently published by Hanwha Q CELLS [8]. This form of degradation cannot be explained by the mechanisms described above. It occurs on high-performance multi material – a new wafer type with small grains, but only a few dislocations, which yields an efficiency gain of about 2.5%$_{rel}$ [8]. It has been shown that only the lower part (i.e. up to 20–30%) of the ingot is affected by sponge LID, inducing an efficiency loss of up to 10%$_{rel}$. Hanwha Q CELLS has reported the development of an adapted cell process which leads to solar cells that are stable with regard to sponge LID [8]. Nevertheless, an understanding of the physics of the degradation has not yet been acquired, and the degradation process is still under investigation.

LID testing and standards

Since light-induced degradation phenomena affect the efficiency of PV modules during their entire lifetime, the quantification of LID is an important task for yield simulations and of great significance for the cost-effectiveness of PV systems. The initial degradation of solar panels is generally tested during certification in accordance with the IEC 61215 standard [16,17]. To pass qualification, PV modules must demonstrate less than 5% degradation after each test, and, for a full sequence, less than 8%. However, a degradation of 5% would already have a drastic impact on the levelized cost of electricity (LCOE).

Elaborate standards at the module level, with regard to preconditioning and testing conditions, are therefore required in order to generate reliable and comparable values for the quality evaluation of PERC solar modules. The various types of LID effect in high-efficiency solar cells, together with their different material- and solar cell process-induced origins, require well-defined test recipes for temperature, irradiation and electrical operating conditions. An implementation of test set-ups, procedures and standards already at the cell level opens up the possibility of quantitatively evaluating LID sensitivity at its origin – the solar cell. This provides quick access to LID quality control at an early stage of the production chain.

In the literature a number of test set-ups based on sunlight, halogen or Xe lamps are described [16]. Fig. 3 presents Fraunhofer CSP's dedicated test set-up, which allows a comprehensive and quantitative LID reliability test to be performed already at the mini-module or solar cell level. The LED-based solar cell LID tester can be used to transfer the IEC standard module test conditions to solar cell testing [17]; it comprises an LED-based illumination source, a solar cell temperature control unit, and a chuck for electrical measurement and conditioning purposes [18].

The individual definitions of temperature, illumination and cell voltage for the degradation and measurement sequences address the specific LID phenomena described earlier, ranging from B–O LID and FeB LID to mc-PERC LID and sponge LID. The implementation of LEDs with specific wavelengths can increase the sensitivity of the test significantly. The basic measurement principle corresponds to a rapid quantum efficiency test as implemented on LED solar simulators [19]. Compared with a standard quantum efficiency test, only a few wavelengths are used, which reduces the measurement time to less than half a second. Furthermore, the heat impact on the cell is reduced by using light in a well-defined wavelength range, making the temperature control more reliable. Additionally, a test set-up using electrical carrier injection and temperature control for the evaluation of accelerated degradation and regeneration processes was developed, allowing an investigation

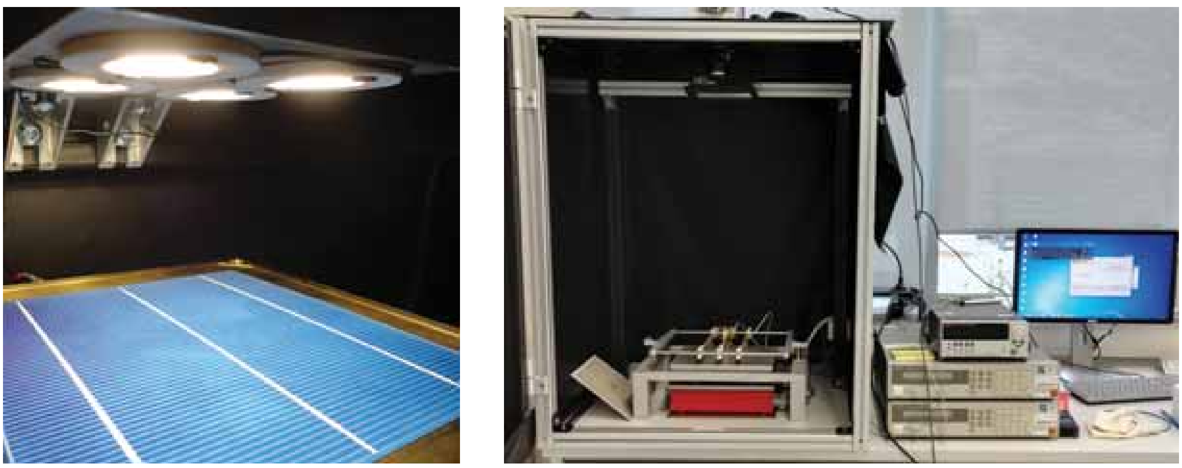


Figure 3. Test set-up of an LED-based light-induced (left) and electrical-induced (right) solar cell LID tester.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and optimization of the corresponding process parameters.

A deep understanding of LID phenomena and the underlying root causes will help to make LID testing of solar cells more comparable to module LID testing. LID metrology tools will help to track down the root causes of material-induced LID along the value chain. Using LED technologies, the monitoring of the affected parts of the solar cell (front or back), as well as crucial processing steps for LID stabilization, can be easily carried out. LID tests at the solar cell level are important for guaranteeing solar cell quality at an early stage of production, as well as for incoming quality control in module production.

Dealing with the root cause of mc-PERC LID

It is necessary to gain a deep understanding of the underlying degradation mechanisms in order to guarantee stable performance of multicrystalline solar cells in a PV module. The physical mechanism causing mc-PERC LID due to light and elevated temperature is not yet completely understood and is currently under investigation. The publicly funded SolarLIFE project [20] is a framework within which some of the major German research institutes work on this task alongside industry partners. The aim of the project is to study the causes of solar cell degradation on medium-to-long timescales; material bulk effects as well as instabilities of the interfaces are also investigated.

Some important results relating to mc-PERC-LID have already been published and are briefly summarized below.

Influence of external parameters on degradation

The mc-PERC LID phenomenon is influenced by temperature, excess carrier concentration, and degradation time. Ramspeck et al. [3] showed that a temperature above 50°C is required in order to observe the entire degradation in under 400 hours, and that the degradation is significantly accelerated when moving up to higher temperatures. The excess carrier concentration is determined by the illumination and operating point of the solar cell (e.g. short circuit, maximal power point or open circuit). A change in the operating mode when switching from open circuit to short circuit can slow down the degradation by a factor of ten, as shown by Kersten et al. [7]. This slower degradation is due to a lower carrier injection in the short-circuit mode.

Without changing the operating conditions (i.e. the carrier injection and temperature), the regeneration process of the mc-PERC LID defects sets in following the degradation [7], in a similar way to that observed for the boron–oxygen complex. The recombination-inactive complexes formed during regeneration are stable, and no further degradation is detected [7].

> "The solar cell process itself, particularly the firing step and the passivation process, also has a significant effect on the degradation."

Impact of cell-specific features on degradation

Even if solar cells are subject to the same external influences, the degradation might appear very different; the reason for this can be the material, the cell process or the pretreatment of the solar cell. Until now, mc-PERC LID has been detected only on multicrystalline samples [3,21,22], which indicates that the silicon material with its specific contaminations has an influence on the degradation. Kersten et al. [7] also detected differences in the degradation after 24 hours of illumination when cells from different regions of the ingot were investigated.

The solar cell process itself, particularly the firing step and the passivation process, also has a significant effect on the degradation. It can be assumed that the hydrogen content within the bulk silicon material induced by the SiN passivation layers plays a role in both degradation and regeneration. Bredemeier et al. [23] showed that a SiN passivated silicon wafer (lifetime sample) fired at lower temperatures exhibits less pronounced lifetime degradation, a behaviour which has also been detected in solar cells [24].

Localization and root-cause analysis of the defect

For a physical understanding of the mc-PERC LID defect, it is necessary to analyse the solar cell in greater detail and investigate the differences in affected and unaffected regions of mc-PERC LID. This can be done using microstructural analysis, which requires the localization of the defects within the wafer or solar cell.

The localization of the degradation source was performed with a focus on both lateral and horizontal inhomogeneities. It was shown that the main component of mc-PERC LID is a reduction in bulk carrier lifetime, indicating the formation of a defect inside the silicon wafer material during degradation. In contrast, the front and rear sides appear to remain stable under degradation conditions [25]; this is reflected in a loss analysis (see

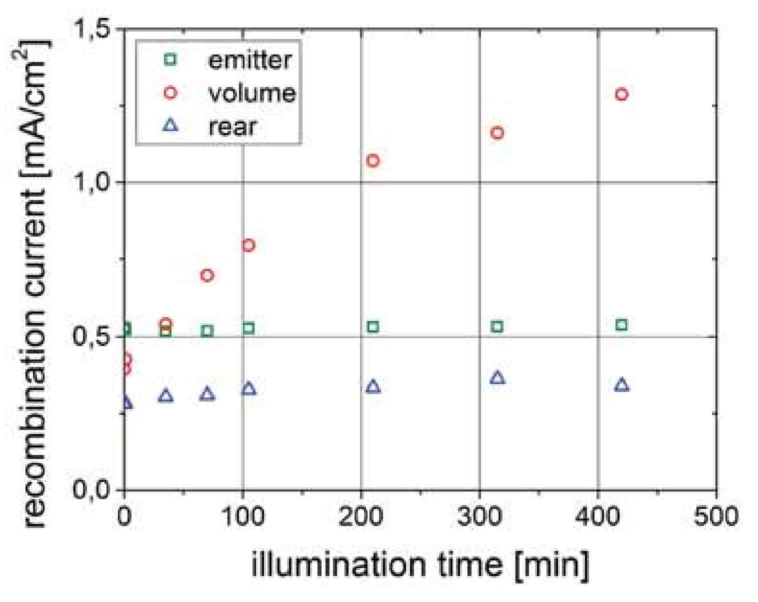

Figure 4. Solar cell loss analysis, showing the impact of mc-PERC LID on recombination currents caused by emitter, cell volume and rear-surface recombination.

Fig. 4) based on quantum efficiency measurements.

Concurrent investigations of lifetime samples and solar cells on a micrometre scale were carried out at Fraunhofer CSP. It was found that the degradation occurs fairly homogeneously over the entire cell area, as seen earlier in Fig. 1. The appearance of localized shunts could be excluded as a source of the degradation. In a cell, variations in degradation are related to structural differences, as grain boundaries and rear contacts show less-pronounced degradation [22,25,26], whereas inside the grains, the degradation does not differ significantly. Differences in the degradation of solar cells on macroscopic lengths scales can be attributed to variations in the cell process, such as temperature variations between the outer and inner regions of a cell [24]. On wafers prepared as lifetime samples, lateral differences in the degradation between individual grains have been detected [22].

Defect model

On the basis of these results, the first defect models have been developed for mc-PERC LID [23,26]: the experimental results show a pronounced mc-PERC LID, which appears homogeneously in intra-grain regions and twin boundaries. The major contribution to the degradation is a change in the bulk material, whereas the surfaces are fairly stable. Compared with the intra-grain regions, a reduction in mc-PERC LID is found at undecorated grain boundaries, independently of the grain boundary type and orientation. Decorated grain boundaries and defect clusters are dominated by other recombination mechanisms and are thus below the detection limit for mc-PERC LID. These results point towards a defect model in which the mc-PERC LID defect is related to an atomic point defect dissolved in the undisturbed crystal structure.

At undecorated grain boundaries, the chemical process leading to the recombination-active defects is inhibited by the large number of structural defects [26]. Bredemeier et al. proposed that the high-temperature firing step dissolves metal precipitates into mobile metal atoms, which are captured by another homogeneously distributed impurity. The complex thus formed, which is relatively recombination inactive, separates under illumination at elevated temperatures, leading to a recombination-active isolated metal defect. A subsequent diffusion of the metal atoms to the surface and to other crystallographic defects has been proposed as the physical mechanism leading to regeneration [23]. A complete and detailed physical understanding has not yet been established, however, and further investigation is necessary.

Implications for PV module operation

The sensitivity of mc-PERC LID has been tested in laboratories under elevated temperatures above 50°C. The degradation is still relevant in the case of module operation, since solar cells inside a PV module can easily reach temperatures of around 50°C and higher. For example, in central Germany the cells inside a module operate at temperatures above 50°C on average, for about 70 hours each year; the temperature peaks at about 62°C. Even higher cell temperatures occur when modules are operated in hot climates, such as desert regions. Thus, losses detected at the cell level can be directly translated into expected yield losses during module operation.

Module degradation in the field, however, takes longer than in accelerated laboratory testing, since the temperatures are typically lower. Kersten et al. [7] predicted that the degradation is complete after 10 years for a rooftop installation in Germany. Regeneration will not become established until after 20 years of module operation under the same conditions. Thus, the regeneration does not proceed fast enough to have a positive impact on the total power output under typical module operating conditions, and the modules remain in the degraded state for many years. Different technological solutions to prevent mc-PERC LID therefore need to be established in order to guarantee a high-efficiency module based on mc-PERC solar cells.

Adapted PERC process

There are different strategies under discussion for avoiding mc-PERC LID at the cell level. First, the solar cell process itself can be adapted to yield LID-insensitive cells. Several solar cell producers and suppliers of production equipment have announced that they are able to produce mc-PERC solar cells resistant to PERC LID [7,25]. While the process details have not been disclosed, the results presented above indicate that the firing step or the SiN layer deposition may play an important role.

Second, additional stabilization processes which lead to stable regenerated cells could be employed. Here, a strongly accelerated degradation and regeneration cycle would have to be performed after cell production in order to transform the cells into a recombination-inactive and stable state before their application in the field. This can be done either by strong illumination or by inducing large currents at high temperatures.

Finally, research activities are focusing on the identification of the contaminations that are relevant to mc-PERC LID. This might eventually lead to an optimized crystallization process which avoids LID issues at the cell level. At Fraunhofer CSP, researchers are working on each of these approaches to prevent LID, by developing a better understanding of the processes involved and by optimizing the relevant solar cell process steps as well as subsequent stabilization processes. Either approach has to be accompanied by a dedicated quality-control process which quantitatively assesses mc-PERC LID.

"Dedicated tests regarding mc-PERC LID at the solar cell level are essential for reliable quality control."

Conclusions

LID is not just a concern with monocrystalline silicon solar cells: this type of degradation has once more entered the spotlight with the introduction of mc-PERC solar cells into mass production. The particular LID mechanism that mainly affects mc-PERC cells can lead to severe power losses of more than $10\%_{rel}$, and is strongly accelerated by the elevated temperatures which can occur under typical module operating conditions.

Some solar cell producers have already addressed the degradation issue, announcing that the solar cell production process can be adapted in such a way that mc-PERC LID is avoided. However, small changes to the solar cell process, such as modified process temperatures or different wafer materials, can lead to substantial performance losses in the PV module as a result of mc-PERC LID. Since the physical and chemical root cause of the cell degradation is not yet fully understood, dedicated tests regarding mc-PERC LID at the solar cell level are essential for reliable quality control.

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LPCVD polysilicon passivating contacts for crystalline silicon solar cells

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ABSTRACT

Contact recombination has long been identified as one of the key challenges for achieving high efficiency of crystalline silicon (c-Si) solar cells. As well as having the ability to extract majority carriers effectively, a contact to a solar cell should ideally be passivating. The combination of a thin oxide and doped polysilicon to obtain low recombination junctions was demonstrated in the 1980s to be a viable candidate for creating passivating contacts to c-Si solar cells. In recent years variations and innovations of this technology have seen intense development and rapid progress towards demonstrating very high (25%) cell efficiencies. This paper presents the progress made by ECN and Tempress in developing and integrating the processing of polysilicon passivating contacts aimed at use in low-cost industrial cell production. The polysilicon is deposited by low-pressure chemical vapour deposition (LPCVD), and the results are presented for in situ as well as ex situ doping processes. Synergy and compatibility with industrial cell processing is demonstrated – for example, the application of hydrogenation from silicon nitride coating layers, and metallization by screen-printed fire-through paste. This demonstrates the potential application of polysilicon passivating contacts to a variety of cell designs in production in the near future. The way in which the passivating and contact properties depend on the layer parameters and subsequent cell processes is analysed and explained. Results are presented for 6" screen-printed bifacial n-type cells with a diffused boron emitter and an n-type polysilicon (n-poly) back contact, with an efficiency of 20.7%, as an industrially relevant application of the polysilicon technology. Ways to improve cell efficiency to > 22% are indicated.

Introduction to passivating contacts

Good contacts to solar cells should extract one type of charge carrier and have low series resistance, while avoiding recombination of the other type of charge carrier. In industrially produced silicon solar cells, contacts are mostly created by heavily doping the surfaces of the silicon wafer; this allows good Schottky contact to a metal electrode for the majority carriers, while at the same time reducing the minority-carrier density and therefore the minority-carrier recombination at the interface of the silicon with the metal electrode.

“Good contacts to solar cells should extract one type of charge carrier and have low series resistance, while avoiding recombination of the other type of charge carrier.”

Alternatives to these diffused junctions that are directly contacted by metal have been described and investigated for many years. One such option is *passivating contacts* (the original terminology ‘passivat*ed* contacts’ seems to have now become superseded by ‘passivat*ing* contacts’). Reviews of the need for and potential benefit of passivating contacts, along with several approaches for creating them, were given by Green in 1995 [1] and Swanson in 2005 [2]. Swanson noted that the most ambitious target level could be given by the radiative limit of the silicon bulk – recombination current density J_0 = 0.27fA/cm^2. A (non-exhaustive) list of the most frequently reported approaches is given in Table 1 (see reviews in, e.g., Young et al. [3], Melskens et al. [4], Cuevas et al. [5]; also several materials are evaluated in Feldmann et al. [6]).

For crystalline silicon solar cells, a passivating but conductive interface, combined with an electrode with a low or high work function in order to properly align the conduction or valence band respectively, has been explored [3–6] (if the passivating interface is omitted, J_0 usually increases noticeably). To create electrodes with suitable band alignment to the silicon, heavily doped silicon can be employed. An advantage of this approach is the existence of feasible and widely known techniques for creating a low-recombination interface between the silicon wafer and a deposited doped silicon layer. Sanyo (later Panasonic) pioneered the development, as well as the application with very high performance, of amorphous silicon heterojunctions [7], where the passivating interface is a very

Passivating interface	Contact material	Reference
Intrinsic a-Si:H	Doped a-Si:H	[7]
SiO_x	Doped a-Si:H	[8]
Intrinsic a-Si:H	Set WF (e.g. TCO)	[9]
SiO_x	Set WF (e.g. TCO)	[3–6]
SiO_x	Highly doped polysilicon	†

† See the various references given in the present paper.

Table 1. The main published approaches for creating passivating contacts. In addition to SiO_x, other thin dielectric interfaces, such as Al_2O_3, are being explored. (‘Set WF’ denotes materials with a well-defined suitable work function in order to align to the conduction or valence band in the silicon; TCO = transparent conductive oxide.)

thin intrinsic amorphous silicon layer, and the carrier selective layer is doped amorphous silicon. Others (e.g. Heng et al. [8]) combine a thin oxide instead as the passivating interface with the doped amorphous silicon. Heterojunctions offer the additional advantage that a minority-carrier band offset enhances the so-called *minority-carrier mirror* effect. SunPower has reported that its Generation 3 interdigitated back-contact (IBC) cells use passivating contacts, but has not given any technical details [10].

Recently, much attention and effort has been directed at the use of doped polycrystalline silicon (polysilicon), in combination with a passivating interface based on a thin oxide. This paper will describe ECN/Tempress's progress and cell development results regarding such polysilicon passivating contacts. Specifically, the polysilicon is deposited by low pressure chemical vapour deposition (LPCVD).

The combination of a thin oxide (SiO_x) and doped polysilicon to obtain low recombination junctions originated in microelectronics, in work on bipolar transistors (see, e.g., Ashburn & Soerowirdjo [11]). This was demonstrated in the 1980s to be a viable candidate for creating passivating contacts on crystalline silicon (c-Si) solar cells [12,13]. The technology appears to have been dormant for many years, at least in terms of the number of published research results. In 2008 Borden et al. [14] published results of polysilicon passivating contacts (or, as they called them, *polysilicon tunnel junctions*) produced by microelectronics processing techniques. Then, in 2014, Feldmann et al. [15] published results for polysilicon passivating contacts produced by a high-temperature anneal of a doped thin amorphous silicon layer deposited by plasma-enhanced chemical vapour deposition (PECVD) on a thin oxide, resulting in a structure called *tunnel oxide passivated contact (TOPCon).*

The polysilicon passivating contact

Fig. 1 shows a schematic of the structure of a polysilicon passivating contact. A key element is the thin oxide layer, which has a reasonably low interface recombination velocity (S_i), supported by a hydrogenation step. This thin oxide layer serves not only for passivation but also as a tuneable diffusion barrier, which is indispensable for keeping most of the dopant within the polysilicon layer, thus avoiding the creation of a typical diffused junction with disadvantageous Auger recombination in the wafer. The doped polysilicon layer, as a result of the induced field effect, reduces minority-carrier density in the wafer at the interface with the polysilicon, while providing good conductance for the majority carriers to the contacts applied to the polysilicon. With regard to passivation quality, there is no fundamental need for the thickness of the polysilicon to be much greater than the Debye length (only a few nanometres in highly doped silicon).

The interfacial thin oxide, in combination with the low minority-carrier density at the interface, results in a low transmission of minority carriers through the interface, thereby assuring minimal recombination in the polysilicon and at the metal contact. Together with the low-level penetration of dopants in the wafer, the result is excellent passivation. The oxide/polysilicon stacks can be contacted by metal, with (in practice) no indication that this increases the recombination of minority carriers generated in the c-Si wafer.

Example model results of the J_0 dependence on the interface recombination velocity and polysilicon doping level are given in Fig. 1(b). The model used is only approximate and is intended for illustration. Model studies have shown that an interface recombination velocity S_i of less than ~10^3–10^4cm/s [16,17] is sufficient for excellent passivation.

The thin oxide will in practice reduce not only minority-carrier transmission but also majority-carrier transmission. Nevertheless, sufficiently low contact resistances have been reported [15,18,19,20] by direct measurement, and have also been demonstrated by the high fill factors (FFs), in solar cells. Defects (pinholes) in the thin oxide can play an important role in determining the transmission of majority and minority carriers into the polysilicon, and can be more important than tunnelling. Furthermore, a small leakage of dopants through the thin oxide appears to be helpful in reducing series resistance [16] and improving passivation [21]. Römer et al. [18] applied a rather thick thermal oxide (>20Å thickness); this was subjected

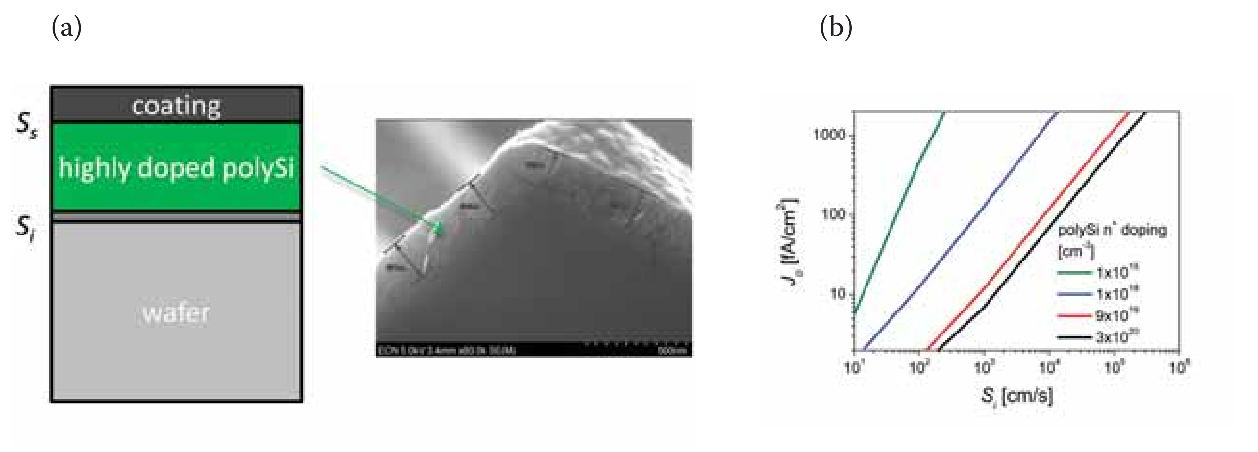

Figure 1. (a) Schematic of the structure of a polysilicon passivating contact. A stack of a thin dielectric (hashed) and doped polysilicon is grown on a silicon wafer. The polysilicon may be coated with metal (for contacting) or a dielectric (for anti-reflection coating, or hydrogenation). The interface recombination velocity S_i is low; the surface recombination velocity S_s does not affect the contact passivating properties and may be high. On the right is an SEM image of one of ECN/Tempress's polysilicon stacks on a textured wafer. (b) Modelled J_0 from PC1D as a function of the phosphorus-dopant concentration in the polysilicon. In the model the effect of the very small transmission of minority carriers into the polysilicon has been replaced by a very low S_s, to render negligible any recombination in or on the polysilicon.

to a high-temperature treatment above 1000°C, which probably decreased the resistance (created pinholes in the oxide).

In ECN/Tempress's results, even when a thin oxide (nominally 13Å thick) is used and 900°C is not exceeded in the process, the contact resistances in the cells, measured by TLM, appear to be inconsistent with a tunnelling model for carrier transport. For simultaneously processed p-type polysilicon (p-poly) contacts and overcompensated n-type polysilicon (n-poly) contacts, with identical oxide, polysilicon deposition and thermal budget, ECN/Tempress found a specific contact resistance ρ_{co} of polysilicon to wafer of about 30mΩ·cm^2 for n-type and 5mΩ·cm^2 for p-type polysilicon [22], with J_0 below 10fA/cm^2 and ~50fA/cm^2 respectively (the p-type J_0 value is quite high, presumably as a result of the low boron doping concentration of 3×10^{19}cm^{-3}, and because of a textured surface). If tunnelling were dominant, a higher ρ_{co} would be observed for p-type polysilicon than for n-type [23]. Recently, Yan et al. [24] also reported a low ρ_{co} for p-type polysilicon.

The excellent low J_0 values of polysilicon passivating contacts are hard to beat by traditional dielectric-passivated diffusions. But conventional high-performance contacts based on local diffusion with metal point contacts can also yield low contact recombination at the cell level, through reducing the contact area. The ratios of specific contact resistance ρ_{co} and J_0 of the metal and the polysilicon are not more favourable for polysilicon: polysilicon combines a J_0 of a few fA/cm^2 with a ρ_{co} of ~10mΩ·cm^2, while diffused metal contacted regions can have a J_0 that is ~100 times higher, but also a very low ρ_{co}, which allows their area to be reduced by a similar factor. However, for metal point contacts, a negative side effect is spreading resistance, which reduces the FF (see, e.g., Glunz et al. [25]). Aspects of the trade-off between area fraction, J_0 and ρ_{co} have been illustrated in detail by other authors [26,27].

"The excellent low J_0 values of polysilicon passivating contacts are hard to beat by traditional dielectric-passivated diffusions."

To summarize, the attractiveness of polysilicon passivating contacts derives from being able to:

- achieve an excellent J_0;
- avoid Auger recombination from heavily diffused areas in the wafer;
- avoid process complexity and the spreading-resistance effect related to metal point contacts.

Industrial LPCVD of polysilicon passivating contacts

This section will focus on ECN/Tempress's studies of n-type polysilicon passivated contacts. Polysilicon layers grown in a high-throughput LPCVD furnace are employed. An LPCVD process has the advantage of creating very conformal and pinhole-free layers; this ensures that the underlying interfacial oxide is protected against subsequent doping steps and chemical treatments. For mass production, batches of up to a few hundred wafers can be processed, with excellent process uniformity [28].

The thin oxide was produced by thermal oxidation (Th.Ox.) or wet-chemical oxidation (NAOS: nitric acid oxidation of silicon). A reliable absolute thickness measurement is not straightforward; in this work the thickness was estimated by spectroscopic ellipsometry on mirror-polished wafers, with the resulting typical values of 13 to 15Å corresponding to good performance. A high repeatability and tuning of this thickness at the 1Å level is possible. A slightly greater thickness can result in a noticeably reduced FF, whereas a slightly smaller thickness can lead to increased dopant diffusion into the wafer. Of course, this depends on the precise doping processes and thermal budgets, as well as on other process parameters [18,20]. Excellent contact resistance and passivation have been obtained with these thin oxides.

The main focus was on n-type polysilicon, where the LPCVD layer is intrinsic, and subsequently doped by $POCl_3$ diffusion [28,29] (Fig. 2): this results in fast deposition, a tuneable doping level, low diffusion into the wafer, and excellent J_0. In situ p-type doped polysilicon for cell processing has also been investigated [28,30]. Alternatively, in situ doping during LPCVD to create n-type polysilicon, and BBr_3 doping of intrinsic polysilicon to create p-type polysilicon, are in principle also possible [18,31]. However, in situ phosphorus doping during LPCVD has been reported to reduce deposition speed [32], and BBr_3 doping of an oxide/polysilicon stack can cause damage to the thin oxide and

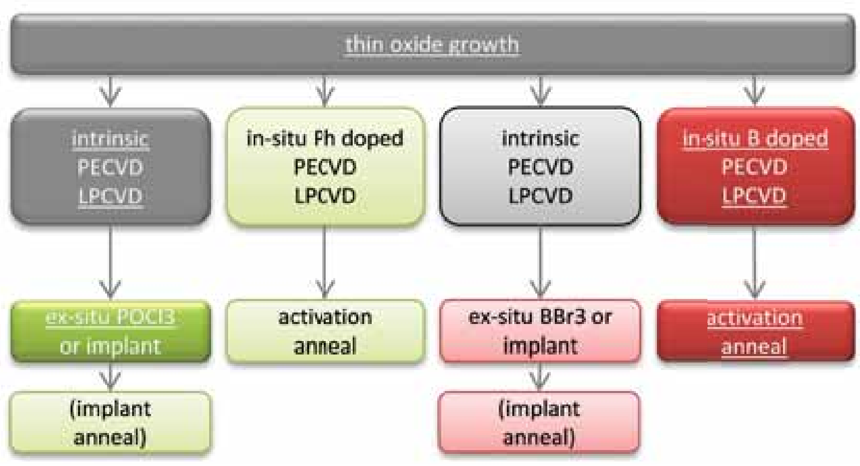

Figure 2. Examples of deposition and doping methods used in creating an n-type or p-type polysilicon passivating contact. (The approaches reported in this paper are underlined.)

thereby result in too much diffusion into the wafer [28].

The application to industrial cell processing is an important aspect, so with this in mind the following were used:

- Hydrogenation from SiN_x:H coating layers deposited by PECVD.
- Contacting of the polysilicon by fire-through screen-printed metallization, without adding significant contact recombination.

In other reported studies hydrogenation is often carried out by an extra processing step, such as a forming-gas anneal, but hydrogenation from SiN_x:H eliminates the need for this. The second point, contacting by screen-printed metallization, has the potential benefit for industrial application of the passivating contact as basically a drop-in replacement for a diffused back-surface field (BSF). With a screen-printed metallization grid, an additional advantage is that a bifacial cell is possible. In view of the use of fire-through metallization, relatively thick layers of polysilicon have so far been investigated.

n-type polysilicon

Fig. 3 shows active phosphorus concentration profiles, measured by electrochemical capacitance–voltage profiling (ECV), in polysilicon layers with thicknesses of 70 and 200nm. The intrinsic polysilicon layers were doped by $POCl_3$ diffusion at three different temperatures. It is noticeable that the thin oxide can be an excellent diffusion barrier. However, a high diffusion temperature together with the use of NAOS oxide resulted in significant diffusion into the wafer. The corresponding R_{sheet} values are also indicated on the graphs. In the results obtained here, the mobility is at best around one-half to one-third of that in monocrystalline silicon, and it can be enhanced somewhat by hydrogenation.

The polysilicon layers in Fig. 3 showed a strong correlation between the sheet resistance and the diffusion temperature. This indicates that the mobility heavily depends on the diffusion temperatures, which is perhaps related to continued crystallization of the polysilicon during the diffusion. After exposure to the lowest diffusion temperatures, the apparent mobility is much lower (approximately one-tenth) than that for monocrystalline silicon.

Fig. 3 also presents the evolution of the recombination parameter J_0 through subsequent processing steps of PECVD SiN_x:H deposition, firing and SiN_x:H removal. An average J_0 per side of less than 10fA/cm^2 was already achieved without a particular hydrogenation step. A rough correlation between the initial J_0 values and the doping levels and leakage can be observed. The higher initial J_0 of the 200nm-thick layers with high R_{sheet} is probably due, at least partly, to the lower doping level, which increases sensitivity to the defects at the interface. For the 70nm layers with Th.Ox., the doping level and J_0 are in the same range as that for the most heavily doped 200nm layer. In the case of the 70nm polysilicon/NAOS stacks, the initial J_0 is probably dominated by the effects of phosphorus leakage through the oxide. After $POCl_3$ diffusion at the highest temperature (72Ω/sq.), the high J_0, probably due to Auger recombination or increased interface defect density, renders the J_0 unsuitable for practical applications.

Improved J_0 values were observed after PECVD SiN_x:H deposition, in particular for the 200nm n-type polysilicon layers with a low doping level. The benefit of SiN_x:H deposition is attributed to the hydrogenation of the SiO_x/wafer interface. The firing of the SiN_x:H layer did not significantly change J_0. Likewise, the removal of the SiN_x layer by wet-chemical etching did not change J_0, as expected, since this etching step should not change the hydrogen passivation of defects at the SiO_x/wafer interface, which is protected by the polysilicon top

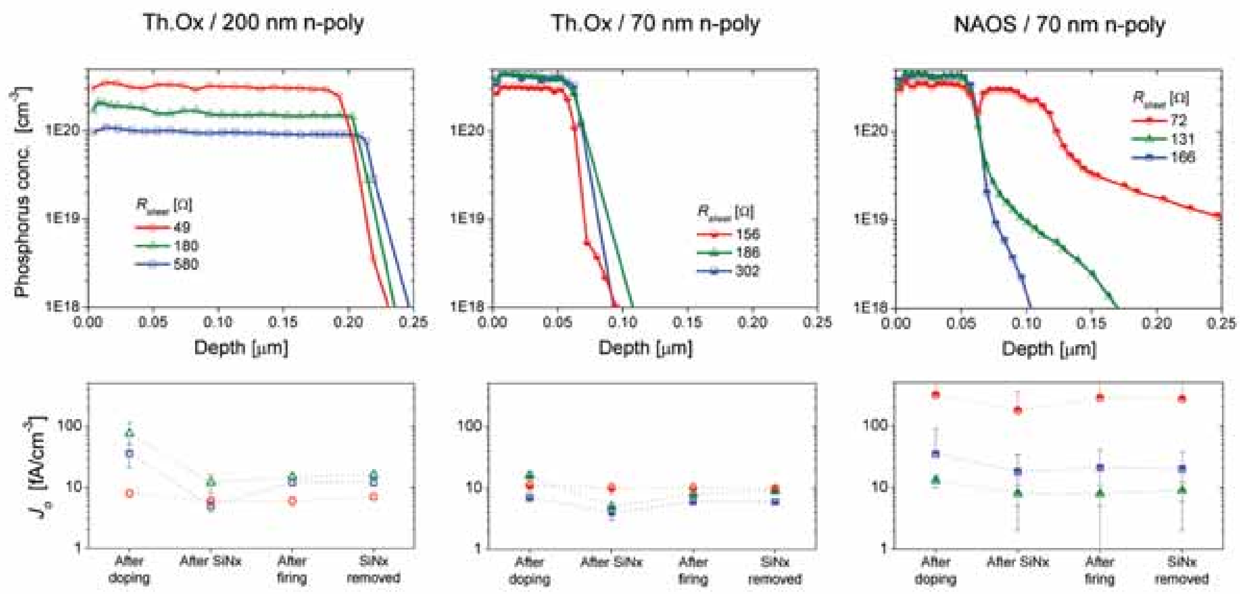

Figure 3. Phosphorus-doping profiles (top row) of several n-type polysilicon/SiO_x/Cz-Si stacks, with the corresponding R_{sheet} values, on polished Czochralski (Cz) wafers. Three different $POCl_3$ diffusion temperatures (the same for all stacks) were used for doping, with high to low temperatures corresponding to low to high R_{sheet} values. Evolution of the surface passivation quality (bottom row), through a sequence of process steps. All J_0 values are per side, and are the average of up to 15 points on three wafers, where the error bars depict standard deviations. J_0 was derived from lifetime measurements using the Sinton WCT-120 tool.

layer. A forthcoming publication [33] will report in detail the polysilicon hydrogenation processes.

Fig. 4 shows the evolution of average J_0, in this case for textured wafers; importantly, it includes fire-through contact metallization. Although the initial J_0 for textured surfaces is larger than for polished surfaces by more than the surface area ratio, after PECVD SiN_x:H deposition the J_0 values are comparable. After the fire-through of a metal contact grid, some degradation of J_0 occurred, the extent of which depends on firing parameters and paste.

p-type polysilicon

Fig. 5 shows the results for p-type polysilicon. In order to properly carry out the boron doping of the polysilicon ex situ, one needs a considerably higher thermal budget than that for n-type doping. This, combined with the fact that silicon oxide is a much worse diffusion barrier for boron, makes the fabrication of a p-type doped polysilicon passivated contact by BBr_3 diffusion much more difficult. Tempress has developed in situ boron-doped polysilicon growth in an industrial LPCVD furnace. An optimization of hardware and growth process results in a uniformly doped polysilicon. A mild anneal temperature can be used to activate the dopant, thus avoiding damage to the underlying interfacial oxide.

The p-type polysilicon is more dependent on surface properties and hydrogenation than n-type polysilicon. An excellent J_0 of 21fA/cm^2 can be obtained on a polished surface after hydrogenation by PECVD SiN_x:H, which is reduced to 12fA/cm^2 by the firing. The p-type polysilicon on a textured surface demonstrated significantly higher J_0. It should be pointed out that the boron concentration of 3–4×10^{19}cm^{-3} achieved so far is lower than that of a typical industrial BBr_3-diffused emitter. It is expected that increases in the polysilicon doping level will lead to an enhancement of the surface passivation and to a reduction in J_0, especially for textured surfaces.

Interestingly, these p-type polysilicon layers can be compensated to n-type by either ion implantation or $POCl_3$ diffusion, resulting in values of J_0 and implied open-circuit voltage iV_{oc} as good as those for non-compensated n-poly (Wu et al. [30], and similar work reported earlier by Reichel et al. [34] and Römer et al. [35]).

Table 2 shows a summary of the best passivation characteristics measured for the samples in Figs. 3–5. For industrially suitable processes, these are already very useful improvements over diffused junctions, even before contact metallization. It is noted that even lower J_0 values, of less than 1fA/cm^2, have been reported in

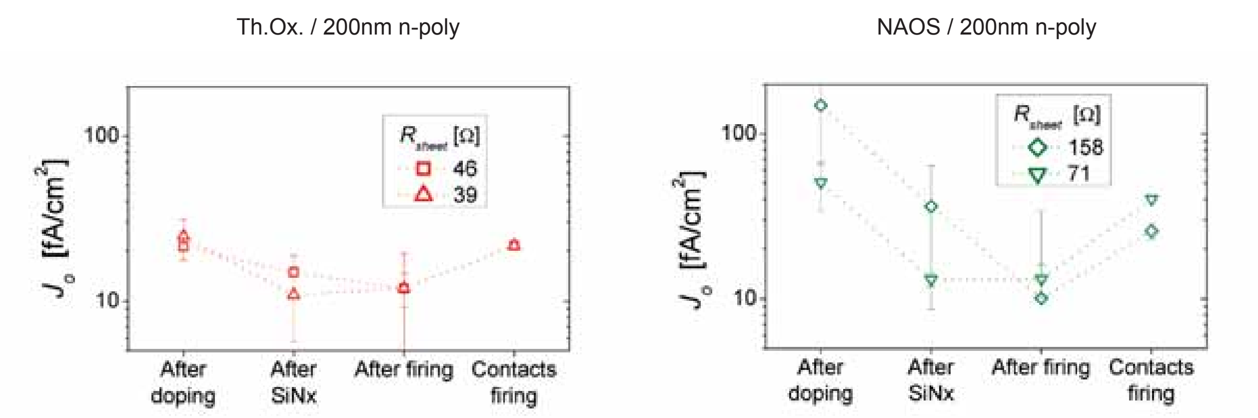

Figure 4. Evolution of J_0 through the process steps relevant to cell production, for textured wafers with 200nm n-type polysilicon, over several test runs. The highest diffusion temperature in Fig. 3 was used for Th.Ox., and the middle temperature for NAOS.

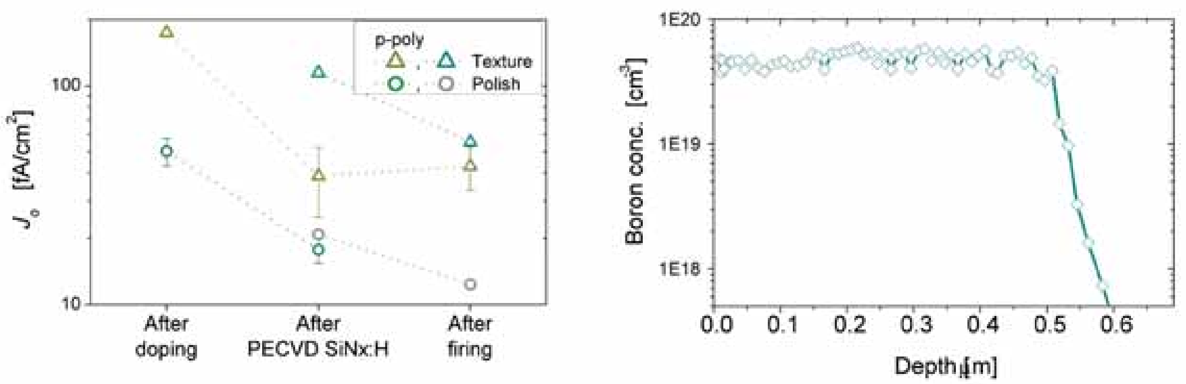

Figure 5. Development of average J_o with SiN_x deposition and firing over several test runs, and ECV doping profile of in situ doped p-type polysilicon/SiO_x passivating contacts.

the literature for n-type polysilicon passivated contacts on polished surfaces [36]. For textured Cz wafers, the recombination currents of ~4.2fA/cm^2 (Table 2) achieved in this study for n-poly are, to the authors' knowledge, the lowest reported to date.

	iV_{oc} [mV]	J_0 [fA/cm^2]	Lifetime [ms @Δn=10^{15}cm^{-3}]
Wafer surface = polished			
n-type, after doping	~731	~3.4	~5.0
n-type, after SiN_x	~743	~2.2	~6.6
n-type, after SiN_x and firing	~734	~5.2	~9.4
p-type, after SiN_x and firing	~715	~12	~1.6
Wafer surface = textured			
n-type, after SiN_x and firing	~732	~4.2	~6.2
p-type, after SiN_x and firing	~682	~55	~0.7

Table 2. Best passivation characteristics of polysilicon passivating contacts on PV-grade Cz wafers obtained in this study. ('Lifetime' = effective minority-carrier recombination lifetime; iV_{oc} = implied V_{oc} determined using a Sinton WCT-120; phosphorus-doping level = ~3×10^{20}cm^{-3}; boron doping level = ~4×10^{19}cm^{-3}.)

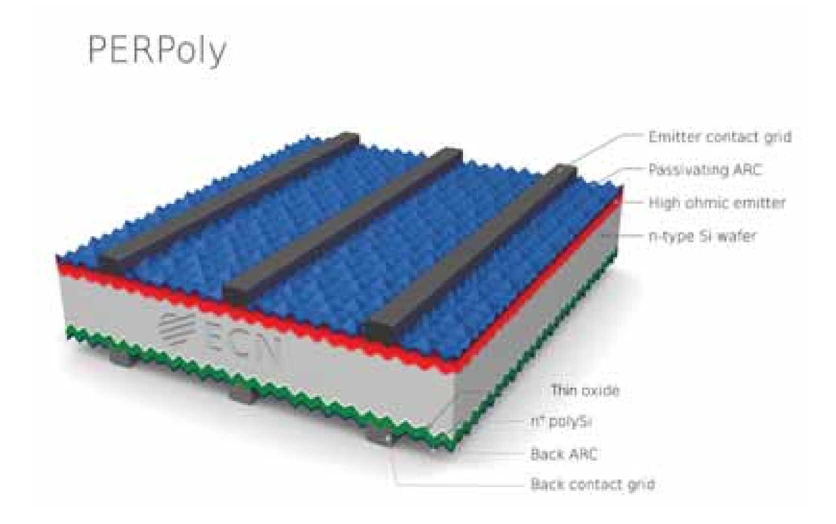

Figure 6. Schematic of the bifacial n-type solar cell design discussed in this paper – PERPoly (passivated emitter and rear polysilicon). The cell features an n-type polysilicon/SiO_x back contact.

Application to industrial bifacial n-type cells

Various c-Si cell design variations making use of polysilicon passivating contacts are conceivable, using the polysilicon for one or both of the contact polarities. A uniform polysilicon layer can be used at the rear of a cell as the emitter or base contact. Here the results for an n-type cell with a front diffused boron emitter and an n-type polysilicon back contact (Fig. 6) will be elaborated on. This kind of cell with an n-type polysilicon back contact has been widely investigated in recent years, but what differentiates ECN/Tempress's development is the use of a bifacial metallization with fire-through paste, and the full 6" cell size combined with an LPCVD process.

Table 3 lists the status of n-type cells with a front boron emitter and a polysilicon back contact that have been reported in the literature. The designation *PERPoly* (passivated emitter and rear polysilicon) is proposed for the cell design with a polysilicon back contact, in line with the PERT, PERC and PERL acronyms.

ECN/Tempress's n-type cell process on industry-standard 6" Cz wafers has been developed using only the tools currently available to the industry. A diffused boron emitter is used, in order to remain close to ECN/Tempress's industrial n-PERT process. A diffused boron emitter can yield very high performance (low J_0), and is therefore a good match for a high-performance back passivating contact.

The PERPoly cell process is expected to be feasible using a comparable number of process tools to that required for PERC cells, although at the moment some more-elaborate chemistry is still used. A BBr_3-diffused industrial-type uniform emitter with a sheet resistance of 70Ω/sq. was employed on the front side. The emitter was passivated with Al_2O_3 deposited by atomic layer deposition (ALD), and coated with PECVD SiN_x:H; the rear-side polysilicon was also coated with SiN_x:H. Fig. 7 shows that iV_{oc} before metallization is approximately 700mV and fairly uniform over the wafer. In recent tests using a higher emitter sheet resistance, the iV_{oc} was increased to slightly more than 700mV, and the total J_0 was reduced to less than 45fA/cm^2.

Poly deposition	Poly doping	Back contact	Emitter	Front contact	Size [cm^2]	η [%]	Ref.
PECVD	In situ	Ag PVD	BBr_3, SE	Litho/PVD/plate	4	25.1	[25]
PECVD <20nm	In situ	Ag PVD	Implant	Screen print	239	21.2	[37]
LPCVD 40nm	In situ	Ag PVD	Implant	Screen print	132	20.9	[38]
PECVD 50nm	In situ	Al PVD	BBr_3	Not specified	4	20	[39]
PECVD 32nm	$POCl_3$	Al PVD	BBr_3	Litho/PVD	4	20.8	[20]
LPCVD 200nm	$POCl_3$	Screen print	BBr_3	Screen print	239	20.7	[29]

Table 3. Status of front- and back-contact cells with polysilicon passivating contacts.

In the cell process tests, only the 200nm-thickness polysilicon has been employed so far. The front and back metal grids were screen printed using fire-through pastes and co-fired.

"The PERPoly cell process is expected to be feasible using a comparable number of process tools to that required for PERC cells."

Table 4 presents an overview of the best I–V results for the bifacial cells. A best cell efficiency of 20.72% (spectral-mismatch-corrected, FhG ISE-calibrated n-PERT reference cell, AAA Wacom system, in house) was obtained, with a V_{oc} of 675mV. The cell efficiency distribution over the six cells of the best group, with a back contact of NAOS/n-poly, was an average of 20.67% with a standard deviation of 0.05%. The main loss mechanisms will be briefly described in the following sections.

Diffused emitter and contact recombination

An analysis and comparison of the half-fabs and cells shows that V_{oc} is mainly limited because of the diffused boron emitter and contact at the front side. This is not surprising, as the rear J_0 is only ~10% of the front emitter J_0, and, after contacting, the difference will be even greater.

The bulk lifetime of the cell half-fabs before metallization is about ~3ms on average, and the total J_0 close to 60fA/cm^2; together this results in an average iV_{oc} of ~693mV. After contact firing, the cell V_{oc} decreases to 675mV. The effect of the fire-through grid, with metallization coverage of around 10%, on the J_0 of the n-poly back contact was estimated on the basis of Fig. 4 to be ~13fA/cm^2; the front contact grid is known to contribute about 60fA/cm^2, because of a specific J_0 of 2,500fA/cm^2 for the fire-through metallization. This results in the breakdown of recombination currents shown in Table 5.

Current loss and bifaciality

In addition to the usual reflection losses, some of the loss in J_{sc} is due to free-carrier absorption (FCA), and

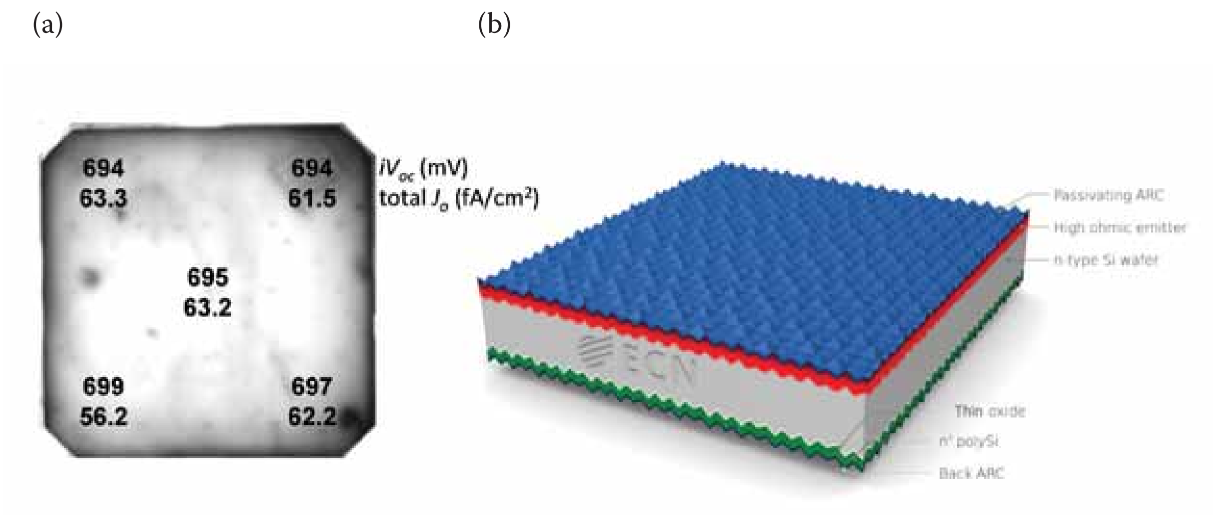

Figure 7. (a) Photoluminescence image of the solar cell half-fabricate (half-fab), with iV_{oc} and J_0 obtained at five locations. (b) Structure of the half-fab. R_{sheet} of the 200nm-thick n-poly is approximately 70Ω.

	J_0 n-poly* [fA/cm^2]	J_0 F+B half-fab* [fA/cm^2]	Bulk lifetime [ms]	iV_{oc} half-fab* [mV]	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	pFF [%]	η [%]
Group ave. (6 cells)					674	38.8	79.1		20.67
Best cell	7.7	56.2	6.68	699	675	38.8	79.1	82.8	20.72
Best cell rear response					669	31.3	79.6		16.66

* Best spot

Table 4. Results for the PERPoly cells of ECN/Tempress (this study). Both cell sides were textured. Polysilicon thickness was 200nm. The best cell results are shown, as well as the best J_0, iV_{oc} and bulk lifetime obtained on half-fabs. J_0 F+B is the J_0 of the front and back sides together. The rear metallization coverage is approximately 10%.

Back n-poly	Back contact	Emitter	Emitter contact	Bulk	Total
7	13	50	60	8	138

Table 5. Estimated distribution of the recombination losses (in fA/cm2) of the cells listed in Table 4.

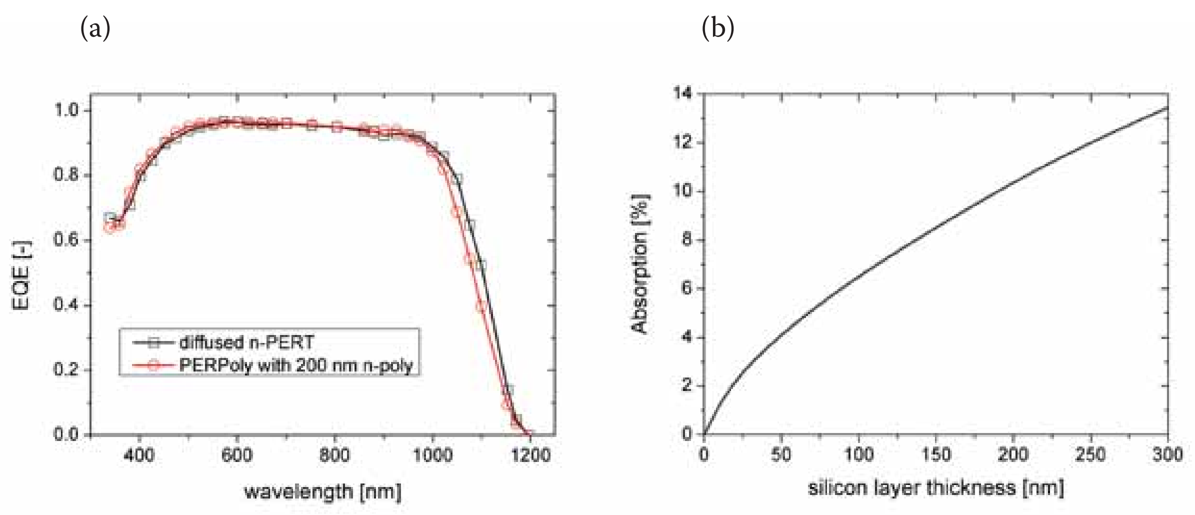

Figure 8. (a) EQE of a PERPoly cell compared with an n-PERT cell, showing in particular the difference due to FCA in the range from 1000 to 1200nm. (b) The absorption of AM1.5 spectrum in thin crystalline silicon as an approximation of the loss in a polysilicon layer when used at the light-incident side of a solar cell.

absorption with carrier generation in the polysilicon. Since the n-poly back contact is quite heavily doped to a low sheet resistance, the FCA is significant compared with bifacial n-PERT cells with a diffused BSF, as visible in the external quantum efficiency (EQE) plots in Fig. 8. The total FCA in the n-poly was evaluated by ray tracing analysis to be approximately 0.9mA/cm^2 for a thickness of 200nm and a phosphorus-doping level of 3×10^{20}cm^{-3}. This FCA can be significantly reduced by decreasing the polysilicon thickness or doping level, if the contact metallization allows. However, because of the reduced carrier mobility in the polysilicon, the FCA in a bifacial design with polysilicon will probably always be somewhat higher than in a corresponding bifacial design with a diffused BSF.

The PERPoly cells have around 80–85% bifacial performance (with rear full-area 200nm-thick n-poly; ~50Ω/sq.), which is ~10% less than for equivalent n-PERT cells with a diffused BSF. This extra 10% loss is in agreement with the estimated absorption of short-wavelength photons in the polysilicon, approximated by the absorption of regular crystalline silicon (see Fig. 8(b)).

Resistive loss

The FF of the PERPoly cells is similar to the typical FF of equivalent n-PERT cells with a diffused BSF, and it seems that there is no significant series resistance (not more than about 0.1Ω·cm^2) in the polysilicon/oxide/wafer junction. This is in agreement with the TLM measurements described earlier.

Outlook

On the basis of the experimental results obtained, a qualitative description of the key features of the polysilicon passivating contact can be given. The thin interfacial oxide layer needs to be sufficiently thin to not limit the transmission of the majority carriers (allowing high FF); however, it should be dense enough to serve as a diffusion barrier, so that most of the doping is contained in the polysilicon layer. Slight dopant in-diffusion into the c-Si wafer is not harmful for the passivation properties, and can be additionally beneficial for the transport of the majority carriers.

The polysilicon layer needs to be sufficiently highly doped to allow adequate lateral transport for the application of bifacial grid metallization and also for the field effect passivation. The polysilicon must be of adequate thickness in order to block any penetration by the fire-through paste into the thin oxide interface. In this study the 200nm polysilicon thickness did not completely avoid contact recombination, but it is expected that, after optimization, the results will be improved and will allow thinner polysilicon as well. The thinner and more lightly doped the polysilicon is, the lower the parasitic absorption losses will be.

It has been observed that, particularly for textured samples, the hydrogenation of the interface defects is very important, and that PECVD SiN_x:H is a very effective hydrogenation source for this purpose.

Fig. 9 presents a roadmap towards achieving 22% efficiency using industrial process equipment and materials. First, the parasitic absorption in polysilicon needs to be reduced by making the layer thinner or by using lighter doping. Second, the total J_0 can be further reduced to 50fA/cm^2 by implementing a higher R_{sheet} emitter (25fA/cm^2 or lower should be possible for a passivated boron emitter) along with less-penetrating fire-through pastes, or a selective emitter (a specific emitter contact J_0 below 500fA/cm^2 will be required). Finally, the resistive losses need to be reduced by optimizing the thin interfacial oxide, optimizing the front and back contact grids, and reducing the wafer resistivity.

Conclusions

This paper has presented ECN/Tempress's studies of polysilicon passivating contacts and their application to the rear side of a high-performance bifacial n-type solar cell with fire-through screen-printed metallization and processed on 6" Cz wafers. This cell design has been named *PERPoly* (passivated emitter and rear polysilicon). The polysilicon/SiO_x passivating carrier-selective contact structures were produced using an LPCVD-based process. The cell manufacturing comprised, in addition to the LPCVD step, processing that uses only a small number of industrial tools, comparable to current n-PERT process flows on the market. A highest efficiency of 20.7% was achieved for the PERPoly cell, along with an average cell V_{oc} of 674mV. As an added benefit, the cells

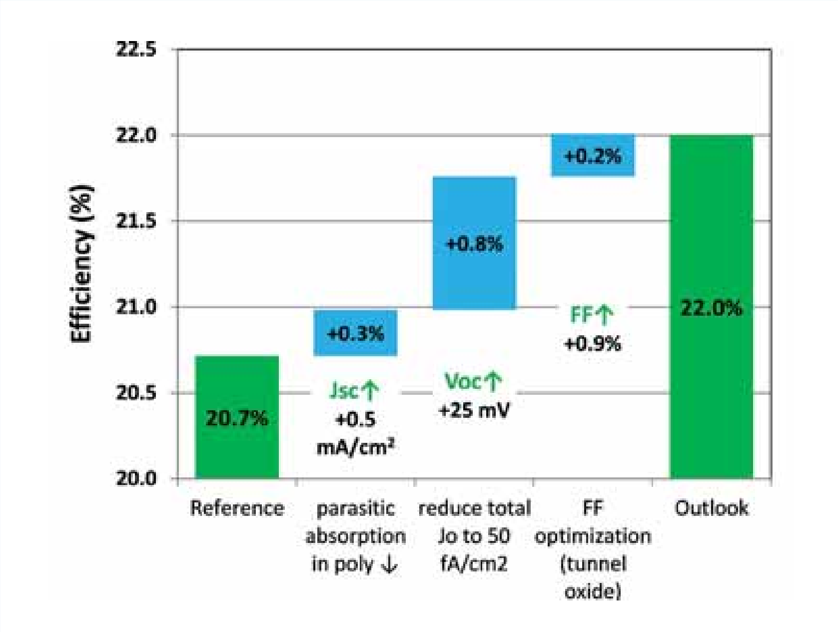

Figure 9. Roadmap towards achieving a 22%-efficiency PERPoly cell.

are bifacial with a bifaciality factor of greater than 0.8. To the authors' knowledge, these are the first 6" cells employing LPCVD for the polysilicon, and also the first cells employing a polysilicon passivating contact with fire-through screen-printed metallization.

> "A highest efficiency of 20.7% was achieved for the PERPoly cell, along with an average cell V_{oc} of 674mV."

The way in which process parameters influence the passivating contact effectiveness was described. Excellent passivation was obtained on polished and textured surfaces, with recombination current densities J_0 of ~2fA/cm^2 and ~4fA/cm^2 respectively. p-type contacts demonstrated a J_0 of ~12fA/cm^2; it is expected to reduce this by using a higher boron doping level in the polysilicon. The effect of the fire-through grid on the J_0 in the case of the 200nm-thickness n-poly contact was evaluated to be in the range 10–20fA/cm^2.

These results demonstrate the high potential of this technology for augmenting current cell processes, with a lot of headroom in the future in terms of performance. Achieving 22% seems feasible through making a number of improvements, especially on the emitter side. This brings the use of polysilicon passivating contacts closer to becoming a reality in low-cost industrial solar cell processing.

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Status of FolMet technology: How to produce PERC cells more cheaply than Al-BSF cells

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ABSTRACT

R&D activities related to solar cell production technology generally aim for higher cell efficiencies and lower production costs in order to decrease the levelized cost of electricity (LCOE). Today the passivated emitter and rear cell (PERC) is poised to become the preferred state-of-the-art cell architecture. 'FolMet' technology – a new metallization and contacting upgrade – therefore has particular relevance to PERC gains. By means of single laser pulses, conventional aluminium foil is mechanically fixed onto the cell's rear side, and local electrical contacts are formed at the same time. Coated foil enables the use of standard interconnection and module technology, which makes the FolMet procedure easy to implement in existing production lines, as well as offering outstanding potential for reducing the total cost of ownership (TCO). This paper summarizes the current state of research regarding laser process development, PERC process chain simplification and cell efficiencies, module integration and reliability, and the cost of ownership calculation.

Introduction

In the first attempts to create a rear electrode from aluminium foil at Fraunhofer ISE in 2005, 15µm-thick aluminium foil from a discount store was simply applied to a wafer and fired in a fast firing belt furnace. In the next development stage an adjusted laser-fired contact process was used to successfully increase the adhesion between the foil and the wafer [1]: the foil is locally melted by means of several single laser pulses from a pulsed nanosecond infrared laser. If enough laser power is applied, the foil is partially penetrated by the initial pulses, resulting in melting throughout the foil. The molten aluminium penetrates the dielectric layer of the passivated emitter and rear cell (PERC) and forms an electrical contact to the silicon, as well as a mechanical bond to the solar cell. The adhesion was sufficiently increased, and FolMet technology was invented as a metallization concept for PERC solar cells. The procedure is shown in Fig. 1; the approach was first published in 2007 [2], and a patent was granted in 2008 [3].

> "The handling of the aluminium foil is extremely important for process quality."

From the outset, the handling of the aluminium foil is extremely important for process quality, since wrinkles lead to an incomplete non-contacted area. In 2011 a foil-handling automation

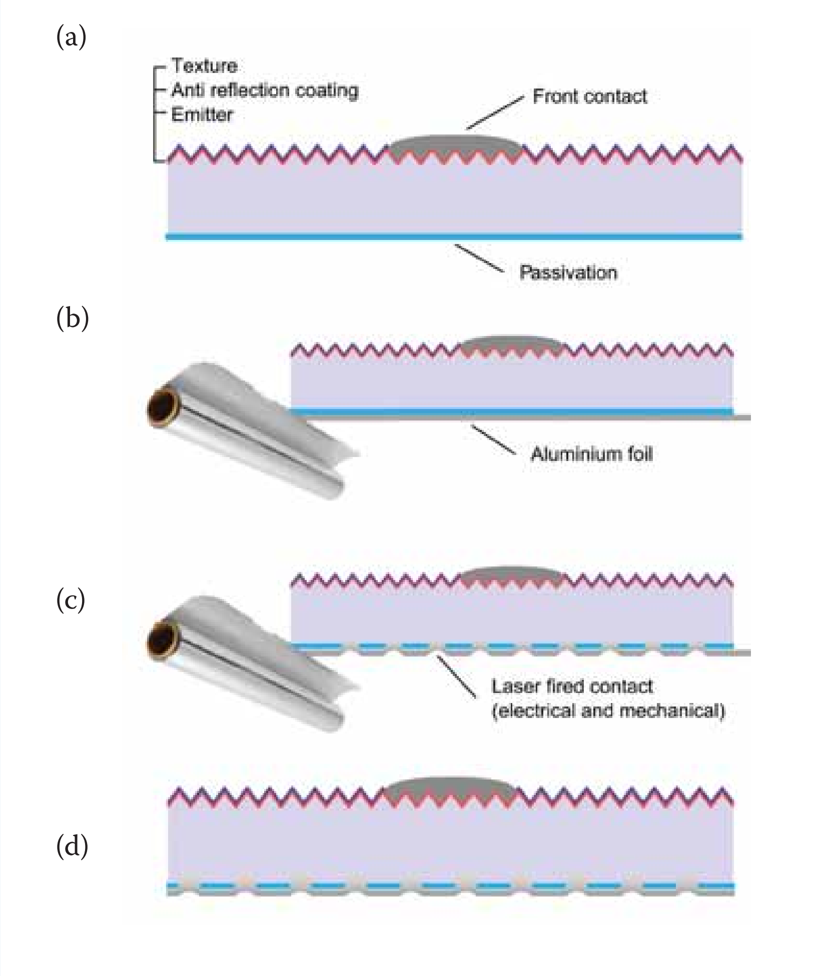

Figure 1. Process flow of the FolMet approach: (a) a precursor cell with passivated rear side and finished front-side contacts; (b) aluminium foil is rolled onto the passivated rear side; (c) laser-fired contacts are applied; (d) the foil is cut out along the wafer, yielding the ready-made solar cell.

[4] was constructed, and efficiencies above 21% were achieved with high-efficiency cells for the first time [5]. At the beginning of 2013 Fraunhofer began the publicly funded project 'FolMet' with its partner Innolas-Solutions. Since then, an alpha pilot-line tool has been set up at Fraunhofer, and different issues were investigated, such as laser process optimization, adaptation of the process chain, cost of ownership and module capability. The results of this project demonstrate the huge potential of FolMet technology to further increase the efficiency of PERC solar cells, as well as to significantly decrease production costs. On the other hand, the results also highlight the remaining challenges for a successful commercialization of the technology.

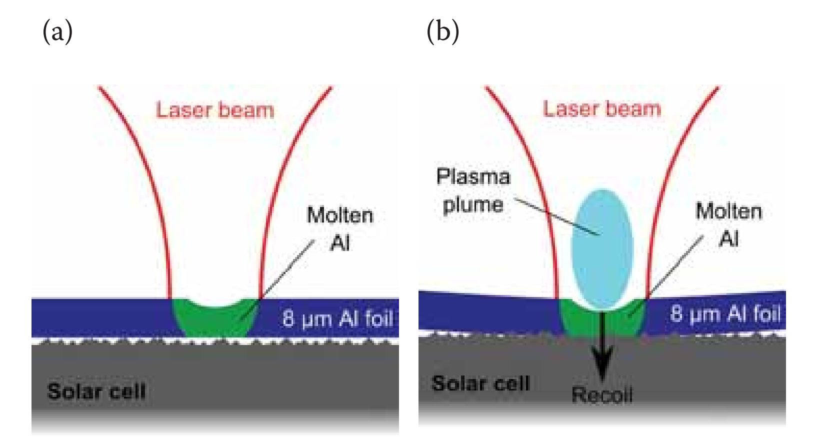

Figure 2. Schematic cross sections of the rear side of a solar cell during the laser contacting process: (a) penetration depth of the melting aluminium front (green) through the solid aluminium foil (blue), with a total thickness of 8µm; (b) plasma plume (cyan) of the evaporated material, leading to a recoil downwards to close the air gap between the foil and the solar cell (grey) under the irradiated area.

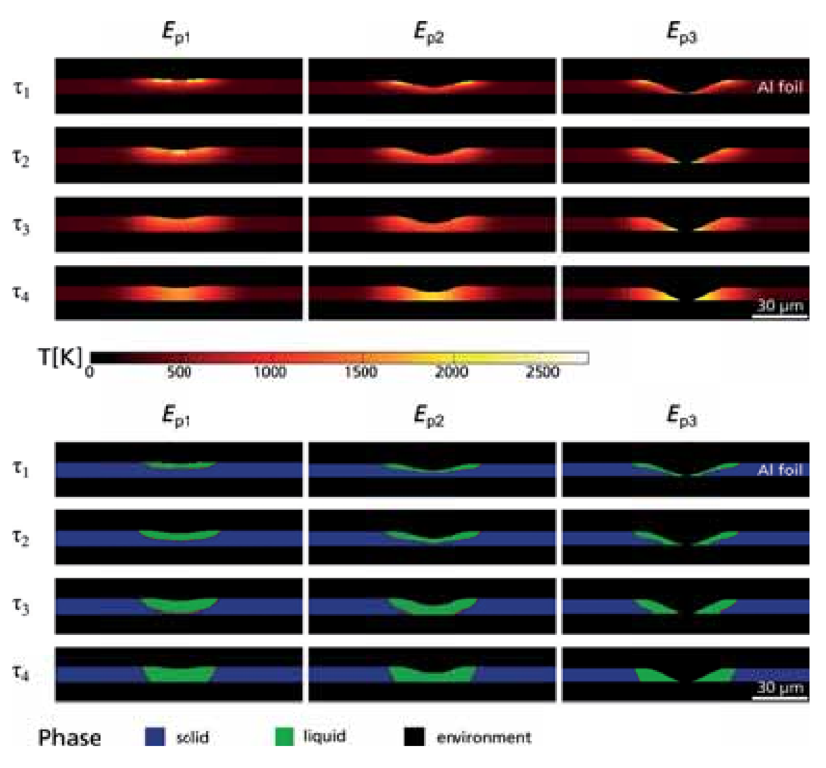

Figure 3. Influence of three different pulse energies ($E_{p1} < E_{p2} < E_{p3}$) at various pulse durations ($\tau_1 < \tau_2 < \tau_3 < \tau_4$) on the maximum temperature distribution (top) within the aluminium foil, and the corresponding phase (bottom) [7].

Current status of the laser process development

Process simulation and acceleration

The aim of the laser process is to alloy local contacts which not only provide sufficient mechanical adhesion of the foil, but also possess excellent electrical properties. To achieve any mechanical adhesion whatsoever, the foil has to be locally pressed towards the silicon surface during the alloying process. This can be realized by using a laser intensity that is sufficiently high to cause local surface heating of the foil above the evaporation temperature.

In the current process model a so-called *plasma plume* is formed, and its recoil pressure pushes the foil towards the silicon wafer (Fig. 2). To simultaneously create a permanent adhesion, the region of laser-melted aluminium must stretch over the entire thickness of the foil in order to guarantee a coating of the foil–wafer interface. Furthermore, the molten aluminium front, which is penetrating right through the foil, has to reach the interface before the plasma plume dissipates. The motion of this melting front, as well as the appearance of the plasma plume, can be tuned by choosing an appropriate laser pulse energy and pulse duration.

To better understand the influence of the above-mentioned laser parameters, a comprehensive simulation based on the finite-differences method was carried out in cooperation with Laserinstitut Mittweida [6,7]. The pulse energy E_p and the pulse duration τ were varied. The results in Fig. 3 illustrate the phase changes during the process. For a constant pulse energy E_{p1} (leftmost column), increasing the pulse duration leads to a greater melting depth. On the other hand, increased pulse energies result in deeper penetration of the foil by the melting and evaporation fronts; a laser power that is too high, however, can lead to a complete evaporation of the material, leaving behind hardly any molten material for wetting and contact formation. These results were recently experimentally validated [7,8]. It appears that a large process window exists, which allows further room for improvement, for instance in terms of optimization of the quality of the local back-surface field (BSF). However, all processes which produce sufficient adhesion of the foil have so far also yielded low-ohmic electrical contacts.

A scanning system was also evaluated: this allows the appropriate process to be quickly applied to a complete 156cm × 156cm solar cell. With that system in place, process times of less than one second, acceptable for industrial production, were demonstrated.

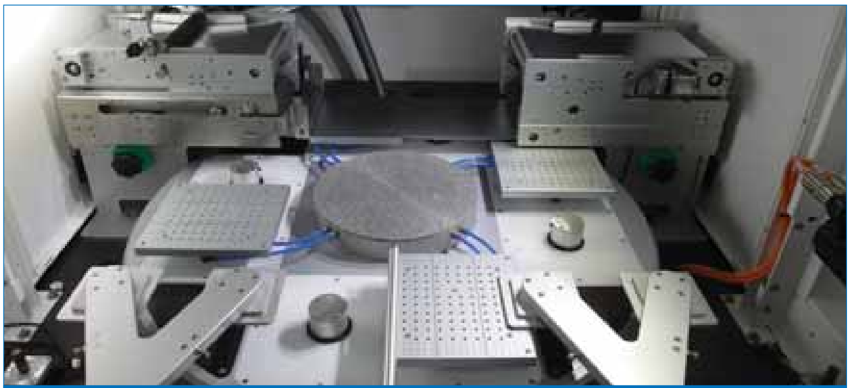

Figure 4. The FolMet alpha tool with an integrated automated foil-handling system, installed at Fraunhofer ISE.

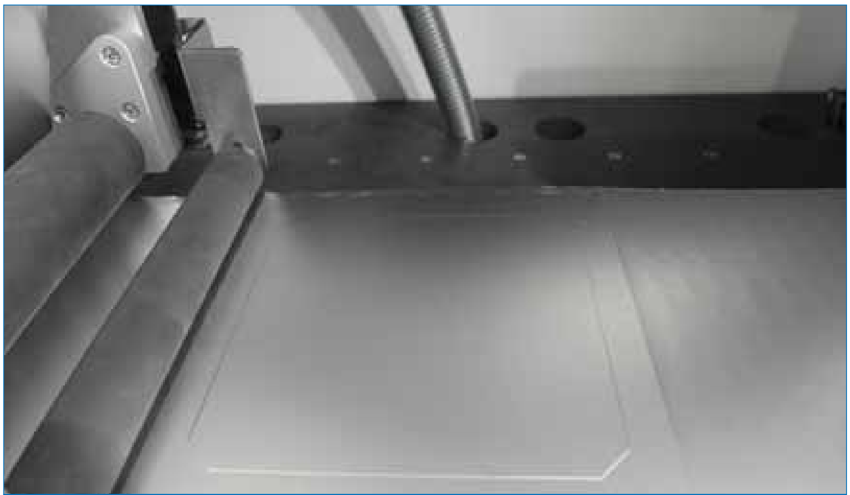

Figure 5. Homogeneous attachment of the foil onto an industrially sized solar cell precursor before the laser process begins.

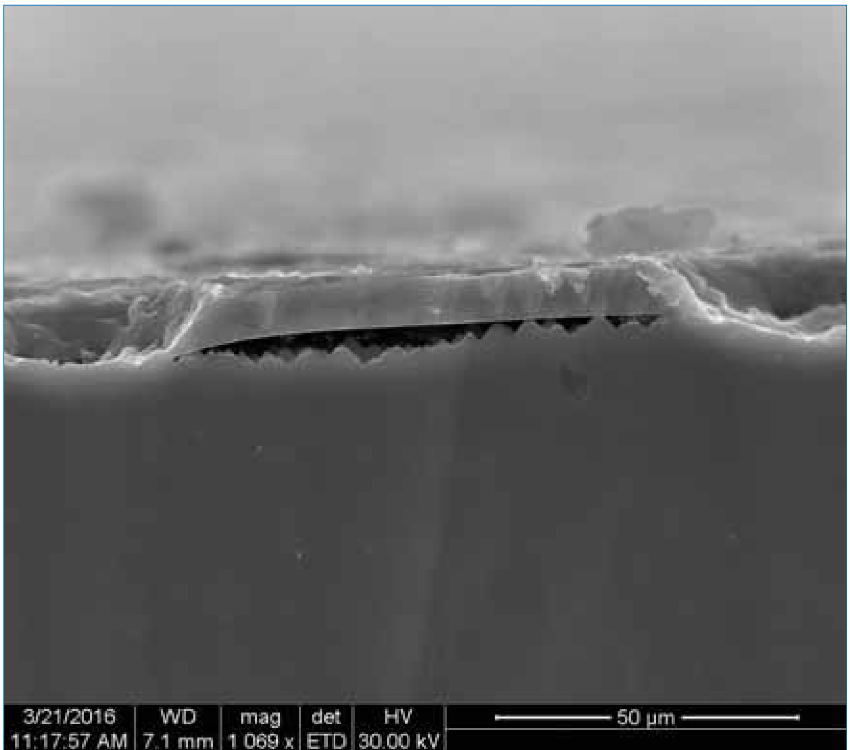

Figure 6. SEM image showing a polished cross section of a textured silicon wafer, covered by an 8µm-thick aluminium foil. On the right and left sides of the image, the foil is fixed onto the wafer by a laser-fired contact. Between these contacts a gap between the foil and the silicon wafer is clearly visible.

Tool development

Within the FolMet project, Fraunhofer's partner Innolas-Solutions developed an alpha pilot-line tool, which is based on its well-known turntable (TT) platform (Fig. 4). A foil-handling system was developed and integrated, automatically feeding foil from a 20kg roll, which is sufficient for performing the rear metallization of more than 28,000 cells. The foil is applied onto the wafer, and local contacts are formed using the laser process previously described.

Next, the foil is cut out along the edges of the cell, and the leftovers of the foil are automatically removed. The tool enables homogeneous attachment of the foil to the whole wafer before laser processing begins (Fig. 5); this, in the authors' opinion, is one of the most important requirements for FolMet technology. The throughput is still limited, however, because of the integrated laser contact formation process. In cooperation with Innolas-Solutions, a beta machine, with a target throughput of up to 2,000 wafers/hour, is currently under development.

"Homogeneous attachment of the foil to the whole wafer before laser processing begins is one of the most important requirements for FolMet technology."

Advantages of the technology

FolMet technology offers various advantages over common PERC metallization technology, which increase the efficiency potential of the cells and allow a significant reduction in costs at the same time.

Enhanced rear-side reflection

With the FolMet approach, the electrical losses are decreased. This can occur, for instance, because of the higher conductivity of the foil compared with the porous and impure post-alloy Al paste, or because of the smaller non-metallized non-contacted area along the wafer edge as a result of the limitations of screen printing in aligning to the wafer edges.

More significantly, however, the optical losses are reduced. In the first internal quantum efficiency (IQE) measurements taken in 2007 [2], the enhanced reflection of the rear side of a cell metallized with an aluminium foil became evident. Different ray-tracing simulations have indicated that an air gap between the foil and the wafer is responsible for this phenomenon, which was independently predicted in parallel by Z. Holman. In the case of FolMet, the existence of this gap was recently verified experimentally by scanning electron microscope (SEM) images on polished cross sections, as seen in Fig. 6. Not only does the air gap significantly increase the overall rear-side reflection for customary passivation layer stacks from Al_2O_3/SiN_x (as seen in Fig. 7), but it also allows the optimization of the stack in terms of surface passivation and costs, almost independently of its optical properties. A cost of ownership analysis reveals the considerable impact of reducing or completely eliminating the SiN_x capping layer.

To analyse the impact of capping layer thickness on the photogenerated current density J_G, simulations using the PV Lighthouse wafer ray tracer [9] were carried out (Fig. 8). For this, a random-pyramid-textured front and rear was utilized, as well as a 75nm-thick front-side SiN_x layer with a refractive index of 2.03 and a 6nm-thick Al_2O_3 layer. The rear-side SiN_x layer had a refractive index of 1.99, and the air gap was assumed to be 3µm thick. The consistently high J_G values for low thicknesses, and even without any capping nitride at all, demonstrate that theoretically a very thin Al_2O_3 layer, which could also be deposited by atomic layer deposition technology (ALD), yields the highest short-circuit current densities.

The influence of such PERC rear-side passivation layer stacks on the open-current voltage V_{oc} potential were investigated by measuring implied V_{oc} (iV_{oc}) using the quasi-steady-state photoconductance (QSSPC) method [10]. For this, samples were prepared with state-of-the-art cell front-side architecture, but without electrodes, and a rear side featuring a 20nm Al_2O_3 passivation by plasma-enhanced chemical vapour deposition (PECVD) and different capping layer thicknesses.

Since the SiN_x and Al_2O_3 layers require a high-temperature treatment in order to achieve maximum passivation quality, all samples were measured before and after the mandatory fast firing process. The results shown in Fig. 9 clearly underline that without a firing step, thicker layers lead to higher iV_{oc} values, probably because the wafer temperature increases during the deposition for such layers. However, after the mandatory firing step, the highest iV_{oc} values can be achieved, even without any capping layer. Unlike screen printing and firing, the FolMet approach does not impair the passivation in any way. Thus, FolMet technology yields excellent optical and electrical cell performance by the use of a significantly simplified rear passivation.

The next step was to investigate whether or not these excellent properties can be preserved at the module level. Solar cells with 0nm-, 10nm- and 100nm-thick SiN_x capping layers were therefore fabricated and their optical properties measured. FolMet was used for the metallization, while a 2µm-thick electrode created via physical vapour deposition (PVD) served as a reference. The cells subsequently underwent a standard module lamination process, and the IQE was measured. The results show that the IQE levels of the FolMet-metallized cells for both 10nm and 100nm SiN_x capping layer thicknesses are the same after lamination, and that these cells clearly outperform the reference cells (Fig. 10). This demonstrates that the thin air gap is not affected by the lamination process.

In addition, the V_{oc} potential of modules featuring FolMet-metallized cells with reduced SiN_x capping was measured after several state-of-the-art endurance-testing procedures, such as damp heat, humidity–freeze and temperature cycling. The results (see 'Module testing' section) clearly show no degradation at the module level. This again demonstrates that, in combination with FolMet, the SiN_x layer can be reduced by at least 80%, to a thickness of 20nm. Total elimination of the layer still seems feasible, but it has not yet been possible to fully demonstrate this at the module level.

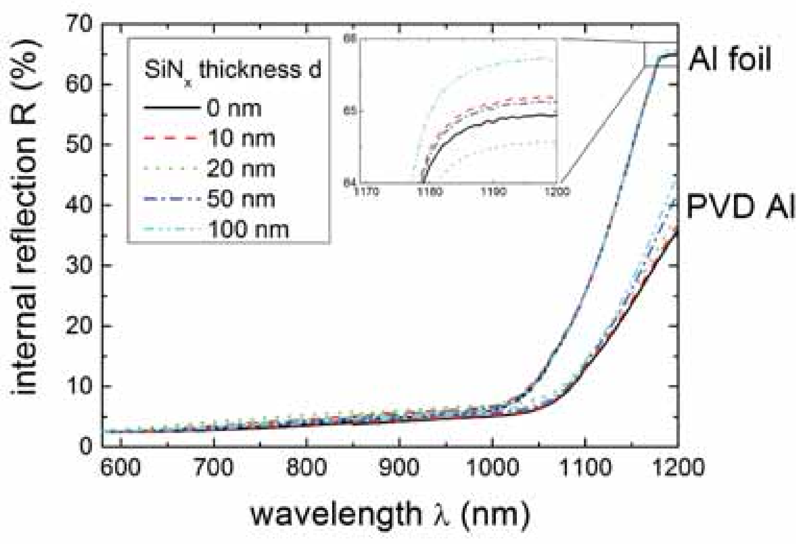

Figure 7. Measurement of the internal reflection in the 600–1,200nm range, after foil attachment and laser-fired contacts, as a function of SiN_x capping layer thickness [11].

		V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η[%]
LCO (39)	Mean	657	38.9	79.1	20.2
	Best cell	659	38.1	79.4	20.4
FolMet (24)	Mean	659	39.3	78.4	20.3
	Best cell	660	39.5	78.8	20.5

Table 1. Comparison of the measured *I–V* parameters for 39 standard LCO PERC cells and 24 cells metallized with FolMet [12].

High-efficiency potential

The high-efficiency potential of the FolMet concept has already been demonstrated several times. In 2013 the FolMet approach was directly compared with the common PERC process featuring local contact opening (LCO) by laser, in combination with Al screen printing [12]. A precursor wafer from the pilot line of partner Roth & Rau was used, and the LCO reference group was fully processed at its facility. The precursors are made of large-area 156mm × 156mm magnetically grown Czochralski silicon wafers (MCz), with a base resistivity of ρ = 1.0Ω·cm.

The front side covers an emitter that has a sheet resistance of approximately 80Ω/sq. and is passivated by a PECVD SiN_x layer. In addition, to obtain lower-reflection properties, a second layer was deposited on top of the SiN_x. This side also features standard screen-

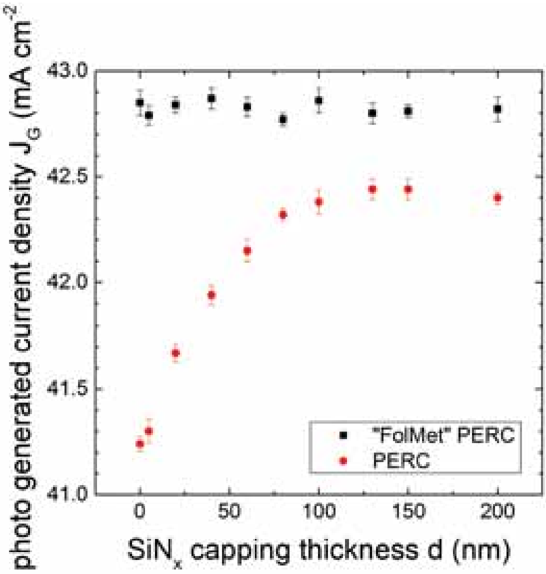

Figure 8. Simulation (PV Lighthouse) of the photogenerated current density of a FolMet rear side (black) and customary screen-printed PERC rear metallization (red), as a function of different SiNx capping layer thicknesses (assuming random-pyramid-textured front and rear sides) [9].

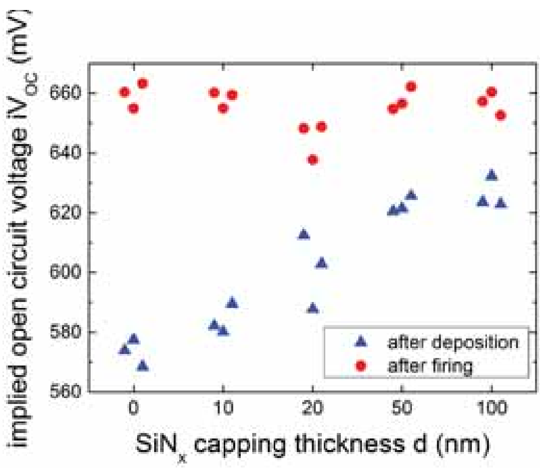

Figure 9. Implied V_{oc}, measured directly after deposition of the capping layer, and after fast firing [11].

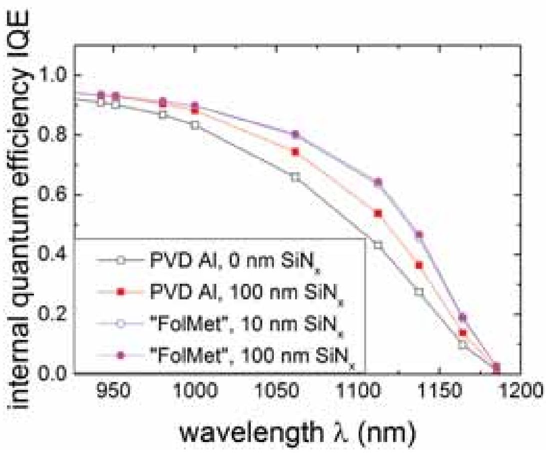

Figure 10. IQE measurements of cells with FolMet and PVD metallization, featuring standard Al_2O_3 passivation with different SiN_x thicknesses after lamination.

printed and fired contacts. The rear side is wet-chemically polished and passivated by a 120nm-thick Al_2O_3/SiN_x stack, deposited by PECVD. Of these precursors, 39 were finished with the common LCO process flow, and 24 were metallized using FolMet.

The FolMet group achieved the highest average efficiency (20.3% mean value), as well as the highest value for the best cell (20.5%), as shown in Table 1. The smaller fill factor (FF) of this group is most likely due to the significantly reduced contact fraction of the rear side compared with the LCO group. The remarkable increase in short-circuit current density J_{sc} of the FolMet-metallized cells is caused by an improved internal reflection and thus a higher IQE in the long-wavelength range. The highest V_{oc} values are also achieved with foil metallization. Despite the inferior quality of the local BSF compared with the standard PERC cells, the FolMet approach benefits from much smaller contact fractions and from the fact that there is no harmful influence on the passivation quality between the contacts.

> "FolMet technology was successfully combined with a laser-structured and plated front side, and efficiencies of 21.0% were achieved on a large-area solar cell."

In 2014 Fraunhofer ISE published efficiencies of 21.0% on large-area 156mm × 156mm solar cells with a 10nm SiN_x rear-side capping, which again were processed from precursors made by partner Roth & Rau [11]. Then, in 2015, for the first time FolMet technology was successfully combined with a laser-structured and plated front side, and efficiencies of 21.0% were achieved on a large-area solar cell (Table 2). Featuring a typical 100nm-thick SiN_x layer on the rear, this cell was almost silver free and was completely processed at Fraunhofer [13].

Simplified cell manufacturing

The full potential of FolMet technology can be exploited when making the foil solderable for standard module interconnection (see next section); Fig. 11 shows the exceptional simplification of the process chain for this case. Two extensive screen-printing processes, as well as the commonly used laser contacting opening processes, are completely replaced by the single FolMet process. In addition, FolMet enables the use of a substantially reduced rear-passivation process, and further facilitates the optimization of the front-electrode firing process, which today is always a trade-off between best front- and rear-contact qualities.

Simplified interconnection technology for conventional module integration

An important constraint of today's metallization technology is that it must facilitate solderability for standard interconnection technology. It therefore entails ordinary silver pads, which are printed on the wafer to achieve similar conditions to those of the front-side electrode, since the front and rear electrodes are simultaneously soldered to symmetric interconnection ribbons. These pads need an extra printing and drying step, consume costly silver, lead to a non-contacted p region on the rear side of the solar cell, and often require an elaborate adaptation of the soldering conditions in order to achieve a proper solder connection of sufficient strength.

The FolMet approach offers the possibility to work with single-side pre-coated foil; hence new materials other than silver can be utilized which are cheaper and offer a better compatibility with tin-coated copper ribbons, resulting in improved long-lasting solder connections. Finally, these materials do not affect the solar cell, since they are deposited only on one side of the foil, which faces away from the silicon. Local contacts can therefore be applied homogeneously, and no regions have to be left out. Such foil coatings are both easy and cheap to manufacture using a roll-to-roll process, before the foil is attached onto the solar cell, thus reducing the mechanical stress to a minimum.

Three different roll-to-roll deposition technologies are currently under investigation. Among these is a wet-chemical process that was developed at Fraunhofer ISE [14]. The Al foil is dipped in a wet-chemical solution for 90–180 seconds at room temperature. After the foil has been rinsed and dried, standard Sn/Ag/Pb-coated Cu ribbons can be soldered onto it using conventional contact or infrared soldering at standard temperatures, between 240 and 275°C. The average peel force of the ribbons was about 1.1N/mm (90° peel test), which complies with the DIN EN 50461 standard (>1N/mm). Several mini-modules were fabricated with this technology (Fig. 12) and have successfully undergone various standard testing procedures (see 'Module testing' section).

Total cost of ownership (TCO) analysis

The most distinct advantage of FolMet technology is its cost-saving potential. A detailed TCO analysis was therefore conducted of the production costs of different process sequences which are required to perform the metallization and contacting of the rear side; Al-BSF, standard PERC and FolMet PERC were compared. The firing process is not considered, since it is a necessary step in all of the three approaches because of the front-side contact formation.

"The most distinct advantage of FolMet technology is its cost-saving potential."

The economic analysis features a bottom-up calculation of industrial cell production sequences. The underlying cost model conforms to the Semiconductor Equipment and Materials International (SEMI) standards E35 (calculation of cost of ownership) [15] and E10 (equipment reliability, availability, maintainability and utilization) [16]. The model takes into account all costs related to equipment, building and facility, labour, spare parts, utilities, process consumables, waste disposal and yield loss.

For the most part, industrial equipment and material suppliers were consulted for data. In the case of the FolMet process, all costs refer to an industrial production case and are based on estimations which take into account experience gained with

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η[%]
Mean (6)	658	40.2	78.8	20.9
Best cell	658	40.3	79.1	21.0

Table 2. Latest *I–V* results of industrial-sized PERC solar cells featuring FolMet metallization technology.

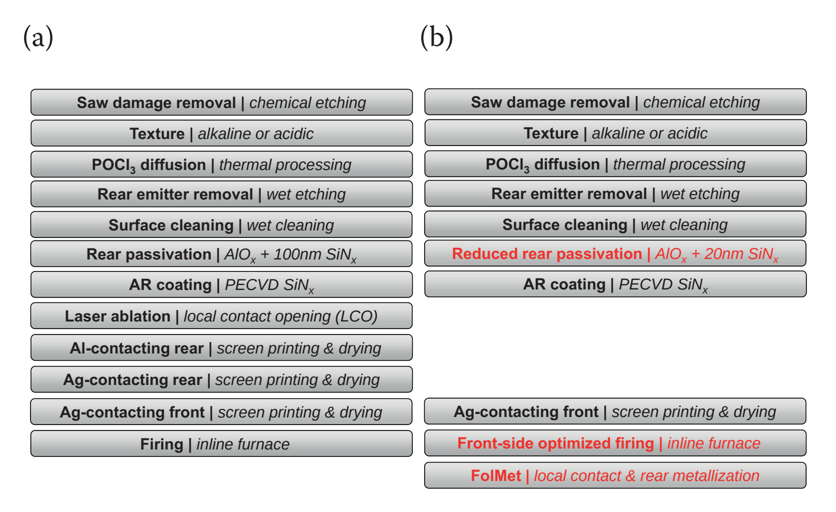

Figure 11. Schematic representation of the process flow of: (a) a state-of-the-art PERC production process; (b) a FolMet PERC production process.

Figure 12. One of the first four-cell mini-modules made from FolMet PERC solar cells (using pre-coated aluminium foil) in combination with standard PV soldering technology.

Fraunhofer's alpha tool. The cost of consumables includes the aluminium foil, which was single-side coated using the wet-chemical process described earlier. Again, the cost associated with an industrial roll-to-roll coating process was estimated on the basis of lab experience regarding consumables and waste disposal. For the coating machine, data were sourced from an established tool supplier in this field.

In Fig. 13 the production costs per cell are shown in €¢/cell, broken down for the different process steps and cost categories. It can be seen that the standard PERC rear electrode requires the most processes, which consequently results in the most expensive production costs at 17.25€¢/cell. The Al-BSF cell requires only two screen-printing processes (apart from firing), which amounts to production costs of 10.03€¢/cell. Even cheaper than conventional Al-BSF processing is FolMet technology: it also requires just two processes, namely passivation and FolMet, with resulting production costs of 8.84€¢/cell. It should be noted, however, that the indicated labour costs take into account typical German salaries; therefore the cost advantage presented will be lower for Asian production sites, since labour is required in advance for the screen-printing process steps. Nevertheless, the cost estimations for FolMet technology were carried out in a conservative fashion.

An upgrade capex of €300k is assumed for the integration of a foil-handling system within industrial laser equipment. With this conservative assumption, no capex-driven cost reduction is expected with the use of FolMet. However, the key cost advantage of the FolMet concept is the reduction in the material cost of the back contact: the aluminium and silver paste is replaced by a solderable aluminium foil. It therefore appears that the costs for one PERC cell with an efficiency potential of more than 21% can be cut down, to even below those for one of today's Al-BSF solar cells.

Module testing

A durability and lifespan analysis of modules is always an important aspect with new technologies. In the case of FolMet, the relevance is even greater for several reasons. First, materials other than Ag are used to provide solderability. Second, the foil is fixed onto the wafer only at the local contacts, and thus on about 1% of the cell area; an investigation into whether thermal broadening results in internal friction, which can lead to detachment or rupturing of the foil, is therefore necessary. Third, the influence of a reduced SiN_x capping layer on the rear side needs to be analysed.

To these ends, several one- and four-cell mini-modules were fabricated during the last few years, featuring either a glass or a polymer backsheet on the rear side; cells with 10, 20 or 100nm SiN_x were used. Standard interconnection technology was employed for soldering Sn/Ag/Pb-coated Cu ribbons on top of the coated Al foil. EVA was used as an encapsulation material, and standard lamination process were applied.

To avoid any influence of light-induced degradation (LID), the modules were exposed to a light intensity of 0.2 suns for 36 hours at a temperature $T < 40°C$ in order to fully activate the boron–oxygen complex. Next, the most-relevant accelerated ageing tests were performed: from the authors' perspective, these are humidity–freeze for 10 cycles (HF10), temperature cycling for 200 cycles (TC200) and damp heat for 1000 hours (DH1000),

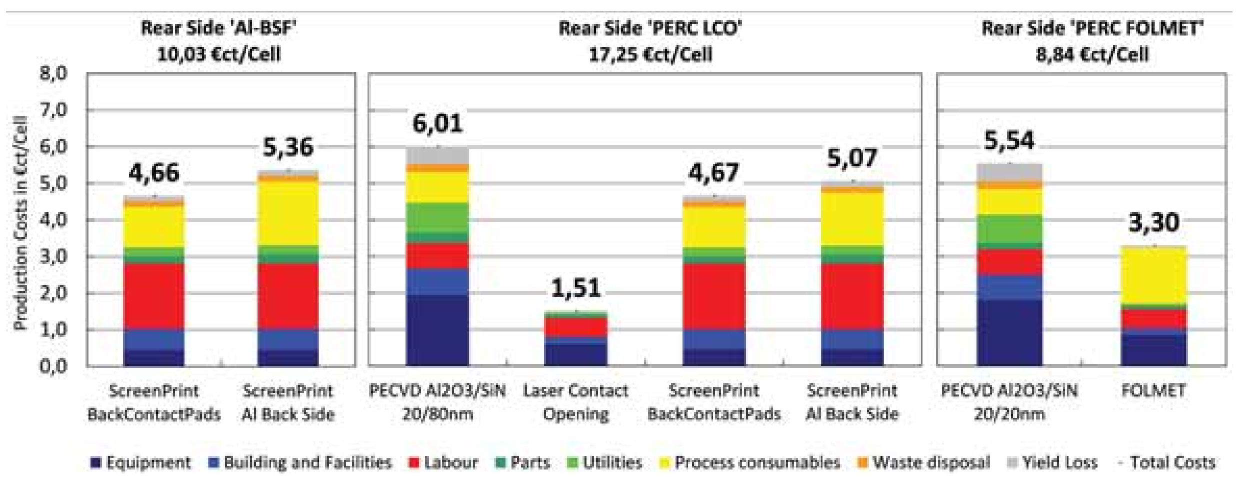

Figure 13. Production-cost analysis of the back-end process chains required for manufacturing the rear electrode. Three different approaches are compared – Al-BSF, standard LCO PERC and FolMet.

all in accordance with IEC 61215. *I–V* measurements were carried out both before and after each test.

In order to pass a test, the maximum power drop must not exceed 5%$_{rel}$; however, among the frequently tested variations, not all modules passed these tests. Nevertheless, it has recently been shown that all three tests can be passed with the use of a similar configuration of cell and module design featuring a reduced SiN_x layer thickness of 10–20nm and an aluminium foil with a solderable layer. Table 3 presents the results of these tests: there is a strong indication that solar cells with a FolMet metallized rear side can be successfully integrated in long-lasting modules which satisfy the necessary standards.

		V_{oc} [mV]	I_{sc} [A]	FF [%]	P_{mpp} [W]
HF10	Initial	2610	8.77	72.51	16.60
	After	2630	8.78	72.15	16.63
	Rel. dev. [%]	0.6	0.1	–0.5	0.2
TC200	Initial	632.8	9.11	75.08	4.33
	After	628.6	9.10	74.00	4.23
	Rel. dev. [%]	–0.7	–0.1	–1.4	–2.2
DH1000	Initial	630.1	9.08	74.91	4.28
	After	616.8	8.90	75.07	4.12
	Rel. dev. [%]	–2.1	–2.0	0.2	–3.8

Table 3. Measured *I–V* parameters of mini-modules before and after humidity–freeze (HF10), damp-heat (DH1000) and temperature-cycling (TC200) tests.

Summary and outlook

The current state of development of the so-called *FolMet* technology has been presented. A first alpha tool has been set up at Fraunhofer ISE, enabling proper handling and attachment of the Al foil. The laser process is thoroughly understood, and the parameter space for the most-relevant laser parameters is well known. A significantly process acceleration has already been demonstrated, allowing process times below one second to be realized.

FolMet technology offers improvements in the optical properties of the cells and modules, and significant simplifications in the process flow at the same time. The technology further allows easy integration into standard module lines by the use of solderable foil. This feature can be easily achieved by cheap roll-to-roll deposition processes, which offer several additional advantages. With a coating developed in-house, mini-modules created using a standard interconnection soldering technique could already be successfully manufactured today. Moreover, such modules have passed the most-relevant module endurance tests, namely humidity–freeze, damp heat and temperature cycling.

> "FolMet technology offers improvements in the optical properties of the cells and modules, and significant simplifications in the process flow at the same time."

On the basis of Fraunhofer's FolMet experiences, as well as with data from an industrial partner, a cost of ownership calculation was performed. The results not only demonstrate the significant cost-saving potential compared with standard LCO PERC technology, but clearly indicate that the FolMet approach can push down costs per cell even below those of today's Al-BSF cells, while still allowing cell efficiencies of above 21%.

To carry on the development of this promising technology, and to prepare its readiness for industrial production, a publicly funded project has been initiated in collaboration with several industrial partners. The focus of this will be: 1) the development of a beta machine with a higher throughput; 2) further optimization of the laser process; 3) the benchmarking of different foil-coating processes for solderable layers; and 4) a detailed long-term stability analysis.

Acknowledgements

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About the Authors

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Thin Film

News

First Solar to introduce 400W large-area CdTe thin-film modules

First Solar is planning a major revamp of its next-generation CdTe modules by introducing new production lines capable of producing large-area 'Series 6' modules with 400W output and significantly lower production costs currently achievable with its smaller form factor modules.

The company said that the large-area modules were expected to be produced with around 19% conversion efficiencies with production line equipment development underway.

First Solar noted that production tool orders were perhaps a year away from being placed, using technology and scale of equipment developed in line with flat panel displays, with dedicated 'greenfield' production facilities taking around 18 months to ready for potential ramp in late 2019.

The Series 6 modules were said to offer significant production cost reduction advantages over previous modules, which have remained at US$0.65/W capex level. The large-area modules and new production line technology would also enable higher throughput levels than previously achieved; at around 103MW capacity per line.

First Solar noted that any final decisions on timing of the new technology introduction have yet to be made and will be market demand driven.

Credit: First Solar

First Solar is introducing new production lines to manufacture its 400W large-area 'Series 6' modules.

First Solar news

First Solar launches new Series 5 module

First Solar's Annual Analyst Day event revealed the planned launch of the new Series 5 module, a three-horizontal-stacked module unit the equivalent size and form factor of conventional c-Si 72-cell modules, widely used in utility-scale PV power plant projects.

First Solar said it expected strong interest in the new module format from EPCs and project developers that would have liked to use its thin-film modules in the past but found the non-uniform format, fixings and racking systems to be deterrents. Apart from the claimed higher energy density factor over a c-Si module, Series 5 would seem to bring the company in line with, rather than ahead of, its 72-cell c-Si rival.

The Series 5 module system should initially be available in late 2017, with fleet production line module efficiencies in the 17% range.

Credit: First Solar

First Solar is supplying 230MW of its modules for projects being developed by Silicon Ranch.

Credit: SolarCity

SolarCity's request that its Silevo module be excluded from the scope of the US-China trade case has been rejected.

Leadership transition at First Solar marks new business cycle ahead

First Solar has announced a planned CEO change that underscores a new business model and cycle ahead, with current CEO, James A. Hughes, to step down and be succeeded by Mark R. Widmar.

The company is shifting emphasis back to module sales as part of a mid-term business plan that takes advantage of its restored cost per-watt advantage and two new module products to be introduced in the coming years.

The intention is to increase module sales on a far broader international base, such as India, Japan, Southeast Asia and Latin America, while concentrating less on PV power plant construction, notably in the US.

First Solar said that Alexander Bradley, First Solar's vice president, treasury and project finance, had been appointed interim CFO, effective 1 July 2016, while a permanent CFO replacement was found.

First Solar to supply 230MW modules to Silicon Ranch

First Solar has entered into an agreement with a subsidiary of Silicon Ranch, one of the US' leading solar project developers, to supply 230MW worth of modules for future projects.

This agreement supplements previous arrangements to supply more than 180MW of modules for use in Silicon Ranch projects in humid climate regions across the States.

In addition, First Solar will be providing EPC expertise for the projects which are scheduled to commence in 2017 and early 2018. Some of the earlier scheduled projects may also use First Solar's balance of system equipment, including its single-axis tracker.

The projects should kick off in Q1 of 2017 when First Solar expects to deliver the first batch of modules.

First Solar nets module order for Vietnam solar projects

First Solar has gained a foothold in Vietnam with a provisional deal to supply modules for a series of projects in the Southeast Asian country.

The US thin-film manufacturer has signed a MoU with Vietnamese developer, Thien Tan Group, to provide modules for a pipeline of projects the local firm is planning to build in the country.

The pipeline is of an unspecified size, but First Solar said construction on the first projects would begin before the end of 2016. The projects will be built across several provinces in Vietnam, with Thien Tan Group developing and owning them.

Incidentally, Vietnam has yet to emerge as a significant end market for solar, despite featuring all the usual prerequisites such as growing demand, high power costs and attractive resources.

Solar Frontier updates

Solar Frontier moves closer to US fab call with 150MW module deal

Japanese thin-film manufacturer Solar Frontier has heralded a 150MW module supply deal in the US as a major step towards its final decision on building a factory in America.

Solar Frontier's US arm said it would supply Cypress Creek Renewables with 150MW of its CIS thin-film modules for a portfolio of solar projects in North and South Carolina, and some of the emerging state markets in the US, including Indiana, Montana and Texas.

The deal marked a major step towards Solar Frontier being able to make a final on decision on whether or not to establish a manufacturing hub in the US.

Aside from the company's ability to build up a business base in America, the other major consideration before Solar Frontier decides on whether to commit to a US fab is the success of its new Tohoku plant in Japan.

Turner and Southern Company's 20MW Solar Frontier PV plant purchase is ninth acquisition for pair

Turner Renewable Energy will be one of the new owners of a 20MW thin-film PV plant in the US constructed by Solar Frontier Americas.

Turner Energy and utility holding company Southern Power, a subsidiary of Atlanta-based Southern Company, formed a strategic alliance in 2010 to develop renewable energy projects. The latest acquisition is Calipatria Solar Facility in Imperial County, California.

Power and renewable energy credits will be sold to investor-owned utility San Diego Gas & Electric under a 20 year PPA.

Solar Frontier Americas said the plant will produce around 52,000MWh of electricity annually from its 130,000 CIS thin-film modules.

The latest acquisition brings the pair's renewable assets in operation or development to 340MW across nine projects. Solar Frontier bought a 280MW pipeline of projects in North America in April 2015.

Rival thin-film firm First Solar will provide O&M for the Calipatria plant.

Finance & legal

SolarCity's Silevo modules to be included in China-US trade case

SolarCity's request that its Silevo modules be excluded from the scope of the US trade case against Chinese products has been rejected in the preliminary ruling.

The company had argued that its 'Triex' cells are an exempt thin-film technology, but SolarWorld, the petitioner in the case, argued that the cells have a crystalline silicon substrate and should be added.

In a statement prior to the preliminary ruling, a SolarCity spokesperson commented that as numerous a-Si thin-film

Credit: Singulus

Singulus has reported an annual loss despite solar-related sales increasing by over 30%.

layers are applied to the c-Si substrate, this renders them outside the scope of Orders.

Any Silevo products imported from China to the US would have to pay duties upfront at customs reducing competitiveness. SolarCity's facility in New York will produce Silevo products by volume making their inclusion in the case dependent on where its cells are produced.

A final decision will be made on 23 June.

Silevo ruling prevents thin-film China trade loophole, says Commerce Department

The potential loophole for China-based manufacturers to circumvent US trade duties by applying a single thin-film layer to their products has been dismissed by the Department of Commerce's ruling against SolarCity's Silevo products.

The department argued that had it excluded Silevo's monocrystalline silicon substrate thin-film cells from the scope of Chinese trade duties, any single thin-film layer product could follow suit.

Silevo had its pilot line in China until it was relocated to California. The company has moved to downplay the impact of any final ruling, scheduled for June.

"The impact of the ultimate ruling will be limited," said Jonathan Bass, SolarCity's VP for communications, "but it's unfortunate that SolarWorld is trying to make solar technology more expensive for customers."

Petitioner SolarWorld welcomed the ruling which highlighted that hybrid products fall within the scope of the order.

Parent company owes Hanergy Thin Film over US$630 million

Distressed PV thin-film producer Hanergy Thin Film finally issued a profit warning and business update in late February that revealed the extent of the dependence on its parent company and its dire financial position.

Hanergy TF said in a financial statement that its parent company, Hanergy Holdings, and other affiliates, owed the company more than US$630 million from past transactions of which around US$334 million was overdue.

Revenue in 2015 from connected transactions with Hanergy Holdings and other affiliates was said to have only amounted to around US$25.7 million in 2015, down 96% from around US$766 million in 2014.

Turnkey a-Si thin-film production line deals signed with Chinese companies via the parent company have since all been cancelled, leaving only US$25 million in revenue for Hanergy TF with other business transactions.

Singulus still expects loss in 2016 despite strong revenue guidance from major orders

Singulus Technologies has reported a loss of €34.5 million (US$39.4 million) in 2015, while forecasting a small expected loss in 2016 on sales guided to be in the range of €115-130 million, compared to €83.7 million in 2015.

Sales increased 25.3 % in 2015, primarily due to two major orders in its solar division. Solar division sales in 2015 accounted for 59.9% of the total (€50.1 million), compared to 22.6% (€15.10 million) in 2014.

Order intake in 2015 increased to €96.6 million, up from €60.6 in 2014. The order backlog at the end of 2015 stood at €26.6 million, compared to € 14.0 million at the end of 2014.

Singulus had liquidity in the amount of €19 million at the end of 2015. Order backlog at the end of 2015 stood at €26.6 million, compared to €14 million at the end of 2014.

CIGS thin-film cells

ZSW takes CIGS thin-film cell to 22% conversion efficiency

The Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) has set a new European record of 22% conversion efficiency for a CIGS thin-film cell, verified by Fraunhofer ISE.

The new efficiency record was made using 0.5cm^2 cells and a series of optimized processes on a laboratory coating machine using the co-evaporation method.

"The technological potential is far from tapped out at 22% efficiency," said Michael Powalla, ZSW board member and head of the photovoltaics division. "It will be possible to achieve up to 25% in the next few years."

ZSW noted that it was now only 0.3 percentage point behind the current world record for a CIGS cell.

Avancis likely customer for 300MW Singulus selenization system order

Singulus Technologies has said that it is close to closing a major contract for a new advanced selenization system, based on its 'CISARIS' platform for CIGS thin-film production.

CIGS thin-film producer Avancis, a previous customer of Singulus, is planning the first 300MW phase of production at a new facility in China and is highly likely to be the customer.

Avancis is currently the only CIGS producer with plans to add 300MW of new capacity in China, especially following the financial woes and lost contracts of Hanergy Thin Film.

Singulus noted that the initial order for production tools required for a 300MW plant in China could be worth "a high double-digit million euro amount" and that it expected to receive confirmation of the order "soon".

Manz retains turnkey CIGS thin-film technology

PV and electronics equipment manufacturer Manz AG has decided to keep its turnkey CIGS thin-film technology after almost a year of undertaking a strategic review, due to lack of orders.

In December, 2011 Manz signed an agreement to take over the CIGS innovation line from Würth Solar but the interest from potential customers failed to materialise during a period of overcapacity in the solar sector and plummeting prices of conventional silicon-based PV modules.

The decision to retain its CIGS technology is based on the potential to better penetrate the Chinese solar market via a 30% stake in Manz being offered to Shanghai Electric Co.

CEO and founder Dieter Manz said: "With Shanghai Electric, we have found a partner with long-term interests…Our future Chinese partner thus will provide additional stability in the company as a financially strong anchor investor together with me as major shareholders."

First Solar goes back to the future

By Mark Osborne, senior news editor, Photovoltaics International

ABSTRACT
Leading CdTe thin-film module producer First Solar is shifting it business emphasis back to module sales after becoming a leading PV project developer as part of a mid-term business plan that takes advantage of its restored cost-per-watt advantage and two new module products that will be introduced in the coming years that are intended to further its competitive position. We analyze the key metrics behind the transition, such as R&D expenditure, module conversion efficiencies and production capabilities and cost reductions.

The significant transition and new product introductions were announced at First Solar's 2016 Annual Analyst Day event in early April.

The company gave the first public insight into its next-generation module technology that not only relies on years of continued CdTe efficiency gains from world records set in both the lab and lead module lines but completely diverges from its existing module form factor.

First Solar is planning on introducing its 'Series 6' modules with 400W output using a completely new tool set for a large-area module. The Series 6 modules are in the league of those originally developed by Applied Materials under its 'SunFab' brand for a-Si thin-film modules, which had some of the key deposition toolset derived from the FPD (Flat Panel Display) sector.

According to Raffi Garabedian, CTO at First Solar, the new technology, which is still under development, would be a major game changer as it would have significantly lower production costs when compared to the smaller form factor modules it has been producing to date.

The impression given during the event was that the Series 6 module would have a 2019 launch onwards and initially exclusively used on its own PV power plant projects as the modules would likely require different mounting system design for fixed ground-mount and single-axis tracker systems as well as assisted mechanical handling systems due to size and weight.

The company noted that production tool orders were perhaps a year away from being placed, with dedicated 'greenfield' production facilities taking around 18 months to build, equip and be ready to potentially ramp in the late 2019 timeframe. Looking back over First Solar's previous manufacturing ramp profiles for its main production facilities in Malaysia, the company is expecting fab construction,

Credit: First Solar

First Solar is shifting the focus of its business to direct module sales once again, backed up by two significant new product launches.

qualification and ramps along similar timelines to before.

The Series 6 modules were said to provide a significant production cost reduction compared to what First Solar has achieved with its previous modules, which have remained at the US$0.65/W capex level. First Solar said the large-area modules and new production line technology would also enable higher throughput levels than previously achieved, which stand at around 103MW capacity per line.

The second significant product development was the planned launch of its Series 5 module, a three-horizontal-stacked module unit the equivalent size and form factor of conventional c-Si 72-cell modules, widely used in utility-scale PV power plant projects. The Series 5 module system would initially be available in a late 2017, with fleet production line module efficiencies in the 17% range.

Pre-assembled at its existing production plants, the Series 5 was said to provide a 'standardized' product offering to potential customers that had previously stayed with c-Si modules to simplify balance-of-system procurement and reduce costs.

Providing a system with an initial 365W (Pmax), First Solar said it expected strong interest in the new module format, enabling the company to tap into EPCs and project developers that would have liked to use its thin-film modules in the past but were deterred by the non-uniform format, fixings and raking systems. This could be a significant market opportunity, according to the company, though a part from the claimed higher energy density factor over a c-Si module, Series 5 would seem to bring the company in line with rather than ahead of its 72-cell c-Si technology rivals.

Underlying the new module product offering would be continued performance enhancements to its current fleet of 30 operating production lines with continued focus on conversion efficiencies as per an updated roadmap.

Figure 1. First Solar revealed its large-area Series 6 module at its 2016 Analayst Day event

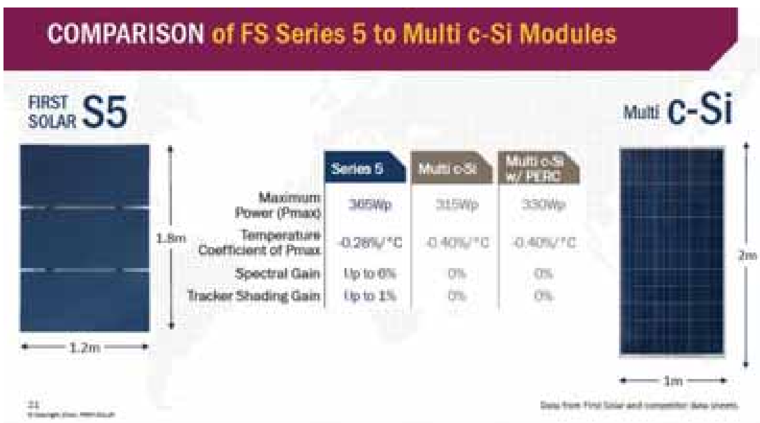


Figure 2. First Solar revealed its Series 5 three-stack integrated module assembly at its 2016 Analayst Day event

Research and development

First Solar's perennial heavy spending on R&D can partially be explained by the proprietary nature of its CdTe production equipment and processes. The company has been ranked first in annual R&D spending for seven consecutive years (2009-2015), according to Photovoltaics International analysis of 12 key PV manufacturers undertaken each year.

First Solar allocated US$130.6 million to R&D activities in 2015, compared to US$143.9 million in the previous year. The lower spending year on year was attributed to reduced material and module testing costs associated with the development cycle of its next-generation modules.

Indeed, R&D spending would seem to have peaked in 2014, yet the company had exceeded annual spending above US$100 million per annum since 2011. Based on R&D expenditure levels in the first quarter of 2016, First Solar is on track to allocate over US$120 million to R&D activities in 2016, suggesting Series 6 module development will be a key focus through to volume production timelines.

Importantly, the company is on track in 2016 to exceed US$1.0 billion in cumulative R&D spending since 2007, the first company to surpass the milestone and around double that of its nearest R&D spending rival, SunPower.

Although the company splits spending between manufacturing and downstream modular power plant developments, emphasis has been intensified in the last three years on thin-film module efficiency gains and line throughput increases.

Conversion efficiencies

Industry-leading R&D spending has returned a number of conversion efficiency records both at the cell and module levels in recent years.

At the beginning of 2015, First Solar reported a research cell with a conversion efficiency of 21.5%. First Solar said in June 2015 that it had surpassed multicrystalline module conversion efficiencies for the first time, with its CdTe module efficiency reaching a record 18.6% corresponding to the company's eighth major update since 2011.

First Solar then set a new world record research cell conversion efficiency of 22.1%, certified at the Newport Corporation's Technology and

Applications Center (TAC) PV Lab in February 2016. According to First Solar, this was the ninth major update to CdTe record efficiency since 2011. The record cell was said to have produced at First Solar's Perrysburg, Ohio manufacturing factory and Research & Development Center using processes and materials applicable to commercial-scale manufacturing.

First Solar noted that in the fourth quarter of 2015 its lead manufacturing lines were producing PV modules with 16.4% conversion efficiency.

At the fleet level, First Solar said it reached average module efficiencies of 16.1% at the end of 2015, with guidance of achieving 16.7% at the end of 2016.

As the module efficiency chart shows, First Solar has achieved around 0.4% to 0.5% efficiency gains per annum at its volume production lines through 2013. However, a major programme implemented in 2014 and completed in 2015 led to a 1.7% module efficiency gain in 2015 and a further 0.6% gain expected in 2016. The company has therefore achieved module conversion efficiencies of more than 0.5% over the last 10 years.

The major upgrade included the implementation of R&D work with equipment upgrades. In basic terms, First Solar's R&D efforts have been able to improve short-circuit currents and fill factor (FF), with increased open-circuit voltage and carrier lifetime, supported by recent record lab efficiencies. Equipment upgrades included high precision laser structuring or patterning of CdTe solar cells.

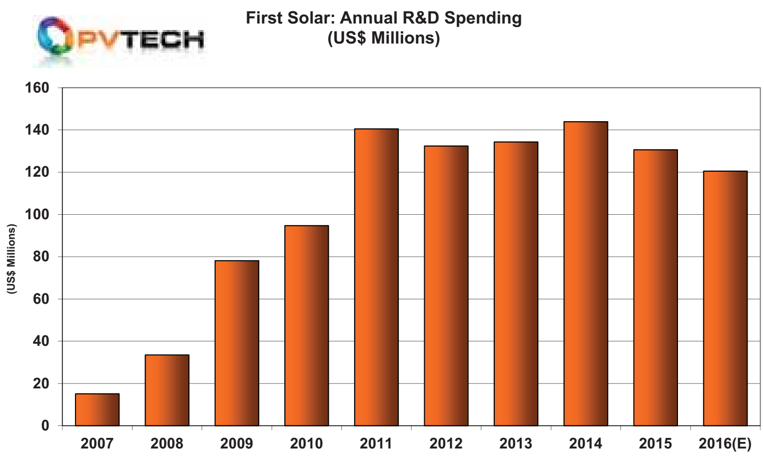


Figure 3. First Solar annual R&D spending (US$ millions)

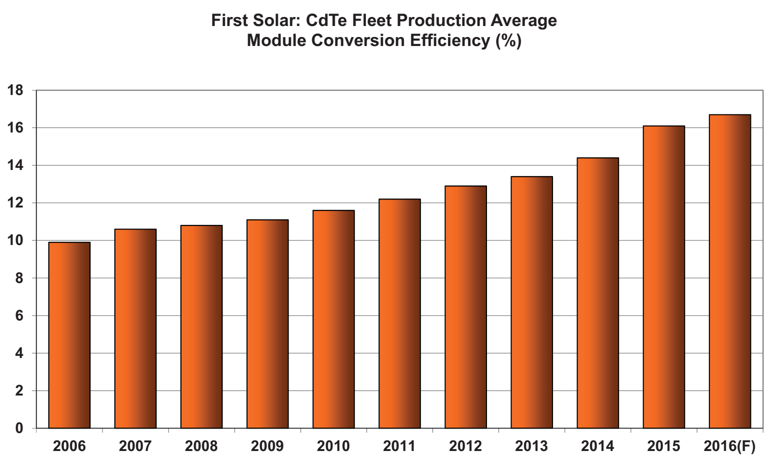


Figure 4. First Solar: CdTe fleet production average module conversion efficiency (%)

First Solar currently expects its research solar cell roadmap to achieve 24% conversion efficiencies over the next one to two-year period. Research modules efficiencies are expected to reach 19.4% in 2016 and 21.7% in the next one to three-year period.

Manufacturing capacity expansions

Expectations ahead of the analyst event had been that due to First Solar's PV project pipeline and third-party demand for its modules, which had combined to push all operating lines to full utilization levels in the fourth quarter of 2015, the company would announce a new wave of capacity expansions.

Some analysts seemed disappointed when Tymen deJong, COO of First Solar, noted that despite the ability to produce one module per second that time figure would not be decreasing just now.

First Solar acknowledged that it had retained the eight production lines (800MW) of equipment previously mothballed after closing its two manufacturing facilities in Germany but had not determined when these lines would be upgraded to existing line efficiency and throughput levels and deployed in an unspecified location(s).

Management highlighted that it would keep all production lines running at full capacity in 2016, which had equated to 3.1GW produced in 2015, up from 2.5GW in 2014, when lower utilization rates and fewer lines were in operation.

In contrast to R&D expenditure since 2011, First Solar's capital expenditures have declined sequentially, reaching a low of US$166.5 million in 2015. The sequential declines are primarily attributed to underutilisation rates and excess capacity to demand during the period.

However, based on First Solar's capex guidance for 2016 (US$300 million to US$400 million) upgrades to both its mothballed equipment and implementation of automated Series 5 module assembly plans are already underway. The company has subsequently noted in its Q1 2016 earnings call that around US$130 million of planned capex in 2016 would be allocated to the launch of its Series 5 product.

Beginning in late 2017, deJong noted that the company could deploy four mothballed lines (400MW) of current Series 4 modules and add a further four upgraded mothballed lines (425MW) in a new facility in 2018.

The ramp of its Series 5 module

system would initially include four lines that will have the stacked module assembly tools added in late 2017 with full production expected in 2018. Additional Series 5 production lines would be added based on market demand.

First Solar noted that a greenfield Series 5 production facility with a capacity of around 450MW would require capital expenditures of around US$300 million, and an 18-month construction timeline.

The impression given was that some existing Series 4 lines would add the assembly tools required for Series 5 modules as and when required. The Series 5 module lines were said to have a calculated capital cost of around US$0.45/W, slightly higher than Series 4 at US$0.35/W, due to the additional stack assembly equipment.

In 2019, First Solar highlighted the potential to start ramping its Series 6 modules that would be housed in a new dedicated facility, but would carry only a capital cost of around US$0.40/W. Around 2GW of Series 6 production could be in operation in 2020, the company said.

Capacity of 2GW of Series 6 modules would require US$800 million in capital expenditure and 18 months construction of a greenfield site, as previously noted. However, a potential capacity expansion roadmap was provided that could take capacity to close to 7GW in 2020.

It should be noted that although emphasis is naturally being placed on the two new product introductions, a significant nameplate capacity of existing Series 3 (small-area) modules will remain in production.

However, a knock-on effect of retaining full utilization rates in 2016 is a slowdown in expected module conversion efficiency gains. Indeed R&D activities being focused on Series 6 development and implementation would also limit improvements in the short-term.

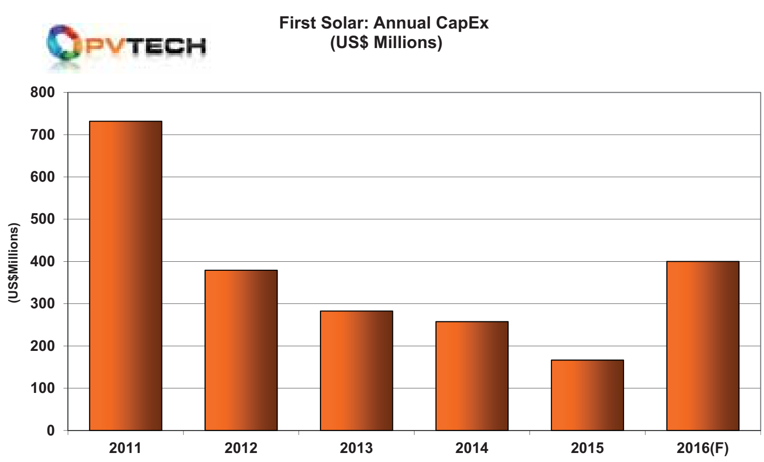


Figure 5. First Solar annual capex (US$ millions)

Figure 6. First Solar's guided potential manufacturing capacity expansion roadmap at 2016 Analyst Day event.

Business model shift

With significant capital expenditures potentially ahead in 2018 through 2020 for the large-area Series 6 modules and to a lesser extent the Series 5, subject to greenfield needs and demand, increasing its PV project completions is likely to strain First Solar's balance sheet.

Highlighting recent well known bankruptcies and distressed companies in the solar sector, management said First Solar would follow a strictly conservative approach to both upstream capacity expansions and downstream project development.

Indeed, the sacrificial lamb in this strategy would seem to be the downstream project development arm, which First Solar will keep at around current annual completion levels, while re-emphasising its earlier status of being a module producer and supplier with the eventual added capacity.

An advantage of a renewed emphasis on module business was claimed to be the better margins achieved with higher efficiencies, new market opportunities with Series 5 and significant margin improvement with the deployment of Series 6.

Management noted that pushing its PV project pipeline further out to the ramp of Series 5 and 6 would only add further margin improvement to its balance sheet, limiting the expected effect of its net cash balance declining through 2020 due to the capacity expansions.

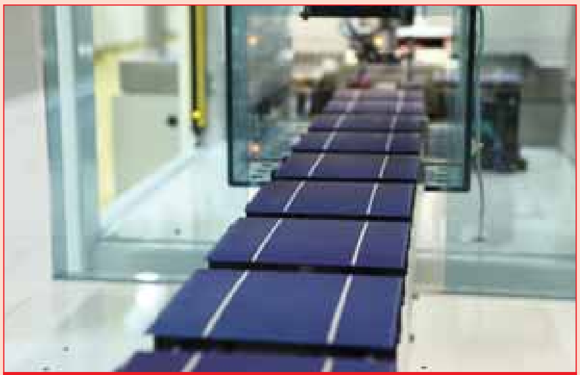
Conclusion

As detailed, First Solar is shifting emphasis back to module sales as part of a mid-term business plan that takes advantage of its restored cost per-watt advantage and two new module products to be introduced in the coming years that further its competitive position. With a shift to large-area thin-film modules, initially championed by Applied Materials a decade ago, First Solar is going back to the future.

PV Modules

News

No end in sight for cost pressures on PV manufacturers – ITRPV



Credit: Trina Solar

Module manufacturers face ongoing cost pressures in the coming year, according to the latest ITRPV report.

PV manufacturing capacity expansions planned this year are expected to push production levels beyond anticipated demand in 2016, creating further cost pressures for suppliers, according to the findings of the seventh International Technology Roadmap for Photovoltaic (ITRPV), produced this VDMA.

Focusing as usual specifically on c-Si rather than thin-film manufacturing, the report alludes to the recent trend of capacity expansion announcements by module manufacturers.

With global demand predicted at around 60GW this year and capacity expansions expected to push total production capacity above the 60GW the roadmap said was in place at the end of 2015, the report said supply would likely outstrip demand this year.

Among the trends for achieving reductions, the roadmap predicts diamond wire sawing will steal significant market share off the current slurry-based process that currently dominate both mono and multi wafer production.

Market

Record year for solar driven by reduced technology costs – IRENA

Global solar capacity grew by 47GW (26%) during 2015 as a result of module prices dropping by as much as 80% over the same period, according to the latest data from the International Renewable Energy Agency (IRENA).

At the end of 2014, solar deployments worldwide stood at nearly 180GW, rising to 227GW during 2015.

The highest regional increase in solar deployment was the 48% growth in Asia with 15GW in China and 10GW in Japan. North America's 8GW saw it surpass European installations for the first time, which stood at 7.6GW.

In the emerging markets, Oceania saw a 1GW solar increase and Africa had 0.9GW installed. Elsewhere, South American solar grew by 517MW over 2015; meanwhile Central America and the Caribbean went up by 577MW. At the end of 2015, Europe accounted for 43% of global capacity.

Manufacturers

JinkoSolar makes 1,500V 'Eagle' modules available in US

JinkoSolar has said that its multicrystalline 'Eagle' modules in 1,500V configuration were being made available in the North American market.

JinkoSolar has previously guided shipments to the US in 2016 to potentially exceed 1.5GW, a key market being utility-scale PV projects which increasingly have adopted 1,500V

Credit: JinkoSolar

JinkoSolar has said it will add 1GW per quarter of new capacity this year to keep up with demand.

modules to lower balance of system costs.

The 1,500V Eagle PV modules for the North American market will also come specified with DuPont's 'Tedlar' polyvinyl fluoride (PVF) film-based backsheets and were said to have passed potential-induced degradation (PID) tests at 85 degrees Celsius and 85% relative humidity.

JinkoSolar adding 1GW of solar module capacity per quarter

JinkoSolar is adding 1GW of solar module capacity per quarter through to the end of the first half of 2016 to meet the "minimum" expected demand for its products. The company guided total module shipments in 2016 to be around 6GW to 6.5GW.

Solar cell capacity is to expand by 200MW in Q1 2016 and by a further 700MW by the end of Q2 2016. Total nameplate capacity by mid-year is expected to reach 3.5GW, up 900MW from 2.5GW at the end of 2015.

The company is expanding module assembly to much higher levels than wafer and cell combined and is adding 1GW of nameplate module capacity in Q1 2016, and a further 1GW by the end of Q2 2016. JinkoSolar plans to reach 6.3GW of nameplate module capacity by the end of Q1 2016, up from 4.3GW at the end of 2015.

SolarWorld posts sales of €212 million in Q1 2016

Integrated PV module manufacturer SolarWorld has reported preliminary first quarter 2016 sales of €212.6 million on product shipments of 341MW.

SolarWorld's sales in the first quarter of 2016 were down from €231 million in the previous quarter but up significantly from €149.1 million in prior year quarter.

Sales were almost identical to those reported in the third quarter of 2015, while shipments were lower, indicating declining ASPs.

Shipments in the quarter, which include modules and system installation kits, were down from 404MW in the previous quarter but up significantly from 202MW in the prior year period.

Shipments were said to have been strong in the US, Germany and Europe.

The company noted that its order backlog stood at over 540MW at the beginning of the second quarter of 2016, while orders totalled over 880MW in early April.

As a result of a strong order backlog, SolarWorld said it expected total shipments in 2016 to exceed 1,390MW, or more than 20% over shipments of 1,159MW in 2015.

Trina Solar hits shipments of 5.74GW and US$3 billion revenue in 2015

Trina Solar has reported full-year 2015 total solar module shipments of 5.74 GW, an increase of 56.8% from 3.66GW in 2014 and revised upward guidance of 5.5GW to 5.6GW.

Total net revenues were US$3.0 billion, an increase of 32.8% from 2014.

The company exceeded fourth quarter shipment guidance of 1.5GW to 1.65GW to reach 1,776.3MW.

The company expects to ship between 1.37GW to 1.45GW of PV modules in the first quarter of 2016, all of which will be shipped to third-party customers.

Trina Solar guided manufacturing nameplate capacity of ingots of 2.3GW by the end of 2016 and wafer capacity of 1.8GW. Solar cell capacity would be 5GW and module assembly capacity would reach 6GW at year-end. Both ingot and wafer capacities will therefore remain unchanged from 2015, while solar cell capacity will increase 1.5GW in 2016 and module capacity by 1GW.

SunEdison teams with Jinergy on 1.5GW integrated n-type heterojunction production plant

Prior to filing for bankruptcy, SunEdison partnered with Jinneng Group to build a 1.5GW integrated n-type monocrystalline heterojunction production facility in Shanxi Jinzhong Industrial Park, Shanxi, China. No financial details of the partnership were disclosed.

Jinergy was established at the end of 2013 and broke ground on its first facility in March 2014 with a claimed 500MW of n-type monocrystalline solar cell nameplate capacity, 600MW of PV module assembly capacity and average cell efficiencies of 18.7%.

The company has also recently claimed to have achieved a monocrystalline PERC efficiency of 21.3% in R&D.

Applied Materials supplied double printing fine line (FLDP) metallization tools to the company.

SunEdison recently announced it was making drastic changes to its upstream manufacturing operations by closing down one of its polysilicon plants and selling its wafer operations in Malaysia to Longi Silicon Materials.

Yingli Green secures module supply deal for 2017

Despite being technically bankrupt, Yingli Green has been in stealth mode over its future viability since reporting Q3 2015 results at the beginning of December last year.

On April 12 Yingli Green announced a 200MW PV module supply deal with an unnamed European EPC firm for PV power plant projects in the Dominican Republic for 2017 onwards.

The company has managed to file only one SEC filing in 2016, which related to one of only seven press releases the company has issued this year. Only one of those at the beginning of the year related to its financial condition with the expected reverse stock split to counter a looming delisting.

In recent years, Yingli Green has been the last publicly listed solar company to report quarterly results and has yet to announce when it will report fourth quarter and full-year 2015 financial results.

Technology

Bifacial PV test site shows 'impressive' yield gains

Early results from a test array in Germany using bifacial 'BiSoN' module technology have indicated significant yield gains compared to a nearby reference site using standard modules.

The bifacial array uses 16 BiSoN modules manufactured by Italian firm MegaCell, which incorporate technology initially developed by German research institute ISC Konstanz.

According to the institute's analysis, the bifacial system demonstrated a daily average production of 1.8kWh/kWp compared to 0.8 produced by traditional monofacial modules.

ISC project manager Joris Libal said this "noteworthy difference" is due to the high incidence of diffused light caused by winter cloudiness. Because in sunny conditions this difference would be lower, as the front efficiency of the module would be proportionately bigger, the overall yearly yield gain from the bifacial module would be less than the +120% recorded during the sample month – between 25 and 40% over a typical year, according to ISC projections.

High-performance solar modules order of the day

At the recent PV Expo in Tokyo, Japan, several international PV manufacturers showcased high-performance PV modules.

Hanwha Q CELLS introduced its proprietary Q.ANTUM cell technology that included a monocrystalline Q.PEAK prototype, which was said to produce up to 305Wp from 60 cells.

Shanghai Aerospace Automobile


Credit: MegaCell

A test array using bifacial 'BiSon' technology has shown promising yield gains.

Electromechanical (HT-SAAE) is also showcased its 'Milky Way' Twin Star bi-facial module, which uses N-PERT solar cells and is compatible with a 1,500V PV system, reducing BOS up to a claimed 10% due to its 20W higher power output compared to first generation Milky Way modules.

Seraphim Solar launched its new 'Eclipse' module at the Expo which archives 310W output power and 19.1% solar energy conversion efficiency, according to the company. The module is claimed to generate 15% more output than conventional modules by optimising the busbar and module design, increasing its active working area to an alleged 50% calorific effect.

Panasonic sets module efficiency record of 23.8%

Panasonic claims to have set a new module efficiency record of 23.8%, a full percentage point higher than the previous record c-Si record.

The company announced a cell conversion efficiency of 25.6% in its silicon heterojunction cells in April 2014 and now claims to hold both the cell and module records.

The milestone has been achieved at research level, not commercial production level, and was authenticated by Japan's National Institute of Advanced Industrial Science and Technology (AIST).

A previous round of efficiency records in October 2015 saw SolarCity's Silevo technology trumped by Panasonic.

The company has also pledged to continue developing its HIT technology to improve efficiency and move improvements from lab to fab.

Last month the manufacturer reportedly suspended one-third of its HIT manufacturing capacity citing low domestic demand.

New Fraunhofer CPV module sets new world record in efficiency

After announcing a new world record in solar-cell efficiency in 2014, Fraunhofer ISE reports that it has set a new benchmark for efficiency at the module level, using concentrator PV (CPV) technology.

According to the Freiburg-based research institute, a new CPV 'mini-module' consisting of four-junction solar cells reached a new world record efficiency of 43.3%.

Andreas Bett, deputy director of the institute at Fraunhofer ISE, said: "This value is a new milestone in the history of CPV technology and demonstrates the potential available for industrial implementation."

Multi-junction solar cells are often utilised in CPC, which is often integrated into regions with a large share of direct irradiation to generate cost-effective renewable electricity.

The 2014 record by Fraunhofer and partners Soitec and French research body, CEA-Leti, achieved a cell conversion efficiency of 46%, the highest recorded conversion of sunlight into electricity.

Back-contact technology: Will we need it in the future?

Radovan Kopecek, **Joris Libal**, **Andreas Halm**, **Haifeng Chu**, **Giuseppe Galbiati**, **Valentin D. Mihailetchi**, **Jens Theobald** & **Andreas Schneider**, International Solar Energy Research Center (ISC) Konstanz, Germany

ABSTRACT

The back-contact (BC) technology currently available on the market is considered to be either highly efficient but extremely expensive (interdigitated back contact – IBC – from SunPower) or, if cost-effective, not very efficient (metal wrap-through – MWT) compared with what is becoming today's new standard: passivated emitter and rear contact (PERC) technology. Something in between, such as low-cost, high-efficiency IBC cells and modules, would therefore be desirable. This paper briefly describes the past, focuses on the present, and forecasts the possible future developments of BC technology in respect of efficiencies, costs and applications.

Introduction

"Which will win?" is a frequently asked question at PV conferences and workshops. "Which will win – thin film, c-Si, p-type, n-type, bifacial, HIT, back contact, screen printing, plating, diamond wire, slurry...?" This is a complex question, the answer to which can only be guessed; some predicted answers to this most important question are given in, for example, the ITRPV [1]. What is known for certain, however, is that of all energy sources, PV will definitely be the winner, which is what Bloomberg has already forecast in their fairly recent study "Energy Outlook 2015" [2]. From 2022 onwards, PV will be the most important energy source in terms of the largest yearly added capacity (around 100GWp/year), with a yearly energy production of 1,040TWh at a cost of, on average, €0.05–0.06/kWh. And with this, the other, more detailed, questions will be easily answered. Even PV niche markets with 10–15% contribution will win, as they will still represent a market of at least 10–15GWp per year.

The geographical technology spread of c-Si manufacturing is quite clear. On the one hand there is China, with standard Al back-surface field (Al-BSF – mostly multicrystalline) p-type technology; on the other there is the rest of the world (ROW), with more advanced technologies, such as (at the moment) passivated emitter and rear contact (PERC), passivated emitter rear totally diffused (PERT), heterojunction (HJ) and interdigitated back contact (IBC). In the coming years China will progressively move to PERC as well, which will become standard in the next five to seven years, whereas ROW (including Taiwan, Korea and Japan) will implement in addition more and more advanced technologies, such as bifacial PERT, HJ and IBC. PV Tech also states that there is a "continued push from a diverse range of cell architectures, with no sign of any significant push to consolidation across the different n-type or p-type, mono or multi, and standard or advanced cell processes being used in production today" [3].

This paper presents a review of back-contact (BC) technology and gives a prediction of which role this technology will play in the future PV market.

> "The very first solar cell, created by Bell Labs in 1954, was actually an n-type BC solar cell."

A short history of back-contact cell and module technology

The very first solar cell, created by Bell Labs in 1954, was actually an n-type BC solar cell [4]. Two decades later, SunPower went into production with a 4-inch IBC solar cell, followed by a 5-inch version. The module assembly was then, and still is today, kept very simple, as the IBC cells are soldered at the edges. Around the year 2000, ECN came up with the 'PUM cell' concept, which was a metal wrap-through (MWT) cell and which also had the front (emitter) connected to the rear side. Standard stringing was not possible at the time, as that technology resulted in a significant bowing of the devices; a new module technology therefore had to be developed.

ECN, Solland and Eurotron were the first to develop the conductive backsheet (CBS) technology for PV, whereby the BC cells are picked and placed on a Cu backsheet. Solland was still focusing on soldering, whereas Eurotron and ECN were using conductive adhesive materials. The current cell technology then was based on mc-Si MWT, and many companies, such as Photovoltec, Sunways and others, had developed their own particular versions. At that time, around 2005, there were a few companies with MWT cells on the market, but hardly any reliable BC module technology existed. This was also the period when selective emitters and PERC technology were slowly penetrating the PV market, and so the advantage of MWT cells was getting smaller and smaller. Yingli together with ECN were developing an n-type version of MWT as well, but it quickly became clear that PERC and nPERT were becoming too powerful and the advantage of nMWT too small.

Today, however, the situation has reversed: there are many module technologies on offer for BC solar cells (see the module section discussion), but there are very few manufacturers producing this type of cell. The only feasible way of launching BC technology on the market is by means of a cost-effective IBC technology in conjunction with a simple module manufacturing process, which will be discussed in this paper.

Many PV experts say that BC technology does not, and will not in the future, demonstrate any benefit compared with two-side-contacted technologies: this is because of progressively thinner fingers and more favourable cell-to-module (CTM) P_{mpp} gains, so that the advantage of no shadowing on the front will become too small to justify the higher process complexity. However, the ITRPV roadmap still forecasts a 2%abs higher efficiency in 2026 for IBC technologies compared with other technologies, as well as a market share of more than 10%, which will equate to around 12GWp/year volume at that time (see Fig. 1).

The reason for this 10% market share is not only the high forecast efficiency

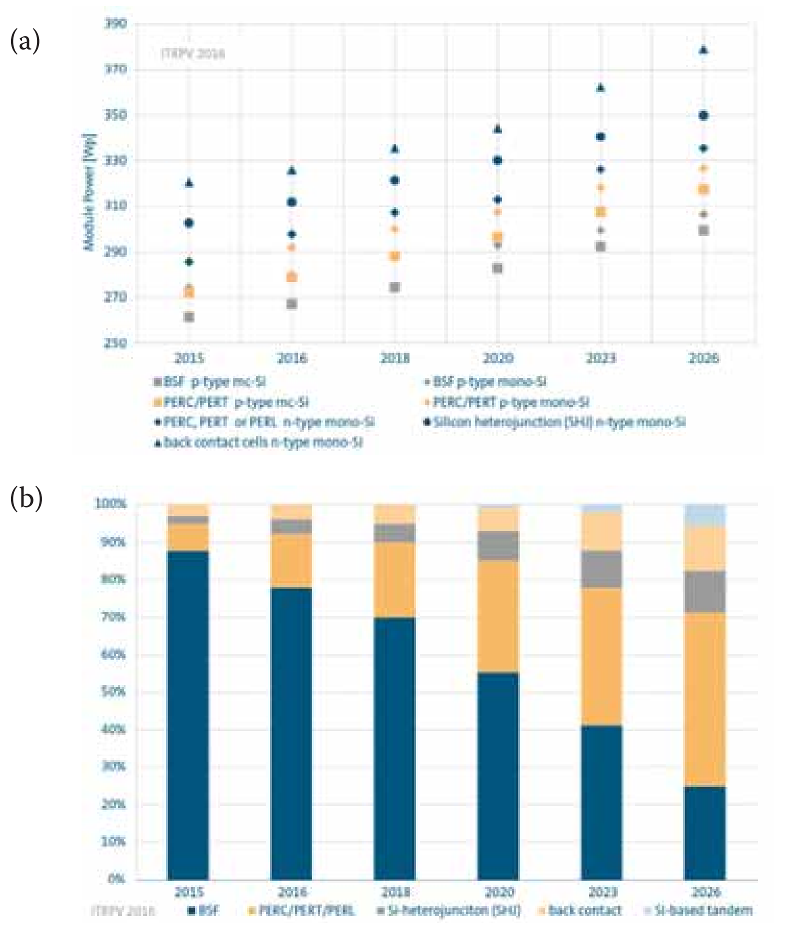


Figure 1. (a) Efficiency forecast for different technologies; (b) corresponding market shares. (Source ITRPV [1])

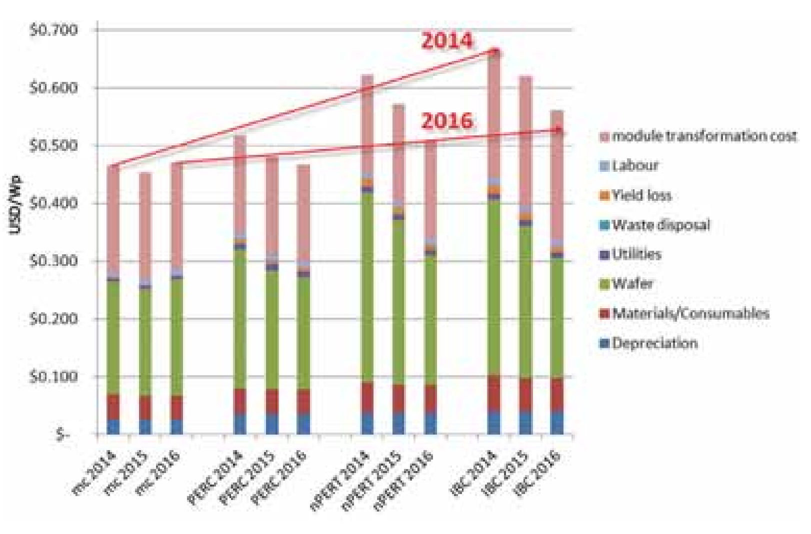


Figure 2. COOs for different low-cost c-Si technologies.

but also the advantages such as:

- Perfect front-side module homogeneity (no metal contacts on the front).
- Simple process for different colours (no contact firing through a black or coloured layer needed).
- Single print step for metallization (if appropriate paste is used).
- Simple process for passivated contacts (all passivated contacts on the back).
- Simple interconnection and better yield for thin cells (picking and placing of cells on a conductive backsheet instead of stringing).
- Higher shadowing tolerance (since an IBC cell can itself act as a bypass diode).

In the authors' opinion the IBC solar cell and module technology will have at least a niche market in the future for rooftops and building integration in, for example, the EU, Japan and the USA. These niche markets will, however, be huge and will gain in importance as time goes on.

Time for monofacial c-Si

For many decades mc-Si technology has dominated the market because of the much lower cost of the mc-Si wafers. In around 2005, however, mc-Si wafer producers started to increase the directional solidification quality by the introduction of seed crystals at the bottom of the crucible. This is when the so-called *quasi-mono* wafers first started to gain interest on the PV market; however, scientists began to realize quite quickly that it is not the crystal size but rather the dislocation density that is the more important for mc-Si wafer quality. On the contrary, the grains have to be small and not large: Taiwanese scientists were the first to discover that small crystals have fewer dislocations, and the technology of high-performance (HP) mc-Si material started to develop. As the HP material also uses seed crystals, and the crystallization is slower than for standard directionally solidified mc-Si wafers, the costs in this case are slightly increased as well. On the other hand, the costs for Cz-Si crystallization are lower, and for the first time, in 2016, we are in a situation where the wafer prices for mc-Si and Cz-Si are the same. This has the consequence that, again for the first time, PERC Cz-Si modules show similar (or even lower) manufacturing costs per Wp than standard mc-Si Al-BSF modules.

This can be seen in Fig. 2, in which the cost of ownership (COO) for different module technologies is summarized. The COO is calculated for an Asian production site with 100MW capacity only. It can be clearly seen that the major difference in costs per Wp when comparing different technologies are hidden in the wafer costs (green bars). In the past, when mc-Si wafer costs were much lower than those of p-type and n-type Cz-Si, the lowest costs per Wp were claimed by the standard Al-BSF module. This is now changing in favour of Cz-Si technologies, and is even more apparent when the levelized cost of electricity (LCOE) is considered, as will be seen in the next section.

Time for high-efficiency technology

Fig. 3 shows the corresponding LCOEs for the different technologies depicted in Fig. 2. At the system level, the higher costs for high-power devices are recovered by the lower BOS costs, because the higher the module power is, the lower the balance of system (BOS) costs are.

If we think in terms of cost/Wp, the high-efficiency devices PERC, nPERT and IBC are getting closer and closer to mc-Si modules, as the wafer costs for mono c-Si devices are approaching those for mc-Si. As regards cost/kWh, some mono c-Si technologies are more cost-effective than mc-Si technology. If bifaciality is considered, the LCOE can be reduced to a level never reached before.

Time for back-contact solar cells?

Several different BC technologies have in the past been considered to be of interest to the PV market, namely metal wrap-around (MWA), MWT, emitter wrap-through (EWT) and IBC. In this section the geometries, as well as the advantages and disadvantages, of all these concepts will be described.

First, the geometries of MWA, MWT and EWT cells are shown in Fig. 4 [5]. Of these, the **MWA** cell (Fig. 4(a)) is the simplest – however, the cell needs to be cut into pieces, as the busbars are located only on the edges. At the time of its conception, MWA was not considered to be an attractive option, because of the low scalability of the solar cell. Today, however, with a new awareness of using 1/2, and even 1/3 or 1/4, stripes of 6-inch cells in order to lower the CTM resistive losses, the MWA cell could be appealing for the shingling technique, which is currently growing in popularity. Many companies (e.g. Solar City and SunPower) are now working on shingling instead of stringing.

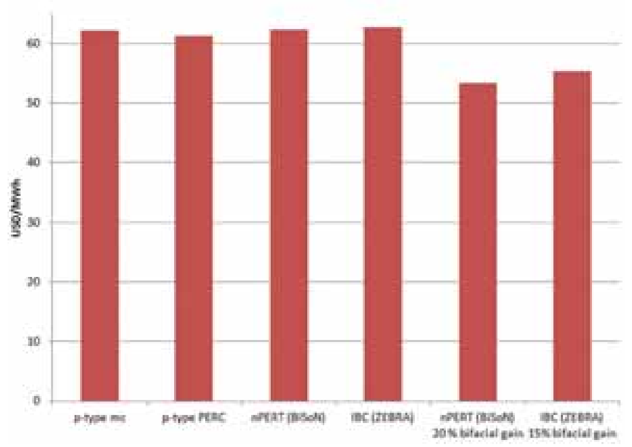


Figure 3. LCOE for different low-cost c-Si technologies in 2016 for southern Spain (yearly global horizontal irradiation = 1,800kWh/m².).

MWT technology requires the least effort to use 6-inch solar cells and to realize a contact on the rear side of the cell. Two different approaches have been used: one by ECN and Solland, and the other by Photovoltec and Sunways. The first consortium used 16 larger holes with unit cells around these holes in the form of an organic structure, whereas the others used the standard H-pattern cell structure with several holes for each rear busbar. This technology was developed for p-type mc-Si as well as for Cz-Si wafers: however, it quickly became evident that the upcoming technologies, such as PERC and PERT, would surpass the advantage of MWT. Yingli started to adapt n-type MWT technology from ECN as well, but with little success. It is now commonly accepted that if a BC cell should come on the market, it would have to be an IBC one.

Advent Solar and a few other companies have tried to introduce

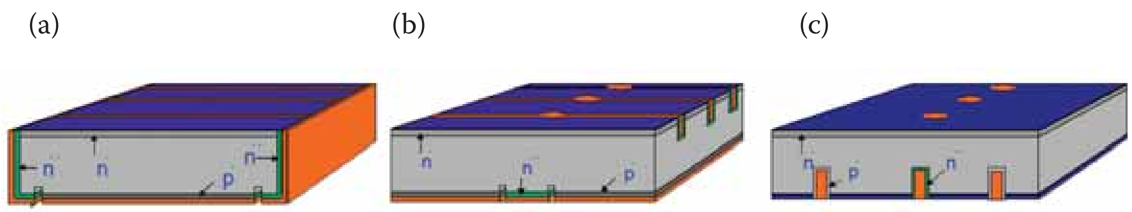


Figure 4. Different BC concepts: (a) MWA, (b) MWT, and (c) EWT [5].

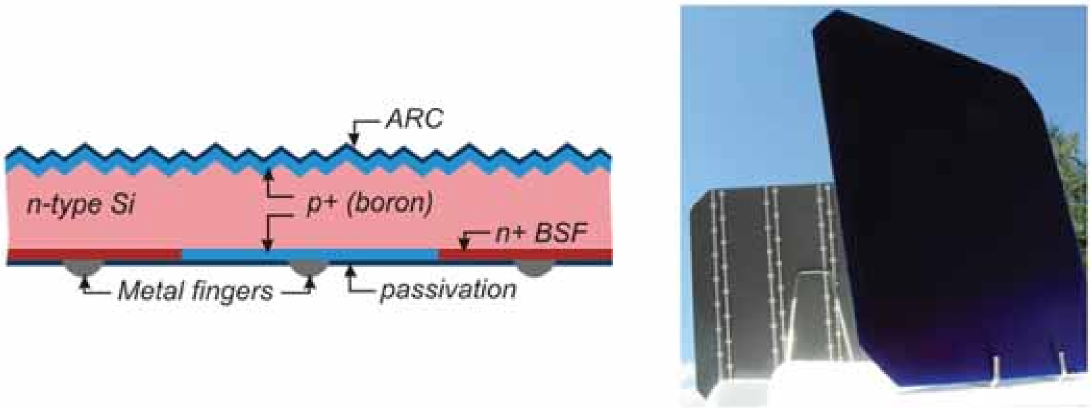


Figure 5. The ZEBRA IBC concept.

PV Modules

Company/Institute	Area [cm^2]	Efficiency [%]	Process	Reference
Sharp	4	25.1	SHJ-IBC	[6]
ANU	4	24.4		[7]
ISFH	4	23.4	Implanted	[8]
imec	4	23.3	Diffused, evaporated	[9]
ipv Stuttgart	4	23.2	Laser doped	[10]
FhG ISE	4	23.0		[11]
Panasonic	156	25.6	SHJ-IBC	[12]
SunPower	121	25.2	Diffused, plated	[13]
Trina Solar	239	23.5	Diffused, SP	[14]
imec	239	22.7	Diffused, evaporated	[15]
Samsung	155	22.4	Implanted, SP	[16]
Bosch	239	22.1	Implanted, SP	[17]
ISC Konstanz	239	22.0	ZEBRA, diffused FFE, SP	[18]
ipv Stuttgart	156	21.9	Laser doped, SP	[19]
ECN	239	21.3	MERCURY, diffused FFE, SP	[20]
DuPont	239	21.3	Paste diffused FSF, SP	[21]
Hareon	239	19.6	Diffused FSF, SP	[22]

Table 1. Different IBC technologies on small and large areas (SP=screen printed, FFE=front floating emitter, FSF=front-surface field, SHJ=silicon heterojunction).

EWT to the market. This technology has no front metallization at all. The carriers collected on the front emitter are transported through the emitter to the back contact; therefore, thousands of holes are needed, which is a complicated process and results in a fragile device.

IBC technology, which is illustrated schematically in Fig. 5 for the ZEBRA IBC concept, became available on the market many years ago from SunPower, and a number of other companies have since tried to simplify this technology.

Table 1 summarizes the different IBC technologies from different companies and R&D labs, and the efficiencies achieved on small and large areas. Not only do the small- and large-area capabilities make a difference, but also the costs associated with the processes are an important factor.

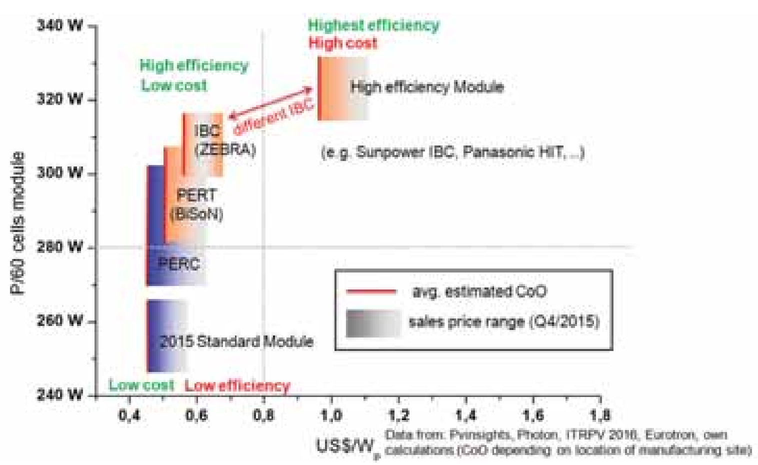


Figure 6. COOs for different low-cost (left) and high-efficiency (top right) technologies.

> "The highest efficiency modules no longer justify the high costs, as the gap in efficiency in mass production with the low-cost solar cells is gradually closing."

The COOs of the different technologies in Fig. 2 are illustrated in a different way in Fig. 6: this alternative representation depicts not only the costs and selling process, but also the attainable power for a module incorporating 60 6-inch solar cells. Two different regions can clearly be seen: 1) low cost and high efficiency (upper left); and 2) high cost and highest efficiency (upper right). The highest efficiency modules no longer justify the high costs, as the gap in efficiency in mass production between them and the low-cost modules is gradually closing.

By way of example, for *cost-effective IBC solar cells* the ZEBRA concept, which is currently being developed within ISC Konstanz's HERCULES FP7 EU project [23], will be described next. In this project it is proposed to develop innovative n-type monocrystalline c-Si device structures based on two-side-contacted (SHJ) and back-contacted (IBC) solar cells with alternative junction formation, as well as hybrid concepts (homo-heterojunctions). These concepts have been identified as the most promising technologies for achieving ultra-high efficiencies using industrially relevant processes. The HERCULES strategy is to transfer the developed processes to an industrial scale by considering all the major cost drivers of the entire

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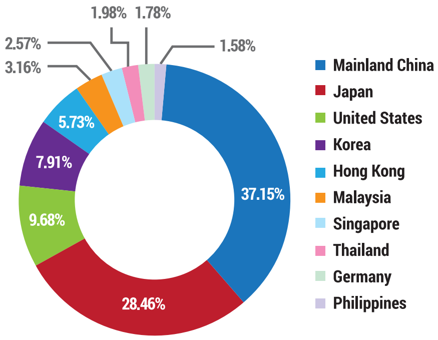

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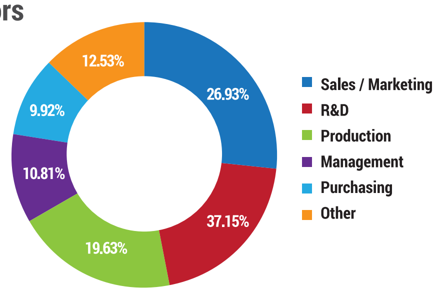

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manufacturing process chain. The final objective is to obtain both high-efficiency solar cells and modules using adequately simple process sequences.

Within the HERCULES project, ISC Konstanz is further improving and industrially piloting its low-cost and high-efficiency ZEBRA technology. Industrially available techniques for mass production – such as conventional diffusion processes, PECVD deposition, and screen printing and firing-through metallization – are used in the fabrication process for the ZEBRA cell concept. Moreover, the concept features a front floating emitter, which significantly improves carrier-collection efficiency for device geometries with large pitch and base regions. (See Fig. 5 for a schematic cross-section of the ZEBRA cell concept, together with an actual photograph of the prototype solar cell.) The best ZEBRA cell fabricated so far on a large-area substrate has an efficiency of 22%; in pilot line production, an average efficiency of 21.5% was demonstrated.

Additionally, as a result of their open rear-side metallization grid, the ZEBRA cells are bifacial; this allows the fabrication of bifacial modules, which could significantly boost the energy yield as compared with cells having a fully covered rear side. ISC Konstanz has demonstrated that such a bifacial module would typically generate an energy yield 15% greater than that of a module with similar cells but monofacial [24]. This is significant because it also means that – if installed in a suitable manner (i.e. ground mounted) – such a bifacial module (with about 300Wp) would produce an energy yield similar to that of the currently best-performing SunPower module (with 345Wp) fabricated with 24%-efficiency cells.

Back-contact modules

The module integration of BC cells at an industrial level is mainly realized by variations of two current technologies: 1) specially adapted tabber–stringer tools, with which the cell–cell contact is established by soldering or conductive adhesive gluing of ribbons; and 2) the CBS approach, where BC cells are glued on top of a conductive metal foil covering the full rear side of the module and structured to provide cell–cell interconnections as well as string interconnections.

Apart from these two solutions, few other industrial module concepts seem to be adaptable to the integration of BC cells, although many new approaches are being investigated by R&D teams all over the world.

Back-contact modules based on tabbing/stringing

The traditional approach used for BC module assembly is the single-sided tabbing/stringing method. The contact between the BC cell and the ribbon can be realized by soldering, electrically conductive adhesive (ECA), or solder paste. In the case of MWT, only point contacts between cell and ribbon are possible; an isolation layer must be introduced locally to avoid electrical contact between a ribbon of one polarity and the cell metallization of the opposite polarity, which would cause a short circuit of the cell. For IBC cells like the ZEBRA cell featuring floating busbars on its rear, this isolation is not needed, and soldering on the full length of the busbars can be realized.

Single-sided ribbon interconnection inflicts high mechanical stress on the solar cell, because this stress is not counterbalanced from the other side. That is the reason why either structured or super-soft ribbon is used to minimize the mechanical stress and hence reduce the bowing. An important advantage of ribbon interconnections compared with CBS is the possibility of assembling a bifacial module by either using a transparent backsheet or assembling a glass–glass module. In this case the bifaciality of back-contacted cells, such as the ZEBRA cell, can also be exploited at the module level, leading to a significant increase in energy yield (kWh/kWp(front)) and thus to a reduced LCOE (€/kWh).

Dedicated equipment for the stringing of BC solar cells with several (up to eight) rear busbars is available on the market from various companies (e.g. Teamtechnik or Somont) and is already being used to produce MWT modules. There are also bespoke solutions on offer, such as the Soltech approach developed in-house; this is based on point-contact stringing of ribbons along the entire cell length (see Fig. 7) through a porous glass fibre sheet which provides electrical insulation.

Another solution for tabbing-based interconnection is edge stringing, as used by SunPower; here, the electrical string current is transported by the cell's metallization. The cell–cell interconnection tabs are located in

Figure 7. Back-contact stringer: MWT cells are interconnected with stress-relieved ribbons using solder paste; a glass fibre sheet between the cell and the ribbons prevents short circuits. (Source: Soltech, MWT WS 2013 Freiburg)

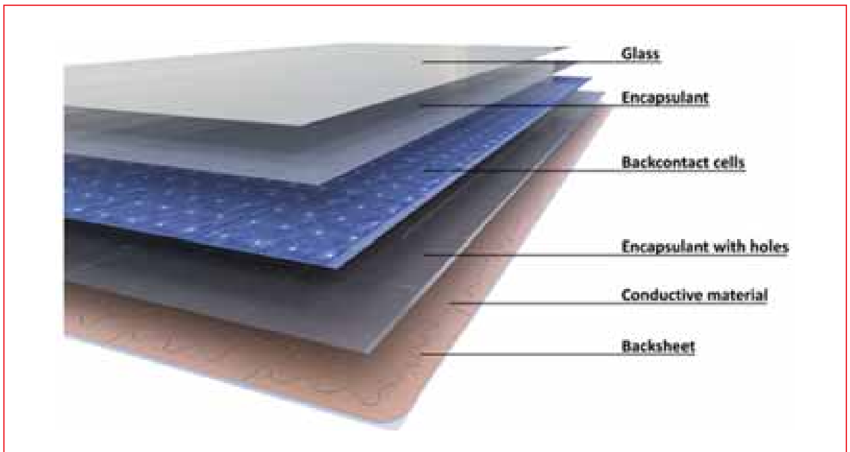

Figure 8. A typical module sandwich for CBS-based modules. (Source: Eurotron)

PV Modules

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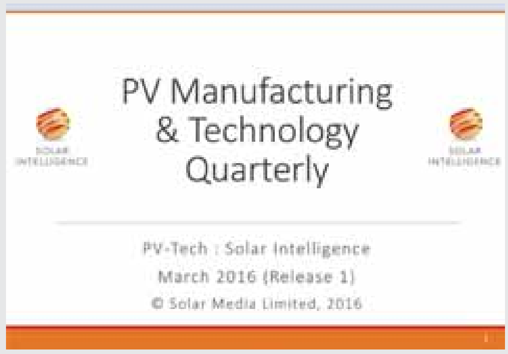

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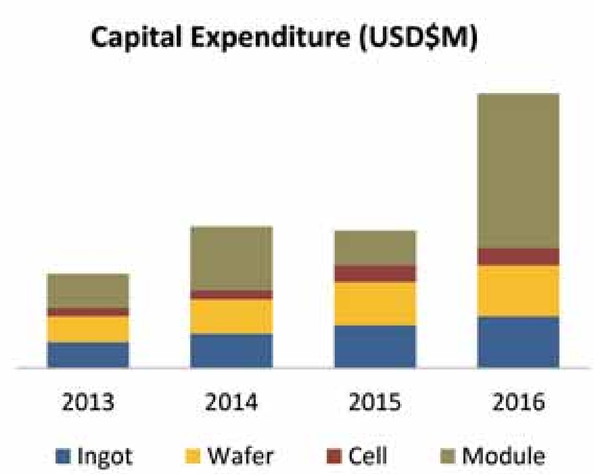

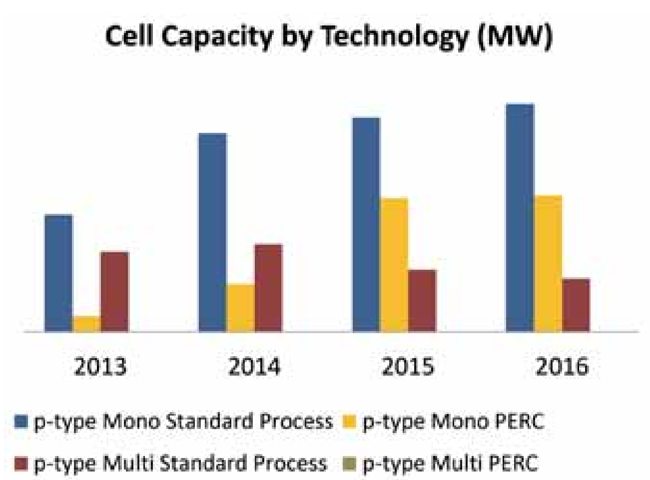

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between the cells, contacting only dedicated pads at the cell edges. The advantage of this method is that the mechanical stress inflicted on the solar cells is much reduced; a limitation, however, is the resistive losses in the cell metallization, which scale with cell size, and thus the maximum cell size is restricted to five inches.

Back-contact modules based on a CBS

The CBS approach was adopted from printed-circuit board production and is only suited to BC cells. It was developed by ECN, TTA and Solland for p-type MWT solar cells, and introduced to the market in 2009 by Eurotron, a daughter company of TTA. Other providers of technology and equipment for module assembly based on CBS are the Italian company Formula E and the Finnish company ValoE. At the moment, only Eurotron's equipment is used in industrial module production by a few companies producing MWT modules (to the authors' knowledge, the most powerful MWT module, generating a power output of 300W, is produced by Nanjing Sunport Power Co. Ltd).

A typical module sandwich including the CBS is composed of glass, front encapsulant, BC cells, rear encapsulant with local openings to electrically contact the cells, and the CBS (see Fig. 8).

The conductive layer, which is the basis of each type of CBS, is around 35µm thick (depending on the supplier), with a total weight per cell area of more than twice the mass of the ribbon needed to interconnect a three-busbar cell. This results in a very low series resistance related to the P_{mpp} CTM losses. The CBS is mostly made of copper or of aluminium coated with a thin layer of copper to aid contact (e.g. Hanita Coatings' DuraShield). The metal covers almost the entire module area and is only interrupted by small isolating trenches, which define conduction paths for both polarities. These isolation trenches are formed by mechanical milling, by laser or by wet chemical etching. To avoid corrosion the copper layer requires a suitable finish, such as ZnCr (e.g. Krempel's AKACON BCF) or treatment with an organic surface protectant (OSP – e.g. Isovoltaic's Icosolar TPC 3480) on the side facing the solar cells.

For most CBS concepts the rear encapsulant provides electrical isolation between the CBS and the cell; the encapsulant is locally opened by mechanical punching or laser. The typical CBS also includes a stack of polyethylene terephthalate (PET) and Tedlar (or similar material) on the rear side to protect against environmental influences. The EBfoil BYS, developed by EBfoil and produced by Coveme, even goes one step further: this is a stack system consisting of a rear encapsulant with a dielectric layer combined with a CBS composed of PET layers, a copper or aluminium conductive layer, and a primer layer. After structuring the two components according to the desired module circuit design, the stack is used as a single sheet that combines the CBS and the rear-side encapsulant. Other concepts, such as 'contacfoil-connect' by Eppstein Technologies, consist of simply a structured copper sheet and a dielectric layer for electrical isolation between cell and copper, which is locally opened by laser. In the module assembly process, the rear encapsulant is placed behind the CBS, followed by a standard backsheet or Eppstein's 'contacfoil-back'.

The electrical contact between BC cells and the CBS is accomplished by ECAs, although solder paste can be a cheaper alternative. In both cases the conductive ink is applied locally onto the CBS or the rear side of the cell by stencil printing or dispensing during module assembly. The printing image matches the openings in the isolation layer to allow contact formation. The BC cells have to be placed precisely on top of the rear module stack using a pick-and-place unit. ECA gluing or the use of solder paste introduces very low mechanical stress compared with soldering. Usually, after cell placing the finished sandwich is flipped before lamination. During lamination the low ohmic electrical contact between the cell and the CBS is established. One drawback of this contacting procedure is that no electroluminescence (EL) inspection of modules prior to lamination is possible.

Using the above-mentioned methods, ISC Konstanz and Eurotron collaborated to adapt the MWT module technology to fit the needs of the ZEBRA back-contact back-junction cell within the framework of the HERCULES project, which has received funding from the European Union's 7th Framework Programme for Research and Technological Development under Grant No. 608489. The first prototype back-contact module comprising 60 ZEBRA cells was assembled in Q3 2015 and featured a 300Wp power output, as shown in Fig. 9. This result demonstrates the potential of a concept which yields an initial power level that common technologies can only get close to because of their physical limitations.

Other methods for back-contact module assembly

Although many alternative approaches for assembling BC modules have been investigated by various research centres and R&D teams around the world, most do not go beyond the mini-module level. Some interesting concepts are listed below, without claiming to be complete.

In a publicly funded project called InGrid (No. SOLARERANET2-093, Grant No. 325821), for example, ISC Konstanz in a consortium with STRE, Prodintec and Gwent investigated a BC module solution based on printing an interconnection circuit directly on top of

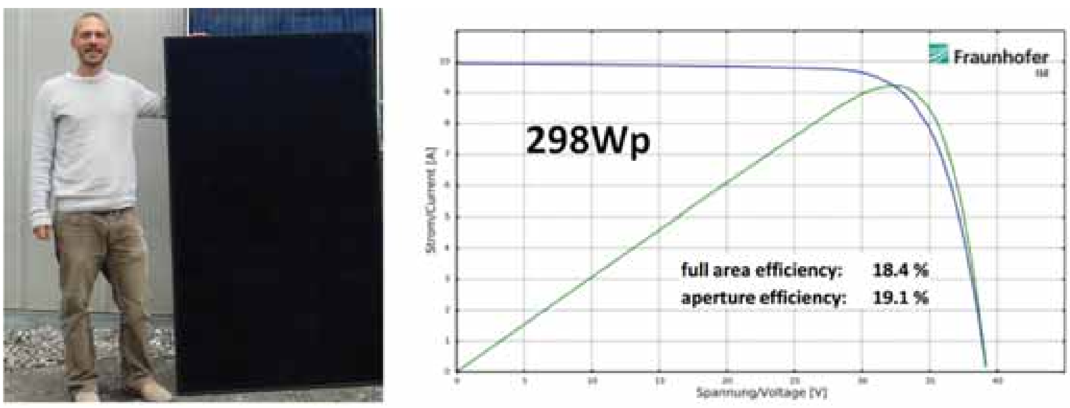

Figure 9. ZEBRA Eurotron Module certified at FhG ISE CalLab. The second-best module was sent for certification.

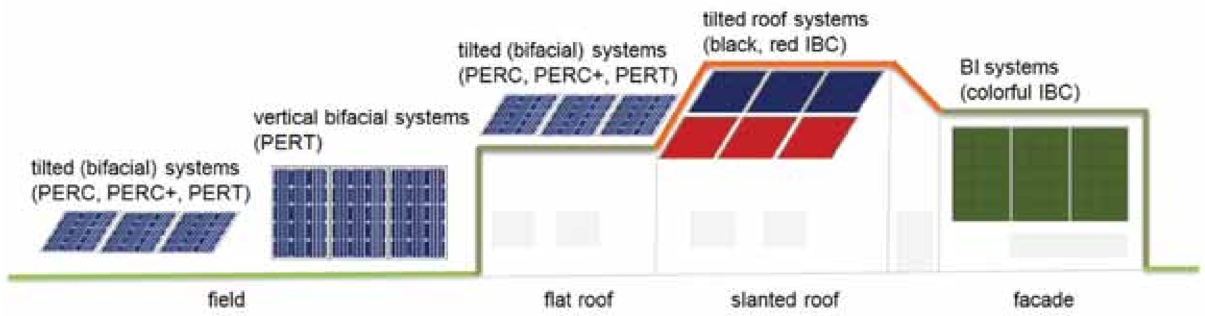

Figure 10. Split for (bifacial) PERT (and PERC+) and IBC (and PERC) applications.

the rear encapsulation layer, which would dramatically simplify the module assembly.

Together with Soltech, imec developed a method they call *woven fabric interconnection*. This fabric is a compound material in which thin metal wires and glass fibres are arranged in such a way that cells can be interconnected by the metal wires, while the glass fibres provide electrical isolation where needed.

Concepts such as the NICE module developed by Apollon Solar and Fraunhofer ISE's TPedge technology are well suited to BC module assembly. In both cases the lamination step is replaced by edge sealing of two glass sheets after placing cell strings inside. Fraunhofer ISE installed 70 TPedge modules fabricated in-house with MWT cells on the facade of its lab building in 2015. NICE technology is already used industrially for two-side-contacted cells, but it is also particularly attractive for BC modules incorporating cells with continuous busbars. The electrical cell ribbon contact is established during module assembly solely by mechanical pressure, and thus cell bowing does not occur. In addition, the multi-busbar concept offered by Schmid could be adapted to BC solar cells, provided that the alignment precision of the single wires is sufficiently high.

Back-contact module applications and markets

As already discussed, the applications for BC modules will be found in sectors where more than just electricity generation will play a role; these will be mostly on houses and on building facades. For slanted rooftop applications, black modules will be used; if a roof with red tiles is to be electrified, even reddish modules could be applied. The markets for this are the EU (e.g. the Netherlands is a pure rooftop market), Japan, Australia and the USA.

For the building-integration sector, facades could be equipped with pleasing, colourful modules, and even hybrid modules (electricity and hot water) are under development. As the BC modules use a CBS, the temperature coupling to the solar thermal application on the rear is very effective. BC modules can even be made bifacial: this could be an advantage when, for example, the aesthetics of the system are also important, such as in a flat roof installation.

Fig. 10 summarizes schematically what has been discussed above. On the left side of the image, the major application of PV in large systems using cost-effective PERC, PERC+ and PERT modules can be seen. As regards the building sector (right side of image), aesthetics and small-area requirements (high efficiency) will play a role, which means more and more BC modules will penetrate this particular market.

"The authors are convinced that low-cost IBC cell and module technology will play an important role and assume a strong market position in the future."

Summary

PV technology has a bright future – there is no doubt about it. The authors are convinced that low-cost IBC cell and module technology will play an important role and assume a strong market position in the future. Even though the highest-power advantage is becoming smaller and smaller, there are still a number of applications, mostly in the building segment, that make IBC technology an extremely attractive option.

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Dr. Radovan Kopecek is one of the founders of ISC Konstanz. He has been working at the institute as a full-time manager and researcher since January 2007 and is currently the leader of the advanced solar cells department. Dr. Kopecek received his M.S. from Portland State University, USA, in 1995, followed by his diploma in physics from the University of Stuttgart in 1998. The dissertation topic for his Ph.D., which he completed in 2002 in Konstanz, was thin-film silicon solar cells.

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Giuseppe Galbiati graduated in materials science from the University of Milan, where his studies focused on the characterization of silicon materials and on optoelectronic devices. His expertise extends over interdisciplinary areas, spanning research, engineering and project management. Since 2010 he has been with ISC Konstanz's advanced cell concepts department, concentrating on developing feasible low-cost industrial processes for high-efficiency n-type-based silicon solar cells, with a main research focus of BC cell architectures (IBC and MWT). More recently he has also been working on the optimization of devices for c-PV application in the low–medium intensity ranges.

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Investigation of cell-to-module (CTM) ratios of PV modules by analysis of loss and gain mechanisms

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ABSTRACT

The output power of a solar module is the sum of the powers of all the individual cells in the module multiplied by the cell-to-module (CTM) power ratio. The CTM ratio is determined by interacting optical losses and gains as well as by electrical losses. Higher efficiency and output power at the module level can be achieved by using novel ideas in module technology. This paper reviews methods for reducing different optical and electrical loss mechanisms in PV modules and for increasing the optical gains in order to achieve higher CTM ratios. Various solutions for optimizing PV modules by means of simulations and experimental prototypes are recommended. Finally, it is shown that designing PV modules on the basis of standard test conditions (STC) alone is not adequate, and that, to achieve higher CTM ratios by improving the module designs in respect of environmental conditions, an energy yield analysis is essential.

Introduction

The processing of solar cells into modules leads to different physical power loss and gain mechanisms in the stack. The optical losses result from reflection and absorption in the glass and encapsulant, and the electrical losses are caused by the Joule heating effect in module interconnections. Optical gains are realized through back reflections of light from the backsheet through the cell spacing, from solar cell metallization and connecting tabs, and from the solar cell surface inside the cover stack [1–5].

The ratio of module power to cell power, multiplied by the number of cells integrated in the module, is defined as the *cell-to-module (CTM) power ratio*. This factor quantifies the general loss/gain percentage in a PV module [6], and its importance can be explained by means of an example. The efficiency of some of the top solar cells recently launched on the market is about 21.25±0.4% for multicrystalline solar cells, while the corresponding PV module incorporating these cells demonstrates an efficiency of 19.2±0.4% [7]. This corresponds to a reduction in module efficiency of almost 2%$_{abs}$, or a CTM ratio of 90%, which equates to almost 18 years' R&D work on improving the efficiency of multicrystalline solar cell technology [7,8].

According to the International Technology Roadmap for Photovoltaics [6], with advances in PV and module technology it is expected that CTM ratios of over 100% will be achieved by reducing the electrical and optical losses and increasing the optical gains at the module level, as seen in Fig. 1. (Note that 'CTM' is still occasionally used to refer to cell-to-module *power* losses; however, since the losses are nowadays expected to be 0% and below, the CTM power ratio is more widely used.)

This paper reviews different methods for increasing the CTM ratio of PV modules by modifying module integrations and employing different module designs. Optical effects in PV modules are discussed, along with possible solutions for reducing the optical losses and increasing the gains. Also presented are various modifications of module interconnections and connecting tabs in order to decrease electrical losses by means of alternative measurement and simulation methods. Furthermore, the impact of environmental conditions

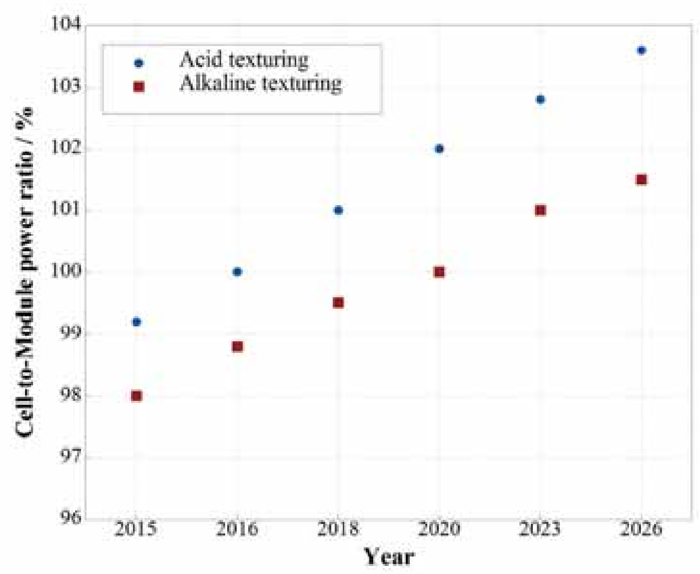


Figure 1. Expected trend of the CTM power ratio over the next 10 years [6].

on module performance is analysed, and possible solutions and tools are proposed for increasing the CTM ratios with regard to different locations and climates.

"A higher CTM is achievable by reducing unavoidable electrical and optical losses and by enhancing direct and indirect optical coupling gains."

Power gain approaches

Basically, a higher CTM is achievable by reducing unavoidable electrical and optical losses and by enhancing direct and indirect optical coupling gains. Electrical losses in the module are ohmic losses due to the interconnection in the module and bypass diodes in the case of shading conditions. Optical losses are caused by light reflection and absorption in the front stack of module materials, as well as by light incidence on inactive module areas, such as the module perimeter, cell interspaces and top contacts. Direct optical coupling gains result from improved index matching at the front cell interface after lamination. Indirect optical coupling gains can be obtained by redirecting light from inactive module areas to the cell.

Fig. 2 shows the relevant loss and gain mechanisms that occur in the different regions of a typical c-Si solar module, i.e. in the front layer stack (mechanisms 1–5), in the cell interspace/module border areas (6 and 7), on the top contacts (8 and 9), and in the electrical interconnection (10). The indicated numbered effects and possible related CTM improvements are discussed in the following subsections.

A suitable method for predicting the total power of a module has proved to be a sequential consideration of the mechanisms, where a certain loss/gain factor is calculated for each effect [3]. In the determination of the individual factors, the whole system needs to be considered: an example of this is that the reflection loss at the glass/encapsulant interface is (as will be explained below) determined by the glass, the encapsulant, and the spectrum hitting that interface, as well as by the spectral response of the present cell.

In module evaluation and design, the optical and electrical interactions between the different module components need to be considered. For the top-contact design in particular, the optical and electrical effects influence each other; for example, the optical shading losses of the front contacts are reduced by using smaller tab widths, but, at the same time, smaller tabs cause higher resistive losses. The electrical losses in the interconnection should always be taken into account. In the optimization of the efficiency of a module, the product of all loss/gain factors has to be maximized. A cost–benefit analysis, however, is also essential, especially in the case of commercial modules.

Optimization of the module stack (mechanisms 1–5)

On a light path through the front layers of a module, the targeted optical losses for reduction are (with reference to Fig. 2) the reflection at the glass/air interface (1), the absorption inside the glass (2), the reflection at the glass/encapsulant interface (3), and the absorption inside the encapsulant (4). With regard to the CTM, the reflection at the encapsulant/cell interface (5) is usually a gain. This is due to the fact that a larger fraction of light is coupled into the cell surface after lamination, because the high refractive index of the cell ($n_{SiN} \approx 2$ and $n_{Si} = 3.8$ at $\lambda = 680$nm) better matches that of the encapsulant materials ($n_{encapsulant} = 1.48 \ldots 1.50$ at $\lambda = 680$nm) than that of air ($n_{air} \approx 1$).

The change in light intensity at the reflecting interfaces under consideration and inside the corresponding absorbing layers can be calculated using the Fresnel equations [9] if the optical spectroscopy data

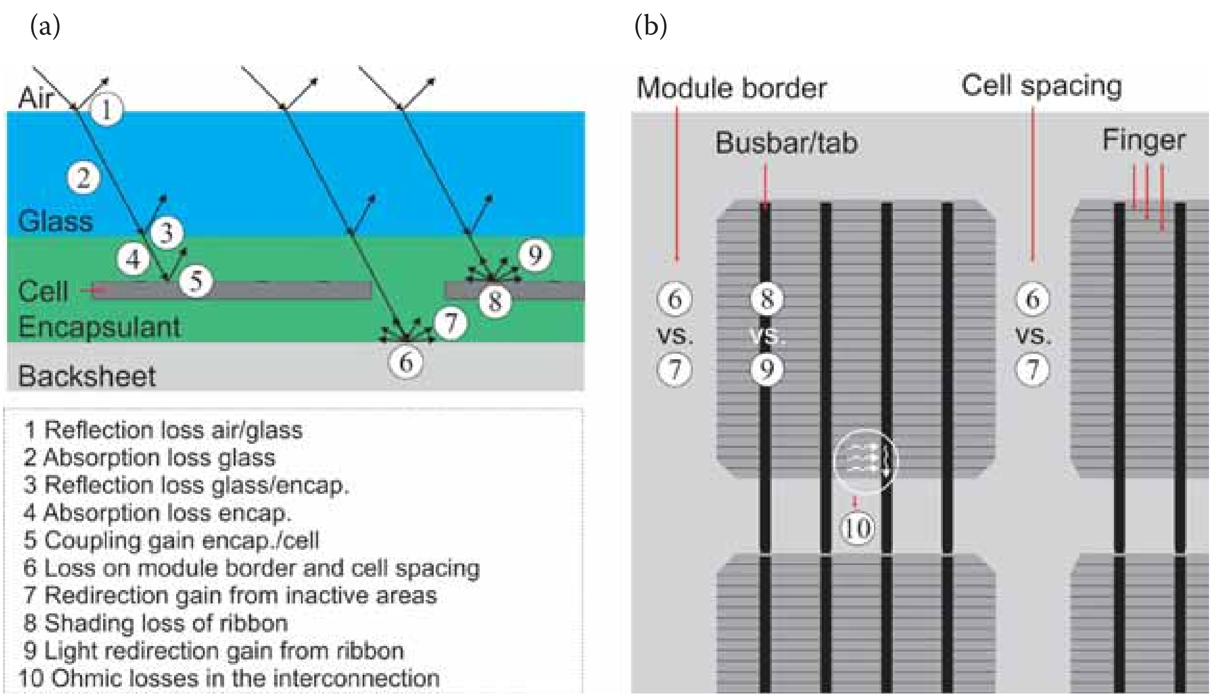
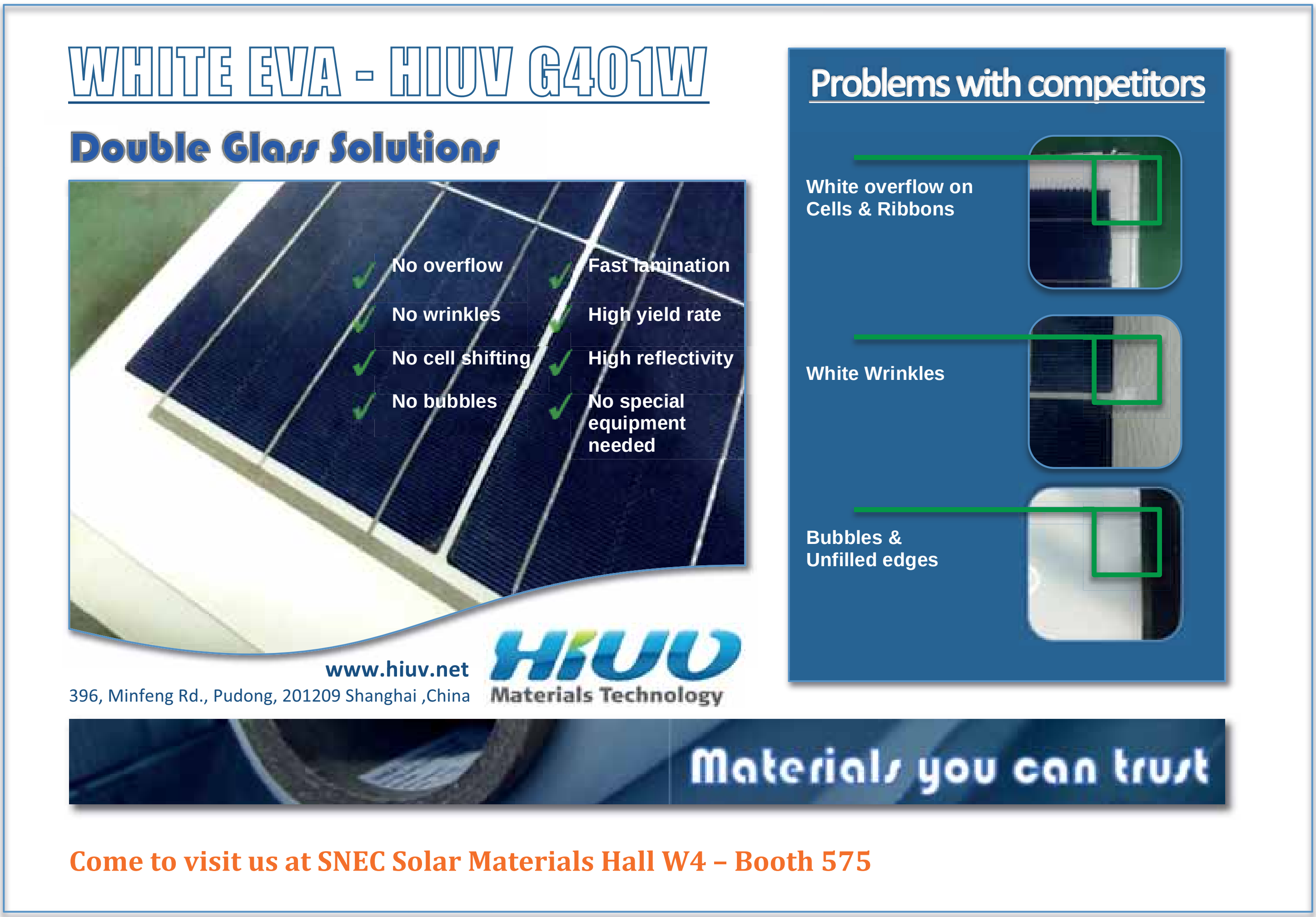


Figure 2. Schematic cross section (a) and top view (b) of a typical crystalline Si-based PV module, showing the different loss/gain mechanisms described in the text.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of the material are known. In the case of thin layers, interference effects have to be considered in an electric field description; this can in principle be done analytically, but is usually calculated numerically by the so-called *transfer-matrix method* [10]. If the effects of structured interfaces or regions need to be determined, it might be necessary to perform numerical simulations – for example, finite element calculations.

Considering the standard case of vertical incidence on a planar interface between layer *j* and layer *j+1*, the Fresnel equations can be simplified, and the reflection coefficient, given by the ratio of reflected and incoming intensities, is then:

$$R_{\theta=0^\circ} = \frac{\left(n_{j+1} - n_j\right)^2}{\left(n_{j+1} + n_j\right)^2} \quad (1)$$

Correspondingly, for a simple air/Si interface a large amount of light intensity R = 35% (see values above) is lost. Theoretically, this loss can be reduced to about 10% by the distribution of the large refractive index difference Δn over several smaller steps.

Materials with optimal refractive indexes, however, are not available. Although a very good index matching between glass and encapsulant is possible, in the case of the other interfaces (i.e. air/glass and encapsulant/Si) anti-reflection (AR) coatings or light-trapping structures are the best options for reducing reflection losses.

The integral reflection loss at the air/glass interface (mechanism 1) can be reduced from about 4% to below 1% by introducing a single AR layer. A popular AR layer for glasses is nanoporous SiO_2, since it has the required low (effective) refractive index n, the specific value of which can be designed by the volume fraction of the pores.

The optimum refractive index of an AR layer is intermediate to those of the materials on either side, i.e. $n_{AR} = (n_j \times n_{j+1})^{1/2}$. Its optimum thickness is $d = \lambda/(4 \times n_{AR})$, leading to zero reflection at the design wavelength λ by destructive interference. Of course, multilayer AR coatings can suppress reflection over a broader spectral range. However, with regard to the achievable additional efficiency gain, the added costs of multilayer coatings have to be taken into account for the economic production of solar modules.

The absorption loss inside the glass (mechanism 2) can be minimized by a proper choice of mineral glass, such as the extra-clear, low-iron, soda-lime silica glass. Besides the glass composition (transition metal ion impurities cause absorption losses in the relevant spectral range, and network modifiers determine the UV absorption edge), the glass quality (glass defects cause scattering losses) is of relevance.

The reflection loss at the glass/encapsulant interface (mechanism 3) can easily be reduced to below 10^{-3}, since suitable encapsulant materials with the same refractive index as glass ($n_{glass} \approx 1.5$ at λ = 680nm) are available (EVA, PVB, TPSE – all having a refractive index between 1.48 and 1.5 at λ = 680nm).

The absorption loss inside the encapsulant (mechanism 4) is more critical. Because of its reactivity, EVA is usually doped with UV blockers, causing the UV-absorption edge of the EVA to already set in at 380nm. Since such UV protection is not necessary for PVBs and silicones, they provide much better UV transmission.

From an optical optimization point of view, when choosing an encapsulant the index matching to the glass is more important than index matching to the cell surface. The reflection at the encapsulant/Si interface can be more effectively influenced by the surface texture and the silicon nitride AR layer of the cell. Thus, an improvement related to mechanism 5 requires an optimization at the cell level, which is not discussed further in this paper.

In general, the effects of different module materials depend on the particular set-up. The loss factor, which is the relevant quantity in module design, is a weighted total integral intensity loss over the relevant spectral range. The integral is weighted with the spectrum incident on the corresponding layer and the spectral response of the solar cells under consideration. In Fig. 3(a) the combined weighting function, i.e. the product of both functions, is shown for an irradiated AM1.5g sun spectrum and selective emitter (SE) cells with a high UV spectral response. By means of this weighting, the fact that the module materials need to be optimized with respect to the spectral distribution of the available (and also convertible) light intensity is taken

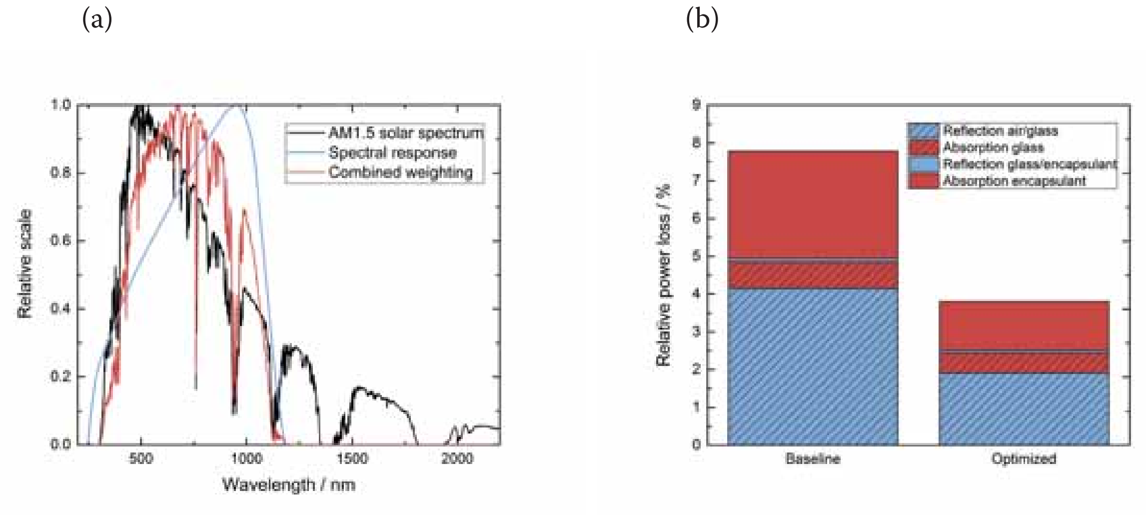

Figure 3. (a) Irradiated AM1.5g solar spectrum [12], spectral response function of selective emitter (SE) cells, and resulting weighting function. (b) Relative power losses due to various optical processes in the front stack of a baseline module compared with a module optimized with an AR coating on glass, thinner glass and high UV transmittance encapsulant [11].

into account. In the example given next, the performance of the material is relevant between approximately 300 and 1100nm, where the design wavelength should be at about 675nm, in other words at the maximum of the combined weighting function.

Example: Effects of AR coating, thinner glass and high UV transmission encapsulant

To illustrate the effects of various innovative technologies, in the following example the different loss factors for mechanisms 1–4 are determined for a baseline and an improved solar module. Both modules are prepared with SE solar cells. In essence, the baseline module is built with standard solar glass and EVA encapsulant, whereas glass with an AR coating and reduced thickness (2mm instead of 3.2mm) and PVB encapsulant is used for the improved module. The experimental investigations of the modules and the module materials used are presented in Schneider et al. [11].

Here, the factors are calculated with the combined weighting function given in Fig. 3(a) by using the optical transmittance and reflectance spectra of individual and combined module materials. The resulting power losses are summarized in Fig. 3(b). The relative power loss of mechanisms 1–4 is about 8% in total for the baseline module investigated. The largest contribution to the power loss, being about 4%, stems from the reflection at the air/glass interface. By introducing an AR layer onto the glass, this loss could be significantly reduced for the optimized module, as seen in Fig. 3(a). The difference in the absorption loss originates from the reduced glass thickness, but the effect is small, since the low-iron glass utilized has only minor residual absorption losses. The reflection loss at the glass rear-side interface is even smaller, because the refractive index of both encapsulant materials matches very well that of the glass, resulting in the reflection loss at the glass/encapsulant almost vanishing for both modules.

The absorption loss inside the encapsulant, on the other hand, has a large impact, but is significantly reduced when using PVB instead of EVA. Here, the above-mentioned higher UV transmittance of PVB basically explains the positive effect; a larger part of UV light reaching the cell can be used for electrical power generation. Especially in the case of the SE cells considered here, this effect is significant, because SE cells yield a relatively good UV response. In total, the relative power loss is reduced from about 8% to below 4% by all the innovative technologies used in the improved module. The results could be verified by means of flasher measurements on mini-modules and on standard-size modules.

Optimization of cell interspaces and module border areas (mechanisms 6–7)

A portion of the incident radiation on a module hits the cell interspaces and module borders first rather than the solar cells themselves, and thus cannot directly be used for power generation (mechanism 6). The absolute efficiency of the solar module decreases in proportion to the size of those inactive areas. The corresponding optical efficiency loss can be reduced by minimizing these areas and by a proper choice of module geometry and cell format; for example, full-square wafers yield a higher fraction of active areas on a module than pseudo-square or round wafers.

The ability to reduce the distance between the cells, however, is limited. The cell space within a string is mainly limited by mechanical stress caused by tabs between the front contact of one cell and the back contact of the neighbouring cell. A minimum distance between strings is basically imposed because of positioning-accuracy challenges and lamination-induced shrinkage of the encapsulant, which can bring adjacent strings into contact and thus cause short circuits. With regard to the dimensioning of a module, a compromise between cost and benefit needs to be found.

In this context, it must be in particularly borne in mind that these inactive areas do not negatively affect the module power. On the contrary, the partial redirection of light from inactive areas to the cell (mechanism 7) provides an extra current and thus additional power. This gain can be achieved by means of reflections from the inactive areas, since a part of that light is reflected back at the glass/air interface and thus partially redirected to the cell. This light-recycling effect is a decisive step towards the ambitious goal of achieving a CTM well above 100%.

Example: Effect of a white backsheet

As an example, for state-of-the-art white backsheets it has been shown, by light-beam-induced current measurements (LBIC), that illumination of the area next to a cell generates typically 20% of the short-circuit current obtained from direct cell illumination. If the space between neighbouring cells is also considered, the relative amount is doubled to 40%. For a typical cell efficiency of 18%, the efficiency of the cell interspaces is thus greater than 7%. In the case of a standard module with 5mm cell spacing, the additional total cell interspace area with 7% efficiency is about $0.1m^2$; this corresponds to approximately 3% more power [13].

Optimization of the top-contact design (mechanisms 8–9)

Cell shading due to the front-side metallization (mechanism 8), i.e. fingers and contacting tabs, can be reduced by minimizing the widths of these contacts; however, series resistance losses increase with smaller contact cross sections. Thus, an optimization with regard to these

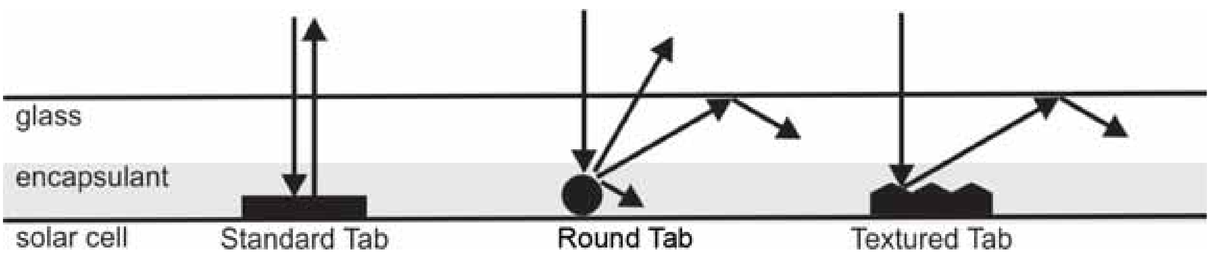

Figure 4. Schematic of the reflection paths produced by various tab technologies [13].

optical and electrical losses would suggest that contacts with high aspect ratios (i.e. having small widths and large heights) are necessary. However, with high aspect ratios come stiffer tabs, which can induce cell breakage during module processing and operation [14].

One option for improving the CTM is to obtain an indirect coupling gain on the top contacts (mechanism 9) by using improved tab geometry. In Fig. 4 the light reflection paths following vertical incidence are shown schematically for three different tab geometries.

Standard tabs reflect normal incident light straight back and thus do not generate a gain. For *round tabs*, depending on the region where light hits the wire, different cases are possible: hitting the first region, light can be reflected sideways towards the cell; entering the second region, light is reflected to the glass/air interface at such an angle that it is totally reflected back to the glass. The reduction in the effectively shaded area of a wire can be easily calculated and is 70.7% for the first region and 35.7% for the second [15]. In the third case, light hitting this region is either reflected back through the glass or partially reflected at its surface, depending on the specific angle. *Textured tabs* are designed in such a way that they reflect vertical incident light sideways so that it reaches the glass/air interface at angles greater than the critical angle for total internal reflection, and is thus redirected to the cell.

Example: Effect of light-harvesting strings
Turek and Eiternick [5] and Schneider et al. [11] compared modules built with light-harvesting strings (LHS, textured tabs made by Schlenk) and without them: LBIC measurements taken on both modules are presented in Fig. 5. The results indicate that illumination on a standard tab produces 5% of the short-circuit current generation of the actual cell, whereas for LHS this proportion is increased to 75%. This extra current means that the total current and power of the investigated module is enhanced by 3%, a value that is in agreement with directly measured short-circuit currents, where an enhancement of 2.5–3% was found.

Reduction of electrical losses in the interconnection (mechanism 10)

Electrical losses at the module level are mainly due to the losses in the cell and string interconnections (mechanism 10). Cell interconnections cause optical losses by partially covering the active area of the solar cell, while electrical losses result from the current passing through the tabs [3,4]. Advances in module technology are expected to optimize the optical and electrical losses in order to achieve higher CTM power ratios.

Electrical losses decrease by increasing the tab width, whereas optical losses increase linearly with increasing tab width. The optimum tab width for harvesting maximum power should therefore be determined by considering both electrical and optical losses. Moreover, the electrical losses are related to the square of the current passing through the tabs; thus by changing the module design and decreasing the operating current of the solar cells, the electrical losses can be significantly reduced [2,4]. The use of cut solar cells in combination with a rearrangement of the interconnection designs is a good way of reducing electrical losses and increasing the CTM ratio [4].

> "PV modules with half-size cells demonstrate better performance than conventional PV modules because of the higher optical gains and lower electrical losses."

Example: Half-cell modules
PV modules with half-size cells demonstrate better performance than conventional PV modules because of the higher optical gains and lower electrical losses [16,17]. According to the experiments performed on monocrystalline cells by Hanifi et al. [4] and Eiternick et al. [18], when solar cells are cut in half the efficiency of the cells slightly decreases, by about 1.1%$_{rel}$, because of the laser-scribed edges. As illustrated in Fig. 6, the measured full-size cells have an average efficiency of 19.4%, and the half-size cells exhibit a lower efficiency after the laser-cutting process. The reduction in efficiency, however, is offset after the fabrication of one-cell modules: half-cell modules demonstrate 19.1% efficiency, which is 0.7% higher than in the case of full-cell modules. These results explain the 94.8% CTM ratio for full-size cells and 98.4% for half-size cells, when the losses due to the laser-scribing process are considered [4].

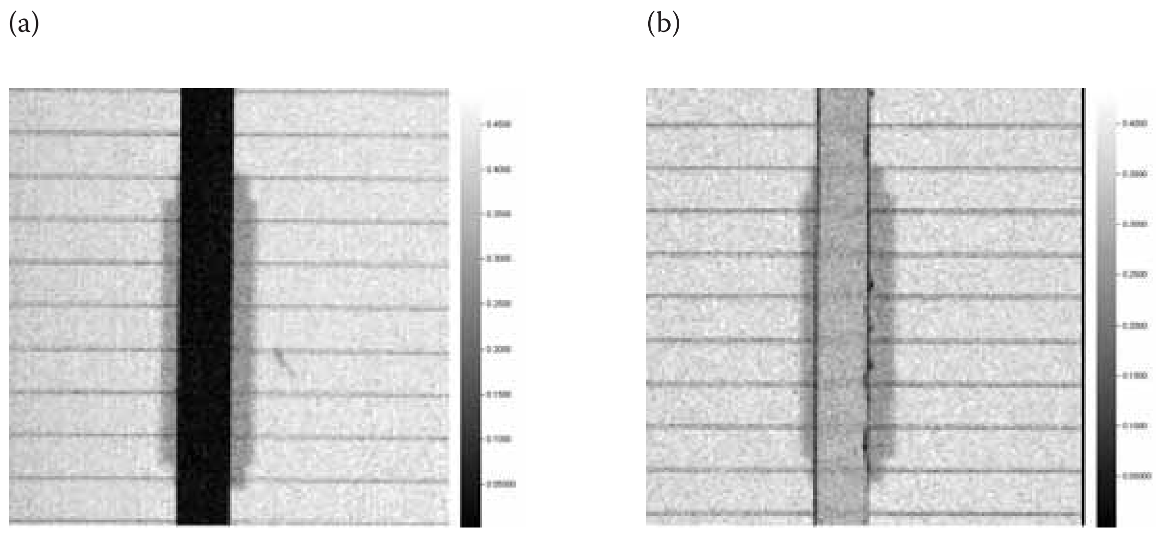

Figure 5. Light-beam-induced current images: (a) without light-harvesting strings (LHS); (b) with LHS. The current generation from the tab regions is significantly improved [11].

Half-cell modules generate half the current of full-cell modules; therefore, the electrical losses of the connections of half-cell module are one-quarter those of full-cell modules [17]. New module designs require a rethinking of the tab dimensions when optimizing the electrical losses in module interconnections. Fig. 7 shows the simulation results for the optical, electrical and overall losses of a module with two half-size cells, and for a module with one full-size cell, in respect of different tab widths at standard test conditions (STC). The cells are monocrystalline with three busbars, and their electrical properties are measured before and after the module fabrication. At STC the optimum tab width for standard cells is 1.7mm. By cutting the solar cells in half, the power loss decreases by 2.14%. By reducing the tab width of half-cell modules to 0.8mm, 0.92% more power can be gained. It can be concluded that the optimum tab width for half-cell modules is around 0.8mm, which is almost half the optimum tab width of the full-cell layout. The use of a narrower tab width for a half-cell layout therefore leads to an increase in the CTM ratio and to a reduction in material consumption [4].

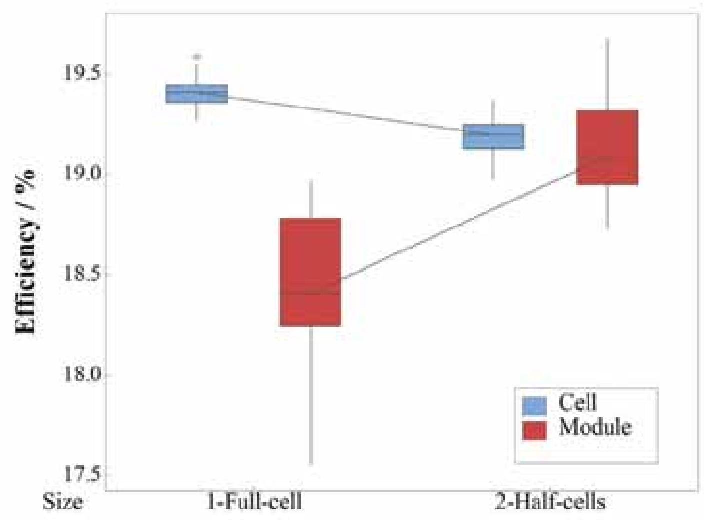

Figure 6. Efficiencies of half-cell and full-cell concepts at the cell and module levels. Losses due to the laser-cutting process are compensated for at the module level [4].

It should be noted that the extra optical gain resulting from the additional cell spacing in half-cell modules is not included in the simulation results.

From power to energy

Spectrally resolved CTM

Higher CTM ratios can be achieved by using different technologies in module integration. Solar cell technology, as the most important part of module integration, can play a significant role. Monocrystalline solar cells have alkaline-based textures with good optical properties which lead to better quantum efficiency compared with multicrystalline solar cells with an acid-based texture – see Fig. 8(a). The lower texture quality of multicrystalline cells brings with it higher reflection losses and thus decreased initial cell efficiency in air. A higher coupling gain when embedded into a module is therefore made possible, which yields a higher CTM ratio, especially in the UV and near-IR ranges, as a result of indirect optical coupling of the reflected light. This becomes evident when the external quantum efficiency (EQE) of mono-Si and multi-Si cells and modules are compared, as shown in Fig. 8(b).

"It is important to understand the loss mechanisms at different irradiation levels, especially low-light conditions."

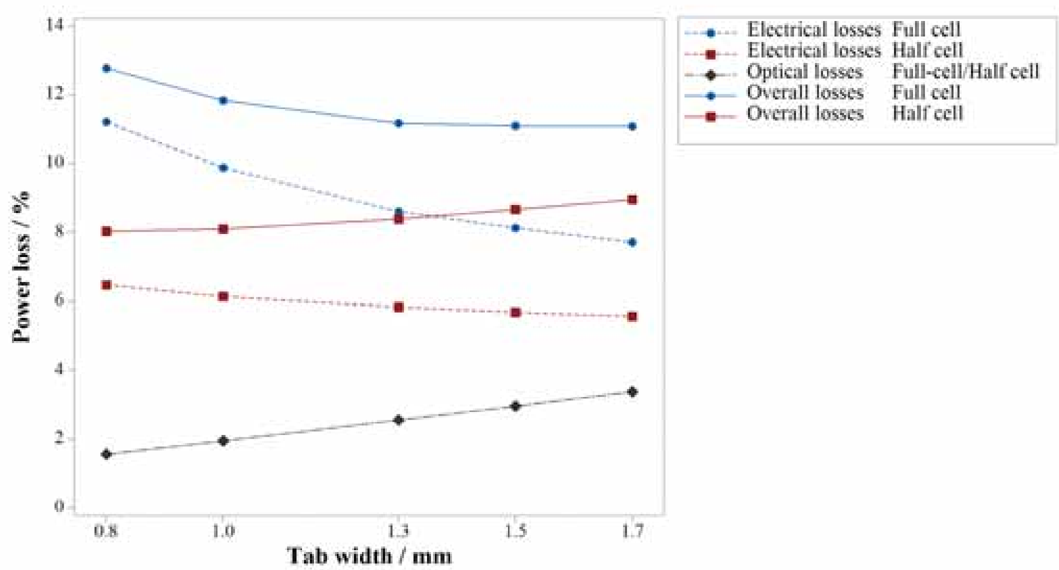

Figure 7. Optical shading, electrical and overall losses of three-busbar, full-cell and half-cell modules as a function of tab width at STC, without considering other optical gains in the module. The optical losses for both modules are the same [4].

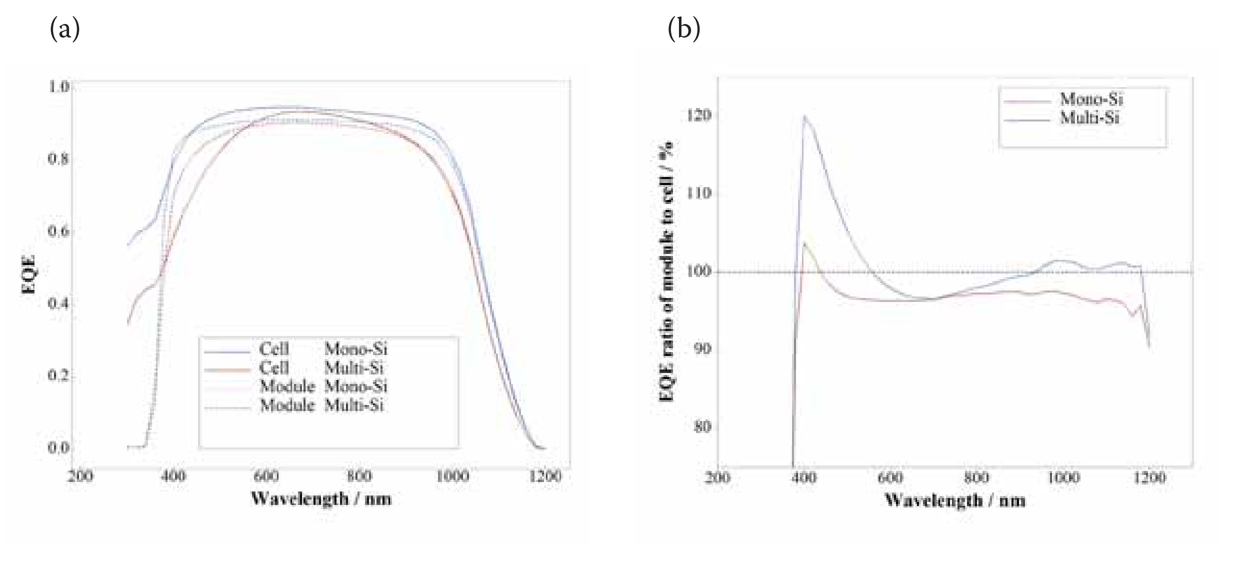

Figure 8. (a) Measured EQE for multi-Si and mono-Si solar cells and their corresponding mini-modules. (b) Measured module-to-cell EQE ratio for these two technologies.

Light-intensity-resolved CTM

Most of the efficiency evaluations of PV modules are referred to STC. It is important, however, to understand the loss mechanisms at different irradiation levels, especially low-light conditions. Fig. 9 shows the simulation results for the efficiencies of half-cell and full-cell modules described in the earlier section on interconnection electrical loss reduction, with two optimized tab widths and at different irradiation levels.

At high irradiation levels the electrical losses are the major reason for power loss in full-cell module interconnections, whereas half-cell modules demonstrate better performance at high levels because of reduced electrical current. The overall power loss trend in half-cell modules, however, indicates that the optical losses caused by the tabs are the dominant loss mechanism in full-cell modules at high irradiation levels.

In low-light conditions the optical losses are the dominant loss mechanism for both types of module [4]. Therefore, in locations with low irradiation levels, there could be a benefit of higher efficiencies with modules having narrow tab widths than with modules having wider tabs.

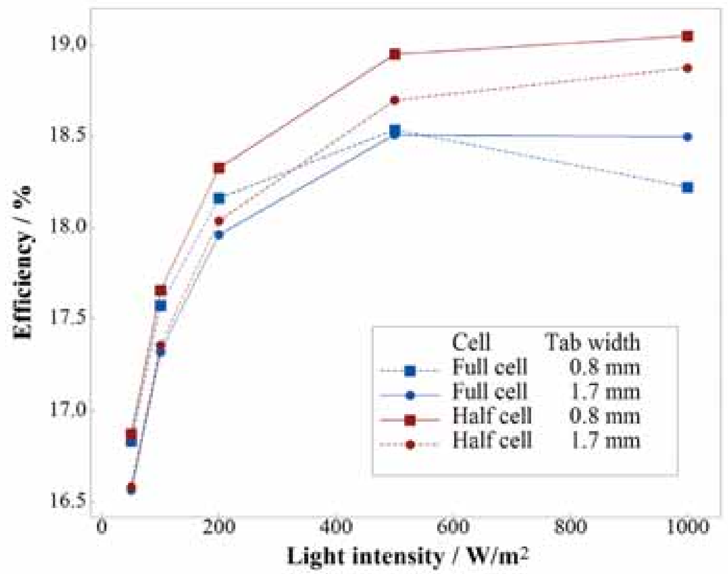

Figure 9. Efficiencies of half-cell and full-cell layouts with respect to irradiation, for two optimized tab widths. The continuous lines on the graph represent the optimized tab widths.

Energy yield in different locations

As mentioned in the previous section, the loss mechanisms at various irradiation levels are different for full-cell modules. This explains the need to consider energy yield calculations when determining the best module design for different locations in order to increase the CTM ratio.

Fig. 10(a) demonstrates the periods (average hours per year) of different irradiance levels determined for a moderate climate (Germany) and a desert climate (Morocco). The data used were accumulated between 2012 and 2014, without considering the night time. The results demonstrate the more frequent occurrence of high-level irradiation in a desert climate than in a moderate climate, which leads to higher electrical losses in module interconnections [4].

The simulation results of the energy yield based on the overall loss results for the modules mentioned in the section on interconnection electrical loss reduction are shown in Fig. 10(b) [4]. These results confirm that the energy yield of half-cell modules is consistently higher than that of a full-cell layout, because of the reduced electrical losses. Furthermore, the changes between electrical and optical losses at different irradiation levels cause the optimum tab width for a full-cell module to shift to 1.3mm from the 1.7mm already simulated for STC. In this case, compared with full-cell modules the half-cell modules benefit from a greater energy yield of 1.52% and 2.20% for the moderate (Germany) and desert (Morocco) regions respectively [4]. It can be deduced that it is not sufficient to consider just STC when

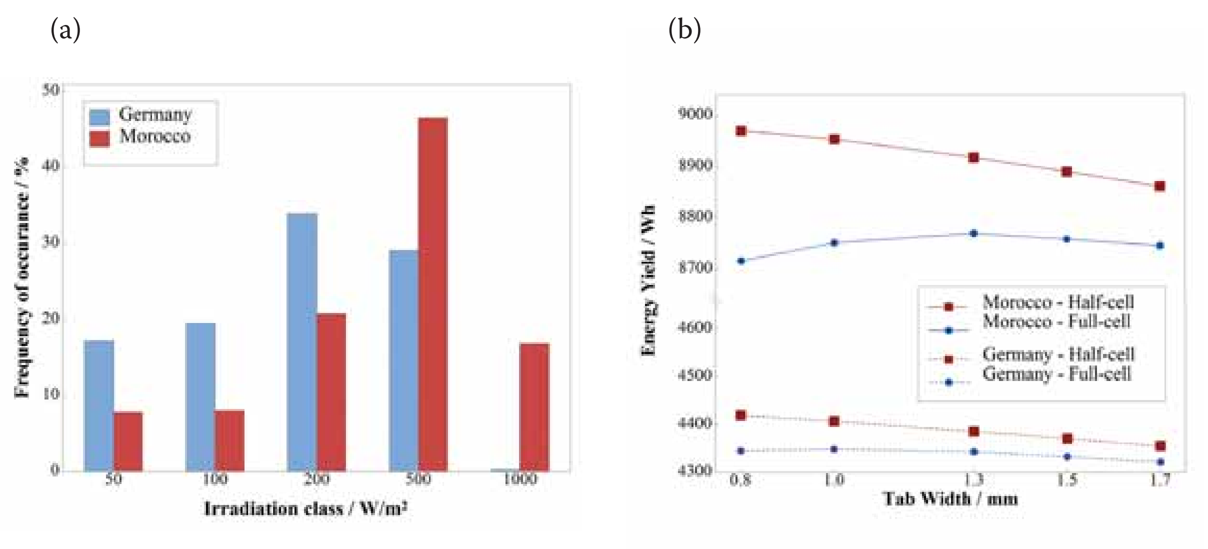

Figure 10. (a) Relative frequency of average annual irradiation over three years, along with the corresponding irradiation levels, in Morocco and Germany for 2012 to 2014; (b) related energy yield calculations for the half-cell and full-cell mini-modules using different tab widths [4].

analysing the losses. Energy yield analysis is a tool that can be used to quantify the module behaviour under different environmental conditions in order to propose better module designs.

Conclusions and future work

In the work presented in this paper, the different loss and gain mechanisms in PV modules were reviewed. It was also shown that with the use of novel module designs, it is possible to minimize the losses and increase the gains. The conclusions can be summarized as follows:

- The interaction of individual layers and components is important.

- By modifying module integrations – such as glass thickness, backsheet or tabs – the optical losses and gains can be optimized.

- Modules with cut cells demonstrate better CTM ratios because of lower electrical losses and higher optical gains.

- Cutting solar cells leads to a slight decrease in cell efficiency, but this loss is offset at the module level.

- The efficiency of half-cell modules can be increased by using a narrower tab width.

- The cell type and sensitivity are important. For solar cells with lower efficiency (multi-Si) due to the different reflectance of the cell surfaces and direct coupling gain, a higher relative CTM gain than for high-efficiency mono-Si cells is achievable.

- A better UV and near-IR response makes multi-Si cells more suitable for extreme climates, such as in highlands and deserts.

- The dominant loss mechanisms for tabs vary with different irradiation levels. Electrical losses are the dominant power loss mechanism for full-cell modules at high-irradiation levels, while optical losses are behind the main power loss in low-light conditions. In the case of half-cell modules, optical losses are the major cause of power loss in both irradiation conditions.

- Referencing only to STC is not adequate when looking to optimize module design for different locations. Energy yield analysis is a good tool to use for designing modules with higher CTM ratios at different environmental conditions.

- The results show that with the use of novel module technology techniques, it is possible to obtain higher CTM ratios and achieve economic benefits over optimized module integrations.

The optical characterizations presented here were carried out for light with a perpendicular angle of incidence. In order to qualify the behaviour of PV modules under irradiation at different angles of incidence and in different locations, energy yield measurements are also recommended.

> "With the use of novel module technology techniques, it is possible to obtain higher CTM ratios and achieve economic benefits over optimized module integrations."

In this paper the investigation of the response of standard mono- and multicrystalline solar cells was presented; the behaviour of other cell concepts – such as bifacial and PERC cells or other cell designs (e.g. cells with more than three busbars or multi-wire technologies) – is proposed for future studies.

Besides the effect of module integrations on CTM ratios, the role that the electrical interconnection and novel module designs can play on loss and gain mechanisms in PV modules is another consideration. A half-cell layout has been compared with a layout incorporating standard-size solar cells, but other designs – such as one-third or one-quarter cell layouts – should be investigated.

Finally, the yield of solar modules in non-STC conditions (such as in deserts) by taking into account the irradiation was discussed. However, other environmental conditions, such as temperature, also need to be considered.

Acknowledgements

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Dr. Marko Turek studied physics at Dresden University and received his Ph.D. in the field of condensed matter theory from the University of Regensburg. Head of the team working on the electrical characterization of solar cells at Fraunhofer CSP, he focuses on the loss analysis of solar cells and modules, advanced characterization methods, and the development of new test methods and devices.

Prof. Joerg Bagdahn has a diploma and a Ph.D. in materials science from the Technical University of Chemnitz and Martin Luther University Halle-Wittenberg respectively. The director of Fraunhofer CSP since 2007, he has held a 'Photovoltaic Materials' professorship at Anhalt University of Applied Sciences since 2009.

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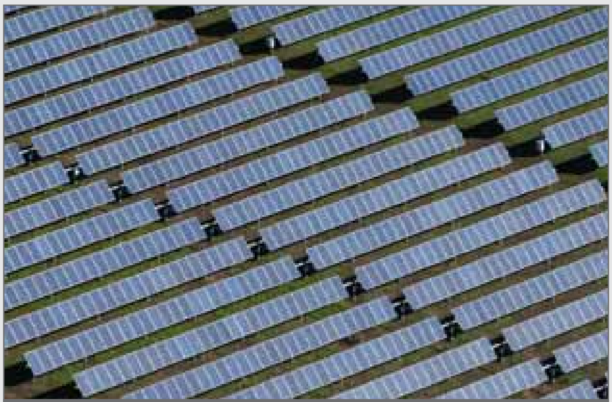
Market Watch

SunEdison's upstream suppliers hit hardest with US$321 million owed in bankruptcy



Credit: SunEdison

SunEdison's upstream suppliers look set to be hit hard by the company's Chapter 11 bankruptcy proceeding.

Bankrupt renewable energy firm SunEdison owes its upstream suppliers more than US$321 million, according to papers filed with the Bankruptcy Court for the Southern District of New York.

Primarily a fabless company, SunEdison has been trading some in-house polysilicon and wafer production with producers of solar cells and modules via outsourcing that would ultimately be used in its downstream PV power plant projects.

Court documents indicate that PCS Phosphate, a producer of silicon tetrafluoride, used for the production of polysilicon has become the largest supplier victim of SunEdison's bankruptcy, owed over US$193 million.

SunEdison announced in February 2016 that it would permanently close its Pasadena, Texas polysilicon production facility by the third quarter of 2016.

The closure would result in one-time impairment and restructuring charges of US$363 million and approximately US$10 million to US$13 million in restructuring charges that were expected to occur in 2016.

The significant debt owed to PCS Phosphate could indicate that SunEdison was struggling with liquidity issues long-before its last quarterly conference call in November 2015.

High up the debt list is PV module assembly subcontractor and single-axis tracker supplier, via its NEXTracker acquisition, Flextronics International (Flex), which is owed over US$44 million.

Several major PV module suppliers have also been embroiled in the bankruptcy, which include 'Silicon Module Super League' (SMSL) members, Trina Solar and JA Solar, owed US$10.52 million and US$10.38 million, respectively.

Market updates

Saudi Arabia hits renewable reset button with new 9.5GW target

Saudi Arabia has confirmed a new 9.5GW renewable energy target as part of its 2030 Vision initiative to move its economy away from reliance on oil.

The plan was revealed in April and includes a combination of asset sales, subsidy reforms and the creation of a US$2 trillion sovereign wealth fund.

The country famously announced a US$109 billion solar investment plan in 2012 but has seen little in deployment since. Under the new goals, manufacturing will also be targeted, and foreign investment in projects will be encouraged as part of public-private partnerships. This model has already proved successful in other Gulf economies, notably the UAE.

"Even though we have an impressive natural potential for solar and wind power, and our local energy consumption will increase three fold by 2030, we still lack a competitive renewable energy sector at present," said an English version of the Vision 2030 plan posted on the country's state news website. "To build up the sector, we have set ourselves an initial target of generating 9.5GW of renewable energy. We will also seek to localise a significant portion of the renewable energy value chain in the Saudi economy, including research and development, and manufacturing, among other stages."

China PV installs surge past 50GW milestone

China installed 7.14GW of new solar power capacity in the first quarter of 2016, according to figures released by the country's National Energy Administration (NEA). Total cumulative solar capacity in the country is now 50.3GW.

The quarterly figure is up 48% compared to the same period last year.

Frank Haugwitz, Beijing-based founder of solar consultancy AECEA, said there is more to come. "It is no surprise to see such a high number, because, traditionally Q1 witnesses the final execution of roll-over projects from 2015. As well, in September 2015 a good 5.3 GW were additionally approved and their deadline in order to qualify for last year's feed-in tariff (FiT) is the end of June," he said.

While there has been no official target or quote for PV deployment released for 2016, Haugwitz noted that a vague, unofficial indication of 15GW has been mentioned publicly.

Credit: GCL System Integration Technology

Cumulative PV capacity in China has now surpassed the 50GW mark.

Credit: Yingli Green

Yingli Green has delayed its fourth-quarter and full-year 2015 results as it continues to struggle financially.

News

Brazilian Development Bank accredits 17 solar equipment manufacturers

The Brazilian Development Bank (BNDES) has qualified 17 solar equipment manufacturers to receive funding in Brazil.

Of the accredited companies, five are domestic companies that produce PV panels locally, seven produce inverters and two manufacture trackers that follow the sun's trajectory throughout the day. Meanwhile, another five produce central junction boxes for PV applications. One of the panel manufacturers can supply modules to utility-scale projects, while another four are geared towards residential and commercial rooftop applications.

In order to be accredited, BNDES verifies that the manufacturer is compliant with local content requirements, which is a prerequisite to receiving funding from the development bank.

BNDES offers financing to PV players that follow a progressive nationalisation plan for equipment manufacturing including a level of local content compliance. For example, to qualify for funding, from 2018 all junction boxes, inverters and support structures used in projects need to be sourced locally.

The bank is currently in the process of qualifying another three foreign-based manufacturers and one Brazilian manufacturer.

Grid integration and financing issues will hinder India's 100GW solar target - Bridge to India

Grid integration and availability are the key challenges ahead for India's solar sector, according to the latest report from consultancy firm Bridge to India.

The 'India Solar Handbook 2016,' which included a survey of chief executives for the first time, reported that grid issues are the major bottleneck to the country's 100GW by 2022 target and as a result the country is expected to deploy just 40-60GW instead.

Maintaining investment and lending appetite at aggressive tariff levels was another main challenge and Bridge to India said that policy intervention would be key to sustaining its growth in the sector.

In any case the country is still expected to become the fourth largest solar market globally in 2016 behind China, the US and Japan with 5.4GW of expected new capacity in the year.

Despite the bottlenecks cited, Bridge to India described the sector as being in "full bloom". However, financing capacity remains an issue with tariffs reaching well below five rupees per unit of late and many developers struggling to raise capital with banks seemingly reluctant to lend to projects with these tariffs. As a result, progress in 2017 and 2018 will not be as fast as expected.

Company news

Yingli Green delays financial reporting on liquidity issues

Struggling major solar PV manufacturer Yingli Green Energy has officially delayed filing its fourth-quarter and full-year 2015 results as it needs more time to gauge its overall liquidity issues.

Yingli Green noted that it expected to disclose in its annual report that there remains substantial doubt over its 'going concern' status, which proved to be a shock for the industry in its 2014 filing.

Yingli Green said it expected a loss for 2015 in the range of RMB5.8 billion to RMB5.9 billion (US$894.1 million to US$909.7 million), compared to a net loss of RMB1.3 billion in 2014.

Revenue is expected to be in the range of RMB10.0 billion to RMB10.2 billion (US$1.54 billion to US$1.57 billion), decreased from net revenue of RMB12.9 billion in 2014, due primarily to falling PV module shipments on the back of liquidity issues.

Yingli Green said that module shipments were 2,357MW in 2015, down from 3,101MW in 2014. Shipments in 2015 were at the low end of previous guidance of 2.35GW to 2.40GW.

TerraForm Power bullish in wake of SunEdison bankruptcy

TerraForm Power has moved to allay fears that it could become entangled in SunEdison's Chapter 11 bankruptcy proceedings, however its original IPO filing warned of the risks of losing its sponsor.

In an SEC filing posted towards the end of April, the yieldco reiterated that it and sister company TerraForm Global were separate entities and that none of its "significant" power purchase agreements with the off-takers of its projects included a break provision in the event of bankruptcy at SunEdison.

"TerraForm Power and its sister company, TerraForm Global, are not part of the SunEdison bankruptcy filing and have no plans to file for bankruptcy themselves," the statement said. "TerraForm Power and TerraForm Global are publicly listed companies that are separate legal entities and are traded separately on Nasdaq. The equity interests of TerraForm Power and TerraForm Global in their respective wind and solar power plants that are legally owned by their respective subsidiaries are not available to satisfy the claims of creditors of SunEdison.

"While TerraForm Power's relevant review remains ongoing, the Company has not identified any significant power purchase agreement that includes a provision that would permit the offtake counterparty to terminate the agreement in the event of a SunEdison bankruptcy."

R&D spending laggards Canadian Solar and JinkoSolar continue redemption

Annual analysis by *Photovoltaics International*'s sister website, PV Tech, of 12 major PV manufacturers' R&D spending behaviour again highlights that two 'Silicon Module Super League' (SMSL) members, Canadian Solar and JinkoSolar, continue to lag behind rivals, despite climbing the SMSL ranks and top 10 manufacturers' rankings, based on PV module shipments.

JinkoSolar had long been the perennial R&D spending laggard but in 2014 the company increased spending by 60% to US$17.3 million, climbing two ranking positions, also new record for the company.

In 2015, JinkoSolar increased R&D spending a further 28% to around US$22.2 million, another record and crossed the US$20 million barrier that previously, in 2014, had been occupied by five of the 12 companies covered in the analysis since 2007.

The other R&D spending laggard, Canadian Solar also increased expenditure in 2015 by around 41% to US$17.05 million, compared to US$12.05 million in the previous year, but remained within the US$20 million barrier and spending remains below the peak of US$19.8 million set in 2011.

R&D spending by Canadian Solar as a percentage of revenue in 2015 stood at 0.5%.

Solar PV technology trends for 2016

Finlay Colville, Head of Market Intelligence, Solar Media

ABSTRACT

Solar photovoltaic manufacturing is benefiting today from increased allocations by leading producers for capex into new facilities and technologies. Capturing these trends in March 2016, the PVCellTech conference in Kuala Lumpur, Malaysia, hosted by *Photovoltaics International*'s publisher, Solar Media, provided a fascinating insight into what can be expected during the second half of 2016. Leading the drive to higher cell efficiencies and panel powers are efforts to increase the production of passivated emitter rear contact, or PERC, cells. This new trend can be seen to be driving the internal roadmaps of all silicon cell manufacturers, in addition to competing n-type and thin-film providers.

After several years of underinvestment in cell production technologies, there has been increased focus over the past 12-18 months, with panel powers for the industry-standard 60-cell p-type modules now reaching and exceeding 260W in mass production. While much of the growth from 240W to 260W-plus has come from improvements in wafer quality, changing process flows for advanced cell production looks set to form the basis for shifting power levels for this module type to 270-290W over the next few years.

The recent PVCellTech conference during March 2016 in Kuala Lumpur saw almost every leading c-Si cell producer talk about internal roadmaps, challenges confronting manufacturing today and opportunities to move cell efficiencies above the 20% level in mass production. The conference revealed however a broader mix of technologies, each seeking to differentiate with different combinations of cost and efficiency. This included n-type variants and p-type mono approaches, with much of the p-type mono and multi efforts currently focused on increasing the percentage of in-house cell capacity converted to PERC.

These new investments at the cell stage are also pivotal to wafer supply to the industry, incorporating silicon consumption levels and ingot growth methods, and also encompass the plans of thin-film producers, especially First Solar, to react again to progress made by competing c-Si market offerings.

This article summarizes the key themes that emerged from the PVCellTech event in Malaysia, reviews what the 2016 cell production landscape is expected to look like by year-end and compares the technology roadmap recently announced by First Solar just after the PVCellTech event was concluded.

The findings reveal the emergence of a highly vibrant sector today, where technology innovation is set to be elevated in importance as a route for companies to differentiate product offerings and their roles in driving panel power levels to increasingly higher levels in the next two to three years.

Credit: Hanwha Q CELLS

Technology innovation is set to grow in importance as PV manufacturers seek ways to differentiate themselves from competitors.

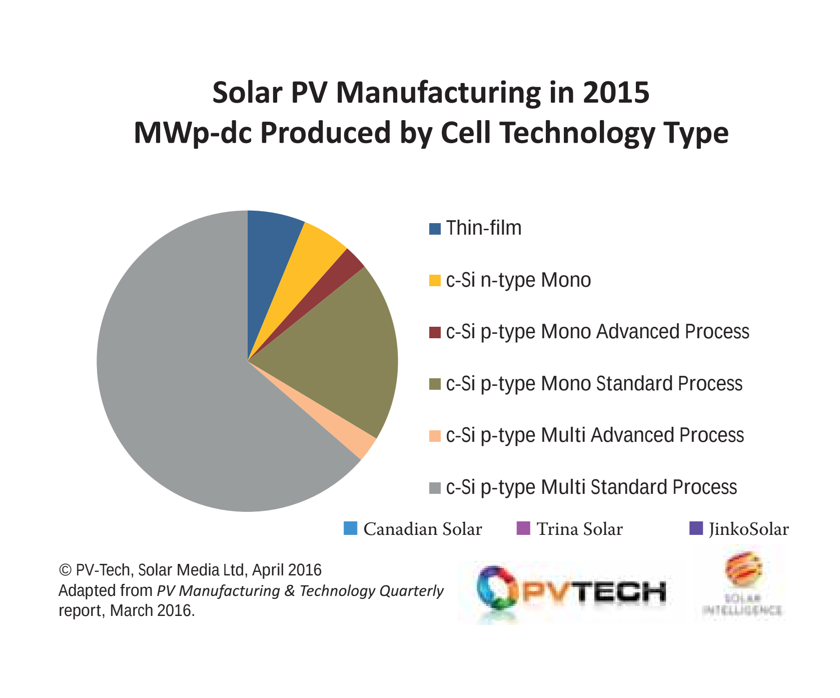


Figure 1: Approximately two-thirds of solar PV capacity produced during 2015 was based on standard p-type multi cells, reflecting the preference of cell producers in China, Taiwan and Southeast Asia. Advanced p-type offerings in 2015 highlight the initial impact of adding rear passivation layers also.

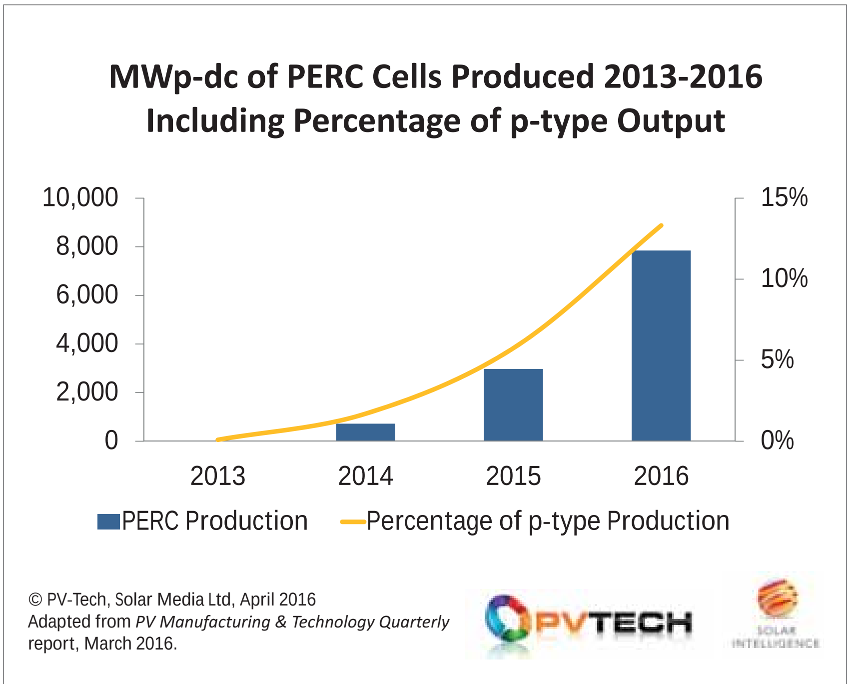


Figure 2: PERC production has seen strong growth from 2015, with the biggest impact set to occur during 2016, with PERC-type cells accounting for more than 10% of all p-type c-Si output by MW volume.

Solar PV manufacturing technology at the end of 2015

Solar manufacturing in 2015 was still adjusting to the changes in end-market demand that had occurred following the days of European end-market dominance, with the requirements for panels shipping to countries such as Japan, China, India, the US and a post-trade-constrained European market being somewhat different.

Indeed, the impact of these changes has driven so many changes through the upstream sector, driving decisions to add certain levels of new capacities within China and across Southeast Asia. In addition, the choice of technologies used in new factories within and outside China has also created a somewhat artificial segmentation within the industry today, and has almost been the most important factor in how the PV technology roadmap evolved until the end of 2015.

Central to this has been the addition of new cell capacity outside China and Taiwan, in order to circumvent import costs associated with serving end-market module shipments to Europe and the US. In contrast, increased end-market demand from countries such as China and India has created a captive market for China-based cell and module capacity, where average selling prices are amongst the lowest seen in the industry today.

Figure 1 shows the breakdown of cell production during 2015, with thin-film included here also to allow capturing the underlying technologies used for all modules shipped to the end market for the year.

Increasing PERC production in 2016

There was little doubt during 2015 that the main drive for p-type cell manufacturers was to overcome the challenges in implementing PERC into mass production, and the conclusions from the event captured this clearly. While much of the effort from industry leaders such as Hanwha Q CELLS, REC Solar and SolarWorld had been as a result of in-house R&D that extended back many years, the other segment of c-Si manufacturing that had been seeking to overcome manufacturing challenges can be seen to come from Taiwan, and in particular from Sunrise Global Solar Energy and Gintech. Understanding how to eliminate light-induced degradation was a key topic each producer highlighted as critical to making PERC work in a manufacturing environment.

As with every new technology being introduced into solar cell manufacturing, there are always claims and counter-claims, and during 2014 and 2015 there was no shortage of announcements in the press related to company plans for PERC technology implementation. In fact, there was barely a company that did not claim to be either working on PERC or showing a PERC-based module at a trade exhibition globally.

However, the litmus test remains what is genuinely being produced in mass production by cell makers, and this can only be tracked bottom-up through detailed analysis across the different cell producers that supply the industry today. This removes the hype, prevents spurious data being communicated and ultimately frames the level to which PERC has been taking market share away from standard p-type cell production (both mono and multi).

Figure 2 reveals the true extent of

PERC production, and shows as a percentage of p-type cell production only. While early adopters were able to ship initial volumes to the market in 2013 and 2014, it was 2015 that represented the first real growth phase for the technology. Success during initial production lines at a small subset of cell producers then had the effect of pulling in competitors to the field, but also resulted in the early movers committing to upgrading more existing and new lines to be PERC-capable.

Indeed, these trends were clear to see when looking at equipment orders placed on key tool suppliers such as Meyer Burger (the dominant PECVD suppliers) and laser tool suppliers Innolas and 3D-Micromac. Much of the new order intake for these companies was based on shipment schedules weighted to the second half of 2015 and the first half of 2016. In fact, the level of new order intake, coupled with the relatively few equipment providers during 2015, had led to a backlog of tool orders and push-outs that will ultimately see much of the 2015 order activity being spread across most of 2016.

Renewed focus on n-type production

The other key finding from PVCellTech was an uptick in the aspirations of new cell producers and the equipment supply chain to promote n-type cell manufacturing. Here, the conclusions are less compelling however, with the 2016 production landscape not directly suggesting any immediate change to the status quo in the industry.

In some respects, there still appears to be a great deal of faith put on the 'International Technology Roadmap for Photovoltaic' (ITRPV) report predictions for n-type market share going forward, in particular for heterojunction-based variants. This is not new for the solar industry, as there has always been emphasis placed on reaching the highest efficiencies with the most exotic cell architecture, often underestimating the barriers to entry or competitive companies' roadmaps.

Based purely on what is being made today, and what will likely be produced between now and the end of 2016, it would be relatively easy to dismiss the aspirations of companies such as Silevo (part of SolarCity), TetraSun (part of First Solar) or various new entrants that have chosen to bypass p-type manufacturing altogether. However, the reality is that in 2016, n-type supply to the end market will remain dominated by SunPower, Panasonic and LG Electronics, with the original plans of Mission Solar Energy having been downsized since original goals were set before mass production had been achieved.

More than once during the two-day Malaysia event in March, questions were raised as to whether the new efficiency roadmaps for p-type mono and multi cell production, that were all leading to mass production activity north of 20%, were in effect making some of the n-type approaches almost obsolete in the industry today.

If this is the case, then n-type market-share gains would come purely from the success of advanced cell variants that only SunPower and Panasonic have managed to move from R&D to mass production until now. In this respect, the big difference today with the new n-type advocates and these two companies would appear to be the role that equipment suppliers are playing, in particular with PECVD and PVD tools.

In the past, SunPower and Panasonic were instrumental in creating equipment and supply-chain specifications that have until now remained the critical IP that allows them to operate their cell architectures at high volume and low cost. Whether the new cell entrants, operating somewhat differently with equipment suppliers, can replicate this formula is likely to be one of the key factors that will determine whether n-type end-market contributions will have a greater number of suppliers in 2017 and beyond.

Secondary impact on thin-film roadmaps

Aside from the impact that PERC introductions to p-type cell production have had on the plans for n-type cell producers, there is also the cumulative effect on thin-film manufacturing in general. However, in contrast to the roadmaps from before 2010 that considered all types of thin-film types to be a direct threat to c-Si, any discussion of thin-film largely falls on one company: First Solar.

While it is true that just two companies dominate thin-film production today (First Solar and Solar Frontier), only First Solar is providing indications of adding new capacity and technology over the next few years. Coupled with its extensive R&D spend and allocations to manufacturing capex each year, the case for isolating First Solar as the main thin-film threat to c-Si today is more compelling.

While PVCellTech focused on c-Si cell manufacturing, it was equally relevant and revealing to then learn about First Solar's PV technology roadmap plans during April 2016. In this respect, as discussed below, First Solar's plans are every bit as relevant as the prospects for n-type capacity increases.

In the past few years, First Solar has been increasing average fleet efficiency levels (at the module level) at incremental rates that are above those seen across the whole c-Si community. Coupled with bringing back mothballed production lines, First Solar is nonetheless moving towards a ceiling on capacity by the end of 2017 at the 4GW mark. To move beyond this either requires additional production lines using the same panel size used today (0.6x1.2m), and the related facilities/infrastructure to house the new production lines.

Instead of committing to this route, First Solar is now proposing to introduce new capacity based on a 3X jump in panel size, first through back-end assembly of the smaller panel size to form a thin-film equivalent of the 72-cell module size, and then by having front-end full large-area deposition on glass panels measuring 1.2x1.8m.

While far from set in stone as a roadmap deliverable, and potentially subject to changes in production plans at First Solar, it nonetheless is a significant move from a technology standpoint, and every bit as ambitious as the new GW entrants to heterojunction cell capacity ramping.

In both cases however, the driver can be seen to be p-type c-Si and in particular the efficiency gains on multi wafers/cells that were simply never considered possible a decade ago in the industry. Common to all though is a new focus on manufacturing and technology that, regardless of the winners and losers, is certain to reshape and redefine solar PV manufacturing in 2017, and will likely again be the source of stimulating debate by the time we reach March next year and PVCellTech 2017.

About the Author

Dr. Finlay Colville is Head of Market Intelligence at Solar Media, the parent company that also publishes PV Tech and Photovoltaics International. Prior to this, Dr. Colville was Head of Solar at NPD Solarbuzz between 2010 and 2014. As the leading market analyst tracking PV manufacturing, technology and equipment spending trends, Dr. Colville has been active in the solar industry for more than a decade. Prior to NPD Solarbuzz, he held various senior sales and marketing positions at leading capital equipment supplier, Coherent Inc. He holds a BSc. in Physics from the University of Glasgow, and a PhD in Nonlinear Photonics from the University of St. Andrews, Scotland.

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Meyer Burger confirmed as leading PV equipment supplier for 2015, but what next?

Despite year-end push outs for PERC upgrades, Meyer Burger was comfortably the leading PV equipment supplier by recognised revenues for 2015, marking the end-point of a challenging repositioning in strategy for capital equipment supply to the PV industry in the past four years.

Meyer Burger was one of the major beneficiaries during the previous (but somewhat artificial) PV capex upturn cycle of 2008-2011, alongside companies such as Centrotherm, GT Advanced Technologies and Applied Materials. Back in those days, jostling for leading supplier status had an entry ticket of at least US$1 billion annual revenues. Today, the numbers are much more humble but, importantly, seeing moderate year-on-year increases.

What makes Meyer Burger's return to pole position particularly interesting is that this time around the revenue pull has not come from Meyer Burger's legacy organic-based wire saws, but from the PECVD based technology tool set that came through the acquisition a few years ago of Roth and Rau.

Few equipment suppliers have managed to make a transition across the value-chain in the past, far fewer have dominant market-share status, and in this respect much credit has to be given to Meyer Burger.

The main driver of course was the saturation and oversupply of the wafering segment that had been Meyer Burger's core competence in the past. But to say that the market for c-Si cell PECVD tools simply rebounded at around this time is certainly not the case. In fact, the route back into PV through the Roth and Rau PECVD tools was not via the traditional new line installs, but from technology upgrades.

This makes the achievements all the more impressive. During the last 10 years, PV equipment suppliers have constantly been pushing upgrades to the PV industry, mostly when orders for new line tooling had dried up. Few of these attempts have succeeded, with Applied Materials' screen-printing upgrades for front-side metallization being one of the isolated cases over the last three years.

Meyer Burger's rebirth in PV today has come from being the clear market leader in supplying PECVD tools for PERC upgrades, and new line installs going for PERC from the start. In fact, it is hard to see how PERC could have the importance today in the solar industry, were it not for Meyer Burger.

However, with every opportunity comes challenges, and Meyer Burger has no shortage of these today. Granted, having a strong order book, and being the supplier of choice for the key tool in the new hot upgrade that is PERC, is a good problem to have and every other PV equipment supplier would give their right arm to have this problem today!

From the PERC side, the challenges are rather obvious, and ones that any capital equipment supplier has to face when introducing a new tool that everyone wants tomorrow:

- How do you regulate in-house manufacturing output, while keeping up the significant levels of R&D that are necessary?
- When do you press the button on stepping up per-week tool shipments, particularly when the solar industry capex swings of the past have been severe enough to take a tool supplier from hero-to-zero overnight?
- What resources are put into the interaction with other key tool types (such as the laser process that has its own set of process challenges), not to mention getting the entire cell line re-tweaked for overall efficiency gains?

Source: Meyer Burger

Meyer Burger's PERC tool technology has helped it become the leading PV equipment supplier – for now.

But the bigger question probably relates to whether you put all your eggs in one basket and go full steam ahead with PERC, or retain a more cautious approach to having a diversified tool set. And this is where there are probably daily strategy meetings taking place at Meyer Burger; the answer is far from easy.

Here, we probably come up against the one question mark today with Meyer Burger in terms of the approach for c-Si cell equipment supply, in terms of ring-fencing heterojunction as the platform to grow or diversify from PERC (or simply PECVD) tool supply.

In March at our PV CellTech conference in Kuala Lumpur, one of the massive takeaways related to the huge efficiency improvements for p-type mono and multi, and the debate often centred around whether this made some of the n-type variants now obsolete. That question is, and will always be, debated, but what you can't argue with is that p-type advances can only push out any large-scale transition to heterojunction line builds from the existing GW cell leaders.

So, in this respect, having heterojunction tooling as a key in-house strategy is probably a good thing, but the key question is what your expectations are for revenues coming from this in the next two to three years. And whether allocating considerable in-house resource to heterojunction will have an adverse effect on the low-hanging fruit today – PERC.

Ironically, the one company that may do more to push out any heterojunction interest from the mainstream p-type c-Si cell manufacturing industry is Meyer Burger, due to PERC on p-type! So the timing of in-house resources to PERC and heterojunction could be the most important thing for Meyer Burger in the next 12 months. Again, what a nice problem to have today!

This is an edited excerpt from a blog post that originally appeared on www.pv-tech.org

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