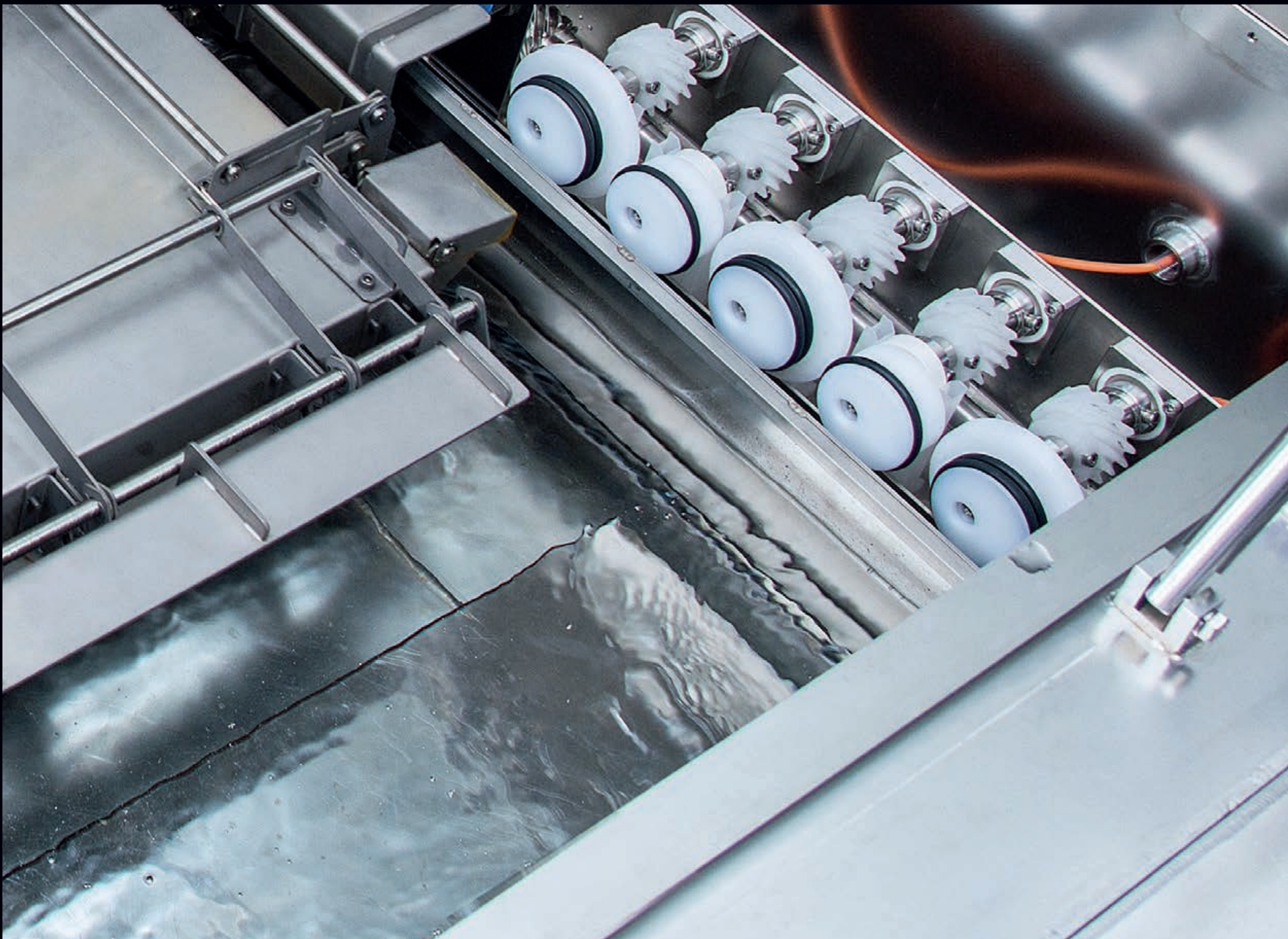
Twenty Eighth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS



TNO Routes to increasing efficiency and reducing the cost of thin-film solar panels

Hanwha Q CELLS Shunting-type potential-induced degradation: How to ensure 25 years' service life

IMEC The use of silicon epitaxy in advanced n-type PERT and IBC silicon solar cell designs

Institute for Energy Technology, Norway Boron–oxygen-related degradation in multicrystalline silicon wafers

TÜV Rheinland Minimizing measurement uncertainties: Challenges for power measurement of high-efficiency c-Si PV modules

Suntech Operational sustainability in the field versus the laboratory: PV modules and insulation resistance

Second Quarter, May 2015

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Web: www.pv-tech.org

Publisher: Tim Mann

Head of Content: Ben Willis
Deputy Head of Content: John Parnell
Commissioning Editor: Adam Morrison
Sub-Editor: Steve D. Brierley
Senior News Editor: Mark Osborne
Reporters: Andy Colthorpe, Tom Kenning
Design: Tina Davidian
Production: Daniel H Brown, Sarah-Jane Lee

Sales Director: David Evans
Account Managers: Adam Morrison,
Graham Davie, Lili Zhu

Cover image: Manz's inline chemical bath deposition system for thin-film technology.

Image courtesy of Manz, Reutlingen, Germany.

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Foreword

In the past few issues of *Photovoltaics International* we have tracked in detail plans being implemented by the leading module manufacturers to expand production capacity. That process began tentatively last year as end-market demand began to catch up with the chronic overcapacity that had built up in the preceding years, prompting industry-wide upheaval.

Our latest capacity expansion report (p.11), a unique resource in the industry, reveals that while that activity was maintained throughout much of 2014, spiking in a strong final quarter of 2014, announcements of new capacity slowed slightly in the opening quarter of this year. Nevertheless, all the signs point to the pace picking up again later this year as manufacturers look to take advantage of the surge in activity expected in the US at the back end of this year and into 2016, in anticipation of the cutting back of the solar investment tax credit at the end of that year.

One interesting trend to observe in the latest analysis was the sign that investment is once again being made in ingot/wafer manufacturing. This is one part of the value chain that had seen only limited activity in the latest wave of expansions owing to previous overcapacity.

Another definite trend now is the prevalence of advanced cell concepts in company plans, in particular passivated emitter rear cell (PERC) technology. This has featured in a number of recent announcements, notably that of SolarWorld, which has said it will upgrade all its 700MW solar cell production capacity in Germany to PERC technology.

The extent to which new cell concepts will be adopted is underlined in the latest issue of the International Technology Roadmap for Photovoltaic (ITRPV), which we analyse in depth on p.80. Among the many trends explored in the ITRPV, it predicts that over the next decade PERC will become a major player among the emerging cell technologies, becoming the biggest market share holder by 2025.

As usual, this issue of *Photovoltaics International* also includes cutting-edge papers from some of the sector's leading scientists. A team from Hanwha Q CELLS explores in depth the issue of 'shunting-type' potential induced degradation in PV modules (p.59). This is one of the most severe forms of the PID problem in modules, but the Hanwha Q CELLS team suggests ways in which it can be reversed and allow a module to see out its full 25-year lifetime.

And remembering that crystalline silicon is not the only show in town, scientists from TNO in The Netherlands look at the prospects for improving efficiencies in CIGS thin-film solar panels (p.46). This area has seen some progress in recent weeks, with two new CIGS module efficiency records appearing within a day of each other. The TNO report explores ways in which these conversion efficiences can be pushed even further.

All the signs are that the upstream PV industry is making a slow but steady return to health, bringing to the fore technologies that have been under development during the recent difficult period. In that context, *Photovoltaics International*, with its dedication to shedding light on the state of the art in PV technology, has never been more relevant to your business. We hope you find this issue as valuable as ever.

Ben Willis
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.

Julia Hamm, president and CEO, Solar Electric Power Association (SEPA)

SEPA is an educational non-profit organization dedicated to helping utilities integrate solar power into their energy portfolios. Prior to leading SEPA, Julia Hamm worked as a senior associate at ICF International where she supported the US Environmental Protection Agency with implementation of its ENERGY STAR programme. She holds a Bachelors of Science in Business Management from Cornell University.

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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[1]imec, Leuven, Belgium; [2]Kuwait University, College of Engineering and Petroleum, Electrical Engineering Dept., Safat, Kuwait; [3]KU Leuven, Leuven, and University of Hasselt, Diepenbeek, Belgium

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News

Fluor to build REC Silicon's JV polysilicon plant in China

Construction and engineering firm Fluor Corporation has been awarded a contract to build the Shaanxi Non-Ferrous Tian Hong REC Silicon Materials (TianREC) fluidized bed reactor polysilicon plant in China.

REC Silicon entered into a JV to circumvent import duties imposed on overseas polysilicon producers in retaliation to US anti-dumping duties. REC Silicon has all of its polysilicon production in the US.

The TianREC polysilicon plant is expected to cost around US$1 billion with 18,000MT (metric tons) of granular polysilicon production capacity as well as an additional 1,000MT of Siemens polysilicon and 500MT of silane gas loading.

REC Silicon is using a new 3,000MT third-generation FBR plant in the US to act as the proving ground for the large-scale plant in China.

Source. REC Silicon

Fluor is to build REC Silicon's FBR silicon plant in China.

New facilities

JinkoSolar's new 500MW fab based in Malaysia

Tier-one PV manufacturer JinkoSolar has said its first major overseas solar cell and module manufacturing facility is based in Penang, Malaysia.

JinkoSolar has confirmed that the Malaysian fab would have an initial solar cell capacity of 500MW and 450MW of PV module capacity, and to be operational in May 2015.

The company expects to spend around US$100 million on the facility, which will use high-efficiency multicrystalline technology, which is expected to be passivated emitter rear cell (PERC) based.

The main reason for selecting Malaysia is believed to be due to the well-established PV manufacturing supply chain.

The underlying reason for the overseas plant was to circumvent US anti-dumping duties and increase its market penetration in North America.

JA Solar to partner on 400MW Southeast Asia cell and module plants

Tier-one PV manufacturer JA Solar is planning to partner on both solar cell and module production in Southeast Asia to expand its shipments to the US market and avoid anti-dumping duties.

The company said that plans to build approximately 400MW of solar cell capacity in the region sometime in the second half of the year could be accelerated, should its petition on duties in the US not be successful.

Management noted that due to its limited module shipments to the US in 2012 and 2013, JA Solar had not been included in initial duty evaluations. The company is therefore hoping to be given a specific duty rate that would enable it to ship more modules to the US at competitive rates.

Onyx Solar to open new BIPV production lines in Spain

Building-integrated PV specialist Onyx Solar is to begin work on a new factory in Spain.

Onyx Solar will build the new facility at its existing headquarters in Avila, Spain. The initial production line will only cover around 8,000 square metres of floor space. However, Onyx claims the facility can be ramped up to 140,000 square metres.

The company said it was aiming to hit this level of production with an unspecified timeframe.

Upgrades and Expansions

Zhongli Talesun's PERC cell 'Hipro' module to be produced in Thailand

Tier-one PV manufacturer Zhongli Talesun Solar expects to ramp its recently announced 500MW cell and module production plant near the end of year, which will produce PERC-based cells for its new 'Hipro' 285W+ modules launched at SNEC 2015.

Talesun said that the new PV modules

Source: Fabrica_01

Onyx solar is to built a new factory in Avila, Spain.

would deploy solar cells with 20.3% conversion efficiencies, providing module conversion efficiencies of 17.55%.

Trial production of the new Hipro module as well as the initial ramp of the plant is expected by the end of this year, providing Talesun the opportunity to target US and European markets, known to demand higher efficiency modules for residential and commercial markets.

SolarWorld adding 500MW of monocrystalline ingot production

SolarWorld is planning to add a total of 500MW of monocrystalline ingot production at the former Bosch solar manufacturing facilities in Arnstadt, Germany, and upgrade all 700MW of solar cell production at the site to next-generation PERC technology.

The introduction of monocrystalline ingot production at the Arnstadt facility was said to create an additional 60 jobs to the 830 already employed at the facility, which was said to be running at full capacity.

Ingot production is expected to begin ramping in the second quarter of 2015. SolarWorld's production site in Freiberg, which houses wafer slicing equipment, will convert the ingots into wafers.

Meyer Burger is seeing strong demand for its PERC upgrade technology.

Meyer Burger adding capacity allocation for PERC equipment assembly

Major PV equipment supplier Meyer Burger said it would be adding further in-house capacity to meet strong demand for its MB PERC upgrade cell technology, primarily due to orders received for its MAiA 2.1 system platform.

Meyer Burger said that new MAiA 2.1 orders since the beginning of 2015 had surpassed CFH18 million (US$18.06 million) and would therefore exceed its budgeted production capacity for the MAiA platform for the whole year by June.

The company said that it would be increasing its production capacities at its main plant in Hohenstein-Ernstthal to meet delivery schedules.

Bentek expanding solar product manufacturing capacity by 40%

PV OEM power distribution products producer Bentek has increased its manufacturing capacity by 40% with the opening of a new facility in San Jose, California.

The new facility will do the design, testing and manufacture of the firm's expanding line of PV solar products.

Bentek now has more than 100,000 square feet of manufacturing capacity with the addition of the new 50,000 square-foot facility in San Jose. It allows for greater


Source: Singulus Technology

Singulus Technology is undergoing financial restructuring.

capacity in its existing facility to meet the continued growth in its manufacturing services business in 2015.

Restructuring

Singulus plans debt swap as part of restructuring efforts

PV equipment maker Singulus Technologies will undergo a financial restructuring as it looks to reduce its debt.

In a statement the company said it would look to swap debt related to its corporate bond for shares.

In March, the company reported heavy losses of €51.6 million (US$55.9 million) for 2014 but stressed that a strong order book meant it was likely that it would incur only small losses for 2015

According to Singulus, it has €60 million of orders lined up. These include a major order for CIGS equipment from Hanergy.

No capacity expansions planned by Yingli Green on debt issues

Tier-one PV module manufacturer Yingli Green Energy has said it would not be adding new manufacturing capacity in 2015 as it focuses on its high debt ratios and the need to restructure over US$2 billion of its US$4 billion debt this year.

In a conference call to discuss fourth quarter and full-year earnings, Yingli Green management noted that capital expenditure in 2015 would be pegged at between US$50 million to US$70 million, which would be allocated to production line upgrades and maintenance only.

Smit Ovens to restructure operations

PV manufacturing equipment specialist Smit Ovens has filed for bankruptcy in the Netherlands to restructure its operations.

The company issued a brief note confirming the start of bankruptcy proceedings but highlighting that the company expected to continue operations and would be working to "minimize impact on the business of our customers".

Recently, Smit Ovens received new orders valued at US$9.0 million from PV thin-film customers in the US and Asia. Equipment included active selenization systems as well as activation furnaces for CIGS thin-film volume production.

After three years of extremely limited capital spending, due to chronic overcapacity across the PV industry, many equipment suppliers are struggling financially.

Meyer Burger and GTAT reach settlement over disputed bill

PV equipment specialist Meyer Burger has settled a disputed bill with GT Advanced Technologies following a US$34.8 million deal.

GTAT, which entered chapter 11 bankruptcy in October last year, had ordered diamond wire cutting systems and related parts thought to be for use in a sapphire facility making screens for Apple. The bankruptcy court in New Hampshire is still to approve the deal with a decision expected in June. If approved, it will free GTAT to begin selling off its equipment.

Court documents also show that while GTAT will take ownership of and sell the diamond wire equipment, Meyer Burger will retain 18 BrickMaster cutting tools that had been loaned to GTAT after cutting equipment previously delivered had failed to meet GTAT's specifications.

GTAT secured US$95 million in financing to cover its costs through the bankruptcy process.

Tool orders

Hanergy TF wins US$660 million equipment and plant deal

Hanergy Thin Film Power Group's thin-film equipment manufacturing subsidiary, Fujian Apollo, has won an order valued at US$660 million to supply 600MW of tools and plant operations to Shangdong Macrolink New Resources Technology.

Hanergy TF said in a financial statement that Fujian Apollo would supply the production line equipment at a cost of US$198 million, while technical services fees related to the equipment order would amount to US$462 million.

The combined sales and service contacts totalled US$660 million.

Shangdong Macrolink New Resources Technology is believed to be a new subsidiary of Macrolink Group, whose annual operating income Hanergy TF said it estimated at approximately RMB55 billion (US$8.8 billion), while its total asset value exceeded RMB50 billion.

SunEdison signs up for Meyer Burger diamond wire saw technology

SunEdison, the world's largest renewable energy developer, is to purchase diamond wire saw technology from tool maker Meyer Burger.

Under the multi-million dollar order, SunEdison will buy Meyer Burger's DW288 water-based diamond wire saws to produce ultra-thin, high-performance mono-crystalline wafers. Further financial details of the deal were not disclosed.

Delivery was expected to begin in the second quarter of 2015 with production using the saws expected before the end of the year.

Meyer Burger also won sizeable orders from SolarWorld to provide 400MW of upgraded PERC equipment and its MAiA 2.1 equipment platform, used for coating the backside of the wafer with aluminum oxide.

Midsummer wins flexible CIGS sputtering tool order

Sweden-based thin-film equipment specialist Midsummer has received a multi-million US dollar order for its 'DUO' a volume production flexible CIGS (copper, indium, gallium and selenium) thin-film solar cell sputtering tool.

The company said the order was placed after the unidentified "multinational corporation" had run extensive testing of the tool at Midsummer's facility in Sweden. The company has been placing orders in recent months with delivery schedules before the end of 2015.

Midsummer noted that it expected to deliver the tool to its customer in October 2015.

Quarterly analysis of PV manufacturing capacity expansion plans

Mark Osborne, Senior News Editor, *Photovoltaics International*

ABSTRACT

In this first quarterly report of 2015 a full first-quarter analysis will be presented, as well as the planned capacity announcements for March and April. Notably this will include Tier 1 manufacturers' plans and a special look at Malaysia and its potential for another wave of companies planning manufacturing operations in the country. Finally, further analysis of the potential renaissance in thin-film production will be provided.

Housekeeping

From time to time, updated or new information is received regarding previous capacity expansion announcements or expansions that were not logged in previous reports. As a result, meaningful changes to previously issued data points are necessary.

In January 2014, JinkoSolar announced it would be taking over the production operations of bankrupt Chinese cell (500MW) and module (100MW) producer Topoint. However, JinkoSolar has since officially announced that the deal was subsequently cancelled, without providing much further information. Considering the scale of the operations that were expected to become restarted capacity, the 2014 cell and module capacity expansions have been adjusted accordingly. In addition, new information regarding small capacity expansions from South Korean monocrystalline cell producer Shinsung (70MW) and South Korean multicrystalline module producer Hansol Technics (100MW) have been included in the revised capacity expansion figures for 2014.

March 2015 capacity expansions

Since capacity announcements for January and February were covered in the previous edition of *Photovoltaics International*, the focus on key developments is confined to March, and a brief analysis of activity in April is given.

An area that has been hit extremely hard by overcapacity over the last three years is the ingot/wafer segment; as a result, only limited capacity expansions have taken place during this period. Other than monocrystalline expansions from Comtec and Longhi and a few others, only GCL-Poly has undertaken expansions with multicrystalline wafer

Credit: JA Solar

Figure 1. JA Solar is looking to build cell and module production through overseas partnerships.

Company	Announcement date	Manufacturing location	New nameplate PV module capacity [MW]	Production/product type
Jetion Solar	Jan-15	Thailand	200	integrated c-Si cell/module
Renovasol	Jan-15	Brazil	70	multi c-Si module assembly
Hanwha Q CELLS	Jan-15	Cyberjaya, Malaysia	230	(relocated) PERC multi c-Si solar cell
Hanwha Q CELLS	Jan-15	Cyberjaya, Malaysia	130	(relocated) multi c-Si module assembly
PT Len	Jan-15	Indonesia	60	integrated c-Si cell/module
Surana Solar	Jan-15	Fab City, Hyderabad, India	110	multi c-Si solar cell
SolarPark Korea	Feb-15	South Korea	600	integrated c-Si cell/module
LG Electronics	Feb-15	Korea	200	n-type bi-facial mono c-Si cells and modules
Zhongli Talesun	Feb-15	Rayong, Thailand	500	integrated c-Si cell/module
Silevo/SolarCity	Feb-15	California, USA	32	(relocated) pilot & R&D line
Waaree Energies	Feb-15	Surat, Gujarat, India	750	multi c-Si module assembly
Empresa de Componentes Electrónicos	Feb-15	Cuba	15	multi c-Si module assembly
Tainergy Tech	Feb-15	Taiwan	300	multi c-Si solar cell
Hanergy Thin Film/ Shangdong Macrolink New Resources Technology	Feb-15	China	600	a-Si thin-film BIPV plant
SolarWorld	Mar-15	Arnstadt, Germany	500	mono c-Si ingot production
SolarWorld	Mar-15	Arnstadt, Germany	700	upgrade PERC cell production
Vietnam Government	Mar-15	Hanoi, Vietnam	20	multi/mono c-Si module assembly
Ener Brazil	Mar-15	Brazil	50	semi-automated c-Si PV module assembly plant
JA Solar	Mar-15	South-East Asia (TBA)	400	integrated c-Si cell/module
JinkoSolar	Mar-15	Malaysia	500	multi c-Si PERC solar cell
JinkoSolar	Mar-15	Malaysia	450	multi c-Si module assembly
Hanergy Thin Film/ Inner Mongolia Manshi Investment Group	Mar-15	China	600	a-Si thin-film BIPV plant
Hanergy Thin Film/ Baota Petrochemical Group	Mar-15	China	600	a-Si thin-film BIPV plant
Flextronics	Apr-15	Ciudad Juarez, Mexico	200	multi/mono c-Si module assembly
Eclipse Brasil	Apr-15	Limoeiro do Norte, Ceará, Brazil	100	multi c-Si module assembly
Orange Solar Power	Apr-15	Netherlands	70	15MW 'Monoflex' and 55MW multi c-Si module assembly
Hanergy Thin Film	Apr-15	Wuhan, China	10	thin-film GaAs R&D/pilot line
Onyx Solar	Apr-15	Spain	1	c-Si BIPV

Table 1. Capacity expansion announcements in 2015 (January to April).

production when it added 1GW during 2014, but it has not guided further expansions yet in 2015.

It was therefore interesting to note in March that SolarWorld planned to add a total of 500MW of monocrystalline ingot production at the former Bosch solar manufacturing facilities in Arnstadt, Germany, and upgrade all 700MW of solar cell production at the site to next-generation passivated emitter rear cell (PERC) technology. SolarWorld said that its module manufacturing capacity stood at 1.6GW. The solar cell upgrades will also permeate through to increased capacity, but it is too early to calculate the meaningful capacity increase this will provide the company; therefore no expansion figure has been included with the monthly and quarterly analysis, but the expansion has been listed in rolling the first-quarter table of announcements.

Monocrystalline cell expansions also featured via a deal struck between Korea-based producer Shinsung Solar Energy and project developer SunEdison. In a new supply agreement, SunEdison is expected to purchase a total of 1,223MW of mono-Si solar cells from Shinsung through 2017, an increase of 660MW from a supply contract signed almost a year ago. The deal highlighted that Shinsung had planned to increase cell capacity in December 2014 to accommodate increased demand for high-efficiency cells that were not impacted by US anti-dumping duties. Shinsung is increasing capacity by 70MW to bring nameplate capacity to 420MW, almost the same figure that SunEdison is expected to purchase on an annual basis.

PV equipment and module production-line specialist Spire Corporation said it had delivered and started the installation of a 20MW PV module line for a government agency in Vietnam. The company said the module production line was located outside of Hanoi and could be used for the assembly of both monocrystalline and multicrystalline modules, as well as being a centre for research activities and training and demonstrations.

Brazilian project developer and distributor Ener Brazil is planning to build a 50MW semi-automated c-Si PV module assembly plant with Meyer Burger equipment and technology. Ener is currently seeking funding for the project but expects to close on a financial deal in the next few months, which could see tool installation in the fourth quarter of 2015. The facility is expected to produce around 204,100 of 245W c-Si modules per annum.

Major Tier 1 PV manufacturer JA Solar is planning to partner in both solar cell and module production in Southeast Asia to expand its shipments to the US market and avoid anti-dumping duties. In an earnings call to discuss fourth-quarter and full-year results, management noted that plans to build approximately 400MW of solar cell capacity in the region sometime in the second half of the year could be accelerated, should its petition on duties in the USA not be successful. JA Solar noted that it was seeking partnerships in overseas cell and module plants in order to keep capital expenditure down to around US$30m, with module assembly primarily outsourced under an OEM agreement.

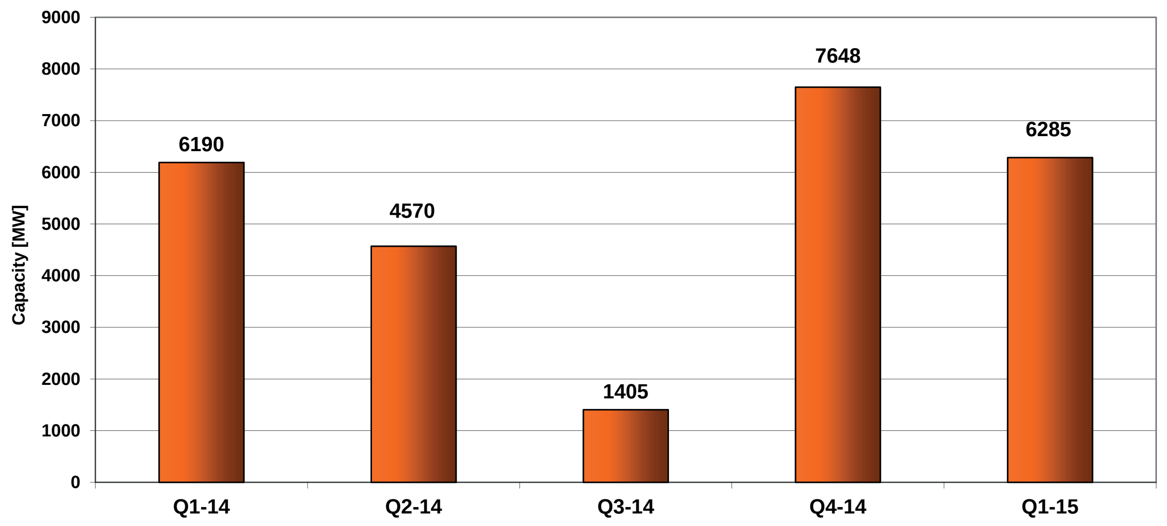

Figure 2. Cell/module manufacturing capacity expansion announcements by quarter.

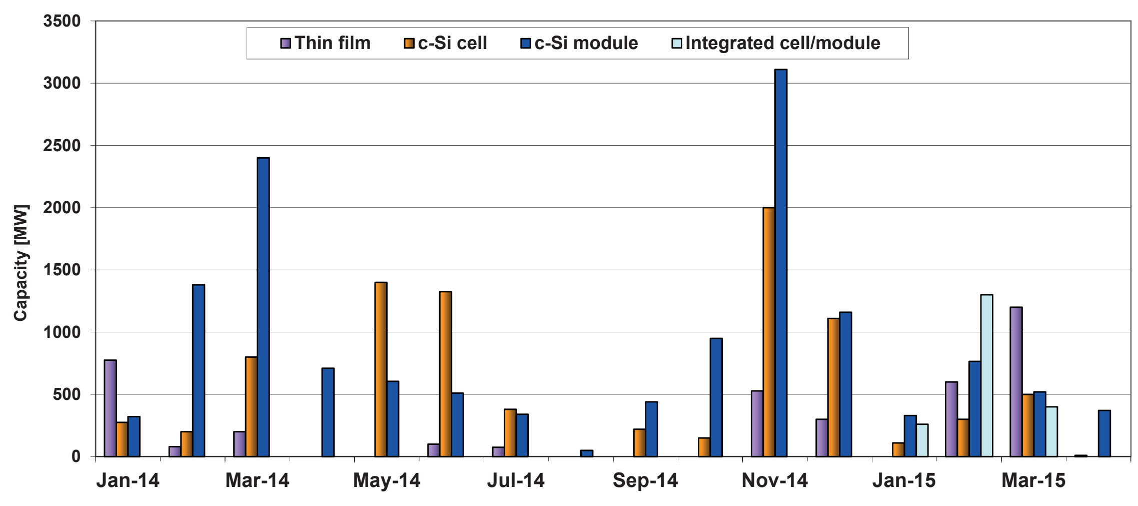

Figure 3. Cell/module manufacturing capacity expansion announcements by month.

Major Tier 1 PV manufacturer JinkoSolar has finally said its first major overseas solar cell and module manufacturing facility is to be based in Penang, Malaysia. It confirmed that the Malaysian fab would have an initial solar cell capacity of 500MW, and 450MW of PV module capacity. The company expects to spend around US$100m on the facility: high-efficiency multicrystalline technology will be used and is expected to be PERC based. JinkoSolar reiterated that it anticipated that the facility would be operational in May 2015.

An expected announcement in the first quarter that did not materialize was from Chinese manufacturer Wuxi Suntech. It confirmed in March that a proposed manufacturing facility in South Africa remained on hold until details of the fourth round of the country's national renewable energy programme are finalized. The company said that it was still considering establishing the facility, but was awaiting clarification of the local content rules in the fourth round of the renewable-energy independent power producer procurement programme before proceeding. Rivals, such as JA Solar, JinkoSolar and SunPower, have established small module assembly lines in South Africa for meeting previous local content rules.

> "Compared with 6,190MW in first quarter of 2014, a total of 6,285MW of new capacity plans were announced in the first quarter of 2015."

First quarter 2015 analysis

Compared with 6,190MW in the first quarter of 2014, a total of 6,285MW of new capacity plans were announced in the first quarter of 2015 (see Fig. 2); this was a continuation from the momentum built up in the fourth quarter of 2014, when around 7,648MW of new capacity was announced.

The Hanergy Thin Film Power Group Ltd announcements, however, should be treated with a level of caution; excluding its a-Si BIPV production plants for third parties, around 4,485MW of effective capacity announcements were therefore made in the quarter. This is more in line with reality, especially taking into account Tier 1 announcements from the likes of Jetion, SolarPark Korea, LG, Waaree, JA Solar and JinkoSolar, which made up the typical bulk of larger-capacity announcements. Indeed, at around 4.5GW in the first quarter of 2015, the number and scale of announcements had significantly dropped off from the fourth quarter of 2014, indicating once more that capacity expansions are being driven by market demand, primarily on a company-by-company basis.

Again, excluding Hanergy Thin Film from the analysis, the quarter-on-quarter decline in expansions in the first quarter can be attributed to the announcement of plans by a number of Tier 1 manufacturers in the fourth quarter of 2014. Major manufacturers – such as Hanwha Q CELLS, SolarWorld, First Solar, Canadian Solar, JinkoSolar and several others – all announced healthy expansions in the fourth quarter. However, there was notable absence of announcements in the first quarter of 2015 from the two largest producers, Trina Solar and Yingli Green; this compounded the contrast between the figures for the two quarters.

Yingli Green Energy has said it would not be adding new manufacturing capacity in 2015, as it is focusing on its high debt ratios and needs to restructure over US$2bn of its US$4bn debt this year. The company has said that capital expenditure in 2015 would be pegged at somewhere between US$50m and US$70m, which would be allocated to production line upgrades and maintenance only.

With regard to Trina Solar, in early May, as this journal was going to press, the company announced it had selected Thailand for its first overseas plant to meet demand in the USA without attracting anti-dumping duties. As this announcement came in the second quarter of the year it will be covered in detail in our next capacity expansion report. It is likely other Tier 1 producers in China and Taiwan have already decided to establish production in locations such as Malaysia or Thailand to avoid US tariffs, and that official announcements will follow over the next quarter or so.

On a monthly basis, February proved to be the most active for capacity announcements, whereas March claimed that honour in the prior-year period. As shown in Fig. 3, the first quarter was notable for almost 2GW of integrated c-Si cell and module plant announcements driven by several Tier 1 producers. February proved to be the most active month for these types of announcement, although the other two months were also active.

"The first quarter was notable for almost 2GW of integrated c-Si cell and module plant announcements driven by several Tier 1 producers."

Dedicated solar cell capacity announcements in the first quarter totalled 910MW (Fig. 4), indicating continued caution towards cell expansions and towards allocating the required capital expenditure. Dedicated c-Si module assembly announcements totalled 1,615MW. With no major plans announced by Waaree and JinkoSolar, actual dedicated module assembly capacity announcements were significantly lower than either the previous quarter or the same period in 2014 (Fig. 3).

Thin-film analysis

Previous reports have highlighted something of a recovery in thin-film capacity expansions after more than four years of notable bankruptcies,

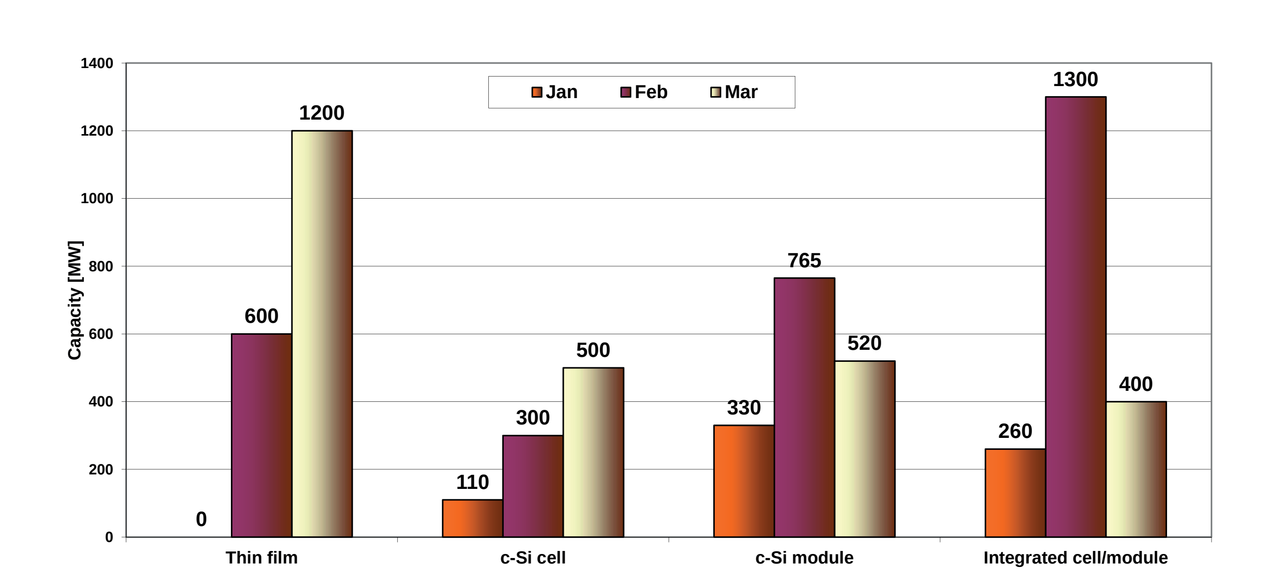

Figure 4. Capacity expansion announcements in Q1 2015 by product type.

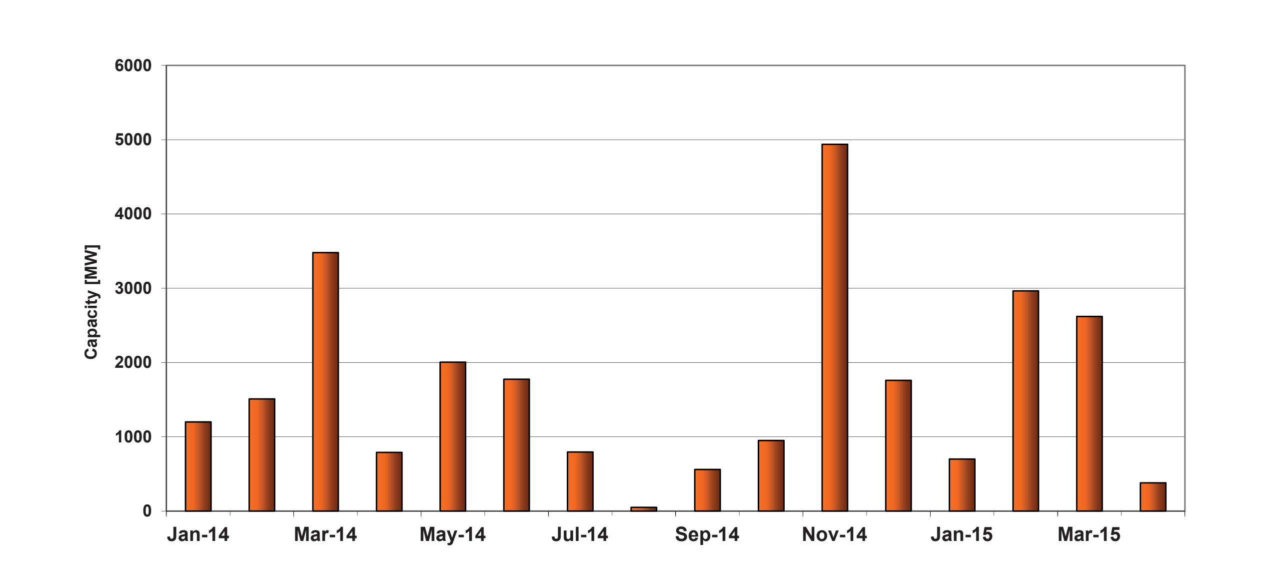

Figure 5. Cell/module capacity announcements by month.

closures and exits. The recovery results predominantly from just three companies: First Solar, Solar Frontier and Hanergy Thin Film.

The real force remains CdTe leader First Solar, which is currently operating a total of 30 manufacturing lines after restarting some idled lines in Malaysia later last year. According to the company, each line at the end of 2014 was able to produce approximately 2,500 modules per day, equating to around 70,000 modules in total across its lines. However, when First Solar's efficiency and throughput roadmap are combined, it is estimated that the company would have around 3GW of capacity from those 30 lines in operation by 2017, up from a nameplate capacity of around 1.8GW at the end of 2014.

First Solar therefore has room to expand capacity in order to meet a certain level of shipment growth and end-market demand with relatively low capex requirements. Indeed, the company also has 10 lines in storage after closing its two manufacturing plants in Germany, equating to around 1.3GW of nameplate capacity as they stand. As a result of the excess warehoused capacity, First Solar has a potential manufacturing capacity of around 4.3GW. This would suggest that capex requirements, excluding relocating the 10 stored lines (perhaps for installing in a new facility in India), will remain low for several years to come. First Solar has made a 5GW pledge to India's 100GW installation target by 2022 and hinted at manufacturing in the country.

The real conundrum in the thin-film sector remains Hanergy Thin Film and parent company Hanergy Holding Group. Last year's announcements of plans to build CIGS plants in China based on the acquired company's technology are not an issue, especially since the company has been placing orders with suppliers for equipment deliveries later in 2015. The challenge comes when analysing the credibility of its recent three orders for equipment and plants in the a-Si BIPV market with companies that have no known history of manufacturing, and Hanergy Thin Film's inability to ramp up similar plants for its parent company. As already highlighted, a sizable element of the thin-film revival rests with Hanergy and its acquired companies, and for many reasons Hanergy's plans are being treated with the highest level of caution.

Japan-based CIS thin-film module manufacturer Solar Frontier completed the construction of its Tohoku Plant in March 2015 as expected and plans to start ramping up production immediately. The 150MW Tohoku Plant is also the test bed for ramping up production-ready cell-efficiency gains, previously developed at its Atsugi Research Center, creating modules with conversion efficiencies of 15% and higher. Solar Frontier announced the Tohoku Plant plans in January 2014 and has met the timelines it originally set out. The new plant pushes Solar Frontier's volume production nameplate capacity to over 1GW, including its main Kunitomi Plant with capacity of 900MW in southern Japan. The company has publicly stated its interest in establishing similar-sized fabs in the USA and possibly other booming markets, as First Solar has suggested it might be doing in India.

Therefore, when excluding Hanergy Thin Film from the equation, the prospect of an expansion of thin-film production still holds a level of validity over the next two years.

April 2015 capacity expansions

With effective capacity expansion announcements in the first quarter of 2015 significantly below Q4 2014 and just slightly above Q1 2014, the announcements made in April indicate a further slowdown in the second quarter of 2015. Only a combined 380MW of capacity expansion announcements have been logged for the month of April, down from 790MW in the prior-year period (Fig. 5). Although much stronger levels of planned expansions were seen in the months following the first quarter last year, the current expectation is for muted activity, bar the possibility of new plants being announced by Chinese and Taiwanese producers heading for Malaysia.

In April 2015, Italian module manufacturer Eclipse announced it was planning a 100MW factory in Brazil, with plans to invest around US$8m in the plant, but said it was waiting for local approvals.

Taiwan-based solar cell producer Sunrise Global, a subsidiary of wafer producer Sino-American Silicon Products (SAS), was also said to be planning to expand capacity by 250MW in 2015, taking nameplate capacity to 850MW. This would include the expansion of PERC cell production, as well as the upgrade of around 100MW of existing capacity to PERC.

Following its theme of establishing the manufacturing of acquired technology in China, Hanergy Thin Film Power Group Ltd said it would build a 10MW gallium arsenide (GaAs) thin-film solar cell R&D and manufacturing plant using recently acquired US start-up Alta Devices technology. According to Hanergy Thin Film, the first phase of the plant would include a 3MW production line.

The new facility in Huangpi Linkong Industrial Park, Whan City, is expected to be completed in the next 10 months, while tool installation is envisaged in 12 months. Equipment and manufacturing line testing ahead of initial ramping up of production is expected to start within 18 months (by October 2016).

Conclusion

In the first quarter of 2015 the pace of capacity expansion announcements has clearly slowed, both in number and in scale, when excluding announcements from Hanergy Thin Film. The incredibly strong fourth-quarter activity of 2014 has certainly had a negative knock-on effect in the first quarter of 2015, and looks likely to lead to further softening of activity in the second quarter of the year.

The full extent of the impact of US anti-dumping duties from 2014, however, has yet to materialize with respect to Chinese and Taiwanese companies' manufacturing strategies to circumvent duties by locating production in places like Malaysia.

> "In the first quarter of 2015 the pace of capacity expansion announcements has clearly slowed, both in number and in scale."

With end-market demand in the USA expected to exceed 9GW in 2015, and potentially to be much higher in 2016 ahead of the ITC changes, catching that opportunity for some will be a priority. Announcements could therefore be imminent and on the scale already revealed by JinkoSolar and JA Solar.

Market demand in China is also a factor that could potentially lead to further announcements coming through, as the Chinese government has set a 17.8GW target for the year. With access to the utility-scale market now unfettered, and their own downstream ambitions riding high, Tier 1 suppliers should experience strong product demand, leading to tight supply throughout the year.

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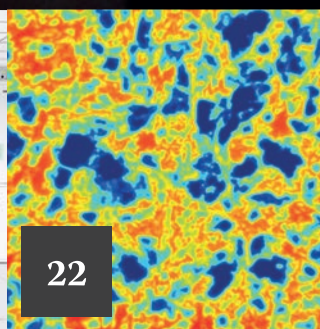
Boron–oxygen-related degradation in multicrystalline silicon wafers

Rune Søndenå, Institute for Energy Technology, Kjeller, Norway



News

Applied Materials and Tokyo Electron cancel merger plans

Semiconductor equipment makers Applied Materials and Tokyo Electron have agreed to terminate plans for a merger after the US Department of Justice (DoJ) warned about loss of competition from the procedure.

The DoJ advised the two firms that a coordinated remedy proposal submitted to all regulators would not be able to replace the competition lost from the merger.

Based on this advice, both firms, which have PV related equipment segments, have agreed there is no realistic prospect of completing the merger. Neither company will face termination fees.

In July 2014 it was announced that the two company names were to be dropped for the new name 'Eteris,' but the merger was never completed.

Gary Dickerson, president and chief executive of Applied Materials, said the merger was an opportunity to accelerate its strategy, but despite disappointment with the cancellation, the company's existing growth plan is "compelling".

Source: Applied Materials.

Applied Materials and Tokyo Electron have decided not to proceed with merger plans.

Records and innovation

Sol Voltaics touts single layer GaAs nanowire coated solar cell efficiency record

Sweden-based nano-material development firm, Sol Voltaics, has claimed a 1-sun record conversion efficiency of 15.3% for a solar cell coated with its gallium-arsenide (GaAs) nanowire array (NWA).

Verified by Fraunhofer-ISE, the efficiency record is claimed to be twice as high as the previous record. The company did not provide information on cell size and other key data such as cell aperture area.

Sol Voltaics uses its 'Aerotaxy' nanowire production technique to create GaAs-based nanowires that are retained in a liquid solution for later deposition on a solar cell.

The company was working on a tandem layer approach that targeted conversion efficiencies of greater than 27% and was seeking industrial partners to further develop the technology for commercial applications.

Suntech unveils carbon composite solar module frame

Wuxi Suntech, the PV module manufacturing arm of Shunfeng International Clean Energy (SFCE), has confirmed the development and testing with Taiwan Carbon Nanotube Technology Corporation (TCNT) of a high-strength, lightweight carbon and glass fibre composite PV module frame.

Modules employing the composite material have already passed a number of tests including the IEC61215 standard testing, IEC61701 salt mist corrosion testing, and a high-strength mechanical load test up to 5400Pa at minus 40 degrees Celsius.

Suntech said the carbon nanotube-enhanced composite frame had greater ability to resist corrosion and eliminate potential-induced degradation (PID) problems from moisture ingress and alike.

DuPont and JinkoSolar to work on next-gen 'Solamet' and 'Tedlar' materials

DuPont and JinkoSolar have signed a strategic collaboration agreement for implementing next-generation solar cell metallization pastes and module backsheet materials as well as downstream co-marketing programs. No financial details were disclosed.

Collaborations with JinkoSolar could

Source: DuPont

DuPont and JinkoSolar are to collaborate on next-gen metallization pastes.

News

include technical development efforts on efficiency, durability and reliability of solar cells using its 'Solamet PV19x' series metallization pastes.

In respect to modules, the companies are considering reliability issues and the use of DuPont's 'Tedlar' polyvinyl fluoride films for backsheet applications.

Plants and production

Heraeus to open metallization R&D centres in China and Taiwan

German PV materials manufacturer Heraeus is to open new R&D centres in mainland China and Taiwan.

The move is the latest in a series of internationalization plays by the metallization paste specialist, which last year moved its main R&D operation to the United States, relocated its PV business unit to Shanghai and began silver paste production in China.

Andreas Liebheit, head of the Heraeus Photovoltaics Global Business Unit, said the move would enable the company to reduce the time it takes to modify its products for key customers. He said Heraeus would be hiring local employees to fill the newly created regional roles in the company.

REC Solar still adding 300MW of new module capacity in 2015

Tier-one module manufacturer, REC Solar, is planning to spend around US$50 million on production upgrades and expansions in 2015 with an extra 300MW of module assembly capacity via two new lines.

Plans remain in place to take total module production to 1,200MW in 2015, while nameplate module capacity is targeted at 1,300MW, which is expected to be complete by the second half of the year.

Multicystalline silicon module conversion efficiencies reached an average of 17.8% at the end of 2014, up from 17.6% at the end of 2013. The company is targeting average conversion efficiencies of 18% by the end of 2015.

REC Solar had been capacity constrained throughout most of 2014, primarily due to capacity limitations at its facility in Singapore.

Market

STR Holdings gets boost from new owner and new business in Malaysia

US-headquartered PV module encapsulant producer STR Holdings has secured a major new exclusive supply contract worth potentially 500MW per annum in volume sales through its majority shareholder, China-based PV project developer Zhenfa Energy Group. Financial details were not disclosed.

Zhenfa acquired a majority stake in STR late last year, an unusual move for a privately owned downstream PV project developer.

Also after several years of diminishing revenue and cash, STR is on the cusp of rebuilding its revenue streams with new customers both in China and Malaysia.

In November last year, STR expanded production at its plant in Malaysia to meet growing demand after the latest round of US anti-dumping duties on Chinese and Taiwanese made solar cells.

STR's Malaysia facility had been earmarked to be ramped down as part of its restructuring efforts but the company had achieved certification with a potential new and 'significant' customer for the facility.

Source: Heraeus

Heraeus is to continue its overseas expansion with the opening of two new R&D centres.

LDK Solar exits bankruptcy proceedings

LDK Solar's chapter 15 bankruptcy proceedings as well as the chapter 11 bankruptcy proceedings in the US have been concluded with the majority of bondholders agreeing to a complex debt for stock swap and a convertible debt scheme due in 2018.

However, LDK Solar remains heavily debt laden with at least US$2 billion owed to a number of Chinese banks.

Through two investment vehicles, the billionaire owner of Shunfeng, Zheng Jianming, has almost a 30% stake in LDK Solar.

Sales updates

GET reduces losses on wafer shipments of 2.2GW in 2014

Taiwan-based solar wafer producer Green Energy Technology (GET) reported a net loss for 2014 of NT$1.96 billion (US$62.9 million), despite higher shipments and utilization rates that remained above 95% in the year.

GET reported revenue of NT$15.2 billion (US$487.8 million) in 2014, a 15% year-on-year increase.

The company generated an operating loss of NT$1.2 billion (US$38.5 million), a 43% reduction in operating losses generated in 2013.

Wafer shipments in 2014 reached 2,220MW, up from 1,980MW in 2013. The company had its strongest wafer shipments in the fourth quarter of 2014, shipping 660MW, a new record for the company.

GCL-Poly ran polysilicon and wafer operations at full capacity in 2014

Leading polysilicon and solar wafer producer GCL-Poly Energy Holdings reported group sales of US$4.8 billion and returned to a profit of US$277.9 million in 2014, operating its polysilicon and solar wafer operations at full capacity.

GCL-Poly reported full-year polysilicon production of 66,876MT, up from 50,440MT in 2013, exceeding nameplate capacity of 65,000MT.

Polysilicon shipments to third parties totalled 15,443MT, down 5.4% and generated revenue of US$335.3 million in 2014. The company reported average selling prices of polysilicon at US$21.7/kg in 2014, compared to US$17.4/kg in 2013.

GCL-Poly reported full-year solar wafer production of 13,098MW, slightly exceeding nameplate capacity of 13,000MW, which was expanded by 1GW through the year.

Centrotherm achieves profitability on revenue of €189.2 million

PV and polysilicon equipment specialist Centrotherm Group reported a return to profitability in 2014 on the back of recovering sales of €189.2 million, driven by an upturn in revenue from PV equipment sales and progress on building a polysilicon plant in Qatar.

The company reported full year 2014 sales of €189.2 million, compared to €119.4 million in 2013, primarily due to bankruptcy restructuring which shortened the fiscal year to eight months.

Centrotherm reported EBITDA of €25.3 million, compared to a negative EBITDA of €4.6 million in 2013.

ReneSola's module shipments up 14% in 2014 reaching 1,970.3MW

Tier-one PV module manufacturer ReneSola reported full-year module shipments above revised guidance at 1,970.3MW, up 14% from the prior year.

ReneSola reported full-year net revenue of US$1,561.5 million, an increase of 2.8% from US$1,519.6 million in 2013. Gross profit was US$209.3 million with a gross margin of 13.4%, compared to a gross profit of US$113.1 million with a gross margin of 7.4% in 2013.

The company reported total solar module shipments in the fourth quarter of 2014 of 488.4MW, exceeding previous guidance and representing an increase of 5.7% from the prior quarter.

Total solar wafer and module shipments in the quarter were 744.3MW, an increase of 12.1% from 663.9MW in the prior quarter.

Shunfeng posts 275.6% revenue increase on higher solar module shipments

Tier-one PV manufacturer and clean energy developer Shunfeng International Clean Energy (SFCE) reported a major turnaround in its business operations in 2014, after integrating Wuxi Suntech.

SFCE reported full year 2014 revenue of RMB5,745.9 million (US$924.7 million), compared to US$246.1 million in 2013, an increase of 275.6%.

The company returned to profitability with a net profit of RMB1,304 million (US$209.9 million), compared to a net loss of US$292.6 million in 2013.

Gross profit margin was 22.1% in 2014, compared to 9.9% in 2013.

Source: Centrotherm

Centrotherm has reported a return to profitability.

Personnel

JA Solar's CTO quits

Tier-one PV manufacturer JA Solar's chief technology officer Yong Liu resigned from the company at the end of March 2015.

JA Solar's COO, Yong Liu, has resigned his post for personal reasons.

Liu also relinquished his position on the board of directors of the company. The resignations were said to be for "personal reasons".

The company has appointed its head of research and development, Dr. Wei Shan, as CTO and Yuhong Fan would fill the vacancy left by Liu on the board.

Fan had served as vice president of JA Solar since July 2011 and general manager of Solar Silicon Valley, the wafer manufacturing arm of JA, since January 2010. Fan has over 18 years of experience in the PV industry.

RENA changes name and CEO

PV wet chemical equipment and materials supplier, RENA GmbH has changed its name to RENA Technologies GmbH. The company has also appointed a new CEO as it prepares to exit insolvency proceedings that will result in Jürgen Gutekunst, founder and former CEO of RENA GmbH leaving the company.

RENA Technologies via its major shareholder, Capvis has acquired the business operations of the insolvent RENA group through an asset deal, which mean that no liabilities are assumed by the newly created RENA technologies.

New owners Capvis and Gutekunst jointly decided not to continue working together in the new company. The new CEO is Lorenzo Giarré with around 20 years of semiconductor equipment supplier experience.

Boron–oxygen-related degradation in multicrystalline silicon wafers

Rune Søndenå, Institute for Energy Technology, Kjeller, Norway

ABSTRACT

Extended crystal defects, such as grain boundaries and dislocations, have long been considered the main factors limiting the performance of multicrystalline (mc-Si) silicon solar cells. However, because the detrimental effects of these crystal defects are reduced as a result of improvements in the solidification process as well as in the feedstock and crucible quality, the degradation caused by boron–oxygen complexes is expected to be of increasing importance. Light-induced degradation (LID) occurs in both p- and n-type crystalline silicon solar cells that contain both boron and oxygen. Because of the fundamental differences in the solidification processes, mc-Si silicon contains less oxygen than Czochralski silicon; nevertheless, the oxygen content in mc-Si silicon is still sufficient to cause degradation, although to a lesser extent than in the case of Czochralski silicon. Whereas B–O-related degradation of 0.5 to 1% abs. can be found in Czochralski cells, the degradation in conventional mc-Si cells is limited to around 0.1 to 0.2% abs.

Introduction

The function of a crystalline silicon solar cell is to generate electricity when exposed to light; it therefore seems like a paradox that the same solar cell degrades under illumination. Cell degradation is caused by recombination-active impurity complexes in the bulk silicon that are activated by illumination or charge-carrier injection. As a result, the electron–hole recombination will increase and thus reduce the minority-charge carrier lifetime in the material: this effect is called *light-induced degradation (LID)*. Several defects are known to affect the performance of a crystalline silicon solar cell upon illumination – these are iron–boron pairs, copper pairs and boron–oxygen complexes. The iron–boron pairs differ in the sense that, depending on the injection level, they may have a positive or a negative effect on the minority-carrier lifetime [1]. The behaviour of copper pairs is reported to be remarkably similar to that of boron–oxygen defects [2]. In mc-Si solar cells additional degradation, not necessarily attributed to the above-mentioned defect mechanisms, has recently been reported [3].

> "Cell degradation is caused by recombination-active impurity complexes in the bulk silicon that are activated by illumination or charge-carrier injection."

The work reported on in this paper focuses on the LID caused by boron–oxygen complexes, hereafter referred to as *B–O-related degradation*. The contribution from copper is assumed to be negligible.

B–O-related degradation

Monocrystalline p-type silicon wafers containing both boron and oxygen generally exhibit a considerable reduction in minority-carrier lifetime, and therefore in solar cell performance, with prolonged carrier injection. Within a day or two of illumination, the lifetime in Czochralski silicon (Cz-Si) is typically reduced to about 10% of the initial lifetime [4]. The reduction in the minority-carrier lifetime may lead to a reduction in efficiency of 0.5% to 1% abs. in a conventional solar cell. This degradation has been attributed to BO_2 complexes because of the dependence of the defect concentration on the concentrations of boron and oxygen in the material [5,6]. Charge carriers activate latent BO_2 complexes, dramatically increasing their recombination activity, thus reducing the minority-carrier lifetime in the material [7].

Experiments on compensated silicon containing phosphorus as well as boron demonstrate a dependency on the net doping p_0 rather than on the total boron concentration [8,9]. Two decay processes describe the degradation kinetics: one fast during the first few seconds of illumination, and one slow on a timescale of hours and days. The fast recombination has been attributed to B_sO_{2i} complexes and the slow one to B_iO_{2i} complexes [8]. As the concentration of the defect is believed to be very low (about $10^{11}cm^{-3}$), no trace of the defect itself has been found experimentally, for example by the use of transmission electron microscopy or deep-level transient spectroscopy [7]. The defect can only be studied indirectly by its effect on the electrical properties of wafers and cells.

B–O-related degradation can be completely reversed by heat treatment above 200°C in the dark; however, renewed degradation occurs upon illumination. In 2006 a regeneration process was presented by Herguth et al. [10]. Simultaneous illumination and heating at intermediate temperatures (<200°C) transforms B–O complexes from recombination-active states into metastable inactive states, called *regenerated states*; these states are characterized by high lifetimes and by defects that are stable under solar cell operating conditions [11]. Complete regeneration and the stability thereof have not yet been demonstrated on multicrystalline wafers.

Typically Cz-Si contains interstitial oxygen O_i in the range 5×10^{17} to $2\times10^{18}cm^{-3}$. In the case of mc-Si, the O_i content is about one order of magnitude lower [12–15]; O_i concentrations of $2\times10^{17}cm^{-3}$ and lower can be expected in current mc-Si wafers. Despite the lower oxygen levels in mc-Si, it is still sufficient to cause some degradation of both the minority-carrier lifetime and the solar cell conversion efficiency. Lifetime decays of 25% [12] and up to 50% [16,17] of the initial lifetime have been reported.

In cells with approximately 15% efficiency, a degradation of 0.1% abs. has been attributed to B–O defects [18]. Cells with efficiencies of 16% show a degradation of about 0.15% abs. [19], while up to 0.2% abs. degradation has been reported for cells with 17% efficiency [20]. Recent results from Hanwa Q-cells are largely in agreement, showing a B–O-related degradation of less than 1% relative [3]. These results also report a considerably higher LID in wafers from the bottom third of high-performance multicrystalline blocks, not related to B–O defects. In an advanced cell structure, namely an mc-Si PERC cell with an efficiency of 18.4%, even higher degradation is found; however, additional performance-limiting effects are suspected in this type of cell [21]. Additionally, in mc-Si that contains more oxygen, higher B–O-related degradation has been found [22].

Studies in which the B–O-related degradation is found to be less severe have also been published [14,23]. For cells with conversion efficiencies below 15%, where other defects limit cell performance, degradation is difficult to measure [18], which may explain the low degradation reported in some studies.

Determination of B–O defects

A normalized defect concentration N_t^* is commonly used for determining the B–O defects attributed to the defect density in mc-Si wafers:

$$N_t^* = \frac{1}{\tau_{\text{BO-activated}}} - \frac{1}{\tau_{\text{initial}}} \quad (1)$$

where the minority-carrier lifetimes τ_{initial} and $\tau_{\text{BO-activated}}$ represent the lifetimes before and after degradation respectively [24]. According to Shockley-Read-Hall (SRH) theory, the B–O-related defect concentration can be related to the measured lifetimes as stated by Equation 1 if the generated defects are the dominating recombination-active defects [25,26].

In the case of mc-Si, however, B–O-related defects cannot be considered the dominating recombination path, because of the considerable spatial variation in lifetime across the wafer. Equation 1 is therefore not directly applicable for quantifying the B–O-related degradation in mc-Si wafers. If the average lifetime across the entire wafer is used, thus interpreting all lifetime-limiting defects as B–O complexes, the defect concentration of B–O complexes will be overestimated, depending on the number of grain boundaries and dislocations in the wafer. Image analysis and evaluation of the high-lifetime areas has therefore been proposed for quantification of the normalized defect concentration of B–O complexes in multicrystalline wafers [17].

Experimental results

Time-resolved degradation of the minority carrier lifetime in an illuminated multicrystalline wafer is shown in Fig. 1. The wafer is phosphorus-diffusion gettered – in other words, a phosphorus emitter is in-diffused, followed by an etch-back process, and the surfaces are subsequently passivated using hydrogenated amorphous silicon. The lifetime is continuously monitored by an automated quasi-steady-state photoconductance (QSSPC) set-up with an external bias light source for in situ illumination between measurements [4,27]. A conventional mc-Si wafer from the bottom part of a block is chosen.

The degradation is divided into a fast decay, occurring in the first 30 seconds of illumination, and a slow decay, which takes place during the following 24 to 48 hours. The timescales of both the fast and slow decays correspond quite well with those of Cz-Si wafers containing comparable amounts of boron. In addition, the initial lifetime in the mc-Si wafers can be recovered by

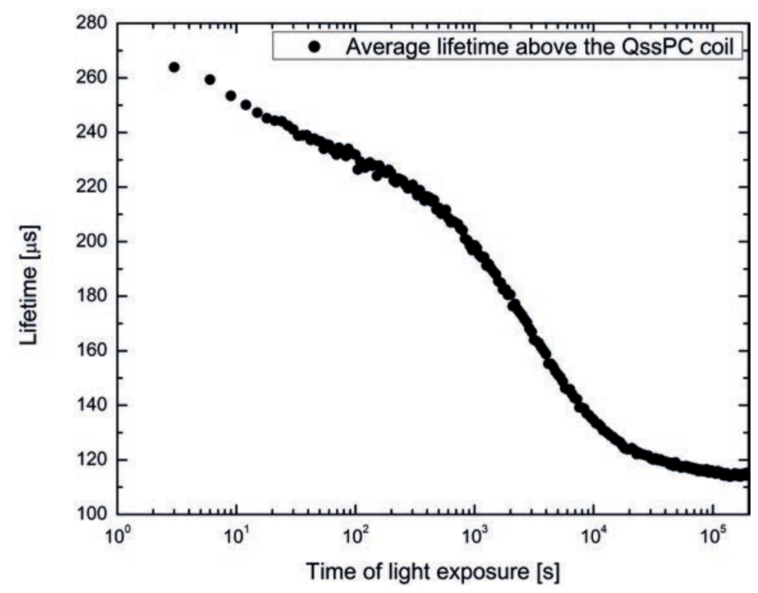


Figure 1. The time-resolved lifetime degradation in an mc-Si solar cell, measured using a customized QSSPC set-up [17]. A phosphorus-gettered wafer from the bottom part of an mc-Si block is shown.

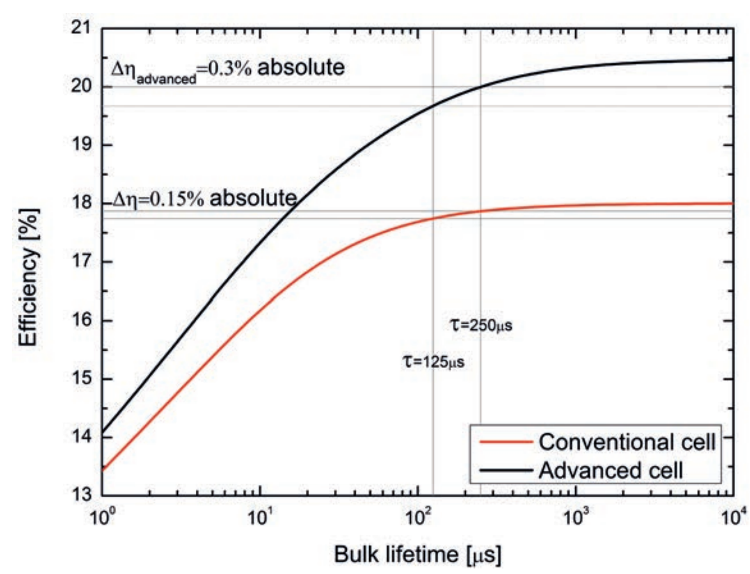


Figure 2. The performance of a solar cell as a function of bulk lifetime. A conventional cell structure is compared with an advanced cell structure having improved surface recombination properties.

subjecting the wafer to a heat treatment for 20 minutes above 200°C. The nature of the recovery mechanism and the timescales of the decay indicate that the degradation mechanism is the same in Cz-Si and mc-Si wafers.

"The degradation is divided into a fast decay, occurring in the first 30 seconds of illumination, and a slow decay, which takes place during the following 24 to 48 hours."

Fig. 1 shows, however, that the fast decay is less pronounced in mc-Si wafers than in Cz-Si ones. The total degradation is also less severe for mc-Si wafers, with a degraded lifetime of about 50% of the initial value for this wafer; this may be a result of the reduced oxygen content in mc-Si, but it may also indicate that other defects contribute to carrier recombination, reducing the initial lifetime in the mc-Si wafer. As the wafer shown is from the bottom part of the multi-block, it is reasonable to assume that the oxygen levels are in the upper end of the range. Less oxygen, and thus less B–O-related degradation, can be expected towards the middle and top parts of the block.

A rule of thumb is that the performance of a conventional cell is significantly reduced when the diffusion length is less than three times the thickness of the device [28]; for 180µm wafers this occurs at a lifetime of approximately 100µs. For purposes of illustration, the performance of a solar cell is modelled using PC1D [29,30]. If a conventional cell structure is assumed, the efficiencies for different bulk lifetimes are as presented in Fig. 2. A reduction in the lifetime from 250µs to 125µs corresponds to a reduced efficiency of 0.15% abs., which is in good agreement with experimental results. The PC1D model does not, however, include other lifetime-limiting defects, such as grain boundaries and dislocation clusters. When considering an advanced cell, for example one with improved surface recombination properties, the efficiency loss due to B–O degradation is estimated to increase to 0.3% abs. PC1D model parameters are given in Table 1.

Lifetime images of the wafers after the initial heat treatment τ_{initial} and after degradation $\tau_{\text{BO-activated}}$ are obtained using band-to-band photoluminescence (PL) imaging [31]: lifetime maps before and after degradation are shown in Fig. 3(a) and (b) respectively. The mean lifetime in the entire wafer is reduced from 150µs to 75µs during 48 hours of illumination; this average reduction across the whole wafer is smaller than the decay indicated in Fig. 1. While the values in Fig. 1 represent the area directly above the QSSPC coil, the average values across an entire wafer are also reduced by the extended crystal defects, i.e. grain boundaries and dislocation clusters. The impact of B–O-related defects in mc-Si is reduced when other defects contribute to limiting the lifetime.

The spatially distributed normalized defect concentration, calculated by means of Equation 1, is shown in Fig. 4. Grain boundaries, dislocations and dislocation clusters are easily adorned with impurity atoms, resulting in electrically active recombination centres. Grain boundaries and dislocation-rich areas are therefore represented as low-lifetime areas in the PL images in Fig. 3. Areas with low initial lifetimes show high defect concentrations, despite having a lower relative reduction in the lifetime. It is clear that crystal defects are also interpreted as B–O defects and erroneously included when calculating the B–O defect concentration N_t^*. The main assumption for calculating the defect concentration and attributing it to the B–O complex was that the relevant defect was the dominating defect mechanism. B–O degradation

Device	Resistivity [Ω-cm]	Thickness [µm]	Emitter [Ω/sq.]	Front SRV* [cm/s]	Rear SRV* [cm/s]
Conventional	1.1	180	60	10^5	350
Advanced	1.1	150	100	2000	10

*SRV = surface recombination velocity.

Table 1. Device model parameters for a p-type substrate with an n-type front emitter.

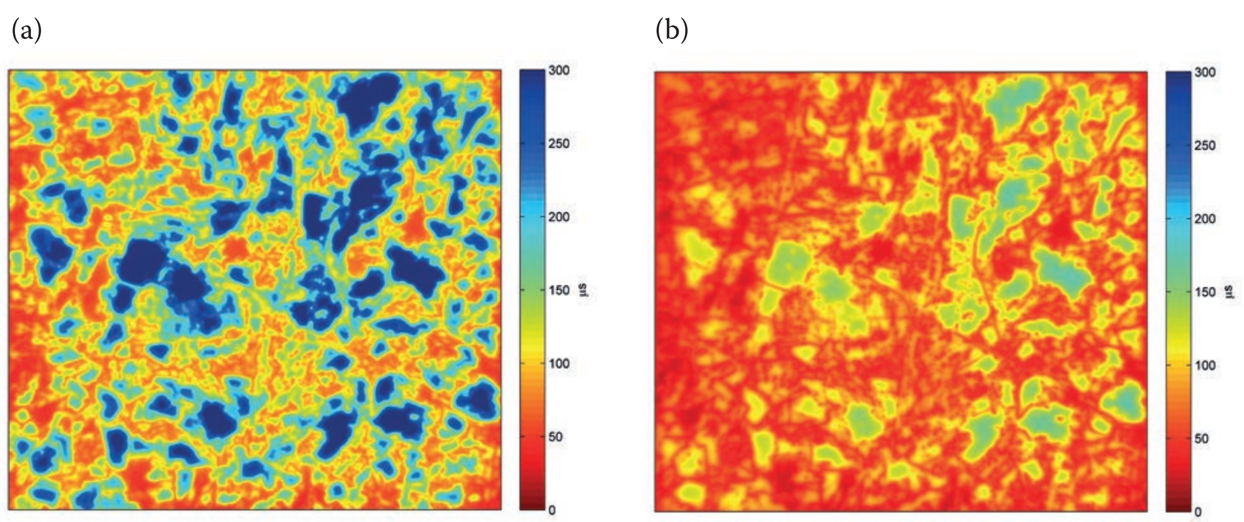


Figure 3. PL images showing the lifetimes in the wafer before (a) and after (b) illumination for 48 hours.

may contribute to reducing the lifetime in these areas, but it certainly cannot be considered the dominating recombination path. Using Equation 1 to calculate N_t^* in mc-Si wafers will therefore result in an overestimation of the B–O defect concentration.

The average defect concentration will include both B–O-related and other recombination centres when an entire mc-Si wafer is considered. The spatial variation in the lifetime in multicrystalline wafers makes it difficult to compare wafers from different blocks, and even wafers from different heights in the same block. Since the area fraction of the wafer covered with extended crystal defects may vary, the magnitude of the overestimation of the B–O defect concentration may also vary.

To compare B–O-related degradation in multicrystalline wafers, an approach using image segmentation has been proposed [17]. Image segmentation by means of the Otsu algorithm separates the lifetime images into two distinct parts: high- and low-lifetime areas. Normalized defect concentrations are calculated in high-lifetime areas only, as shown in Fig. 5. If it is assumed that the B–O defect is the dominating recombination path in the high-lifetime areas, the defect concentration in this segment will yield a more representative estimate of B–O defects. The resulting value can then be used for comparing different mc-Si wafers. Table 2 shows the B–O defect concentrations calculated using the arithmetic mean across the entire wafer, and the calculation based on the high-lifetime segment only.

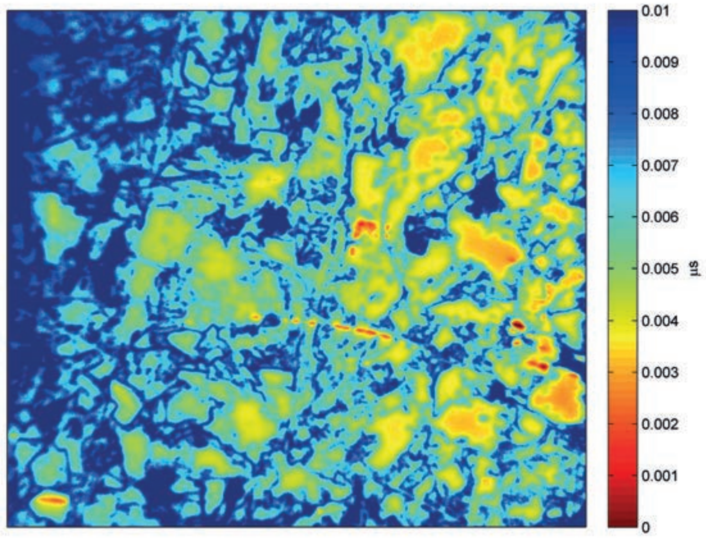


Figure 4. The spatial distribution of N_t^*, calculated using the PL images before and after degradation. High defect concentrations are obtained in areas with low initial lifetimes.

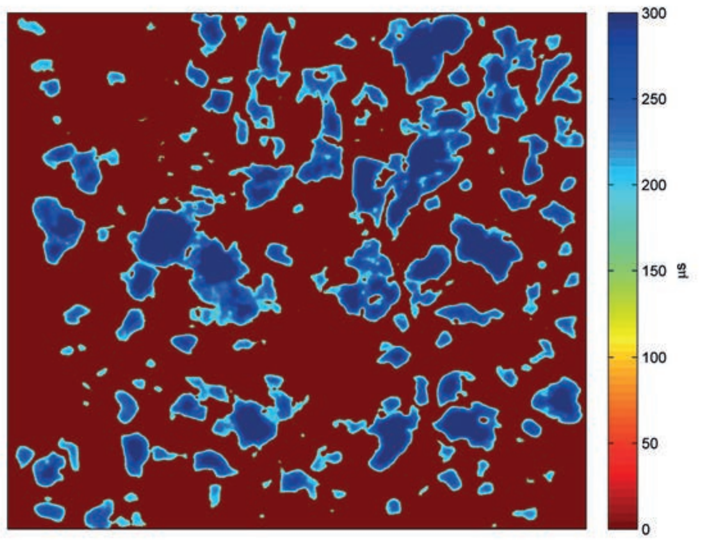


Figure 5. Image segmentation is performed in order to evaluate only the high-lifetime areas. A threshold value is found using the Otsu algorithm.

Area	$\tau_{initial}$ [µs]	$\tau_{BO\text{-}activated}$ [µs]	N_t^* [µs^{-1}]
Arithmetic mean – wafer	150	75	6.7×10^{-3}
High-lifetime segment	246	112	4.9×10^{-3}

Table 2. Normalized defect concentrations N_t^*.

"Normalized defect concentration for the high-lifetime areas may be used for quantification of the B–O-related degradation in mc-Si wafers."

Conclusions

Multicrystalline silicon wafers typically contain less oxygen than Cz-Si wafers. The amounts are, however, sufficient to generate B–O-related degradation under illumination in mc-Si wafers as well. A degradation in performance of mc-Si solar cells of up to 0.2% abs. because of B–O defect complexes has been reported. Lifetime measurements combined with PC1D measurements confirm that the effect may be in this range in conventional solar cells. The degradation is limited in conventional cell structures, but the impact of the degradation is expected to increase when introducing more-advanced cell concepts, such as rear-side passivation.

The degradation curve in mc-Si, including both a fast and a slow decay, shows similarities to the degradation observed in p-type Cz-Si wafers. Because of the similarities in the decay rates as well as in the recovery mechanisms, the LID observed in the mc-Si wafers is attributed to B–O complexes. It is reasonable to assume that mc-Si cells will respond to the same regeneration process as in the case of Cz-Si cells, but a methodology for such a regeneration process has yet to be demonstrated for mc-Si cells.

Conventional approaches to the quantification of B–O-related degradation in monocrystalline silicon are not easily applied to mc-Si, because of the non-uniform nature of the lifetime distribution. In the calculation of the B–O defect concentration, only one dominating recombination mechanism is assumed, which is unlikely to be the case in mc-Si wafers. When image segmentation is used, high-lifetime areas can be evaluated separately; in these areas the assumption that one recombination path dominates is more likely to be applicable. Thus, the normalized defect concentration for the high-lifetime areas may be used for quantification of the B–O-related degradation in mc-Si wafers.

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About the Author

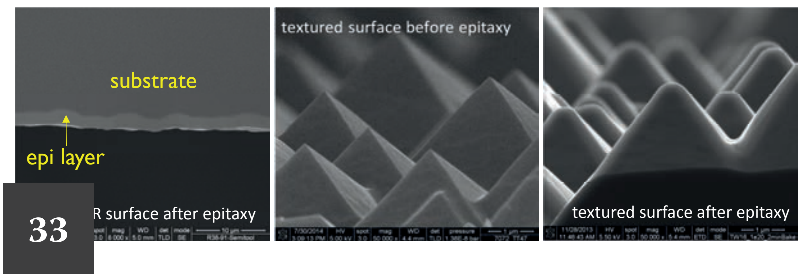
Rune Søndenå is a research scientist in the department of solar energy at the Institute for Energy Technology (IFE) in Norway. He holds an M.Sc. in physics from the Norwegian University of Science and Technology and a Ph.D. in chemistry from the University of Oslo. Rune has worked in the field of silicon-based PV for seven years; his research interests include defects in silicon, wet-chemical processes and thin-film deposition.

Enquiries

Institute for Energy Technology
PO Box 40
N-2027 Kjeller
Norway

Tel: +47 92029610
Email: Rune.Sondena@ife.no
Website: www.ife.no

Cell Processing



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The use of silicon epitaxy in advanced n-type PERT and IBC silicon solar cell designs

María Recamán Payo1, Izabela Kuzma-Filipek1, Filip Duerinckx1, Yuandong Li1, Emanuele Cornagliotti1, Angel Uruena1, Loic Tous1, Richard Russell1, Ali Hajjiah2, Maarten Debucquoy1, Jozef Szlufcik1 & Jozef Poortmans1,3

1imec, Leuven, Belgium; 2Kuwait University, College of Engineering and Petroleum, Electrical Engineering Dept., Safat, Kuwait; 3KU Leuven, Leuven, and University of Hasselt, Diepenbeek, Belgium

News

News

DuPont unveils new metallization paste

Materials supplier DuPont launched the latest generation of its Solamet PV metallization pastes, unveiling Solamet PV19x at SNEC expo in Shanghai, China, in April.

The newest additions can result in efficiency gains of more than 0.15% in solar panels and cells from the company's previous market offering, Solamet 18x.

The new products include a front-side silver paste, Solamet 19A, based on proprietary Tellurium technology.

Additionally, major Taiwanese solar cell producer Neo Solar Power (NSP) is collaborating in a joint development programme with DuPont on the 'Solamet' PV19x series silver pastes.

Another manufacturer, Solartech, set an in-house module output record with the DuPont PERC metallization paste.

Source: Solartech

DuPont has unveiled its latest Solamet metallization paste.

The four busbar design and low light-induced degradation (LID) levels enabled the development of Solartech's Sapphire PV module generating 286W of power. This is said to be the highest power output reported for this type of solar panel.

DuPont also signed a strategic collaboration agreement with Chinese tier-one cell and module producer JinkoSolar.

Innovations and R&D

PV technology roadmap charts course for industry to continue cost-cuttgin drive

The sixth edition of the International Technology Roadmap for Photovoltaic has been released, setting out key measures for continued cost cutting along the crystalline silicon PV value chain.

The roadmap identifies reductions in materials costs, improved manufacturing processes and the shift to advanced cell technologies as crucial objectives for the industry in its attempts to remain competitive.

It reports that 2014 saw some companies begin to turn a profit as a result of their continued efforts to reduce the cost per piece along the value chain.

The roadmap reports that the so-called price experience curve, which has historically seen average selling prices decrease by around 21% for every doubling of cumulative PV module shipments, will continue over the next few years.

UNSW and PV Lighthouse reveal first virtual solar cell fabrication simulator

The University of New South Wales (UNSW) and PV Lighthouse have announced the development and operation of the world's first free access online solar cell fabrication simulator, designed to replicate real world production processes.

Dubbed PV Factory, the solar cell fabrication simulator processes virtual wafers through 12 production steps and provides the user with the electrical output of each solar cell and is being used by engineering students at UNSW, Arizona State University and engineers across the PV industry.

PV Factory was said to integrate sophisticated physics algorithms into a software package that is easy to use and understand, which has been demonstrated by over 500,000 virtual cells processed during beta testing.

Source: David McLeish, Flickr

The University of New South Wales (UNSW) and PV Lighthouse have revealed the first virtual solar cell fabrication simulator.

Suntech upgrading 2.2GW of solar cell capacity to four-busbar technology

Wuxi Suntech, the PV module manufacturing arm of Shunfeng International Clean Energy (SFCE) is upgrading all its cell and module capacity from three- to four-busbar technology to boost performance.

SFCE had expected to complete the re-commissioning of Wuxi Suntech's entire manufacturing capacity by the end of 2014, which included 2.2GW of solar cell capacity and 2.4GW of module capacity.

The upgrade began in December 2014. The move to the four-busbar design would reduce current loss by approximately 10% and create less residual stress on the busbars, in turn reducing the potential for micro-cracks and hotspot formation, which can lead to module power degradation and failure.

ASYS
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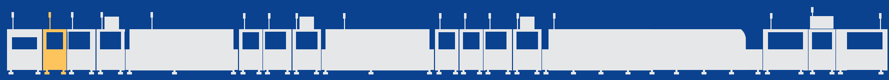
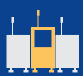
Laser Contact Opening



Inline System



Laser
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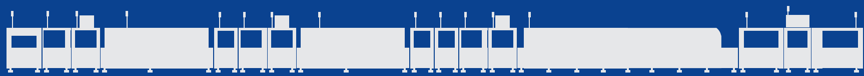

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Source: Neo Solar Power

Neo Solar Power saw only a lackluster improvement in sales in March.

Trina hails milestone for multi-Si module with 19.14% record

China's Trina Solar has claimed a new efficiency record for a p-type multi-crystalline silicon module of 19.14%.

The record was independently verified by the National Center of Supervision and Inspection on Solar Photovoltaic Product Quality (CPVT) in Wuxi, China.

The result was achieved in a prototype module composed of 60 high-efficiency 'Honey Plus' multicrystalline cells incorporating advanced technologies such as back surface passivation, local back surface field and half-cell module technologies. Honey Plus is the brand name for Trina's PERC solar cells, which are now in mass production minus the half-cell technology, which would be incorporated into production lines at a later date.

Pierre Verlinden, vice-president and chief scientist of Trina Solar said: "It demonstrates that multi-crystalline Silicon PV modules can reach an efficiency level that was reserved to the most efficient solar cells before, such as mono-crystalline IBC or heterojunction cells."

Company news

DEK Solar rebranded

PV screen printing equipment specialist DEK Solar has been assimilated into a new 'alternative energy' structure within ASM Pacific Technology (ASMPT), becoming part of ASM Alternative Energy (ASM AE).

ASM AE will include the DEK Solar product offerings as well as ASMPT's PV wafer inspection and module assembly products. The new entity will continue in the PV sector but will also service fuel cell and next-generation battery markets.

ASM AE has upgraded its Eclipse metallization tool to include a new Voice Coil Motor (VCM) technology, designed to improve wafer throughput at over 75,000 wafers per day.

Solartech sales continue slide in March

Taiwan-based solar cell producer Solartech Energy Corp reported further declines in sales for March 2015.

Solartech reported March 2014 sales of NT$503 million (US$16 million, a 13.5% decline from sales of NT$582 million (US$18.4 million) for February, which was a 29.6% decline from the previous month when sales reached NT$826 million (US$26.1 million).

The steep decline in February sales were attributed to the shorter working month and Chinese New Year, however March sales decline may indicate a weakness in overall first quarter demand and pricing pressure for Taiwanese solar cells, especially from key markets such as China.

Rival solar cell producers such as Neo Solar Power and Gintech have also reported mediocre sales for the first quarter of 2015.

Neo Solar Power's sales stay in the doldrums

Major merchant solar cell producer Neo Solar Power (NSP) reported lacklustre sales improvement in March 2015, resulting in sales remaining in the doldrums for the first quarter of the year.

NSP reported March 2015 sales of NT$1,656 million (US$53 million), a 12.9% increase over the previous month.

Non-audited first quarter sales were around NT$4,629 million (US$148.3 million) compared to NT$7,277 million (US$233.1 million) in the first quarter of 2014.

The company noted that sales were starting to recover due to the expected growth in key markets such as China and expected shipments would continue to improve.

Gintech's solar cell sales fall to lowest level in more than two years

Taiwan-based solar cell producer Gintech Energy Corp reported weak March 2015 sales, marking a new low point since 2013.

Gintech reported sales of NT$832 million (US$26.6 million) in March, compared to US$35.9 million in the previous month, having bucked the trend in February for its Taiwan rivals when sales declined due to a shorter month and Chinese New Year.

Sales were down 50.3% year-on-year and down 26.5% month-on-month.

Non-audited first quarter sales were NT$3,073 million (US98.5 million), down 28.3% over the prior year period.

Dutch manufacturer Orange Solar Power's 70MW fab aims to combat European decline

A solar module factory with a 70MW production capacity will be built by Orange Solar Power, a Dutch photovoltaics (PV) manufacturer and supplier, in West Brabant, the Netherlands.

The plant will be built in a two-phase process, with a 15MW production line in the first phase to be completed by Q3 2015. The second phase will add the remaining 55MW. Phase two is scheduled for completion shortly after the first, with the full line pencilled in to be operational by the end of the year.

With the first phase, Orange Solar Power will be producing its 'Monoflex' branded flexible solar modules.

Source: SunEdison.

SunEdison has expanded its monocrystalline cell purchases from Shinsung Solar.

Order news

ACT Aurora to gain first repeat order for inline measurement systems

PV manufacturing process inspection specialist, ACT Aurora Control Technologies has won two supply contracts with PV equipment supplier SEMCO Engineering for its 'Decima' inline measurement system used to monitor solar cell emitter formation.

The orders from SEMCO Engineering are for inline manufacturing equipment to be supplied to two unidentified solar cell producers.

ACT Aurora also expects to supply its first repeat order for two 'Decima' inline production measurement systems with its 'Veritas' software.

The company received a letter of intent from an existing customer to purchase the tools.

ACT Aurora noted that the order is expected to be for its three-track measurement system, which measures three tracks down every wafer as they emerge from the annealing or diffusion furnace at full production rates.

SunEdison doubles monocrystalline solar cell order with Shinsung

SunEdison has expanded its monocrystalline solar cell purchases from Korea-based producer, Shinsung Solar Energy.

In a new supply agreement, SunEdison is expected to purchase a total of 1,223MW of mono-Si solar cells from Shinsung through 2017, up from a supply contract signed almost a year ago of 660MW.

Shinsung is believed to have added capacity and upgraded tools for higher cell efficiencies last year to meet SunEdison's cell requirements for the initial contract through 2016.

MBJ supplying multiple automated EL Testers to tier-one PV manufacturers

PV inspection equipment specialist MBJ Solutions is supplying a large number of SolarModule EL-inline solar cell/module inspection tools to a major tier-one PV manufacturer.

MBJ Solutions said that a customer with manufacturing operations on four continents is undertaking a complete replacement of existing electroluminescence-based manual inspection systems with fully automated SolarModule EL-inline systems.

Over 25 EL inspection systems have been ordered by this customer, according to the company.

MBJ Solutions also noted that it had also received another significant order for its SolarModule EL-inline system, which will be deployed throughout another customer's module production lines.

InnoLas touts nearly 1GW of PERC solar cell laser system orders

PV equipment specialist InnoLas Solutions has received orders equating to almost 1GW of production capacity for its laser systems used for PERC solar cell processing.

Several more solar cell manufacturers are planning PERC cell migrations but have yet to confirm orders.

The ILM-2 laser system is claimed to offer the fastest laser process on the market, which can be adjusted between 1,600 and 3,600wph, with a claimed uptime of >96%.

Markus Nicht, chief executive InnoLas Solutions said: "These process steps offer a cost effective way to increase solar cell efficiency and thus give our customers a competitive edge."

CEA buys HJT and 'SmartWire' equipment from Meyer Burger

PV equipment supplier Meyer Burger is to supply French research centre, Alternative Energies and Atomic Energy Commission (CEA) with equipment to develop high-performance heterojunction (HJT) cells and Meyer Burger's SmartWire Connection technology (SWCT).

The equipment order amounted to over CHF12 million (US$12.3 million) and was part of a new strategic collaboration with CEA and its Institute of Laboratories for Innovation in New Energy Technologies and Nanomaterials (LITEN) to replace its existing solar manufacturing test equipment and technology.

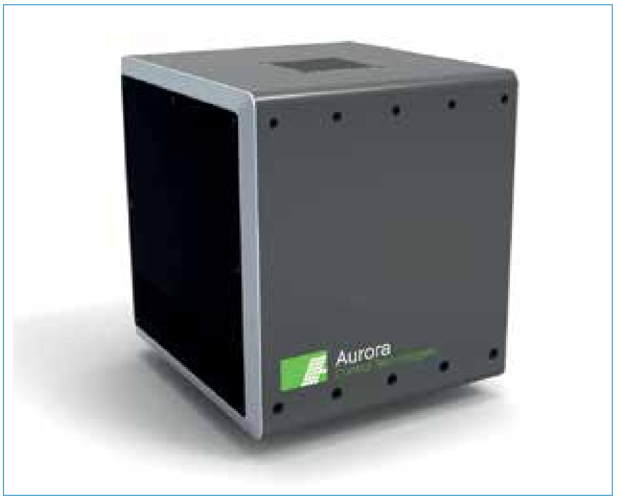
The order includes cell coating, testing and next-generation bifacial encapsulation technology and equipment for HJT cells, a key next-generation platform for Meyer Burger to offer solar cell producers.

The tools would also be used for marathon research tests, to verify the technology developments in an industrial environment.

Delivery and installation of the equipment is scheduled for late 2015.

Product Reviews

ACT Aurora



ACT Aurora's 'Decima 3T' masters higher-density characterization of solar cell emitter uniformity

Product Outline: ACT Aurora Control Technologies has introduced an inline measurement tool, the 'Decima 3T'. In combination with Aurora's Veritas visualization and control system, this new member of the Decima inline measurement product family responds to customer and partner demands for higher-density characterization of solar cell emitter uniformity and the need for seamless integration into diffusion furnace operations, according to the company.

Problem: High-efficiency solar cell processing puts greater demand on the need to provide accurate characterization of solar cell emitter uniformity in volume production environments. This leads to the need for measurement systems that van be seamlessly integrated into diffusion furnace operations.

Solution: The Decima 3T is said to rapidly and accurately profile the sheet resistance over three separate tracks on each silicon wafer after the diffusion or annealing furnace at full production speeds. The tracks are positioned such that intra-wafer uniformity can be characterized for each wafer processed. This enables the complete mapping of the solar cell emitter, a capability that is in significant demand for high-efficiency cell production. The system is designed to allow measurement of up to 5,000 wafers per hour.

Applications: High-density characterization of solar cell emitter uniformity.

Platform: The 3T complements Aurora's existing Decima products by providing a cost-effective and compact package for these high-density measurements, and also includes enhancements for accuracy, repeatability and maintainability.

In tandem with the Decima 3T, Aurora is releasing an upgrade to its 'Veritas' visualization and control product. The Veritas upgrade provides process engineers and operators with the means to monitor and optimize multi-track wafer measurements integrated with the latest generation of diffusion and annealing furnaces through real-time 3D visualization of intra-furnace dynamics, both spatially and by batch.

Availability: March 2015 onwards.

Centrotherm

Centrotherm's regeneration belt furnace reduces LID impact by up to 80 %

Product Outline: Centrotherm is launching the 'c.REG' conveyor belt furnace for monocrystalline p-type solar cell regeneration, which is claimed to achieve a reduction in light-0induced degradation (LID) from 6% to 1%, within less than a one minute processing cycle time. The company showcased the regeneration technology at SNEC 2015 held in Shanghai, China, in April.

Problem: After being exposed to light monocrystalline silicon solar cells suffer performance losses due to light-induced degradation. In general, this effect, which is ascribed to boron-oxygen (B-O) complex in the wafer bulk, lowers conversion efficiency by up to 6% in the long term.

Solution: To avoid B-O-defects, centrotherm developed a regeneration process and the corresponding key equipment, c.REG, which potentially reduces LID to 1% only.

Within the regeneration process boron-oxygen defects responsible for light induced degradation are passivated and transformed into a less active state in order to minimize performance losses. The regeneration process can be implemented directly after fast firing, after sorting or even before module manufacturing and is applicable to both Al-BSF (Aluminium Back Side Field) and PERC solar cells. Process time ranges between 20 and 45 seconds depending on wafer material and pre-processing.

Applications: Regeneration of Cz-Si solar cells.

Platform: c.REG is a stand-alone regeneration equipment based on the modular design of centrotherm conveyor belt furnaces with a small footprint. The process chamber is designed in a modular concept matching different requirements of wafer material with up to three modules possible that is notable for an optimum process sequence, time and calibration.

The system comes with integrated heater and belt transfer handling and has a throughput (at 5100 mm/min) of 3,600 wafers/hr.

Availability: May 2015 onwards

The use of silicon epitaxy in advanced n-type PERT and IBC silicon solar cell designs

María Recamán Payo[1], Izabela Kuzma-Filipek[1], Filip Duerinckx[1], Yuandong Li[1], Emanuele Cornagliotti[1], Angel Uruena[1], Loic Tous[1], Richard Russell[1], Ali Hajjiah[2], Maarten Debucquoy[1], Jozef Szlufcik[1] & Jozef Poortmans[1,3]

[1]imec, Leuven, Belgium; [2]Kuwait University, College of Engineering and Petroleum, Electrical Engineering Dept., Safat, Kuwait; [3]KU Leuven, Leuven, and University of Hasselt, Diepenbeek, Belgium

ABSTRACT

This paper gives an overview of the application of silicon epitaxy as a doping technology in bulk crystalline silicon solar cells. The large degree of flexibility in designing a doped profile in one process step, and the elegant way of locally creating doped regions, or simply achieving single-side doping by selective epitaxy, are presented. Other advantages – such as the absence of subsequent steps to drive in the doped region, to activate the dopants and to heal any damage or remove glassy layers – position the technology as a strong alternative to classical diffusion. Silicon epitaxy is possible on the flat and textured surfaces of solar material, and is compatible with cleaning sequences suited to industrial implementation. The integration of epitaxial layers in solar cells is capable of providing not only high efficiencies but also simplifications of the cell fabrication process, and, therefore, reductions in the cell cost of ownership (CoO). The proof of concept at the cell level has been demonstrated by the integration of boron-doped epitaxial emitters in n-type IBC and PERT solar cells: 22.8% efficiency for IBC ($4cm^2$) and 21.9% for PERT ($238.9cm^2$) devices have been obtained.

Introduction

The epitaxial growth of silicon on crystalline material consists of the regularly oriented growth of a crystalline silicon layer upon the substrate surface, where the substrate acts as a template for the growing layer [1–2]. Silicon epitaxy is possible not only on monocrystalline but also on polycrystalline material [3]. Moreover, the process is not restricted to mirror-polished surfaces, but is also applicable on typical Czochralski (Cz) material used in solar cell fabrication after saw-damage removal (SDR) or anisotropic texturing [4].

The doping of the epitaxial layer takes place by in situ incorporation of the dopant source during growth. In fact, epitaxy enables a high degree of flexibility in designing a doped profile in one process step, as both the dopant concentration and the thickness of the layer can be decoupled. In addition, after epitaxy there is no need for subsequent steps to drive in the doped region, activate the dopants, heal any damage or remove glassy layers.

The selective epitaxial growth of silicon can further reduce the complexity of cell fabrication when it is applied to locally create doped regions or to simply achieve single-side doping. In selective epitaxy, the process conditions are such that the net outcome of the silicon growth is the result of a balance between silicon deposition and silicon etching upon substrates where part of the surface is 'masked' with a dielectric/dielectrics, while the rest is 'free' of dielectric(s) [5]. The overall result is the growth of a

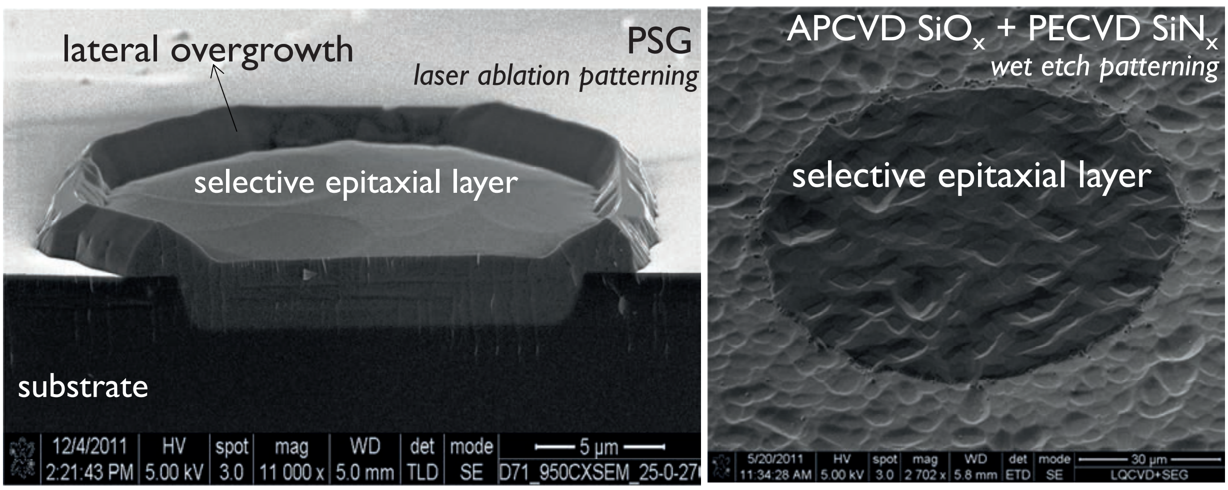


Figure 1. SEM images: examples of selective epitaxial growth on Cz silicon solar wafers using different dielectrics.

silicon layer solely on the areas 'free' of dielectric (Fig. 1). The dielectric can be kept after epitaxy for passivation and optical purposes, or can even serve as an additional dopant source [6].

> "Silicon epitaxy is capable of realizing not only high efficiencies but also simplifications of the cell fabrication process."

In sum, the aforementioned benefits place epitaxy as a strong alternative technology to classical diffusion for creating the doped regions of bulk crystalline silicon solar cells. This paper first gives an overview of the application of epitaxy to bulk crystalline silicon technology; then a proof of concept at the device level is demonstrated for solar cell concepts, such as n-type passivated emitter and rear totally diffused (PERT) and interdigitated back contact (IBC). The integration of boron-doped epitaxial emitters on the rear side of these devices demonstrates that silicon epitaxy is capable of realizing not only high efficiencies but also simplifications of the cell fabrication process, and, thus, reductions in the cell cost of ownership (CoO).

Epitaxy on solar silicon wafers

This section begins by giving a general insight into silicon epitaxial technology; it then continues with a discussion of the impact of the substrate surface morphology, the cleaning prior to epitaxial deposition, the properties of the dielectrics used as a 'mask' during the selective deposition of silicon, and the doping profile capability of silicon epitaxy. The performance of boron-doped epitaxial emitters, used in cell concepts such as n-type IBC and PERT cells, is compared with that of reference boron-doped diffused emitters.

While not within the scope of this paper, the study is equally applicable to phosphorus-doped epitaxial layers.

Silicon epitaxy

In this work, the epitaxial growth of silicon is realized by chemical vapour deposition (CVD): the deposition of the silicon layer takes place by means of chemical reactions and surface absorption through a gaseous phase [1–2]. The process described herein takes place at a reduced pressure (<100Torr) and a temperature between 850 and 950°C. Dichlorosilane (SiH_2Cl_2) is used as the silicon source and hydrogen (H_2) as the carrier gas; however, it is also possible to use other precursors, such as silane or higher-order silanes (disilane, neopentasilane, etc.), or even organic precursors (triethoxysilane, tetramethylorthosilicate, etc.), if a lower process temperature (≤700°C) is required [7]. Diborane (B_2H_6) is employed as the dopant source, but other p-type and n-type sources are also available (BCl_3, PH_3, AsH_3, etc.).

Hydrogen chloride (HCl), which is a silicon-etching agent, is formed as a by-product of the deposition from SiH_2Cl_2. In the selective epitaxial growth of silicon, which is a balance between a simultaneous silicon deposition and etching, the HCl resulting from the SiH_2Cl_2 decomposition may be sufficient to maintain selectivity; on occasion, however, additional HCl needs to be supplied to the main stream for a selective growth [5] to take place. The growth rate for a selective epitaxial process is lower than that for a non-selective process, where no silicon etching occurs and a blanket silicon layer is deposited over the entire exposed surface.

The basic steps of an epitaxial process are temperature ramp-up, hydrogen bake, silicon deposition and cool-down. The hydrogen bake, taking place before the actual deposition step, is a critical step which assists overall in the growth of a high-quality epitaxial layer. One of the main goals of the hydrogen bake is to remove native oxide from the substrate surface by hydrogen reduction. If the native oxide were not removed, the deposition would lead to a highly defective epitaxial layer or a polycrystalline layer, or, in the case of selective growth, little or no deposition. In addition to the native oxide removal, the bake can also assist in annealing crystal damage and cause a desirable surface reconstruction, providing a region near the silicon surface which is free of oxygen [1–2]. There is a suitable trade-off between bake temperature, pressure and time in order to achieve a reduced surface defectiveness. The bake temperature has a key role, and, typically, higher bake temperatures result in lower defect densities. A process occurring at a reduced pressure also tends to provide a lower crystal defect component than a process at atmospheric pressure. The specific conditions also depend on the oxygen and moisture levels inside the reaction chamber [8].

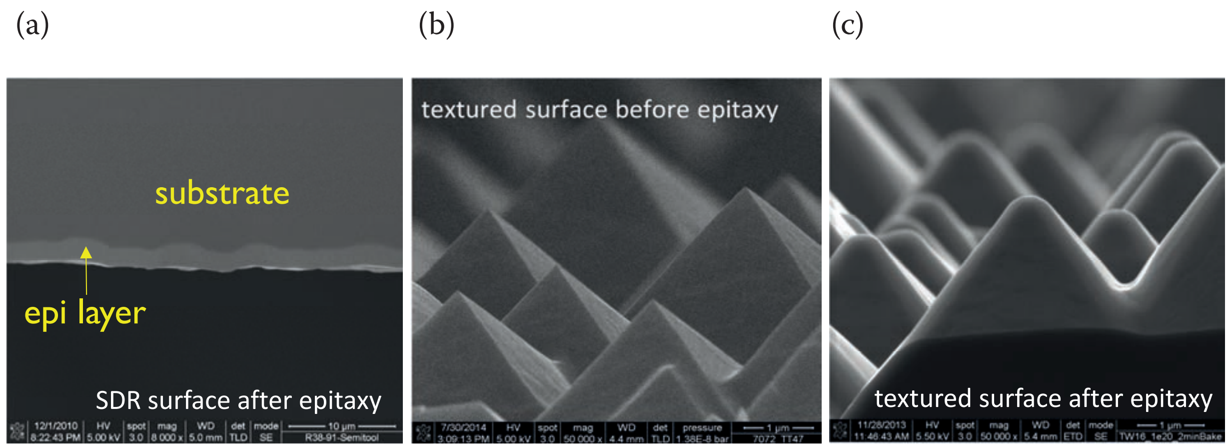


Figure 2. SEM images: (a) epitaxial layer grown on a KOH-SDR (saw-damage removal) silicon surface; (b) KOH-textured surface before epitaxy; (c) epitaxial layer grown on a KOH-textured surface.

The boron-doped epitaxial emitters described here have doping levels in the range 10^{18}–$10^{20}cm^{-3}$ and thicknesses of ≤1µm. The growth rate for these layers ranges between 30 and 750nm/min, which depends not only on the process temperature but also on the possibility of performing a blanket or selective deposition.

Substrate surface morphology

The growth of epitaxial emitters can be realized on the rough surfaces resulting from an SDR process and on the random pyramidal surfaces following an anisotropic texturing process (Fig. 2). The growth of epitaxial layers on those surfaces requires an optimization of the growth conditions and, in a very particular way, an optimization of the bake conditions prior to the actual deposition step.

At the reduced pressure (<100Torr) and the temperature range (850–950°C) normally used to grow these boron-doped epitaxial emitters, a hydrogen bake of at least 2–5min is recommended in order to achieve a sufficient epitaxial quality on both flat and textured surfaces (Fig. 2). In those conditions, a measured total defect density of less than 10^4 defects/cm^2 in the boron-doped epitaxial emitters is confirmed to be sufficient for good performance at the solar cell level.

An investigation [9] of the influence of the substrate surface morphology (Fig. 3) demonstrates that an inline single-side chemical etching process based on $HF{:}HNO_3$ chemistry and realized on KOH-based textured surfaces can lead to values of dark-saturation current density (J_0) as low as those measured on surfaces resulting from an SDR process based on TMAH (14µm Si removal/side). In addition, the epitaxial emitters on textured surfaces produce J_0 values even lower than those using boron diffusion (see Fig. 3).

The better performance of the epitaxial emitter can be attributed to the rounding of the pyramid tips as a result of differences in crystal orientation between the pyramid planes and the peaks and valleys. The pyramid planes have a (111) crystal orientation, while at the peaks and valleys the orientation may be (100) or (110). The {111} planes present the highest packing density, which causes a slower growth rate during silicon epitaxy than on the other planes. The consequence is a thicker emitter on the pyramid tips and, therefore, a rounding of that surface compared with the pyramid planes (see Fig. 2). In the scenario where very thick epitaxial layers are grown, these differences

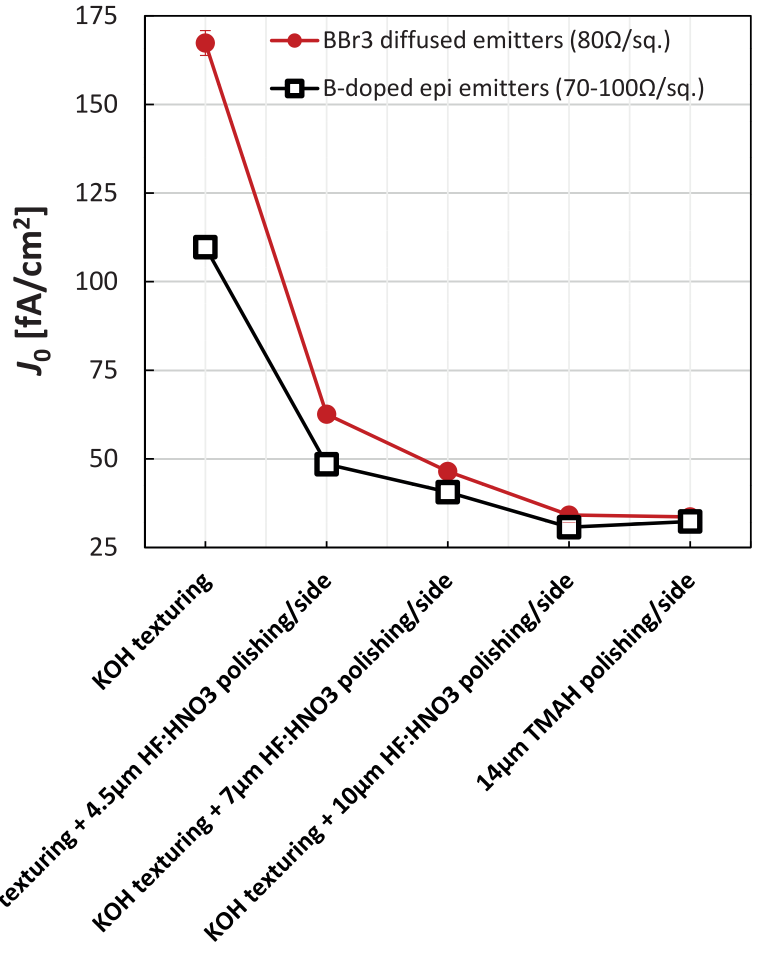


Figure 3. J_0 (extracted at $10^{16}cm^{-3}$) for boron-doped epitaxial emitters and BBr_3-diffused emitters passivated with wet oxide ($\rho_{n\text{-type}}$ = 3.1Ω·cm) as a function of the substrate surface morphology.

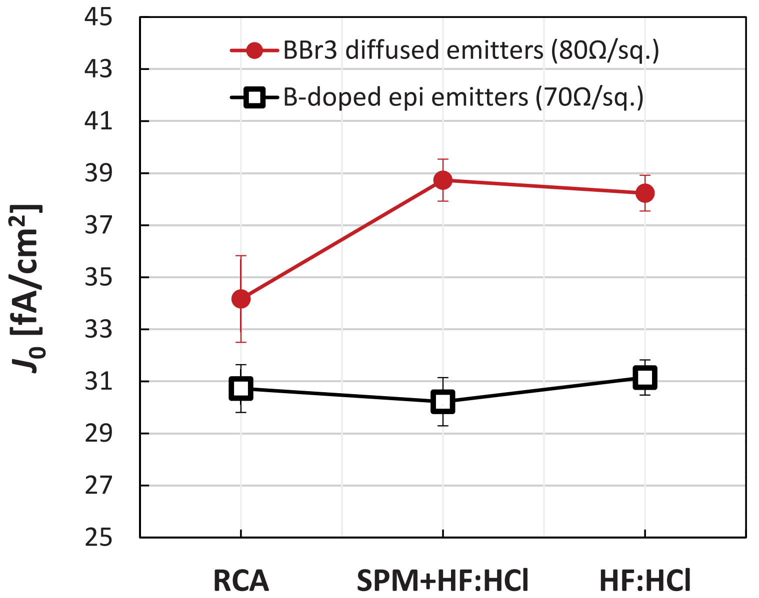


Figure 4. J_0 (extracted at $10^{16}cm^{-3}$) for boron-doped epitaxial emitters and BBr_3-diffused emitters passivated with wet oxide ($\rho_{n\text{-type}}$ = 3.1Ω·cm) as a function of the cleaning method prior to doping.

Cell Processing

could lead to a planarization of the original pyramidal surfaces.

Ex situ cleaning

As with diffusion, the growth of high-quality epitaxial emitters requires the removal of any particles and organic and metallic contamination from the silicon surface prior to the doping process. Wet chemical processes are normally used for the ex situ cleaning. A J_0 study [9] of the performance of the boron-doped epitaxial layers revealed that the technology is compatible with cleaning sequences suited to industrial implementation in PV, such as a simple HF:HCl sequence. J_0 values of around 30fA/cm^2 were measured (Fig. 4) for boron-doped epitaxial emitters (~70Ω/sq.) passivated with a thermally grown oxide, irrespective of the type of cleaning (RCA, SPM+HF:HCl and HF:HCl only) prior to the investigated doping process. The BBr_3 diffused emitter (~80Ω/sq.) also included in this investigation did not perform as well as the epitaxial emitter. In view of these results, 'new' cleaning chemistries – such as those based on the use of ozone as the main oxidizer – have also been successfully implemented and adopted as the reference process. With this line of approach, equivalent J_0 values have been measured when SOM (H_2SO_4:O_3 mixture) is used instead of SPM (H_2SO_4:H_2O_2 mixture).

Dielectrics and selective epitaxy

The selective deposition of silicon on Cz solar silicon wafers can be realized using a 'mask' consisting of a dielectric, or a stack of dielectrics which are of interest in PV applications: chemical vapour deposition (CVD) SiO_x/SiO_xN_y/SiN_x, atomic layer deposition (ALD) Al_2O_3, phosphosilicate glass (PSG), borosilicate glass (BSG) or thermal SiO_2. The patterning of those dielectrics prior to selective epitaxy can be performed using laser etching as well as wet or dry etching processes (see Fig. 1) [9]. Selective epitaxy provides an elegant approach to obtaining locally doped features or single-side doping, since those layers used as a 'mask' to guarantee selective growth can be retained after epitaxy for optical and passivation purposes.

> "Selective epitaxy provides an elegant approach to obtaining locally doped features or single-side doping."

Dielectrics such as plasma-enhanced chemical vapour deposition (PECVD) SiO_x exhibit excellent passivating properties directly after emitter formation by selective epitaxy (Table 1); this results from a post-deposition annealing of the dielectric layer taking place during emitter formation by selective epitaxy. This annealing increases the structural order of

After PECVD SiO_x deposition		T epitaxy [°C]	After epitaxy	
τ_{eff} [μs]	J_0 [fA/cm^2]		τ_{eff} [μs]	J_0 [fA/cm^2]
~10	–	850	1360	9.3
		950	1750	11.6

Table 1. Effective lifetime τ_{eff} (at 10^{15}cm^{-3}) and dark-saturation current density J_0 (at 10^{16}cm^{-3}) for a symmetric structure: PECVD SiO_x (19nm)/n-type diffused region (310Ω/sq.)/n-type Cz wafer (KOH-texturing, 3.9Ω·cm)/n-type diffused region (310Ω/sq.)/PECVD SiO_x (19nm).

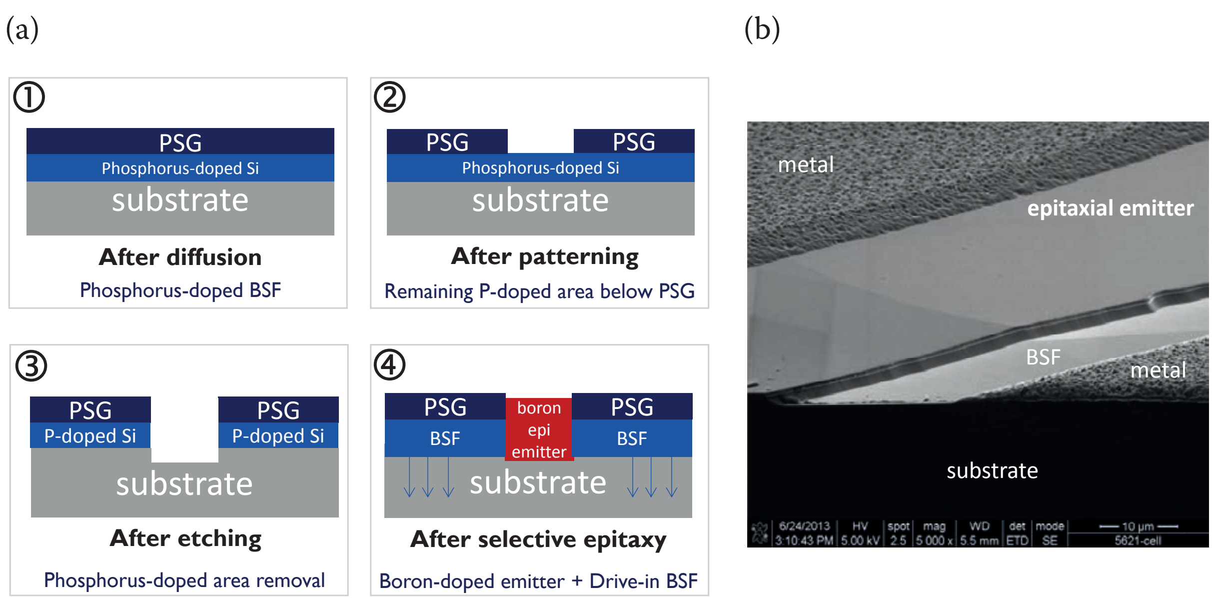


Figure 5. (a) Schematics of the approach used to form the interdigitated junction in an IBC cell using boron-doped selective epitaxy to PSG. (b) SEM image of the final layout of the interdigitated junction in an IBC cell created using this approach.

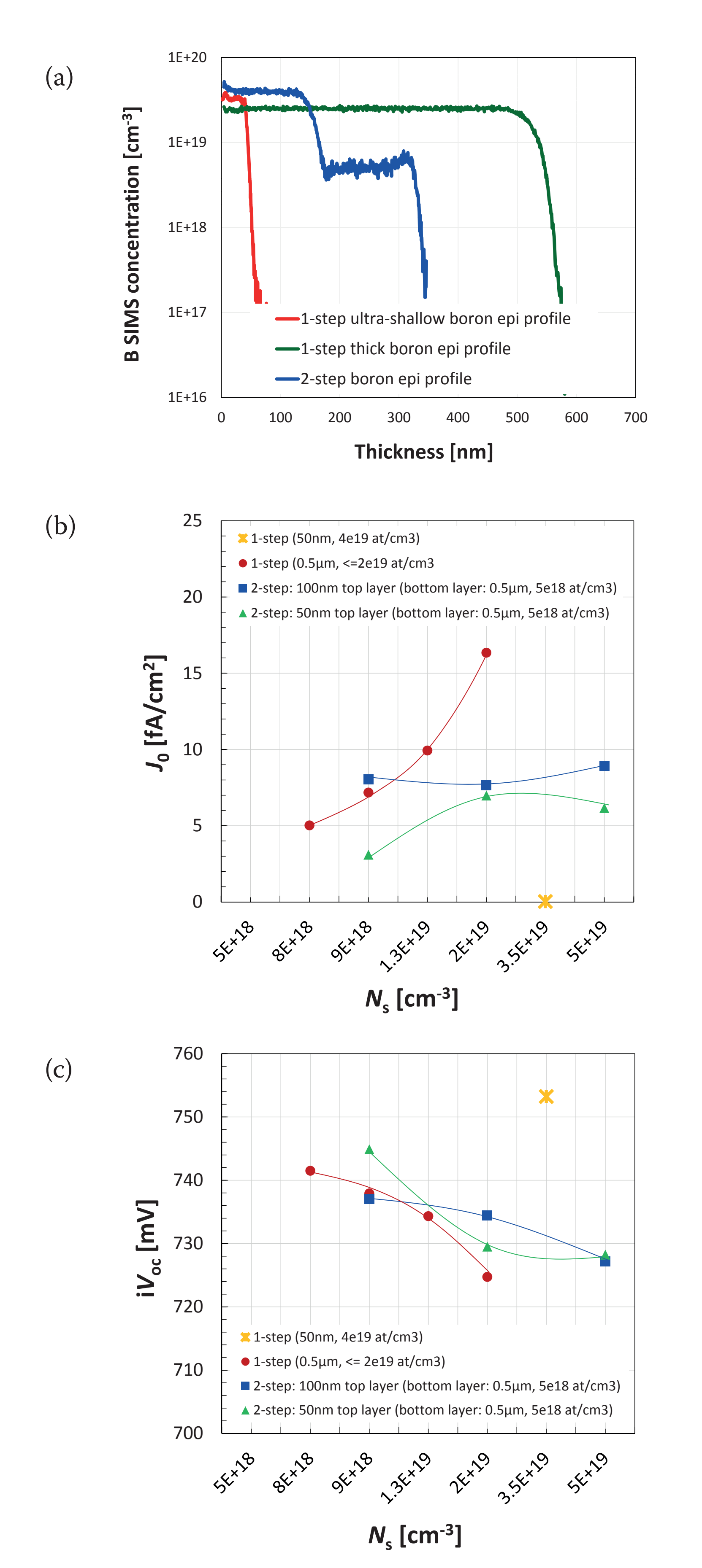


Figure 6. (a) Examples of one-step and two-step boron-doped epitaxial profiles. (b) $J_{0,pass}$ (extracted at $10^{16}cm^{-3}$) for boron-doped epitaxial profiles. (c) iV_{oc} for boron-doped epitaxial profiles.

the dielectric layer and therefore its quality, as observed by IR spectroscopy [10–11] and lifetime measurements by PL-QSSPC (Table 1).

During selective epitaxy, doped dielectrics can be used as a 'mask' too. The advantage here is that the thermal budget associated with the epitaxial process can drive the dopant source into the silicon regions 'masked' by the doped dielectric, while the growth of an epitaxial layer takes place simultaneously in the areas 'free' of dielectric [6]. A specific case of this application has been developed to create the interdigitated rear junction of an IBC cell [9]. Here, a short, low-temperature $POCl_3$ diffusion was carried out to create an approximately 20nm-thick PSG layer, which, after patterning, was used as a 'mask' for the selective growth of the boron-doped epitaxial emitter in the areas 'free' of PSG. While the emitter growth is taking place, a further phosphorus drive-in from the PSG creates the final back-surface field (BSF) profile, with the interdigitated junction of these IBC cells being formed after the selective epitaxial step (Fig. 5).

Advanced doping profiles

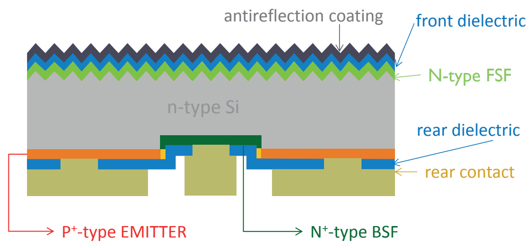
The doping flexibility of epitaxy in a single process step brings the possibility of creating doped regions with a wide variety of uniform box-type profiles by changing the gas flows, modifying the precursors, or adapting the deposition time, temperature and pressure. Ultra-shallow (≤100nm) and thick (≥500nm) one-step as well as two-step boron-doped profiles, passivated with the stack ALD Al_2O_3 (10nm)/PECVD SiO_x (120nm), and with a sufficient surface concentration (N_s) for good ohmic contact with sputtered AlSi 1%, have demonstrated high performance in terms of recombination losses (Fig. 6) [11]. Several one-step and two-step profiles of around 500nm have provided J_0 values and implied V_{oc} values at 1 Sun (iV_{oc}) in the range 4–10fA/cm² and 725–745mV respectively [11]. Values of J_0 < 1fA/cm² and iV_{oc} = 754mV have also been measured for an ultra-shallow and very heavily doped layer (50nm, $4 \cdot 10^{19}cm^{-3}$), where the field-effect passivation is the dominant mechanism [12].

N-type cells with a boron-doped epitaxial emitter

IBC cells

In a first approach, represented in Fig. 7(c) as 'Route A', selective epitaxy was implemented to create

(a)



(b)

IBC flow with BBr_3 diffused emitter
REFERENCE

1. Saw damage removal
2. p⁺ emitter formation (BBr_3 diffusion)
3. Wet oxidation
4. Patterning/Emitter etch
5. n⁺ BSF formation (diffusion)
6. Dry oxidation
7. Texturing
8. FSF formation (diffusion)
9. Dry oxidation
10. Anti-reflection coating
11. Metallization

(c)

IBC flow with B-epitaxial emitter
ROUTE A

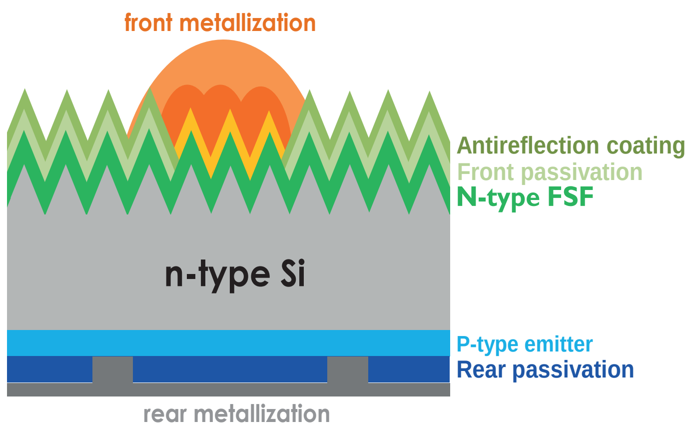
1. Saw damage removal
2. n⁺ BSF formation (diffusion)
3. Patterning/BSF etch
4. p⁺ emitter formation (epi)
5. Wet oxidation
6. Texturing
7. FSF formation (diffusion)
8. Dry oxidation
9. Anti-reflection coating
10. Metallization

Figure 7. (a) Schematic of an IBC cell. (b) Reference IBC flow with a BBr_3-diffused emitter. (c) IBC flow ('Route A') with a boron-doped emitter grown by selective epitaxy to PSG.

		J_{sc} [mA/cm²]	V_{oc} [mV]	*FF* [%]	*η* [%]
Diffused baseline flow (reference)	Average	41.5 ± 0.3	684 ± 3	80.3 ± 0.5	22.8 ± 0.4
	Best	41.7	686	80.7	23.1
Flow with epi emitter ('Route A')	Average	41.8 ± 0.1	684 ± 1	79.1 ± 0.6	22.6 ± 0.2
	Best	41.9	686	79.5	22.8

Table 2. Light *I–V* results for IBC cells (4cm²) fabricated using the reference flow (Fig. 7(b)) and 'Route A' with an epitaxial emitter (Fig. 7(c)).

(a)



(b)

N-type PERT flow with an epitaxial emitter

1. KOH texturing
(2. Rear-side polishing)
3. $POCl_3$ diffusion - *FSF*
4. Rear PSG + FSF removal
5. PECVD SiO_x front
6. Boron selective epitaxy - *emitter*
7. PECVD SiN_x ARC front
8. ALD Al_2O_3 rear
9. PECVD SiO_x rear
10. Laser ablation rear
11. AlSi 1% rear metallization
10. Laser doping (or laser ablation) front
11. $NiSi_x$/Cu front metallization

Figure 8. (a) Schematic of an n-type PERT cell. (b) N-type PERT flow with an epitaxial emitter.

Epitaxial emitter		J_{sc} [mA/cm²]	V_{oc} [mV]	*FF* [%]	*η* [%]
@ 850°C, 500nm, $9{\cdot}10^{18}$cm^{-3}	Average	39.7 ± 0.1	685 ± 1.6	78.9 ± 0.8	21.5 ± 0.3
	Best	39.7	687	80.1	21.9

Table 3. Light *I–V* results for the n-type PERT cells (238.9cm²) fabricated using the flow in Fig. 8(b) with an epitaxial emitter grown on a flat rear surface. Front side: shallow (280nm) diffused FSF below the dielectric, and deep (~2μm) laser-doped region below the metal contact.

		J_{sc} [mA/cm²]	V_{oc} [mV]	*FF* [%]	*η* [%]
Rear flat	Average	39.2 ± 0.1	664 ± 1	79.8 ± 0.2	20.8 ± 0.1
	Best	39.1	666	80.1	20.9
Rear textured	Average	39.3 ± 0.1	660 ± 0	79.3 ± 0.4	20.6 ± 0.2
	Best	39.5	661	79.9	20.8

Table 4. Light *I–V* results for the n-type PERT cells (238.9cm²) fabricated using the flow in Fig. 8(b) with an epitaxial emitter (500nm, $2{\cdot}10^{19}$cm^{-3}) grown on flat and textured surfaces. Front side: non-optimized, homogeneous diffused FSF (400nm) below the dielectric and the metal contact (contact patterning by laser ablation).

the interdigitated junction of n-type IBC cells (Fig. 7(a)) using the PSG formed during the $POCl_3$ diffusion of the BSF as a 'mask' in the selective deposition of the emitter (Fig. 5) [9]. This route, with an epitaxial emitter, directly simplifies the fully diffused reference flow (Fig. 7(b)) by enabling a 40% reduction in the total diffusion and oxidation processing time as well as by omitting some cleaning steps. The main *I–V* results of the first 4cm² IBC cells manufactured on 156cm² Cz silicon solar wafers are summarized in Table 2. The results confirm best cell efficiencies of up to 22.8% for the IBC flow with a selective epitaxial emitter; this value is close to the efficiency of 23.1% for the more complex reference flow with a diffused emitter.

> "The results confirm best cell efficiencies of up to 22.8% for the IBC flow with a selective epitaxial emitter."

The high potential of selective epitaxy to simplify the IBC flow while keeping a high-efficiency performance opens up new possibilities for redefining a simpler fabrication sequence for this type of device and, hence, for reducing the cell CoO [13].

PERT cells

The route for fabricating n-type PERT cells with a boron-doped epitaxial emitter (Fig. 8) relies on single-side processing for the rear-emitter formation by selective epitaxy, and on the dielectric deposition of a PECVD SiO_x/SiN_x stack on the front side and an ALD Al_2O_3/PECVD SiO_x stack on the rear. This approach allows a single-side rear emitter, as selectivity is ensured by the presence of the PECVD SiO_x on the front side. After emitter formation, the PECVD SiO_x can be used as an excellent passivating layer of the n-type front-surface field (FSF) of these devices (see Table 1) [4,11,14].

The *I–V* results for the first n-type PERT cells fabricated using a half-micron-thick epitaxial emitter and a laser-doped front-side metallization scheme are summarized in Table 3. Best cell efficiencies of up to 21.9% (238.9cm²) were measured for an emitter with a uniform doping of $9{\cdot}10^{18}$cm^{-3}.

Although the main focus has been the proof of concept for an n-type PERT solar cell with a flat rear side, epitaxy can also be applied to textured surfaces [4]. The fabrication of n-type PERT solar cells with both flat and textured rear sides, a non-optimized homogeneous diffused FSF and a laser-ablated front metallization scheme [14] confirms the high potential of the approach with an epitaxial emitter on textured surfaces. Both flat and textured surfaces yield comparable cell efficiencies – for the latter, they are 0.1–0.2% abs. lower (Table 4). This difference is due mainly to a drop in V_{oc} of around 5mV. In-house cell CoO calculations confirm that the slightly higher efficiency for a flat rear surface does not offset the reduction in CoO resulting from the omission of the rear-side polishing.

Epitaxial reactor

The growth of the epitaxial layers in this work was accomplished in a single-wafer batch reactor, which, although sufficient for R&D purposes, is not a satisfactory solution for a production line. Actually, the tool concept which would deliver the required industrial throughput for the growth of thin epitaxial layers for PV applications is a *tubular hot-wall reactor* [15–17], for which there are designs capable of realizing the loading of 1200 solar wafers per process chamber [18]. With these systems the CVD process is normally performed at a reduced pressure and at a temperature ranging between 400 and 900°C. In these conditions, the operation is in the kinetically limited regime, where the growth rate is exponentially dependent upon the temperature, which is very accurately controlled.

At the reduced pressure, the gas diffusivity is significantly increased compared with the values at atmospheric pressure. The net effect is a greater than one order of magnitude increase in the gas-phase transfer of reactants to, and by-products from, the substrate surface. Systems operating at reduced pressure can therefore benefit from the following aspects: 1) surface kinetic control is readily achieved; 2) wafers can be vertically stacked and packed very close together; 3) little or no carrier gas is required; 4) epitaxially grown layers feature a better step coverage, conformality and a lower defect density; and 5) deposits on the hot-wall reactors adhere very well and tend not to flake off.

In theory, there are no differences in process and performance between horizontal and vertical hot-wall reactors. Nevertheless, experience has proved the superiority of the vertical design because of practical reasons, such as its more compact layout; therefore the technological improvements have been historically first designed for, and implemented in, vertical furnaces.

With respect to the CoO for the tool, not enough experience has so far been gained in PV to have clear figures for a system dedicated to growing thin epitaxial layers (≤1µm) for bulk crystalline silicon solar cells. Epitaxy is not a technology currently employed in the PV industry, and most of the existing knowledge has been acquired from microelectronics.

The CoO calculations for an epitaxial reactor will depend on the specific tool design, the process conditions (including deposition temperature), the precursors and the carrier gas. All these variables will also determine the final load per batch as well as the growth rate. Compared with a BBr_3 diffusion process, for which the CoO is typically in the range €0.05–0.07/wafer, the CoO for a furnace dedicated to the growth of boron-doped thin epitaxial layers could be in the range €0.08–0.13/wafer. The difference arises mainly from a larger investment cost (CAPEX) for an epitaxial furnace.

The data used in the CoO calculations for an epitaxial furnace have their main origin in a microelectronics setting, where the specifications are more stringent than in PV, because of the need to work in a cleanroom environment and the micro- and nanoscale dimension of the devices in this field. A reduction in the investment costs for a system dedicated to PV could therefore be envisaged, as this system could be designed in more relaxed terms than one for microelectronics. Furthermore, it should also be taken into account that with epitaxy there is no need for subsequent steps, such as BSG removal or the usual boron drive-in, which engender a reduction in the cell CoO. In general, once the first tool exists, and taking into consideration the learning curve, a tendency towards lower figures should be expected for the CoO of an epitaxial PV furnace. Experience should bring down the costs, as long as the process becomes as mature and developed as the well-established diffusion process.

Conclusions

This paper has presented an overview of the application of silicon epitaxy as a doping technology in bulk crystalline silicon solar cells. A general picture was first given of the process conditions for the growth of epitaxial layers on the typical flat and textured surfaces used in solar cells fabrication, as well as of the cleaning before epitaxy. This was followed by a description of the advantages in terms of performance and simplifications associated with the large degree of flexibility in designing a broad range of doping profiles, and with the use of selective epitaxy to create locally doped regions.

> "Epitaxy technology is a powerful alternative to classical diffusion for creating the doped regions of bulk crystalline silicon solar cells."

Finally, the proof of concept at cell level was demonstrated by the growth of boron-doped epitaxial emitters in n-type IBC and PERT solar cells: 22.8% efficiency for IBC ($4cm^2$) and 21.9% for PERT ($238.9cm^2$) solar cells with a 0.5µm boron-doped epitaxial emitter have been achieved. These results prove that epitaxy technology is a powerful alternative to classical diffusion for creating the doped regions of bulk crystalline silicon solar cells.

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About the Authors

María Recamán Payo received her degree in chemical engineering from the University of Santiago de Compostela in 2002, followed by her Ph.D. from the Complutense University of Madrid in 2008. She then joined imec, where she is currently working as a senior scientist on the application of silicon CVD processes in bulk crystalline silicon solar cells.

Izabela Kuzma-Filipek has been working as a senior scientist in the silicon photovoltaics group at imec since 2009. She received her master's in materials science and ceramics from the AGH Cracow, Poland, in 2004, followed by her Ph.D. in 2010 from KU Leuven, Belgium. Her current focus is on integration processes for n-type PERx silicon solar cells with conventional and epitaxial emitters.

Filip Duerinckx leads the iPERx platform in the silicon photovoltaics group at imec. He received his Master of Science in engineering in 1994 from KU Leuven, Belgium, followed by his Ph.D. in 1999. He currently focuses on the performance and economical aspects of n-type PERx silicon solar cells.

Yuandong Li received a master's in electronics engineering in 2013 from Zhejiang University, Hangzhou, China. Since 2013 he has been at KU Leuven and imec in Belgium, working towards his Ph.D., with a focus on high-efficiency silicon wafer solar cells using selective epitaxial doping technology.

Emanuele Cornagliotti received his M.Sc. in 2006 from the Polytechnic University of Turin, Italy, and his Ph.D. in 2011 in electrical and electronic engineering from KU Leuven, Belgium. Since 2007 he has been working as a researcher at imec, where he is involved with the development of industrial silicon solar cells, with a focus on process integration.

Angel Uruena is a silicon PV research scientist at imec, where he focuses on the development of n-type solar cells. He obtained a B.Sc. in telecommunications and an M.Sc. in electronics in 2004 and 2007 respectively, from the University of Valladolid. He received his Ph.D. in electrical engineering from KU Leuven in 2013.

Loic Tous received an M.Sc. (Eng.) in material science and engineering from INSA Lyon, France, in 2009, and a Ph.D. in electrical engineering from KU Leuven, Belgium, in 2014. Since 2014 he has been a PV researcher at imec, working on nickel/copper plated contacts.

Richard Russell received a bachelor's in physics from the University of Exeter, England, and a master's degree in physics from the University of Dundee, Scotland. Between 1990 and 2010 he worked for BP Solar, mainly on Ni/Cu-metallized laser-grooved buried contact cells. He joined imec in 2011, where he leads copper-based metallization activities within the iPERx platform.

Ali Hajjiah graduated with a B.Sc. in electrical engineering from Oklahoma State University, USA, in 1998, and subsequently earned M.Sc. and Ph.D. degrees, in 2003 and 2009 respectively, from Virginia Tech, USA. His research interests lie in III-V semiconductor lasers and solar cells. He is currently an assistant professor in the electrical engineering department at Kuwait University.

Maarten Debucquoy received a Master of Science in engineering from KU Leuven, Belgium, in 2003. Following a postgraduate study in business economics in 2004, he received his Ph.D. in 2009. He then joined the photovoltaics department at imec, where he has led the activities concerning IBC silicon solar cells since 2013.

Jozef Szlufcik received his M.Sc. and Ph.D. degrees, both in electronic engineering, from the Wroclaw University of Technology, Poland. In 1990 he joined imec, where he led research activities in low-cost crystalline silicon solar cells. From 2003 to 2012 he held the position of R&D and technology manager at Photovoltech, Belgium, and is currently the director of the photovoltaics department at imec.

Jozef Poortmans received his degree in electronic engineering from KU Leuven, Belgium, in 1985, and his Ph.D., with a focus on strained SiGe layers, in June 1993. He is currently the scientific director of PV activities at imec and a member of the steering committee of the EU PV Technology Platform. Since 2008 he has been a part-time professor at KU Leuven, and in 2013 became an imec Fellow and part-time professor at the University of Hasselt.

Enquiries

Maria Recamán Payo
imec
Kapeldreef 75
B-3001 Leuven
Belgium

Tel: +32 1628 1478
Email: Maria.RecamanPayo@imec.be

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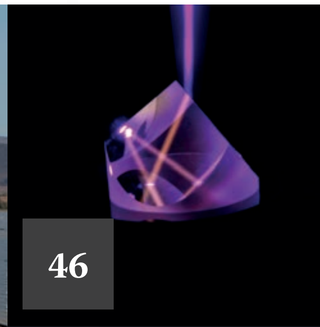
Routes to increasing efficiency and reducing the cost of thin-film solar panels

Joop van Deelen[1], Niels van Loon[1], Marco Barink[1], Marieke Burghoorn[1], Zeger Vroon[1,2] & Pascal Buskens[1,3]

[1]TNO, Eindhoven, The Netherlands; [2]Zuyd Hogeschool, Heerlen, The Netherlands; [3]DWI – Leibniz Institute for Interactive Materials, Aachen, Germany



News

Solar Frontier targets India with 100MW Welspun Renewables supply deal

Source: Welspun Renewables

Solar Frontier is to supply 100MW of its modules to Indian firm Welspun Renewables.

Vertically integrated Japanese thin-film manufacturer Solar Frontier has entered into a 100MW supply deal with India-based renewable energy project developer Welspun Renewables.

Welspun Renewables is expected to use the modules in projects planned to be constructed as part of its overall pipeline totalling around 1GW in 2015.

"Solar energy is a priority sector for meeting India's high demand for clean, renewable and economical energy," Welspun Renewables' director, Sindoor Mittal said. "The government of India has set a target of 175GW of renewable energy by 2022, of which 100GW will be solar energy. Agreement with Solar Frontier brings us one step closer to meeting our green energy commitment. Welspun Renewables is committed to achieving high level quality benchmarks at all of its project sites, and because of this we prefer to work with tier-one technology providers."

Efficiency record race

Manz unveils record-breaking CIGS module

Hi-tech equipment manufacturer Manz has set a new efficiency record for a CIGS thin-film module of 16%, verified by testing house TÜV Rheinland.

Made on Manz's mass production line in Germany, the module incorporates a CIGS cell produced by the company's development partner, the Centre for Solar Energy and Hydrogen Research (ZSW) in Stuttgart, which achieved a 21.7% efficiency record last September.

Manz said the record was achieved by transferring the insights garnered from the ZSW team that developed the record-breaking cell last year into mass production. Other innovations include a new module design to increase the active module surface and measures to reduce optical losses.

Thin-film competition hots up as TSMC Solar breaks day-old CIGS efficiency record

The announcement of a 16% efficiency record for a CIGS module by Manz was trumped just a day later by TSMC Solar, which has reached 16.5% efficiency for commercial-size CIGS modules.

TSMC Solar, a subsidiary of Taiwanese Semiconductor Manufacturing said that the total area efficiency of its 1.09sq metre CIGS (copper indium gallium selenide) modules has been verified by testing house TUV SUD.

Produced at TSMC Solar's manufacturing facilities in Taichung, Taiwan, and supplied with TSMC's own materials, the company's C2 module is claimed to offer an improvement on its previous efficiency record of 15.7%, set in the summer of 2013.

Business news

'Hanergy to Hanergy' sales still dominate

Hanergy Thin Film Power (Hanergy TF) remained highly dependent on parent company Hanergy Holding Group for revenue in 2014, gaining revenue for the sales of a small number of PV plants and limited revenue from thin-film sales to IKEA that were outside group transactions.

Hanergy TF reported total revenue of HK$9,615,028 (US$1.23 billion) in 2014, an increase of 193%, compared to 2013. Gross profit increased 109% to around HK$ 5,504,648 (US$709 million) but gross margin declined from 69% in 2013 to 24.6% at the end of 2014.

However, 62% (US$768 million) of 2014 revenue was from selling a-Si thin-film equipment and production plants to parent, Hanergy Holding Group.

LPKF saw strong solar industry sales in 2014.

Ascent Solar's losses outweigh revenue for 2014

Flexible CIGS thin-film producer Ascent Solar Technologies reported 2014 annual revenue of US$5.33 million on net losses of US$43.3 million.

Ascent Solar's product sales, which target consumer, commercial and military applications in primarily portable energy applications topped US$5.0 million in 2014, supported by US Government R&D projects worth US$323,123. Revenue increased by 308% from the previous year, while R&D project revenue increased by US$124,000 from the prior year.

A key part of Ascent Solar's losses were attributed to research, development and manufacturing operation costs, which totalled U$24.5 million in 2014, compared to US$21.3 million in 2013. Loss from operations increased from US$28.2 million in 2013 to US$33.9 million in 2014, due to an increase in advertising, marketing and promotional expenses, according to the company.

LPKF bucks capex trend with higher solar equipment sales in 2014

Laser equipment specialist LPKF reported strong sales to the solar industry in 2014, despite limited capital spending in the sector.

LPKF said its Other Production Equipment segment, which houses subsidiary LPKF SolarQuipment, which is focused on thin-film module laser scribing technology and tools, experienced a 31% increase in revenue and a 48% increase in profits in 2014.

However, despite the rebound in thin-film laser scribing tools after several years of very low sales to the sector, LPKF reported total group revenue of €120 million (US$134 million), down 8% year on year.

LPKF expects to achieve revenue in the range of €128 million to €136 million in 2015. The company also noted that scriber systems for thin-film solar cells grew by no less than 96.9% in 2014.

Downstream moves

Solar Frontier completes 280MW Gestamp US project buyout

At the end of April, Japanese firm Solar Frontier completed its acquisition of the US project pipeline of developer Gestamp Solar.

Under the deal, Solar Frontier will acquire 10 projects totalling 280MW in the US, primarily in California. First announced earlier this year, the Gestamp deal was billed as Solar Frontier's first significant downstream move outside of its stronghold in Japan, where it has built projects as well as supplying its brand of CIS thin-film modules.

Construction work has already begun on the first of the 10 projects, a 15MW plant in Kern County, California. Discussions are also ongoing with investors about the sale of other projects in the pipeline.

First Solar secures hat-trick of Turkish projects

In early March, US thin-film specialist, First Solar landed interconnection rights for three utility-scale solar PV plants in southern Turkey within the country's latest bidding round.

First Solar was issued with the rights by Turkey's electricity transmission company TEIAŞ under the country's Renewable Energy Resources Support Mechanism (YEKDEM) programme, which ran its second and third round of tenders in late January.

Subject to the company receiving regulatory approval, First Solar will construct plants in the Turkish provinces of Muğla, Burdur, and Urfa with a combined capacity of 19MW AC.

First Solar expects the plants to produce an estimated 31.5 million kWh of electricity per year, enough to power some 14,000 average homes in the country, according to the company.

New directions

Pilot project in Singapore to test Heliatek's BIOPV product

OPV thin-film firm Heliatek is supplying its 'HeliaFilm' substrate to a building integrated organic photovoltaic (BIOPV) project in Singapore that will evaluate its performance and durability in hot and humid climates.


Source: First Solar

First Solar has won connection rights for three projects in Turkey.

Heliatek's regional partner, vTrium Energy, will be implementing the test project, which is being supported by Jurong Town Corporation (JTC, Singapore) and SPRING (Standards, Productivity and Innovation Board, Singapore) as part of a programme to create a base for the future energy mix for Singapore.

The project implementation is expected to start in May and run for at least 18 months.

Hanergy opens thin-film retail stores in China

Hanergy has opened 60 stores and "user-experience centres" in its homeland, China.

The stores are in regions including Shanghai and Guangzhou, with a flagship outlet in Chengdu.

Hanergy has also launched a new online store and a portal on the shopping site Alibaba. It is thought the shops will be used to market Hanergy's residential rooftop PV solutions although the company sells a number of other consumer products including portable arrays for the camping and outdoor leisure markets.

Residential systems will be sold with an initial three-year manufacturer's warranty through the stores.

Oxford PV secures US$12 million for perovskite commercialization

UK-based thin-film start-up Oxford Photovoltaics has secured at least a further £8 million (US$12.1 million) in venture capital funding to further plans to commercialize its blend of perovskite materials under a licensing model.

Oxford PV said the funding was the first of tranche B financing that included existing investors, University of Oxford, MTI Partners, Longwall Venture Partners and Parkwalk Advisors, as well as unidentified angel investors.

The company said last year that it had shifted some of its emphasis to providing conventional crystalline silicon solar cell producers with opportunities to collaborate on integrating a perovskite tandem layer to fast-track commercialization.

Manufacturing

Hanergy TF building 10MW R&D and pilot line for Alta Devices GaAs solar cells

Hanergy Thin Film Power Group is to build a 10MW gallium arsenide (GaAs) thin-film solar cell R&D and manufacturing plant using recently acquired US start-up Alta Devices' technology.

Huangpi District People's Government in Wuhan City has entered into an investment cooperation agreement to facilitate the new operation. According to Hanergy TF the first phase of the plant would include a 3MW production line.

The new facility in Huangpi Linkong Industrial Park, Whan City is expected to be completed in the next 10 months, while tool install is expected in 12 months. Equipment and manufacturing line testing ahead of initial ramp of production is expected to start by October 2016.

Solar Frontier begins ramp of new 150MW CIS thin-film module plant

At the end of March, Japan-based CIS thin-film module manufacturer Solar Frontier completed the construction of its Tohoku Plant as expected, saying it plans to start ramping production immediately.

The 150MW plant is also the test bed for ramping production-ready cell efficiency gains, previously developed at its Atsugi Research Center, creating modules with conversion efficiencies of 15% and higher.

The new plant pushes Solar Frontier's volume production nameplate capacity to over 1GW, having its main Kunitomi Plant with capacity of 900MW in southern Japan.

Routes to increasing efficiency and reducing the cost of thin-film solar panels

Joop van Deelen[1], Niels van Loon[1], Marco Barink[1], Marieke Burghoorn[1], Zeger Vroon[1,2] & Pascal Buskens[1,3]

[1]TNO, Eindhoven, The Netherlands; [2]Zuyd Hogeschool, Heerlen, The Netherlands; [3]DWI – Leibniz Institute for Interactive Materials, Aachen, Germany

ABSTRACT

Most development work in the laboratory is dedicated to efficiency enhancements at the cell level; improvements in efficiency can lead to higher cost-competitiveness of PV. However, the cost of panel manufacturing is an important aspect as well. For CIGS panels the deposition of the active layer is an important part of the cost, and decreasing the layer thickness can reduce costs. Moreover, cost of ownership calculations can determine how much benefit can be expected from thinner absorber layers from a cost perspective; clearly, a thinner absorber will result in reduced absorption. To avoid losses, modelling can be used to predict the efficiency and viable light management strategies. Other efficiency-enhancing technology is related to the fact that most thin-film solar panels are monolithically interconnected. The area loss involved in this type of interconnection, and the trade-off between conductivity and transmittance of the front contact, impose limits on the maximum efficiency. The impact of improving both of these aspects is demonstrated in this paper. A viable way to improve the front contact is by supplementing the front contact with a metallic pattern. The benefit and the impact of different configurations and dimensions of the cell and metallic pattern are presented.

Introduction

The pricing of PV panels is under tremendous pressure. Over the last two decades we have seen a decline in prices far exceeding any predictions; the lower prices have been accommodated by upscaling, cheaper processes and materials. Originally, thin-film solar technology yielded a lower efficiency than its high-end crystalline silicon counterparts. There has recently been a surge in record efficiencies at the laboratory level: an efficiency of 20% is now regarded as being achievable for different types of thin-film cells, with CIGS record efficiencies well above this figure. However, for CIGS in particular, there are numerous manufacturers that have gone bankrupt over the past few years, and the cost competitiveness of this technology needs to be looked into. A cost calculation can reveal the most important cost drivers and indicate which cost-cutting route is the most promising. In the past, indium has often been named as a cost driver, but detailed investigations show that the overall picture is more complex, as material cost is only a part of the total cost.

Because of the current low prices of PV panels, the panel cost contribution is often only half (or even less) of the total cost/kWh. The balance of system costs and maintenance costs have not seen such huge declines as those observed in the PV panel industry. The increase in the efficiency of a solar panel translates into a reduction in cost/Wp for the total system; therefore, the lower the share of the PV panel in the total cost/kWh, the more interesting it becomes to ramp up the efficiency. Major efforts at the laboratory cell level have been seen, along with their translation to industrial processes. Especially for CIGS, the manufacture of thin-film panels with a homogeneous composition and quality over the entire surface is challenging. Furthermore, improved in-coupling of the light is of interest, regardless of the PV technology.

Two other major areas in which innovation results in higher efficiency are better front contacts and reduced losses at the interconnections. Here too it is important to achieve a balance between optimum performance and minimum additional cost. Both cost calculations and innovations are presented, and the different routes to higher cost-competiveness are discussed.

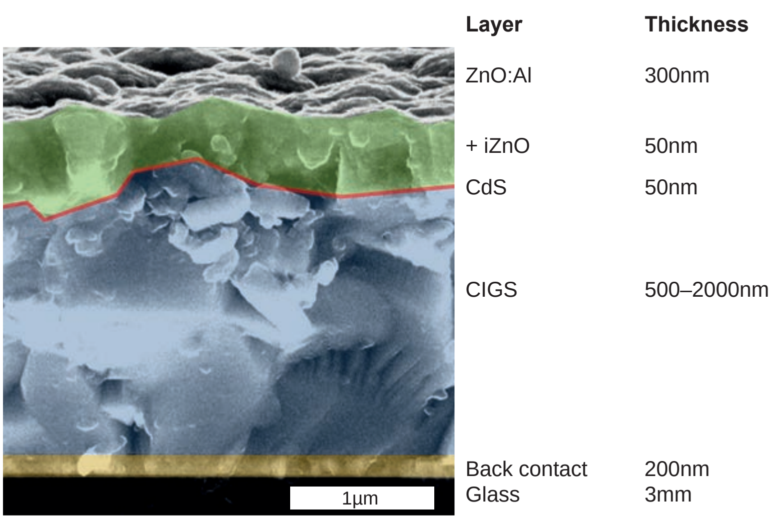


Figure 1. Scanning electron microscope (SEM) image of a CIGS cell stack.

Part I: Cost of CIGS panels

Cost breakdown and CIGS layer

The cost calculation is based on a CIGS material stack; a cross section of such a stack is shown in Fig. 1. The stack consists of sputtered Mo on top of glass, followed by a two-step CIGS deposition process (standard thickness of 2000nm), a chemical bath deposition for the CdS, and sputtered i-ZnO and ZnO:Al. The ZnO:Al is a transparent conductive oxide (TCO), which serves as a front contact [1] and as an interconnection in thin-film solar panels. In addition to the layers shown in the image, the cell is covered by an EVA layer and a top sheet of ultra-clear glass.

Figs. 2 and 3 show the breakdown of costs for a CIGS solar panel. In Fig. 2 it is seen that nearly half of the cost relates to materials, and around half of this is for glass and encapsulation material (see Fig. 3). The much-discussed price of indium is observed in the material cost, but represents only around 10% of this portion.

> "Because CIGS is the largest cost factor compared with the other layers, it can be considered an important cost driver."

In spite of the relatively low percentage contributed by indium to the total cost, the CIGS layer deposition represents about 32% of the total panel cost if a standard layer thickness of 2000nm is used. The related material cost is actually less than 25%. Because CIGS is the largest cost factor compared with the other layers, it can be considered an important cost driver. For this reason, it is interesting to investigate the impact of reducing the layer thickness on both the cost and the efficiency. The main question is whether a thinner CIGS layer will be effective as a cost-reduction strategy.

For this calculation, the layers surrounding the CIGS layer are kept constant. Furthermore, it is assumed that the equipment-related cost of the CIGS scale with the layer thickness to the power of 0.7. The total panel cost versus CIGS layer thickness is shown in Fig. 4. The cost of the total panel decreases if the CIGS layer becomes thinner: from the standard €59.39/m^2 for 2000nm CIGS, the cost falls 25%, to €44.10/m^2, for a very thin CIGS layer of 500nm. Such a significant drop justifies a more detailed investigation of the sensitivity of the overall price to changes in CIGS-related costs.

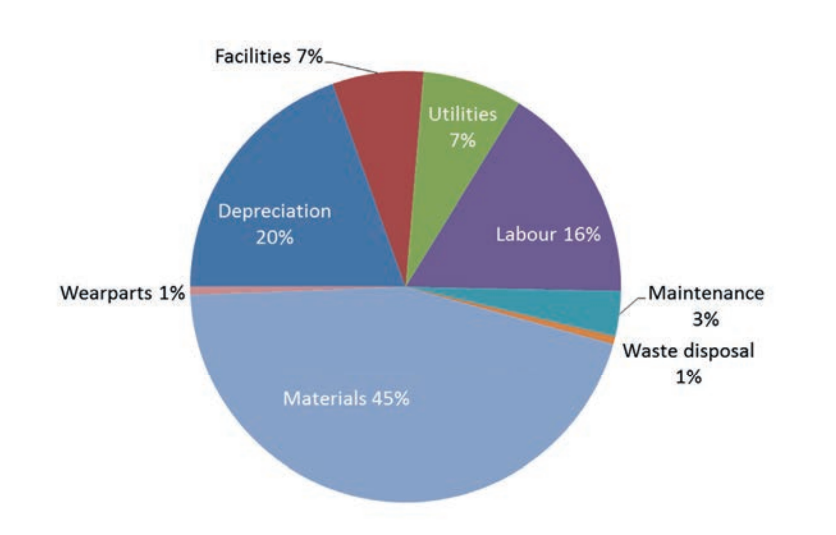


Figure 2. Cost structure of a CIGS panel with a CIGS layer thickness of 2000nm.

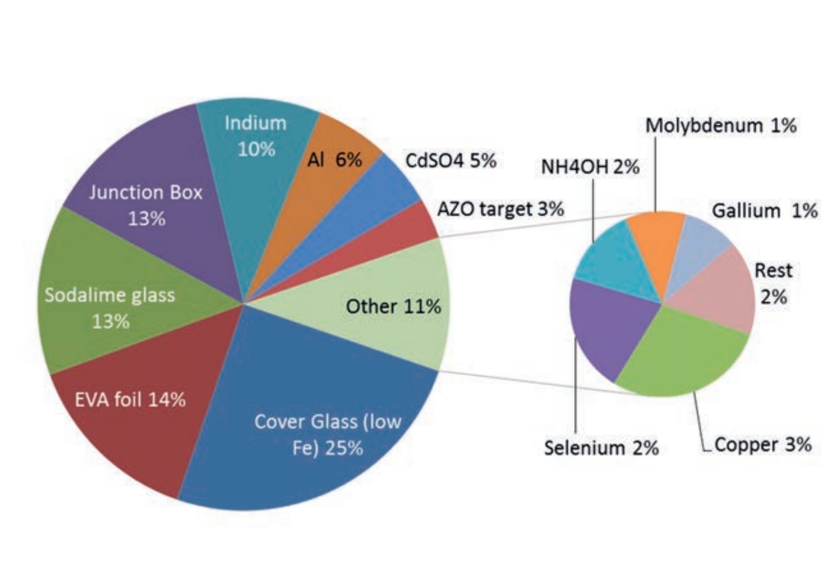


Figure 3. Breakdown of material costs for a CIGS solar panel.

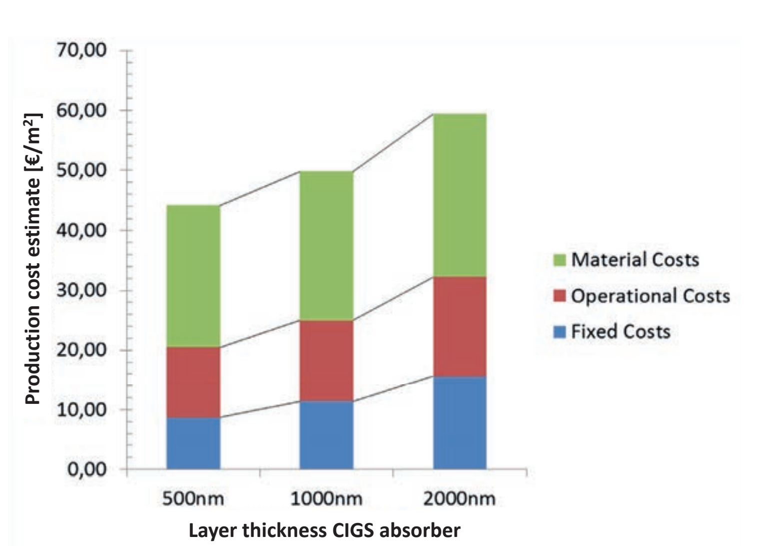


Figure 4. Cost breakdown of a CIGS panel with different CIGS layer thicknesses.

Thin Film

Price fluctuations of materials are often mentioned as a possible bottleneck in the case of CIGS. The impact of the material price on the total panel cost is deemed an important factor. For instance, copper zinc tin selenide (CZTS) cells are a topic of research because of the lower material prices. More specifically, indium prices have undergone dramatic rises and falls; in the past it has been suggested that this volatility might become an important bottleneck in view of potential shortages. To investigate this, the CIGS material price in the model for various CIGS layer thicknesses was changed, as shown in Fig. 5. In the case of standard 2000nm CIGS, a reduction in the materials price of CIGS elements to 10% of the current price will lead to a decrease in cost of about €4/m^2. If the prices of all the CIGS elements inflate to four times the current price, the cost will increase significantly. However, for thinner CIGS layers, the material cost component is much lower and has only a minor impact on the total production cost. Therefore, reduced layer thickness can result in the CIGS technology being less sensitive to material price fluctuations. It is also seen that the impact of a change in the layer thickness is much greater than a change in the material cost. This is because a change in layer thickness reduces both material and equipment costs, in contrast to the case where only the material cost is varied.

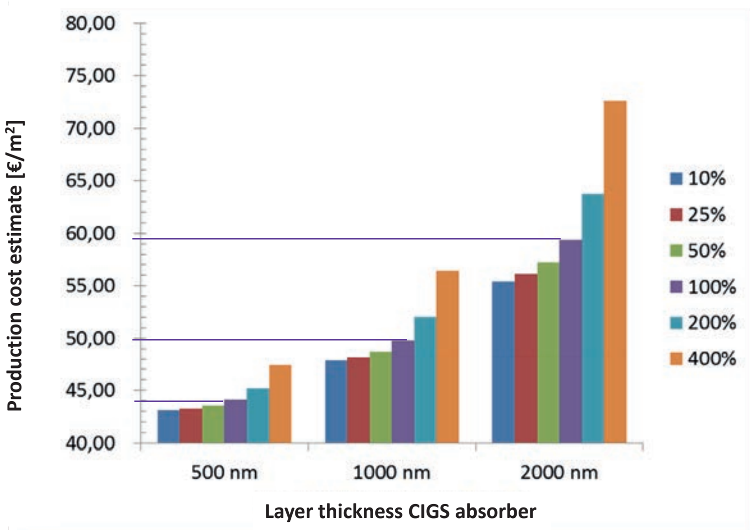


Figure 5. Panel cost as a function of CIGS material cost and layer thickness.

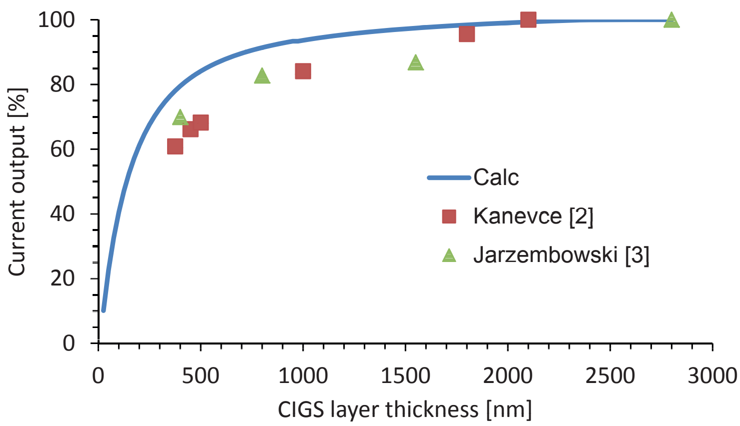


Figure 6. Cell current density as a function of CIGS layer thickness.

Decreasing the layer thickness comes with a penalty of reduced absorption, which translates to lower current density, resulting in decreased efficiency. Fig. 6 shows the current density as a function of the layer thickness, both by calculation and from the literature [2,3]. The impact of the layer thickness is most pronounced for very thin layers. A decrease in layer thickness from 2000nm to 1000nm has a relatively small effect on efficiency, but can be seen to have a significant effect on cost. Also noticeable is that the efficiency obtained from the experiments is lower than that predicted by the model; this can only in part be related to a lower fill factor or voltage. A thinner CIGS layer can also bring about an increased likelihood of recombination, an issue that is currently being investigated. In general, there will always be a trade-off between lower cost and lower output; however, if the lower output can be avoided, it will be a benefit for the thin-film CIGS case, and the potential of light management technology deserves a closer look.

It should be noted that the data in Fig. 6 are for flat CIGS layers. In other words, the light goes through the CIGS layer in a single pass, in a direction perpendicular to the surface; the path length is therefore equal to the layer thickness. This path length can be made longer by the use of light management technology; in the case of thin-film Si, it has been shown that light management technology can enhance the path length of the light in the solar cell dramatically and boost the current density by 25% [4].

Light management

When there is insufficient absorption by the active layer, light management strategies to elongate the path length of the light are an asset. The best method depends on the required path length elongation and on the wavelength range which needs to be elongated. Most light management technology has been aimed at enhancing the performance of thin-film Si. For CIGS, research is still ongoing and there is relatively little information about this topic. Usually, if the CIGS layers are too thin, the light losses are mostly in the wavelength range above 800nm.

> "When there is insufficient absorption by the active layer, light management strategies to elongate the path length of the light are an asset."

Fig. 7 shows an example of a texture that has been used for thin-film Si and is now being applied to CIGS in research. It has been shown that a CIGS cell using such a texture exhibits an increase in current density. However, the texture influences not only the path length of the light, but also the crystal formation, the total surface (and interface) area, and so on. Therefore, for the moment, it is too early to make a statement on the exact optical benefits of the texture for the efficiency. Obviously, such technology would not be without cost: it is estimated that the additional expense would be in the range of €1–2/m^2. This light management technology is designed to compensate for the losses induced by the thinner absorber layer. Actually, it aims to enhance the efficiency compared with a flat design.

There are various ways to enhance the efficiency of thin-film solar cells, regardless of CIGS thickness; Part II of this paper discusses a number of technologies and demonstrates their value for thin-film PV, more specifically CIGS.

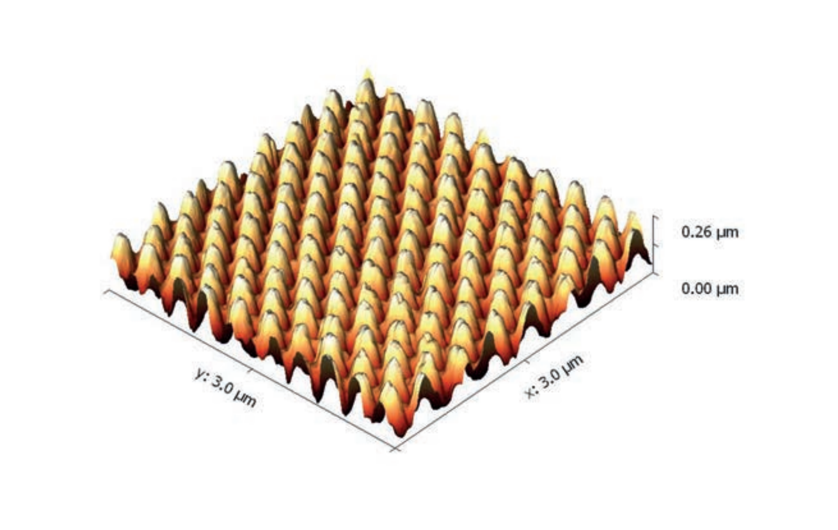


Figure 7. An example of a texture that might compensate for current density loss.

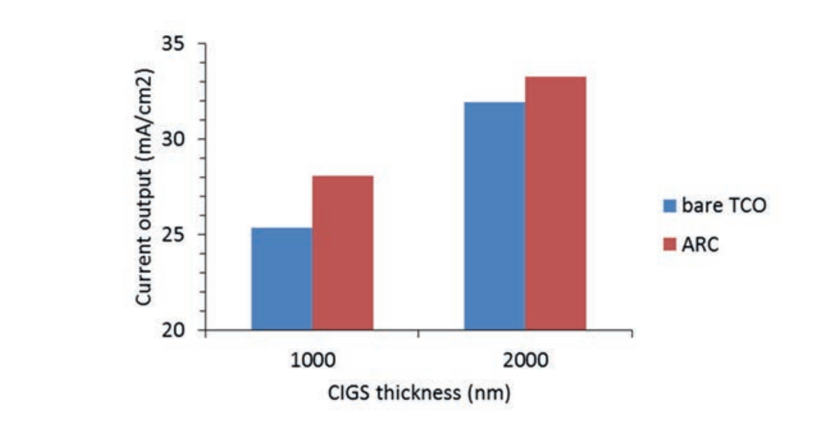


Figure 8. Efficiency increase when using an anti-reflection coating.

Part II: Efficiency enhancement

Anti-reflection coating

In a thin-film solar cell, part of the light is reflected; an anti-reflection coating (ARC) is a way of reducing these losses. Most development efforts focus on minimizing the reflection on the air–glass interface, which, for CIGS, is actually also the interface where most of the reflection losses occur. Because of the layer build-up of CIGS, the internal reflection is lower than experienced in thin-film silicon.

Fig. 7 is an example of a moth-eye texture, which was applied on top of a CIGS cell stack; the corresponding efficiency enhancement obtained from such a coating directly on the TCO is shown in Fig. 8 [5]. The reflection is reduced and the gain in current output is equivalent. Because a bare cell without encapsulation has a higher reflectance, the benefit is larger than would be expected from an encapsulated cell. Nevertheless, this work demonstrates that, even with laboratory cells, the expected gain is achieved. Work is presently under way to test the same technology on fully encapsulated cells [6].

Another example of an approach to texturing is shown in Fig. 9. This new 'light trapping' film technology from Royal DSM N.V. has the potential to improve the efficiency of CIGS modules. With the application of DSM's proprietary technology, it is expected that the efficiency of CIGS modules can be increased. Strengthening the light trapping will increase the output and reduce the $/Wp cost of the modules and therefore the cost of the energy produced.

The DSM technology consists of an outdoor-durable polymeric sheet that can be laminated to the (glass) cover of a PV module. The polymeric sheet features a smart-textured 3D structure, consisting of so-called 'corner cubes', which are tiny cubes pointing upwards. These cubes allow the light to enter the solar module, yet prevent the light from reflecting out of it. Effectively the light is trapped inside the module; as a result the module produces more energy. Depending on the type, location and age of the module, the additional energy can increase by approximately 6 to 12%. Light is also trapped effectively at low incident angles, which increases performance in morning and evening hours as well as under cloudy sky conditions. The technology is currently being evaluated in multiple geographies by a broad range of industrial partners. The film will be first brought to the market as a retrofit solution targeting large existing PV parks. The modules in these parks can reap greater benefits, as these older installations often suffer from higher reflective losses. In due course, the technology will also be applied to new systems.

Figure 9. Example of a multifunctional coating by DSM.

DSM is scaling up the manufacturing technology in preparation for a worldwide product launch and has joined the Solliance CIGS Research Program in order to explore and develop this potential. Solliance is an alliance of TNO, TU/e, Holst Centre, ECN, IMEC and Forschungszentrum Jülich for R&D in the field of thin-film photovoltaic solar energy in the ELAT-region (Eindhoven-Leuven-Aachen triangle).

Improvement of the front contact

The efficiency of thin-film solar panels is considerably lower than that obtained for record-efficiency cells. This efficiency gap is due in part to the larger surface area, which translates into higher demands on the front contact. The current panel configuration consists of stripes of cells approximately 5mm wide, which are interconnected in series, as shown schematically in Fig. 10(a); the current therefore travels a longer distance than in a small laboratory cell.

To meet the demands in a solar panel, the sheet resistance of the front contact is normally around 10Ω/sq.; this is a trade-off between sheet resistance and transmittance (about 5% more optical loss than with the TCO used in small cells) [7]. In addition, the fact that the panel consists of narrow stripes also induces an optical loss at the interconnection between the stripes, which is normally about 350μm wide; for an optimal cell width of 4mm, this loss amounts to 8.8%. Wider cell stripes would reduce these optical losses, but would also induce a higher electrical loss [8]. A higher sheet resistance of the TCO would give rise to a higher transmittance, but the electrical losses would severely limit the cell length [9].

The addition of metal fingers, as illustrated in Fig. 10(b), would enhance the conductivity of the front contact, which allows longer cells. To evaluate the benefit, the calculated efficiencies for cells with and without a finger grid are shown in Fig. 11; these calculations were based on a small cell efficiency of 15.5%. The boundary conditions used for the finger grid are a finger width of 20μm, a finger height of 1μm and copper bulk resistivity.

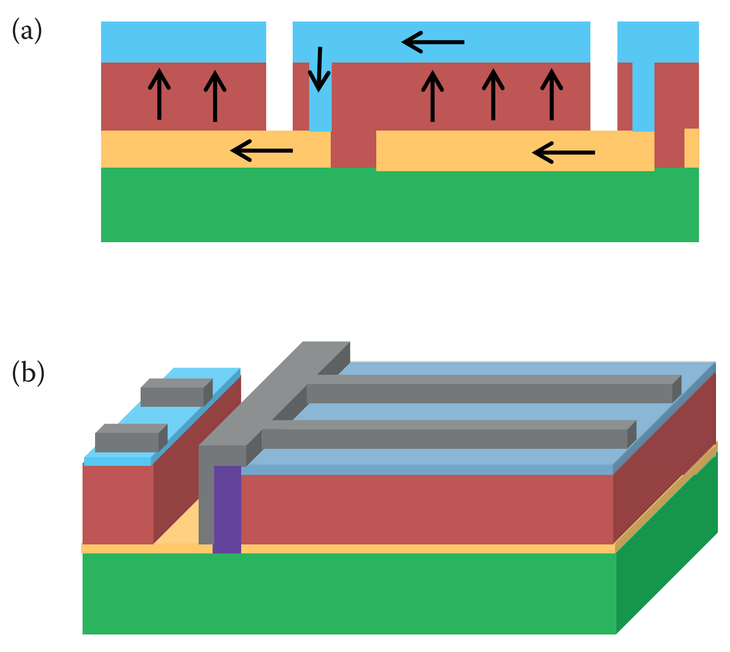


Figure 10. Schematic representation of (a) the classic method of interconnection and (b) a piece of solar panel with a finger grid [9].

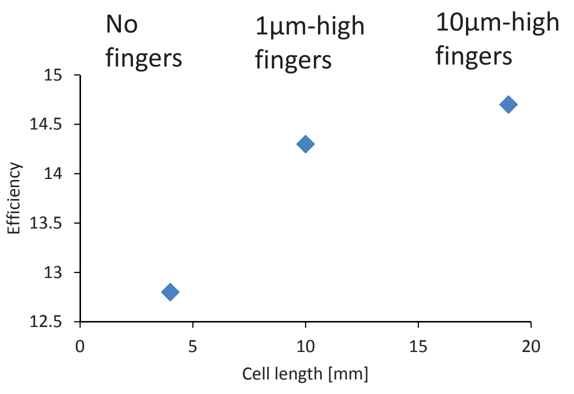


Figure 11. Solar panel efficiency for various front-contact materials; the fingers are combined with a 50Ω/sq. TCO.

> "The addition of metal fingers would enhance the conductivity of the front contact, which allows longer cells."

The optimal cell length is increased and the efficiency is higher too. Initial experimental verifications indicate that cell lengths of 10mm can be obtained with only a small loss in efficiency. These experimental data were based on a single-cell configuration, and no optical losses by interconnection were included. More elaborate modelling was performed in order to determine the best grid and cell configuration, and these results have been reported elsewhere [8,9].

In summary, the TCO sheet resistance and the finger dimensions have a distinct impact – the trends are shown in Fig. 12. In Fig. 12(a) it can be seen that, for a finger width of 20μm, a TCO of 100Ω/sq. is preferable and that increasing the height is beneficial. In practice, however, the 10μm-high fingers are less likely to be mass produced, but serve as an illustration to demonstrate the potential of this technology.

For grid fingers of width 60μm, the efficiency is slightly lower and there is less sensitivity to the TCO sheet resistance. The lower efficiency is due in part to the larger shadow of the fingers; obviously, this shadow is determined not only by the finger width, but also by the space between the fingers.

Fig. 12(b) shows the optimal finger spacing corresponding to the efficiencies shown in Fig. 12(a). A higher TCO sheet resistance requires a lower finger spacing, and wider fingers have a higher optimal spacing. This figure provides some general rules for the design of a finger grid for thin-film PV.

Optical losses from interconnection

As stated above, the interconnection area represents an optical loss. The interconnection is usually formed by three scribe lines and one interconnection area. The total width of this loss area can be minimized by placing the scribe lines as close as possible to each other. In a classic layout, where the isolation of the back contact is filled with the absorber material, some spacing is necessary between the isolation and the interconnection, because the absorber material is actually a semiconductor; this spacing should be at least 100μm [10]. However, if another material is used to fill this gap, the total area that is lost by this interconnection can be significantly reduced.

Fig. 13 shows the impact on the efficiency if the interconnection area is reduced. Two factors play a role here – the surface area losses are lower, but because of this, the optimal cell length is smaller, which in turn reduces the electrical losses. Therefore, a new optimum is found in the trade-off between TCO sheet resistance and cell length; here it is seen that the preferred TCO shifts from 10Ω/sq. to 20Ω/sq. and the optimal cell length decreases.

The cells with a finger grid are longer and therefore less sensitive to the interconnection area. Fig. 14 shows how things would work out if a finger grid were used together with a narrower interconnection area. In short, the maximum achievable efficiency with a finger grid of 20 × 10μm micron would increase to 14.9%, which is only 0.6% below the efficiency of a small laboratory cell.

> "The cost of thin-film CIGS can be decreased significantly if the thickness of the CIGS layer is reduced by 50%."

Conclusions

The cost of thin-film CIGS can be decreased significantly if the thickness of the CIGS layer is reduced by 50%. Further reductions would probably require more extensive light management technologies; development in this direction is currently under way.

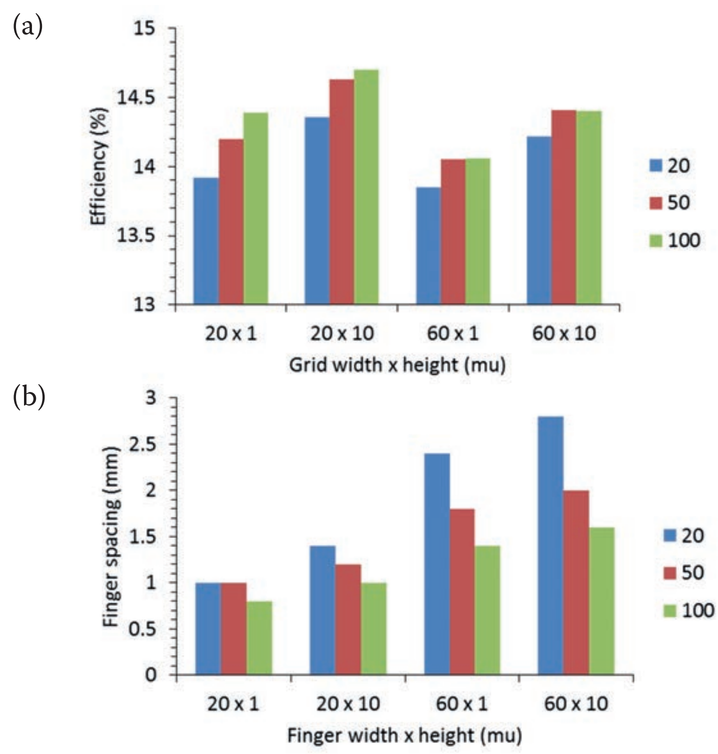


Figure 12. (a) Efficiency as a function of specific finger designs for three different TCO sheet resistances – 20Ω/sq. (blue), 50Ω/sq. (red) and 100Ω/sq. (green). (b) Corresponding optimal finger spacing.

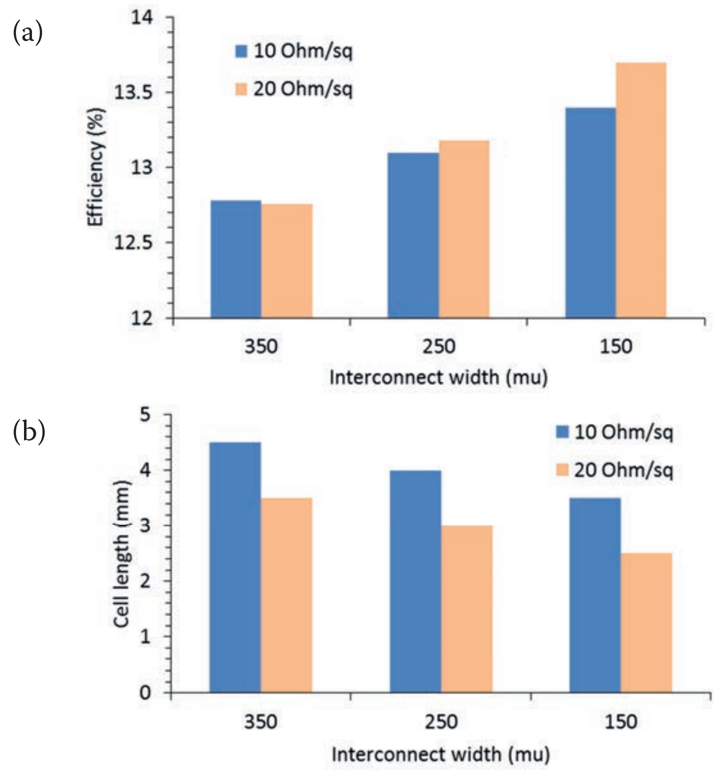


Figure 13. Impact of interconnection dead zone on efficiency and optimum cell length for two TCOs (10 and 20Ω/sq.).

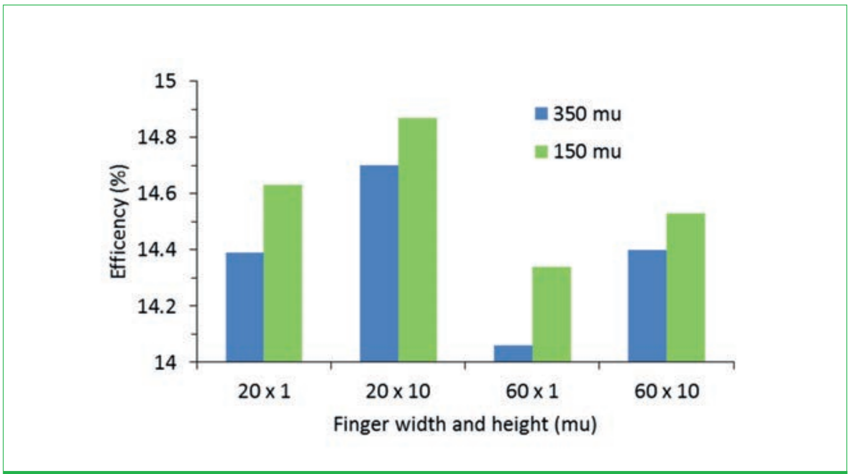


Figure 14. Impact of the interconnection dead zone on efficiency and optimum cell length for CIGS cells supplied with a metallic finger grid.

Increases in efficiency of solar panels can be achieved by improved light in-coupling, highly conductive front contacts and reduced interconnection area; the impact on efficiency has been presented here for various cases. Solliance is working on all these topics with the aim of making thin-film PV more competitive.

Acknowledgements

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About the Authors

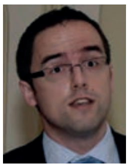
Joop van Deelen is a senior scientist at TNO. In the past 15 years of PV activities he has published 26 peer-reviewed papers, 34 articles in conference proceedings, and four patents, covering a broad range of thin-film PV-related topics. His current work mainly involves light management and transparent conductors, as well as technical and strategic consultancy for companies in various parts of the world.

Niels van Loon is a research scientist at TNO and Holst Centre, where he developed a versatile cost model to predict expected production costs of flexible thin-layer applications in numerous production techniques. His current work involves optimizing thin-film production technologies and techno-economical analyses in the field of thin-film PV.

Marco Barink works as a research scientist at TNO, where he mainly focuses on materials, multi-scale and multi-physics modelling, and topology optimization for problems and new developments in microelectronics, flexible electronics, OLED and PV. His work in PV also involves the optimization of free-form solar cells with free-form metal grids.

Marieke Burghoorn studied at the University of Applied Sciences and worked at Philips before joining TNO. Her activities range from optical characterization to nanoimprinting and synthesis of nanomaterials.

Zeger Vroon received his Ph.D. from the University of Twente on the subject of ceramic membranes. In 1995 he started working at TNO; since 2008 his work has focused on reliability, light management and integration in solar cells. In 2009 he was appointed a coordinating lecturer at the Applied University Zuyd.



Pascal Buskens received his Ph.D. in chemistry from RWTH Aachen University in 2006, and is the author of 15 scientific publications and more than 25 conference proceeding papers, as well as being the inventor of 11 patents. Since 2011 he has been working at TNO, where he currently holds the position of principal scientist; he is also a research group leader at DWI – Leibniz Institute for Interactive Materials in Aachen, Germany. His work at TNO and DWI focuses on the development of optical materials and coatings.

Enquiries

TNO/Solliance
High Tech Campus 21
The Strip
5656AE Eindhoven
The Netherlands

Tel: +31 6106 25 313
Email: joop.vandeelen@tno.nl

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News

New guidelines up the ante on PV module quality

The US National Renewable Energy Laboratory (NREL) has published updated guidance for PV manufacturers aimed at ratcheting up the quality of solar modules.

The document is intended to provide suppliers with guidelines on quality assurance practices ahead of the implementation of a new international industry standard due to be finalized later this year.

The guidelines, 'Updated Proposal for a Guide for Quality Management Systems for PV Manufacturing: Supplemental Requirements to ISO 9001-2008,' have been published under the auspices of the International PV Quality Assurance Task Force.

The task force has produced a draft technical standard, TS 62941, that it hopes will be approved and adopted by the International Electrotechnical Commission (IEC) later this year. Once in place, IEC/TS62941 is expected to become the standard basis for audits of PV module manufacturers and the quality assurance processes they follow.

New NREL guidance aims to improve consistency in module quality assurance regimes.

Testing

JA Solar's PV modules pass TUV Rheinland's high-grade hailstone impact test

Tier-one PV manufacturer JA Solar has said all of its PV module series have passed the 'high-grade' hailstone impact test conducted by TÜV Rheinland. The company said that the TUV Rheinland demonstrated its modules could be deployed in harsh environments.

The high-grade hailstone impact test results in hailstones with a diameter of 45mm striking the glass surface of the modules at a speed of 30.7 metres per second (about 110.5 km per hour), compared to hailstones used in the standard hailstone impact test strike are only 25mm in diameter and strike modules at a speed of only 23 metres per second. The anti-kinetic energy impact performance of JA modules is ten times the original industry standard.

Source: TÜV Rheinland

JA Solar's modules have all now passed TÜV Rheinland's advanced hail test.

Suntech modules pass VDE Institute's enhanced hail test

Suntech's PV modules have received the VDE Quality-Tested certification, placing them as one of three brands globally to have passed VDE Institute's enhanced hail test.

The VDE test uses hail of 40mm in diameter, the 4th level of hail test in accordance with Swiss standards, which uses hail at a speed of 27.5m/s to hit the modules, producing energy no less than 11.1J to simulate extreme weather conditions.

Suntech's modules experienced little or no power loss and met the enhanced standard hail test requirements in extreme weather conditions.

SNEC showcase

Hanwha Q CELLS showcasing new module and Q.ANTUM solar cell

Hanwha Q CELLS, recently merged with Hanwha Solar One, used this year's SNEC expo in China to unveil the latest in its HSL S series modules and high efficiency Q.ANTUM cell range.

The HSL S series modules feature four busbars in their design and are turned out from the company's fully automated production lines. Q CELLS claims HSL S is suitable for use across the three main PV market segments - commercial, utility-scale and residential.

Q CELLS claims "Q.ANTUM has achieved the world's highest efficiency for polycrystalline solar cells at 19.5%", with mass production 60-cell modules registering 18.5% efficiency. Q Cells also showcased a version of the S module for hot environments.


Developing
products for
tomorrow.

Suntech launches next-gen HyPro module line

Chinese tier-one manufacturer Suntech launched its new HyPro module line at the SNEC show in Shanghai in April. Suntech claims the average mass production cell efficiency of HyPro can reach up to 20.5% using PERC technology.

The four-busbar module recently attained the 'Quality Tested' certification from testing house VDE. Suntech said it had made an initial shipment of 236kW of the HyPro module in March.

The module will be available globally this July, for both commercial and residential projects. At peak performance, the HyPro 60 cell module can produce an optimal 290W, whereas the HyPro 72 cell module can produce up to a high 345W.

1GW-plus orders

NextEra Energy places massive 1.5GW PV module supply order with Hanwha Q CELLS

US electricity producer NextEra Energy Resources has signed a 1.5GW solar PV module supply agreement with Hanwha Q CELLS, using its high-efficiency Q.ANTUM cell (PERC) technology produced in Malaysia and South Korea.

The major module supply deal will include shipments starting in the fourth quarter of 2015 through the fourth quarter of 2016, ahead of expected US ITC reductions, which could severely undermine the economics of building utility-scale PV power plants in the country after the reduction in tax credits.

Risen closes 1,200MW construction and supply agreements in Inner Mongolia

An agreement to construct 1,000MW of solar power generation capacity has been made between Chinese PV module manufacturer Risen Energy and the local governments of Wuhai City and Haibowan district, Inner Mongolia, in addition to a further 200MW module supply deal.

The huge deals have been formalized with the signing of an investment framework agreement, with Wuhai City apparently agreeing to make available sufficient land to build the 1,000MW of power plants, as well as supporting Risen Energy with policy guidance and assistance with red tape, such as land use designation. Risen said it will set up a development and construction company to build the 1,000MW capacity over the next three to five years.

Tier-one producers

IHS says Trina Solar in top spot amongst PV module suppliers

In April, consultancy IHS said the top 10 PV module suppliers slightly increased their market share last year, jumping from 48% in 2013 to 49% in 2014. Chinese-based suppliers continue to lead the market, with seven of the top 10 module suppliers hailing from China.

While the same 10 companies listed on IHS' 2013 report are back in this release, the ordering has switched, with Trina Solar taking the top spot in the supplier list after witnessing a 30% unit-shipment increase and 17% gross margin. The company managed to outgain now number two supplier Yingli Green last year. Hanwha Q CELLS also witnessed a big jump, rising from the 10th spot to sixth on the 2014 list.

Source: Trina solar

IHS says the top 10 PV suppliers have increased their market share to 49%, with Trina taking the top spot for the first time.

SolarWorld expects shipments to increase 25% and surpass 1GW in 2015

Tier-one PV manufacturer SolarWorld said that its total shipments increased 55% in 2014 and guided shipments in 2015 to increase a further 25% and surpass 1GW.

In March, SolarWorld reported full-year 2014 financial results in line with

Source: Hanwha Q CELLS

NextEra has placed a 1.5GW module order with Hanwha Q CELLS.


Source: Meyer Burger.

Meyer Burger saw a 56% increase in sales in 2014 and orders grow by 13%.

preliminary guidance that included revenue up 26% to €573 million (US$641 million), compared to €456 million in 2013.

SolarWorld's guided total shipments (wafers, modules and kits) were expected to exceed 1GW in 2015 and generate revenue of over €700 million, returning the company to profitability.

Central America's 'biggest rooftop project' gets Jinko Solar modules

Tier-one manufacturer Jinko Solar has supplied PV modules to what is claimed to be the largest rooftop installation in Central America, a 3MW project in Honduras.

The Chinese company supplied local developer Smartsolar with 11,650 high efficiency PV modules.

The annual output of the plan is 3,815,830kWh, according to Jinko, which claims the project is the largest of its kind anywhere in the region. Construction of the project was completed in March on the roof of a facility owned by EMSULA, a company which bottles soft drinks.

Jinko Solar also announced in March that it had already secured 750MW in module supply deals in the US this year.

Ups and downs in Europe

Vikram Solar teams with European firms for solar cell production

India-based PV module manufacturer Vikram Solar has teamed with Fraunhofer ISE, Meyer Burger and centrotherm to provide its previously announced plans to include solar cell production as part of overall module capacity expansions. Vikram Solar plans to support the establishment of a solar academy in India with support from Fraunhofer ISE.

An agreement signed by the two companies includes Fraunhofer ISE assisting Vikram Solar with the research and development of industrial scale crystalline silicon solar cell and module processing.

Innotech Solar files for insolvency citing 'uncertain' European PV market

In March, PV module supplier Innotech Solar filed for insolvency blaming uncertainty in the European market for its troubles.

The Norwegian firm filed for insolvency in Narvik, Norway, while its German subsidiaries ITS Innotech Solar Module, ITS Halle Cell and Energiebau Solar Power all filed for insolvency in Cologne.

Rudiger Bauch of insolvency practitioners Schultze & Braun has been appointed as preliminary administrator and will consult with the company's creditors, assist its restructure and supervise the economic situation.

Australia news

Australia terminates PV dumping case with no duties

Australia's anti-dumping commission terminated its investigation into alleged dumping of Chinese-made PV modules imported into the country in early April. Although the commission found evidence of Chinese modules being sold in Australia at dumped prices, it concluded that the injury caused by these actions had been minimal and that it would therefore take no further action.

In other news from Australia, the Australian Renewable Energy Agency (ARENA) has allocated up to US$15.2 million for a new R&D round set to help industry-partnered projects looking to develop and commercialize renewable energy technologies.

SPI enters Australia with acquisition of PV distributor

PV project developer Solar Power Inc (SPI) will enter another new regional market, acquiring an 80% stake in a wholesale distribution business in Australia.

Headquartered in Shanghai with operations in various locations, vertically integrated SPI has agreed to purchase 80% of outstanding capital stock held by Solar Juice, a company described by local analysis firm SolarBusinessServices as Australia's leading wholesale PV distribution business by volume in 2013 and 2014.

While the transaction remains subject to closing conditions, SPI claimed the deal is worth around US$25.5 million of SPI common stock. Solar Juice distributes PV panels, inverters and components as well as complete systems.

Equipment suppliers

Meyer Burger solar equipment orders increasing

PV equipment specialist Meyer Burger reported a 56% increase in 2014 sales and new order intake 13% above 2013 levels. Meyer Burger reported full year 2014 revenue of CHF315.8 million (US$328.9 million), compared to CHF202.7 million in the prior year, a 56% increase.

On a regional basis Asia accounted for 49% of net sales, up slightly from 45% in 2013. Europe accounted for 27% of sales in 2014, down significantly from 40% in 2013. Sales to the US accounted for 24% of the total, up from 14% in the previous year. The ROW accounted for just 0.2% of sales, down from 1% in 2013.

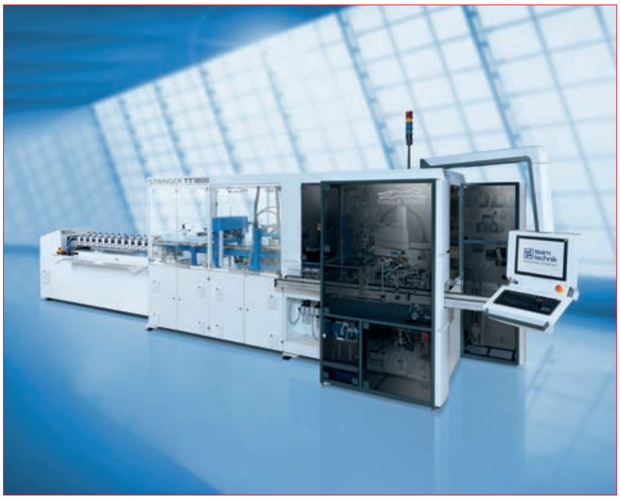
Natcore and Eurotron team on back-contact cell-to-module integration

PV technology start-up Natcore Technology is to work with specialist PV equipment supplier Eurotron B.V, to integrate back-contact cell designs to patterned conductive backsheet-based solar modules.

The aim of the collaboration was said to include adapting Natcore's laser process to a contact design, compatible with Eurotron's back contact technology, which would enable commercial-style modules using standard 156mm x 156mm wafers. The Eurotron Competence Center will host the development work. No timelines or financial details were disclosed when the deal was announced in mid-May.

Product Reviews

Teamtechnik



Teamtechnik's STRINGER TT1800 has two-second solar cell soldering cycle

Product Outline: Teamtechnik has launched its new 'STRINGER TT1800', which has been enhanced with faster solar cell soldering cycles of only two seconds. The faster cycle times provide increased the stringer throughput, equating to 50MWp per year and produce up to 27 modules per hour. Teamtechnik demonstrated the new Stringer TT1800 live at the SNEC 2015 show in April.

Problem: The continued drive to reduce module assembly costs can be met by improving throughput and overall productivity of the stinger system. However, developments including dual-track systems can increase equipment complexity and manpower resources, negating the full potential for cost reduction.

Solution: The STRINGER TT1800's patented down device decouples the soldering from the handling processes. This is said to enable 1,800 cycles per hour on a single-track system. The technology was said to have the lowest breakage rates, while maintaining the maximum wide process window for a stable production.

Applications: Cell to cell stringing in high-volume manufacturing.

Platform: New features of the STRINGER TT1800 also enable the production of full and half-cell strings with up to five busbars. High throughput of two seconds cycle time comes with a low breakage rate: <0.1-0.3%, while providing high system availability of >95%. The company says this is achieved through separation of two processes - ribbon and cell handling, and soldering - which minimizes thermal stress and therefore stress cracks in the solar cells.

Availability: April 2015 onwards.

3D-Micromac

Half-cell laser cutting made easier with 3D-Micromac's 'microDICE' OTF system

Product Outline: 3D-Micromac has launched the 'microDICE' OTF system. The system uses Thermal-Laser-Separation (TLS) for cutting of cells into half cells. By using half cell technology the average module power yield can be increased.

Problem: Cell separation has become relevant for volume production due to the introduction of half-cell module concepts, which allow a substantial power gain. The standard industrial process of p-type cells is based on laser scribing and subsequently mechanical cleaving. The disadvantages of this process are the reduction of the cell efficiency, the reduced mechanical strength and the expensive handling due to the combination of a laser process with a subsequent cleaving.

Solution: microDICE OTF employs TLS for splitting PV cells into half cells. The separated cells are said to show a significantly higher mechanical strength, better edge quality as well as a lower power reduction compared to laser scribing and cleaving approaches. TLS is used in the semiconductor industry's back-end to separate semiconductor wafer in components. The process is based on thermal-induced mechanical stress, generated by a well-adjusted combination of a laser heating and cooling.

Applications: Half-cell cutting in volume production environments.

Platform: The system achieves a throughput of 3,600 cells per hour of incoming full cells. The optical set-up relies on the industry-proven, on-the-fly technology used in 3D-Micromac's laser structuring tools for processing of PERC cells. It guarantees high productivity and price-performance ratio. The laser processing is realized during the continuous transport of the cells under the laser source, whereby the relative motion of the cells is automatically compensated for. Stops for the positioning of the individual cells are completely eliminated. The continual movement of the conveyor belt results in an almost 100-percent capacity utilization of the laser source.

Availability: April 2015 onwards.

Shunting-type potential-induced degradation: How to ensure 25 years' service life

Christian Taubitz, **Matthias Schütze**, **Marcel Kröber** & **Max B. Koentopp**, Hanwha Q CELLS GmbH, Bitterfeld-Wolfen, Germany

ABSTRACT

Potential-induced degradation (PID) of the shunting type (PID-s) is one of the most severe forms of PID, which is caused by the negative potential of p-type solar cells with respect to grounded frames/mounting. Although this negative potential can be completely avoided at the system level, that is not the case for a large number of modern PV systems. PV modules that are able to sustain PID-s stress for at least the duration of their service life are therefore essential. To assess whether modules fulfil this requirement, laboratory tests are currently recommended in which the modules are exposed to a certain constant level of PID-s stress for a given amount of time. These types of test with constant stress levels, however, are only feasible in the case of degradation mechanisms that are not reversible in the field, for which non-coherent stress episodes simply sum up to the total stress. Unlike other mechanisms, PID-s is reversible under field conditions; as a consequence, the level of PID-s of a fielded module is the result of an intricate interplay of phases of degradation and regeneration. This behaviour cannot be replicated in a laboratory test using a constant stress level; the currently recommended laboratory tests for PID-s with constant stress levels are therefore not appropriate for assessing the service life duration, and can only be used for differentiating the susceptibility to PID-s stress and for monitoring the stability of production processes. For monitoring the PID-s resistance of its products, Hanwha Q CELLS uses tests for PID-s with constant stress in accordance with the draft for IEC PID test method 62804. This assures that all the products of the Q CELLS brand come with Anti-PID Technology (APT). The expected service life duration with respect to PID-s is assessed by simulating the interplay of degradation and regeneration under non-constant outdoor conditions that are based on meteorological data.

Introduction

A PV system collects the energy of sunlight, and the challenge is to extract as much of the collected energy as possible in the form of electrical power for use in various applications.

Electrical power is the product of current and voltage; in other words, providing electrical power means providing a current flow together with a voltage difference. Consequently, high currents or voltages have to be present in PV systems in order to obtain a high electrical power output; this means that the constituent parts are subject to a certain level of stress.

In order to keep conduction losses due to current flow as small as

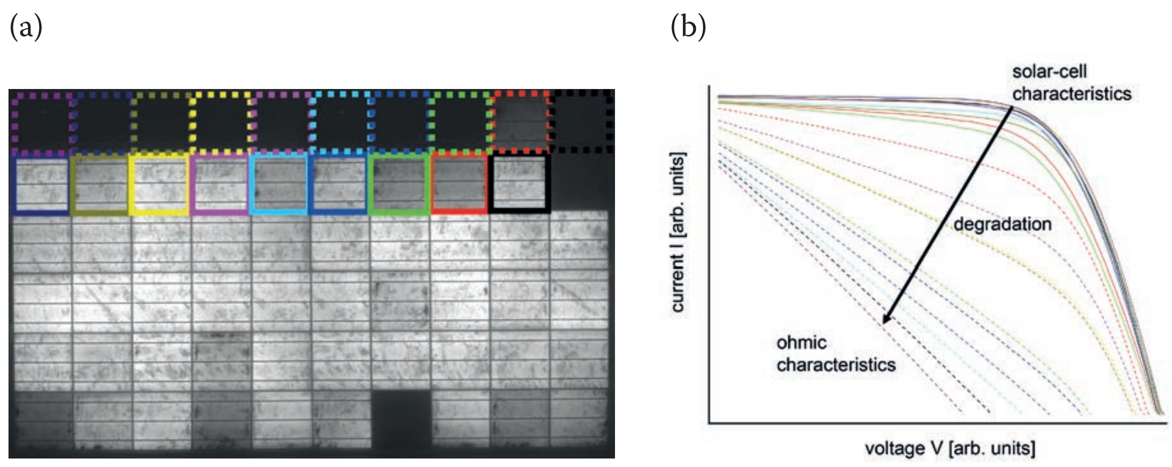


Figure 1. Shunting of solar cells because of PID-s: (a) electroluminescence image of a PID-s affected module; (b) *I–V* characteristics of individual cells that have degraded to different degrees, showing the evolution of PID. The coloured boxes in (a) correspond to the lines in (b) (low PID-s: solid boxes/lines; high PID-s: dashed boxes/lines). (Adapted from Schütze et al. [8].)

possible, there is a continuing trend to obtain high voltages in modern PV systems by connecting more and more modules in series, in so-called *module strings*. Increasingly large differences in the electrical potential of different system parts therefore occur, leading to increased stress levels of the constituents. Special care must be taken if those differently biased parts are positioned close to each other; this is the case, for instance, with PV modules, which usually contain electrically active elements, such as solar cells, and electrically passive (but nevertheless conducting) ones such as metal frames. Potential differences of several hundred volts can be present between those elements within a space of a few millimetres, as the metal frames have to be grounded for safety reasons.

Since the electrical isolation of the different parts is not perfect in practice, large potential differences cause parasitic leakage currents, which can lead to so-called *potential-induced degradation (PID)*. The leakage currents responsible for PID will decrease dramatically with increasing distance of the differently biased parts. The distance of the electrically active parts from the grounded frame can be as little as a few millimetres at the edge of a module, but as much as a few decimetres in the middle of the module. The leakage current, and thus the PID stress, in the case of a large distance will be negligible compared with that in the case of a small distance. Under dry conditions, PID stress will therefore be present only in the outermost regions of the module surface. This situation changes dramatically when rain or dew is present, which make the module surface conductive. Large parts of the module surface can be at the same potential (ground) as the module frame in this case, which leads to almost constant high leakage currents and PID stress for those parts of the module that are wet.

Various kinds of module defect caused by PID have been reported – for example, electrochemical corrosion [1], delamination [2,3] and passivation breakdown [4]. PID, however, seemed to have been limited to thin-film modules [1–3] and specialized cell concepts [4] until 2007; the first case of PID for standard silicon-wafer-based solar cells was reported in 2008 [5]. Awareness of PID began to increase rapidly in 2010, when it became apparent that a certain type of PID can affect all modules containing standard p-type solar cells [6,7]. For differentiation purposes, this effect is called *PID of the shunting type (PID-s)*, since it leads to shunting of the solar cells [8] (Fig. 1). Because of shunting, the generated electrical power cannot be extracted from the solar cells – it is already dissipated within them.

"PID-s can occur when solar cells are exposed to a negative potential with respect to the frame/mounting."

PID-s can occur when solar cells are exposed to a negative potential with respect to the frame/mounting. In today's PV systems, commonly used inverter concepts often result in a so-called *floating potential*, because of the absence of a functional grounding of one of the poles. With a floating potential present, half of a module string is exposed to a negative potential, and therefore to PID-s stress. The PID-s stress increases from the middle of the module string towards the negative pole, while the positive string part remains unaffected, as illustrated in Fig. 2.

The potential distribution as a function of module position in a PV module string with a floating potential present is schematically shown in Fig. 2(a); the resulting PID-s stress that the individual modules are exposed to (red colour), depending on their position in the string, is shown in Fig. 2(b). Note that the indicated homogeneous stress levels for the individual modules are present for wet conditions, leading to a conductive front surface of the modules, only. For dry conditions, only

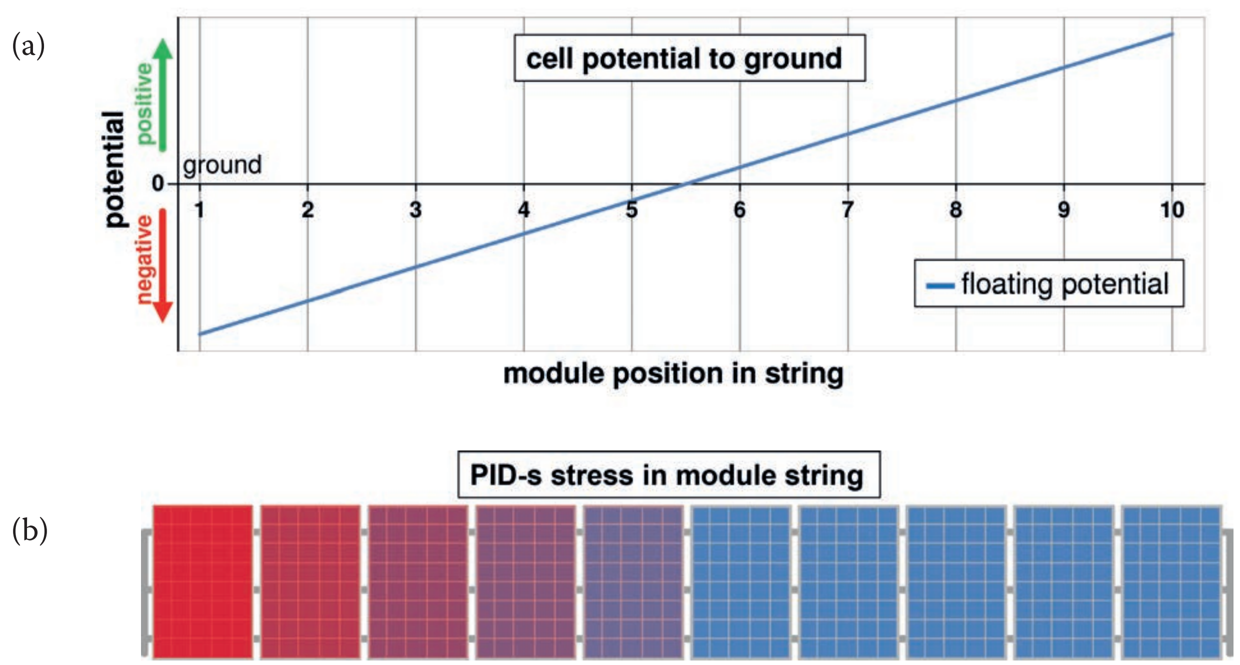


Figure 2. Dependence of PID-s stress on the module position in a string: (a) potential distribution as a function of the module position in a string with a floating potential; (b) resulting PID-s stress (indicated in red) for the individual modules of the string in the case of wet conditions, leading to a conductive front surface. For dry conditions, only the outermost parts of the modules will be exposed to the indicated stress levels, which is usually not sufficient to cause a substantial power loss of the modules.

the outermost parts of the modules will be exposed to the indicated stress levels; this is not believed to usually be sufficient to cause a substantial power loss of the modules from PID-s. Nevertheless, wet conditions (rain or dew) resulting in sufficient stress will always be present during certain periods of time in a field installation. In the case of PV modules that are susceptible to PID-s, this stress can lead to catastrophic power [6,7] and yield [5] losses.

At the microscopic level, the PID-s of the solar cells originates from the migration of sodium ions to the front of the cell. It has been shown that sodium accumulates at the cell surface and attaches to stacking faults that are present in the silicon material [9]. These stacking faults extend from the silicon surface, through the n-type emitter layer, to the p-type bulk of the cell. The sodium accumulation is believed to result in a conducting pathway, shunting the p-n junction [9].

Mitigation possibilities – Anti-PID Technology (APT)

There are a number of different ways to avoid PID-s. Since a negative potential of the solar cells with respect to the frames/mounting is necessary for PID-s to occur (Fig. 2), it is possible to avoid PID-s at the system level by grounding the negative pole of the individual module strings; the solar cells are then always at a positive potential with respect to ground. Unfortunately, most inverters without transformers cannot be grounded this way, because of their architecture; however, by using slightly less-efficient inverters with transformers, it is generally possible to ground the negative pole of the module strings. Most of these inverters are not yet grounded at the mounting. This leads to a floating potential, with half of the module string frequently exposed to PID-s stress (Fig. 2), that can then simply be eliminated by proper grounding.

A second option to avoid PID-s stress is at the module design level, and there are several solutions possible here. Protection from PID-s can be achieved by omitting the metal module frame [10], which has to be grounded for safety reasons. Without a grounded frame, a wet module glass surface will not be in contact with the ground potential, and therefore no potential difference can build up between the solar cell and the front side of the module glass. For standard glass–foil laminates, however, it is difficult to ensure a sufficient stability of the modules without a frame. On the other hand, in the case of glass–glass modules, a frameless design with a back-rail mounting can be feasible. Another possible measure to prevent PID-s is to increase the PID-s resistance by preventing the drift of sodium ions to the cell surface; this can be done by using a high-resistivity sodium-free glass, but such an option is usually cost prohibitive. An easier and less-costly solution is the mitigation of the sodium drift by high-resistivity encapsulation materials [7,8,11,12].

A third option for PID mitigation is at the cell level. Here, PID-s resistance can be achieved by a proper selection of materials in conjunction with optimized design and adjusted cell processes. For instance, it has been suggested that a high refractive index of the silicon nitride (SiN_x) films that are commonly used as an anti-reflection coating (ARC) can prevent PID-s [6,11]. Unfortunately, however, a high refractive index of SiN_x comes with a high light absorption of the ARC films, which reduces the conversion efficiency of the solar cell [11].

The challenge is to find a set-up that successfully prevents PID-s while maintaining the electric cell performance at an excellent level. A combination of materials and process/design parameters which ensures that cells deliver both excellent electrical performance and resistance to PID-s has been implemented by Hanwha Q CELLS – Anti-PID Technology (APT), which comes with all products of the Q CELLS brand.

> “The challenge is to find a set-up that successfully prevents PID-s while maintaining the electric cell performance at an excellent level.”

Testing for PID

Many laboratory PID test methods have been proposed in recent years for verifying and quantifying the PID-s resistance of PV modules. The most common test conditions are:

- Biased damp heat (DH): 60°C/85% RH, module rated system voltage bias (commonly –1kV), 96h.
- 25°C/RH < 60%, module rated system voltage bias (commonly –1kV), grounded Al foil covering the module glass, 168h.
- Biased damp heat (DH): 85°C/85% RH, –1kV, 48h.

The first two test conditions are part of the draft for an IEC PID test method (IEC TS 62804). All these tests have in common the fact that a certain constant stress level is applied continuously for a given amount of time.

These types of laboratory test method are usually applied in order to assess the service life with respect to a particular degradation mechanism. To be feasible, the methods are generally limited with respect to the possible test time and the permitted costs. Simple test methods are desirable which ideally apply the same amount of stress that the module would be exposed to during its desired service life, but in an accelerated manner, i.e. preferably over a period of days or weeks. In the case of most non-reversible failure modes, such as corrosion or mechanical stress issues, the stress a module is exposed to during its service life can be cumulated; this makes it possible to carry out laboratory tests corresponding to service life by applying the same cumulated stress. In principle, the tests can be performed continuously at a constant stress level, and the stress level can often be even higher than in the field. These measures allow the application of the desired cumulated stress in a time much shorter than the service life.

In the following discussion it will be shown that PID-s is a complex failure mode which is reversible under field conditions. For reversible failure modes, however, it is not justified to cumulate the service life stress as can be done for non-reversible failure modes. A simple laboratory test method with continuous and constant stress therefore cannot assess the service life behaviour of a fielded PV module with respect to PID-s.

Nevertheless, PID-s laboratory test methods, like the ones mentioned above, are widely accepted as methods for verifying the stability of the production process and the product quality. Since these methods apply a constant and reproducible PID-s stress to a PV module, the changes in product quality can be revealed by a change in behaviour under PID-s stress. In order to ensure its standards of high quality for all Q CELLS-branded products, Hanwha Q CELLS has established a PID monitoring process in which production samples are tested on a monthly basis using the aluminium foil test described in the draft of the IEC PID test method (IEC TS 62804). In addition, a similar test is also carried out on a weekly basis at the cell level. The results of monitoring module production in 2014 are shown in Fig. 3; the fail criterion (power loss > 5% at standard test conditions – STC) is indicated by a red dotted line. This monitoring is a part of Q CELLS' APT and allows the assurance that APT really is continuously provided with the products of the Q CELLS brand. Since the implementation of APT, including the monitoring process, there have been no PID-s claims relating to Q CELLS-branded products, confirming the excellent level of resistance to PID-s.

The complexity of PID-s kinetics will be presented next, and the resulting PID-s behaviour of modules under outdoor conditions will be demonstrated in order to point out the limitations of laboratory PID test methods with respect to PID-s.

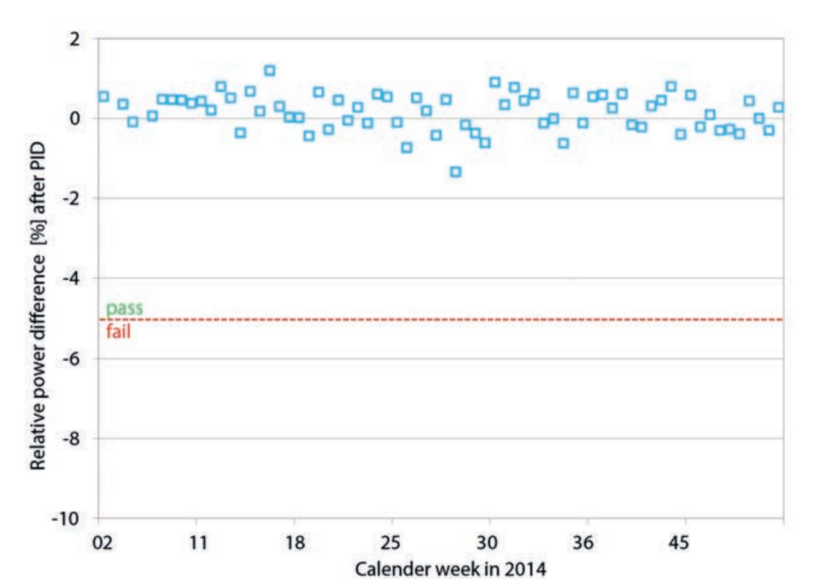


Figure 3. Process control of Q CELLS' module production: weekly monitoring data for 2014.

PID-s and regeneration

The kinetics of PID-s has recently been studied in detail [13–17]. It has been shown that the shunt resistance (R_{sh}) of the solar cell can be used as an early-warning parameter for monitoring the PID-s kinetics. This parameter is highly sensitive to PID-s stress and allows the investigation of the PID-s behaviour of a solar cell long before the onset of power loss. An implied fill factor $FF_{implied}$ can be calculated from R_{sh} [18] in order to estimate the resulting power loss at STC; a significant STC power decrease is only present for values of $R_{sh} < 2k\Omega cm^2$.

In Fig. 4 R_{sh} measurements over time for two different one-cell mini-modules are shown, as recorded in a laboratory test at a constant temperature. The mini-modules were exposed to PID-s stress by covering the glass surface with a grounded aluminium foil and exposing the solar cell to a bias voltage of –1kV relative to ground. The PID-s stress was terminated by switching off the bias voltage.

The R_{sh} values for both mini-modules decrease from the very second the bias voltage is applied, revealing the effect of shunting caused by PID-s; this phase is called the *shunting phase S* (red area in Fig. 4). After the bias voltage is stopped, R_{sh} continues to decrease along the red curve while slowing down, finally levels off and then starts to increase again. The phase starting from the point at which the bias was stopped until the value of R_{sh} at which the bias voltage has been stopped ($R_{sh,bvs}$) is reached again is called the *transition phase T* (blue area in Fig. 4). The duration of this T phase can vary for different types of solar cell and/or module. PV modules may also have no T phase at all, which is the case

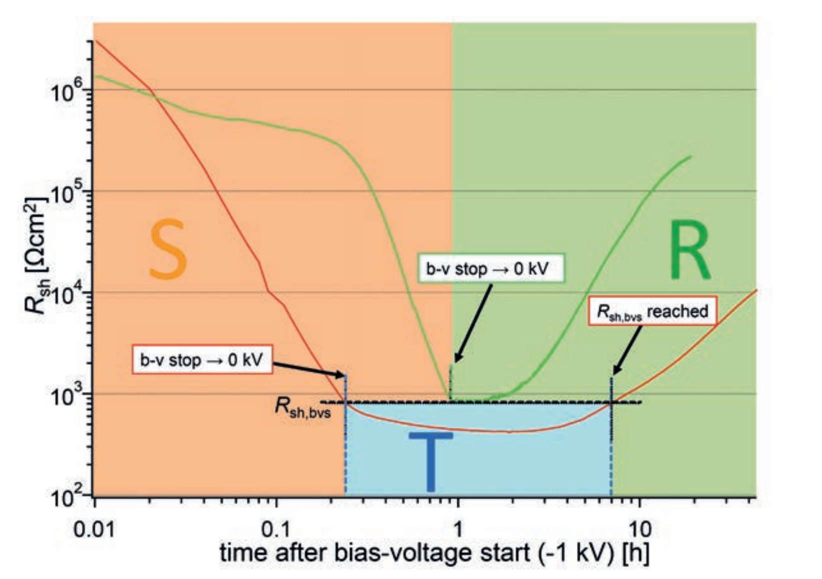


Figure 4. Shunt resistance (R_{sh}) measurements during shunting and regeneration: laboratory measurements for two different one-cell mini-modules at a constant temperature as a function of time after bias voltage (b-v) start (green curve and red curve). The R_{sh} value at the b-v stop ($R_{sh,bvs}$) is indicated by a dashed horizontal black line. The shunting (S), transition (T) and regeneration (R) phases are highlighted by the red, blue and green areas respectively. The green curve exhibits no T phase, in contrast to the red curve.

for one of the mini-modules, indicated by the green curve in the figure.

The following phase, in which the R_{sh} value increases above $R_{sh,bvs}$, is called the *regeneration phase R* (green area in Fig. 4). Regeneration from PID-s has also previously been observed in the field [10,16,17]. It has been found that the shunting, T phase passage and regeneration rates increase exponentially with increasing temperature [13,14]. Between different types of solar cell and/or PV module, the rates observed in the S, T and R phases can vary significantly; this leads to a variation in the resistance to PID-s of PV modules in the field.

PID-s of fielded modules

PID-s stress in fielded modules, even at the negative side of a PV module string, is not always present: only if certain environmental conditions are met is a module subject to PID-s. The key condition is a conductive front surface of the module in the presence of sunlight. Without sunlight (i.e. at night-time), the system is not generating power; no potential difference at all will therefore be present in this case. If, in the daytime, the front surface of the module is not conducting, the potential difference between the grounded frame/mounting of the module and the cells will not be able to drive a leakage current sufficiently large to have a harmful effect, because of the high resistivity of the glass surface [19].

The front of the module can become conductive under certain field conditions by water deposition in the event of morning dew or rain. At night-time, and in the daytime without a wet glass surface, a PV module will therefore generally be free from PID-s stress.

A module – after a transition phase if applicable – will recover from power degradation in the absence of PID-s stress [10,13–17]. This results in an intricate interplay between PID-s and regeneration for fielded modules, which is illustrated in Fig. 5. The upper graph shows schematically the PID-s stress that a PV module mounted at the negative string side is exposed to during two sample days. On the first day, there is only one PID-s stress event present, caused by morning dew. On the second day, two PID-s stress events are assumed, one again caused by morning dew, and the second resulting from a short shower in the daytime. During the shower event, the module temperature is elevated compared with the morning dew events; this results in a significant increase in PID-s stress. For simplification purposes, in this example the temperatures during the daytime and night-time are assumed to be constant; the daytime temperatures on the two days are also assumed to be the same, as are the two night-time temperatures.

The centre graph in Fig. 5 illustrates the resulting R_{sh} behaviour of two different PV module types A and B, as a function of time, while the lower graph shows the corresponding $FF_{implied}$. The R_{sh} kinetics of module type A, represented by the green line, is assumed to exhibit no T phase, and a favourable regeneration behaviour. The R_{sh} kinetics of module type B, represented by the red line, is assumed to show a T phase and a less-favourable regeneration behaviour. It is further assumed that the shunting rates of the two module types are similar and that the initial shunt resistances ($R_{sh,ini}$) are the same.

As a result of the morning dew at the beginning of the first day, an S phase (red area) is present, leading to a decrease in R_{sh} for both module types. The S phase ends with the evaporation of dew, and the R phase (green area)

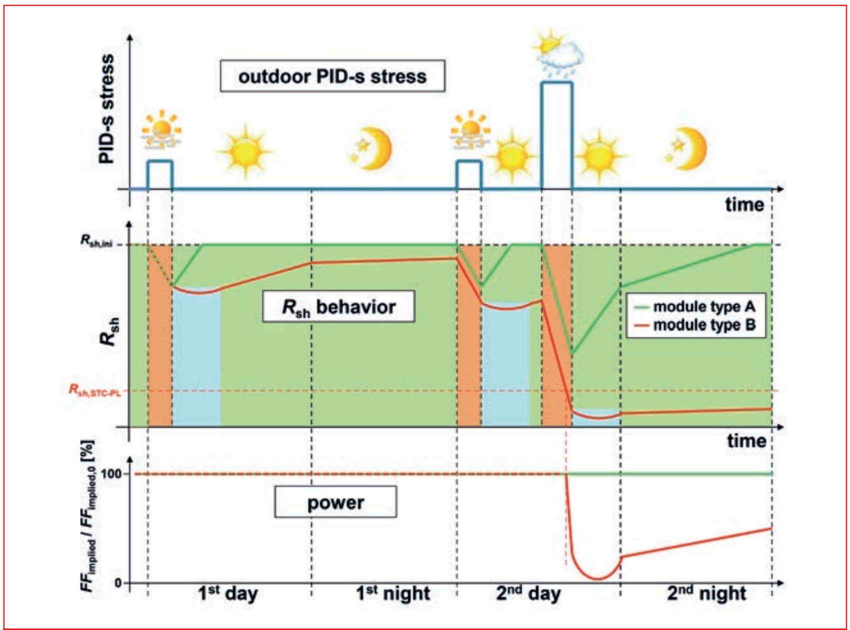


Figure 5. Outdoor PID-s stress and R_{sh} behaviour: the upper graph illustrates the PID-s stress that a fielded PV module is exposed to, mounted at the negative potential side of a module string during two sample days. The resulting R_{sh} behaviour for two different PV module types A and B is shown in the centre graph, by the green and red lines respectively. The S, T and R phases of the R_{sh} kinetics are represented by the red, blue and green areas respectively. The initial R_{sh} value ($R_{sh,ini}$) and the R_{sh} value of the STC power loss onset ($R_{sh,STC-PL}$) are indicated by horizontal dotted black and red lines respectively. A red dotted vertical line marks the start of significant power loss for module type B; this becomes more apparent in the lower graph, which shows the $FF_{implied}$ behaviour that is indicative of the actual power loss.

and the T phase (blue area) begin for module types A and B respectively. Eventually module type B exits the T phase and reaches the R phase as well. Note that module type B generally demonstrates a slower regeneration rate than type A. During the first night, the R phase continues at a lower temperature, leading to a slowdown in the increase in R_{sh} for module type B. At this time, module type A has already completely regenerated.

At the beginning of the second day, an S phase is again present, followed by R and T phases, as on the first day. Note that, until this point, there have been no substantial power losses for both modules, as indicated by the virtually constant $FF_{implied}$. The R phase is then interrupted by a rain event in the daytime, leading to an S phase with an increased PID-s stress because of the increase in temperature. During the rain event, the R_{sh} value of the solar cells incorporated in module type B decreases below the onset value for STC power loss ($R_{sh,\ STC-PL}$), which marks the beginning of the power loss of module type B. This becomes more apparent in the $FF_{implied}$ curve, which indicates an abrupt decrease for module type B. A comparison of the centre and lower graphs reveals the early-warning character of R_{sh}, while $FF_{implied}$ is the most appropriate for evaluating the drop in STC power.

After the rain event, module type B again passes the T phase and eventually reaches the R phase. In spite of the R phase, module type B is not able to sufficiently regenerate, resulting in a major power loss at the end of the two-day period. Module type A, exhibiting a more favourable regeneration rate and no T phase, experiences only a moderate R_{sh} decrease during the rain event and a rapid R_{sh} increase afterwards. The R_{sh} value is well above the $R_{sh,STC-PL}$ at all times, and at the end of the second night it has reached its initial value again. The $FF_{implied}$ curve for module type A therefore remains virtually unaffected, indicating no significant power decrease during the two sample days.

In summary, module type A is resistant to PID-s because of favourable shunting/regeneration behaviour. The PID-s resistance of module type B, however, is not high enough, as a result of unsatisfactory shunting/regeneration behaviour.

Note that in this example both module types demonstrated the same shunting behaviour. Simple laboratory test methods, such as those previously described, would not distinguish the difference in the PID-s behaviours and thus in the PID-s resistances. Those tests cannot therefore be used to determine the reliability of PV modules with respect to PID-s. Accordingly, a laboratory test method cannot predict the resistance to PID-s of modules in the field that have passed tests.

It becomes apparent that the transition/regeneration behaviour of a PV module has a crucial impact on its PID-s resistance. The regeneration effect can also be used to counteract the effect of PID-s on a fielded module by, for example, employing a so-called *PV offset (PVO)* box [20] that applies a positive bias voltage overnight in order to boost regeneration. The disadvantages of this solution are the additional costs and the fact that the installation of the boxes is usually not done before a power loss of the system due to PID-s has been observed; this results in limitation of the loss, rather than prevention.

"The transition/regeneration behaviour of a PV module has a crucial impact on its PID-s resistance."

By investigating the transition/regeneration behaviour together with the shunting behaviour of a PV module in detail, it becomes possible to assess its long-term behaviour in the field, and thus quantitatively determine its PID-s resistance. Hanwha Q CELLS has developed a PID-s model simulating the progression of R_{sh} under real outdoor conditions, taking into consideration shunting, transition and regeneration [14,15]. This model is used to predict the long-term PID-s behaviour of Q CELLS' products and to optimize the APT in such a way that no power loss is present during their service life. The PID-s model will be described next in more detail.

Modelling of PID-s

In the investigation of the long-term R_{sh} behaviour of a PV module, Hanwha Q CELLS began to simulate the PID-s progression under fluctuating environmental conditions, as present in the field. To deal with the fluctuating conditions, the time interval of interest – usually several years – is divided into small time steps, no larger than one hour; the time steps have to be small enough to justify the assumption of constant environmental conditions during those steps. The general process used to model PID-s is illustrated in Fig. 6; the simulation of the service life PID-s behaviour of a fielded module in a specific region is possible with this model.

a) Environmental data

Environmental data for the installation site during the time period of interest have to be obtained, including the ambient temperature T_{amb}, relative humidity RH_{amb} with respect to T_{amb}, solar irradiation on the module plane IR_{mod}, and information about when rain events occur. The model takes into consideration module temperature T_{mod}, relative humidity in the vicinity of the module RH_{mod}, and rain events. The module-specific data do not have to be measured directly but can be derived from meteorological data. If not measured, T_{mod} can be calculated from the measurements of IR_{mod} and T_{amb} by utilizing the nominal operating cell temperature (NOCT) [21]. RH_{mod} can be computed from T_{amb}, T_{mod} and RH_{amb} by using the temperature dependence of the saturation vapour pressure of water [19], which can be referenced in the literature.

b) R_{sh} kinetics and classification

Key to a PID-s model is the determination of the temperature-dependent R_{sh} kinetics in laboratory experiments – two examples of measured R_{sh} progressions of mini-modules were given in Fig. 4. Details regarding the R_{sh} kinetics and its analysis can be found in the literature [13–15]. IR_{mod} and RH_{mod} data are used to assign one of the three phases S, T or R to every

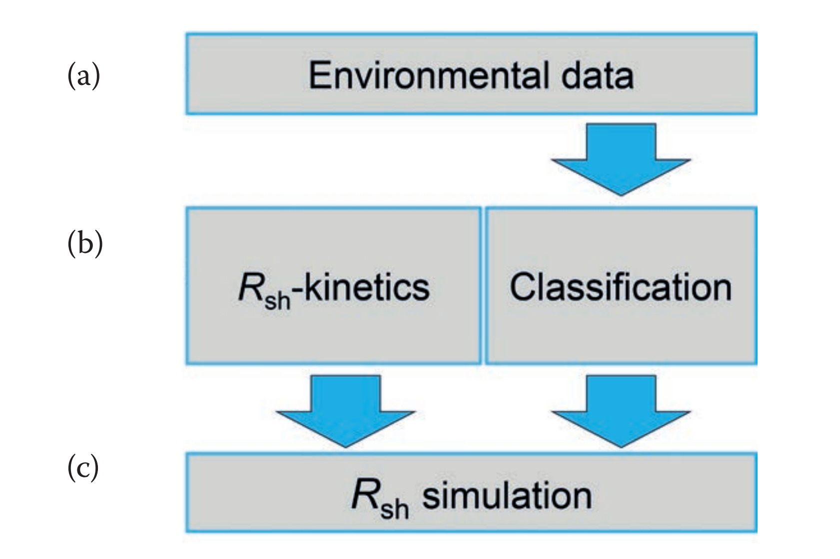


Figure 6. Illustration of the PID-s model procedure: the concept of modelling the long-term R_{sh} behaviour under outdoor conditions. (Adapted from Taubitz et al. [15].)

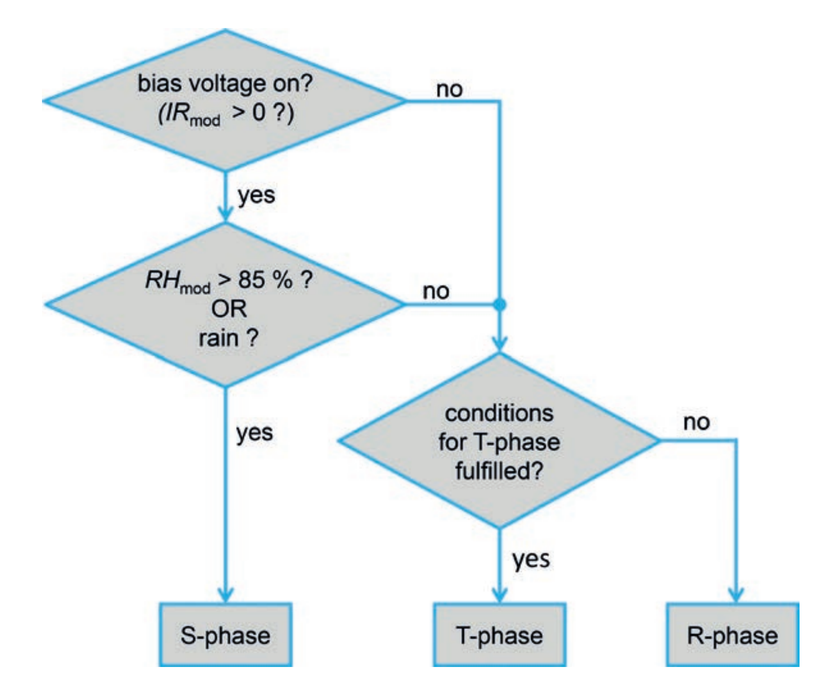


Figure 7. Phase-assignment process for classifying the environmental data, carried out at every time step of the simulation. (Adapted from Taubitz et al. [15].)

individual time step of the simulation; this assignment process is illustrated in Fig. 7.

A time step is assigned to the S phase if the bias voltage is present (IR_{mod} > 0) and the module glass is grounded (RH_{mod} > 85% [19] or rain event). If these conditions are not met, the shunting process is considered to have finished, and the time step is assigned to either the T phase or the R phase. For a time step to be assigned to the T phase, then: 1) the cell type has to exhibit this phase at the current R_{sh} value [14]; 2) the former time step has to be assigned to an S or T phase; and 3) in the case of a preceding T phase, the time elapsed since the beginning of the T phase is not longer than the duration of the T phase.

c) R_{sh} simulation

To describe the R_{sh} progression for the S and R phases, exponential functions were chosen, while for the T phase a polynomial was used [15]. The functions contain fixed and T_{mod}-dependent parameters that have to be determined for the specific module type during the investigation of the R_{sh} kinetics in laboratory experiments [13–15]. Finally the R_{sh} progression is computed for each time step using the experimentally determined parameters of the R_{sh} kinetics, T_{mod} and the classification of the time step.

Model validation

To validate and improve the PID-s model, the R_{sh} progression of framed mini-modules fielded in Thalheim, Germany, at a bias voltage of –1kV was measured and compared with simulation results. A detailed description of the experimental set-up can be found elsewhere [15].

As an example, a comparison between R_{sh} measurements and calculations is shown in Fig. 8. Two one-cell mini-modules, one prone to PID-s (sample type B) and one with APT (sample type A), were investigated. Because of this simple set-up, it is only possible to determine the R_{sh} value without illumination; the periodical measurements are therefore performed at night. The measured night-time R_{sh} values for sample types A and B are shown in Fig. 8 as green and red lines respectively. In addition, simulation results employing meteorological data collected during the time of field exposure are shown for sample types A (dashed green line) and B (dashed red line). Different sets of parameters for the R_{sh} kinetics of sample types A and B were used in the simulation; these were determined using replicas of those sample types in the lab. The T_{mod} used was measured, and the meteorological data were collected in one-minute time intervals.

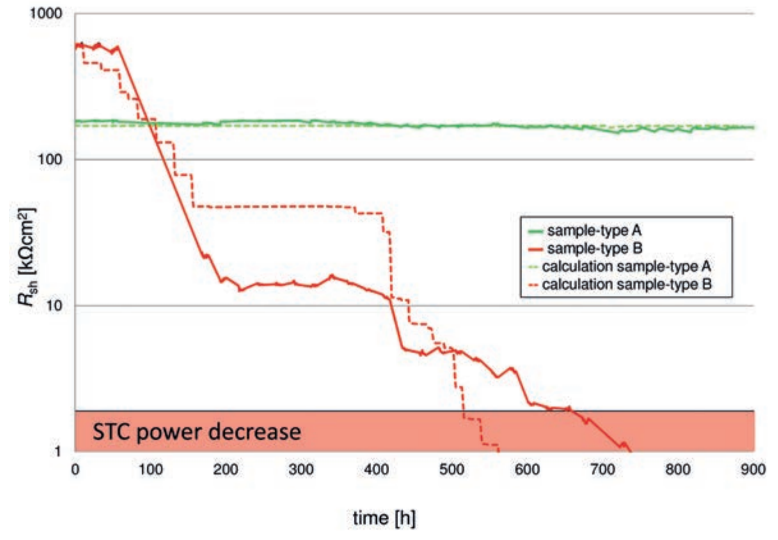


Figure 8. Night-time measurements of R_{sh} over time for two fielded mini-modules, one with APT (sample type A) and one prone to PID-s (sample type B). The corresponding R_{sh} model calculations are also shown (dashed lines).

The first thing to note is that the measurements of the two mini-modules indicate different initial R_{sh} values: whereas for sample type B the intrinsic R_{sh} is about 700kΩcm^2, the value for sample type A is 200kΩcm^2. This difference is due to variations in cell production and does not affect the R_{sh} kinetics caused by PID-s. After 900 hours' field exposure with a daytime bias voltage of –1kV, the sample type A mini-module demonstrates only small changes in the R_{sh} value, revealing no significant impact on the module performance due to PID-s. In contrast, the module of sample type B exhibits a significant decrease in R_{sh}, dropping to a value below that of the onset of the decrease in STC power.

A comparison between measurements and model calculations reveals good qualitative agreement. As predicted by the calculation for sample type A, the PID-s stress does not have a significant effect on the R_{sh} value. For PID-s-prone sample type B, the calculation predicts a rapid decrease in R_{sh}, which is in good agreement with the observed decrease. Nevertheless, there are differences between the model results and the experimental data of the visible progression of R_{sh} for sample type B; these deviations are currently being investigated in detail in order to improve the model and its predictions.

Summary and conclusion

PID-s is one of the most severe forms of PID; in contrast to other types of degradation, the resulting loss of power and energy yield can be very high. A negative potential of p-type solar cells with respect to grounded frames/mounting causes PID-s. Although this negative potential can be completely avoided at the system level, this is not the case for a large number of modern PV systems. PV modules that are able to withstand PID-s stress, at least for the duration of their service life, are therefore essential.

To assess if modules fulfil this endurance requirement, laboratory tests are currently recommended that expose the modules to a certain constant level of PID-s stress for a given amount of time. The stress level and duration of constant accelerated stress tests are usually chosen in such a way that the stress of the complete test is equal to the cumulated stress that occurs under non-constant field conditions during the desired service life. This approach is only feasible, however, for degradation mechanisms that are non-reversible in the field, for which non-coherent stress episodes simply sum up to the total stress.

Unlike other degradation mechanisms, PID-s is reversible under field conditions. Actually, the conditions for regeneration from PID-s are always given, provided no PID-s stress is present; this is always the case at night-time and also on dry days. As a consequence, the level of PID-s of a fielded module is the result of an intricate interplay of phases of degradation and regeneration. This behaviour cannot be replicated in laboratory tests with a constant stress level: the currently recommended laboratory tests for PID-s with constant stress levels are therefore not appropriate for assessing the service life duration of a module, and can only be used for differentiating the susceptibility to PID-s stress and for monitoring the stability of production processes.

"By the use of Anti-PID Technology, Hanwha Q CELLS can guarantee an excellent resistance to PID-s during a module service life of 25 years or more."

For monitoring PID-s resistance of its products on a weekly basis, Hanwha Q CELLS (HQC) uses tests for PID-s with constant stress in accordance with the draft for IEC PID test method 62804. This assures that all products of the Q CELLS brand come with APT. With this technology, Hanwha Q CELLS has implemented a combination of materials and process/design parameters that ensures excellent resistance to PID-s, by considering not only degradation but also the regeneration behaviour regarding PID-s. The expected service life duration with respect to PID-s is assessed by simulating the interplay of degradation and regeneration in non-constant outdoor conditions based on meteorological data. By the use of Anti-PID Technology, Hanwha Q CELLS can guarantee an excellent resistance to PID-s during a module service life of 25 years or more.

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About the Authors

Dr. Christian Taubitz received his Ph.D. in physics in 2010 from the University of Osnabrück, where he investigated the electronic and magnetic structure of magneto-resistant materials. In the same year, he joined the R&D team at Hanwha Q CELLS as a senior technologist. He currently works on the analysis and modelling of PV module failure modes, and specializes in PID.

Matthias Schütze received his Diploma in physics from the University of Halle-Wittenberg in 1998. He then joined the Leibniz Institute for Tropospheric Research in Leipzig, and received his Ph.D., with a thesis topic of the phase transfer of atmospheric trace gases on liquid surfaces. He is currently a senior staff expert in the analysis and modelling of solar cells and modules at Hanwha Q CELLS.

Marcel Kröber received his bachelor's in photovoltaics in 2013 from Anhalt University of Applied Sciences in cooperation with Hanwha Q CELLS GmbH. He is currently working on his master's in renewable energies at the University of Halle-Wittenberg, again in collaboration with Hanwha Q CELLS, with a focus on the investigation and simulation of PID of the shunting type.

Dr. Max B. Koentopp received his Ph.D. in physics from Karlsruhe Institute of Technology (KIT) in 2005. He joined the R&D team at Hanwha Q CELLS in 2009 as a project manager and simulation expert, before advancing to senior manager in 2012. As director of the Analysis & Modeling Department, he is responsible for module reliability testing, cell and module characterization, global test sites, production calibration chains, and device modelling and simulation.

Enquiries

Hanwha Q CELLS GmbH
Corporate Communications

Email: presse@q-cells.com
Tel: +49 (0)3494 6699 10121

Minimizing measurement uncertainties: Challenges for power measurement of high-efficiency c-Si PV modules

Christos Monokroussos, TÜV Rheinland, Shanghai, China, & **Johannes Stang**, TÜV Rheinland, Cologne, Germany

ABSTRACT

High-efficiency (HE) PV technologies, such as heterojunction, back-contact or n-type, can be affected by significant measurement errors compared with conventional technologies; the power measurement of HE crystalline silicon PV modules and cells has therefore been a challenge for the PV industry for at least two decades. To deal with the internal capacitance and the spectral mismatch errors of HE cells and modules, various measurement techniques are currently used: steady-state, multi-flash, dynamic *I–V*, DragonBack™ and dark *I–V* and reconstruction methods, to name a few. This paper discusses the challenges and provides guidance for best practice for acquiring accurate measurements.

Introduction

There are a number of cell concepts on the market that achieve high module efficiencies of 20% or more; among these are selective emitter p-type cells, n-type cells, back-contact solar cells, such as MWT (metallization wrap-through) or IBC (interdigitated back-contact), and heterojunction cells. Most of these cell concepts work with a reduced metallization on the front side to avoid shading effects. While, for example, the IBC concept has both p and n polarities and the junction located on the rear of the device, the MWT concept has both polarities on the rear and the junction on the front of the device.

As a result of increased efficiency and material purity, the module capacitance and carrier lifetime/diffusion lengths have increased. The consequence of the increase in carrier lifetime/diffusion lengths is that the charge carriers of high-efficiency (HE) c-Si PV modules travel longer distances, and thus the PV module becomes spectrally more sensitive in the infrared wavelength range. The high capacitance effect increases with higher voltages; this, together with the improved spectral behaviour, presents challenges for measuring the power of the modules/cells.

> "A crucial challenge for the measurement of HE c-Si PV modules is the spectral mismatch."

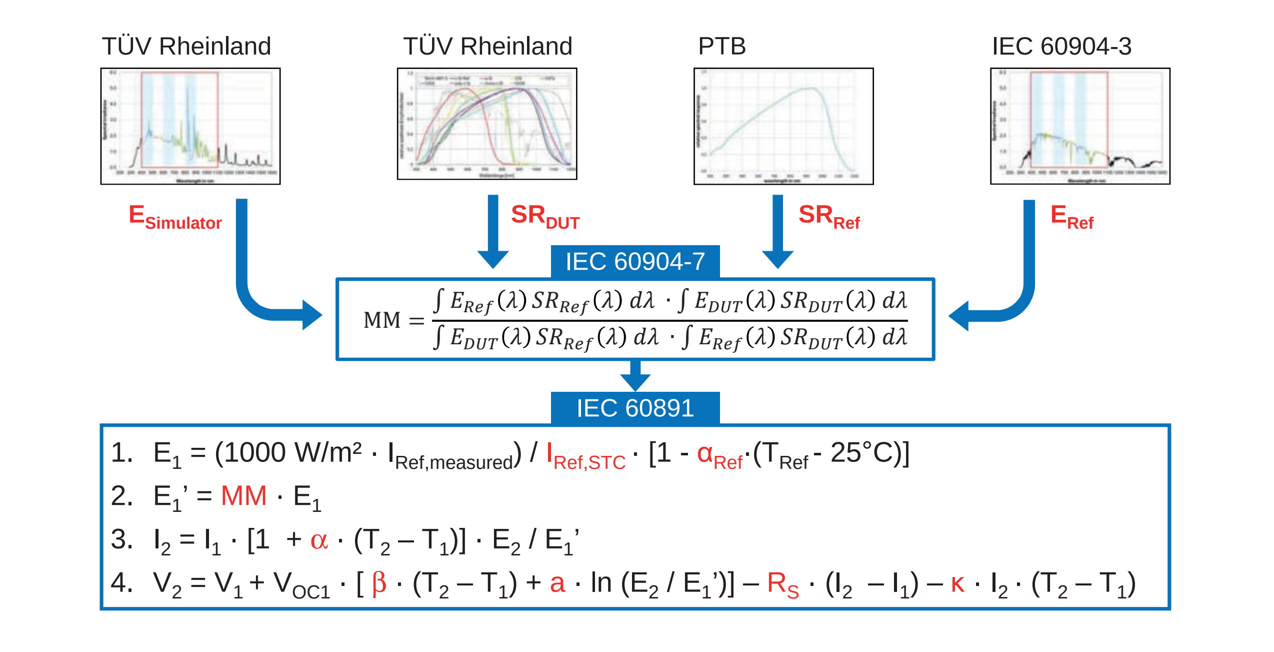

Figure 1. Spectral mismatch and *I–V* curve correction.

Challenges for power measurement

Spectral mismatch

A crucial challenge for the measurement of HE c-Si PV modules is the spectral mismatch, because, compared with standard c-Si PV modules, HE cells have very different relative spectral responses and a significantly higher collection of responses at high wavelengths. The uncorrected spectral mismatch may therefore result in additional measurement errors, potentially exceeding 2%, even for solar simulators with an IEC 60904-9:2007 spectral match A-classification. Because of this, TÜV Rheinland recommends spectral mismatch corrections using a spectral mismatch factor for HE PV modules in particular [1].

The spectral mismatch factor is a correction factor for the irradiance of the solar simulator; it is measured using a calibrated reference device and determined in accordance with IEC 60904-7:2008. The effective irradiance administered to the test module is increased or decreased accordingly to match its output under standard test conditions (STC). The spectral mismatch factor is used to correct the difference between the reference spectral irradiance in accordance with IEC 60904-3:2008 and the measured solar simulator's spectral irradiance in combination with different relative spectral responses of the reference device and the tested PV module [2]. The *I*–*V* curve correction is performed in conjunction with the irradiance and temperature correction in accordance with IEC 60891:2008 (Fig. 1).

In the case of spectral match class A solar simulators, the correction of spectral mismatch can reduce the error contribution to less than 0.4% and significantly improve the accuracy of the performance measurement.

Internal capacitance

The total capacitance of a solar cell consists of the junction, diffusion and transition-carrier capacitances. Junction capacitance, which represents the charge storage in the depletion layer, dominates the cell capacitance in reverse-bias and low forward-bias conditions. Diffusion capacitance corresponds to minority-carrier storage in the quasi-neutral regions of the junction, and becomes significant in forward bias. Transient-carrier capacitance is attributed to the existence of defect and interface states. Diffusion and transient-carrier capacitance have an exponential dependence on the applied voltage; this allows the two to be combined into the free-carrier capacitance [3].

HE c-Si modules are usually highly capacitive, and power measurements can be influenced by sweep-time effects when the *I*–*V* curve scan acquisition times are too fast [4]; as a result, measurement techniques are affected and errors occur. To ensure the power measurement's validity, sweep-time effects can be identified by performing a sweep in both directions, from short-circuit current to open-circuit voltage, and vice versa. The capacitive characteristics depend on the specific technology, and for calibration purposes the appropriate *I*–*V* curve sweep speed needs to be established experimentally.

One solution is to extend the duration of light exposure; however, a longer light exposure can increase the temperature of the cell or module, which can distort the *I*–*V* curve. In addition, the light source has to remain stable for a longer duration, the lifetime of the solar simulator light bulbs is reduced, and the throughput will slow down. To increase the yields and the throughput at the same time, TÜV Rheinland has developed a novel measurement technique: the so-called dynamic *I*–*V* method, which will be discussed later.

Figure 2. TÜV Rheinland pulsed solar simulator.

Figure 3. TÜV Rheinland steady-state solar simulator.

Power measurement techniques

Solar simulators enable the PV industry and testing laboratories to reproducibly determine the *I–V* characteristics of PV devices. In most cases, an indoor pulsed solar simulator (Fig. 2) is used, which delivers *I–V* curves that define the electronic performance of the tested devices. A pulsed solar simulator has the advantage that test conditions, such as temperature or irradiance, can be easily adjusted, thus achieving a high level of reproducibility. Moreover, the tests can be performed independently of changeable outdoor weather conditions.

By adjusting certain parameters, solar simulators can be used in a very accurate way, and uncertainties caused by irradiance and temperature correction can be kept low. Nevertheless, the high capacitance of HE c-Si PV modules complicates the module characterization, because HE c-Si modules often require flash durations that are longer than those achievable by most of the common solar simulators on the market. In spite of this, solutions do exist for measuring the power of a HE c-Si device – for example steady-state, multi-flash and single-flash techniques, among others.

Steady-state measurement

Steady-state solar simulators (Fig. 3) can handle sweep-time effects, because they can be operated with individually adjusted *I–V* curve acquisition times, and with no dependency on the light duration of the optical system. Once the measurement parameter has been adjusted, these simulators usually have a high throughput, and are able to deliver reliable results. The equipment is expensive, however, and maintenance costs are also high (e.g. frequent checks for non-uniformity of light and spectrum, caused by bulb ageing); additionally, the high energy consumption of the system increases the cost per measurement.

The steady-state measurement technique requires a high level of experience and well-trained operators. The temperature, for example, has to be monitored frequently, and in most cases has to be corrected. Even so, temperature non-uniformities over the module area, and positive and negative temperature gradients, can cause errors. Fig. 4 compares measurement results from pulsed and steady-state simulators.

Point-by-point measurement

A rarely used method is the point-by-point *I–V* curve measurement (Fig.

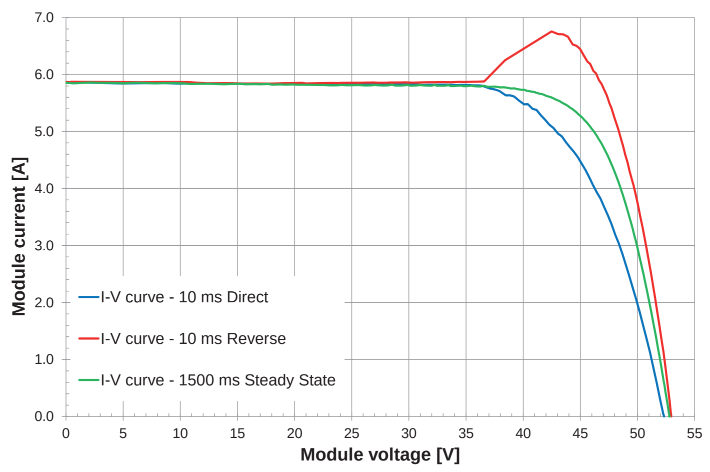

Figure 4. Comparison of measurement results with pulsed and steady-state solar simulators.

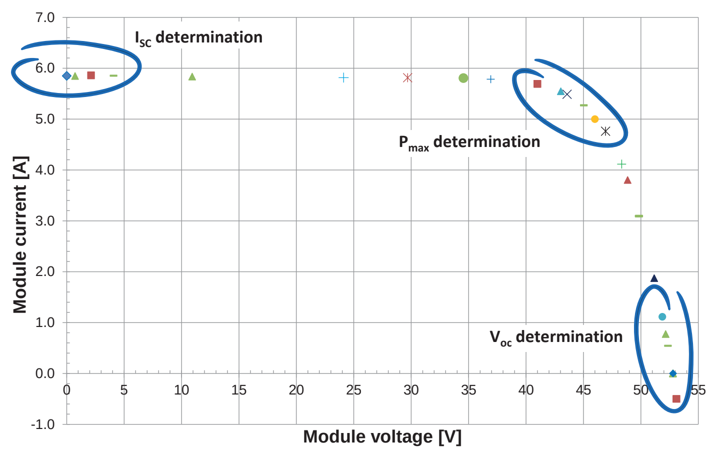

Figure 5. Illustration of the point-by-point measurement method.

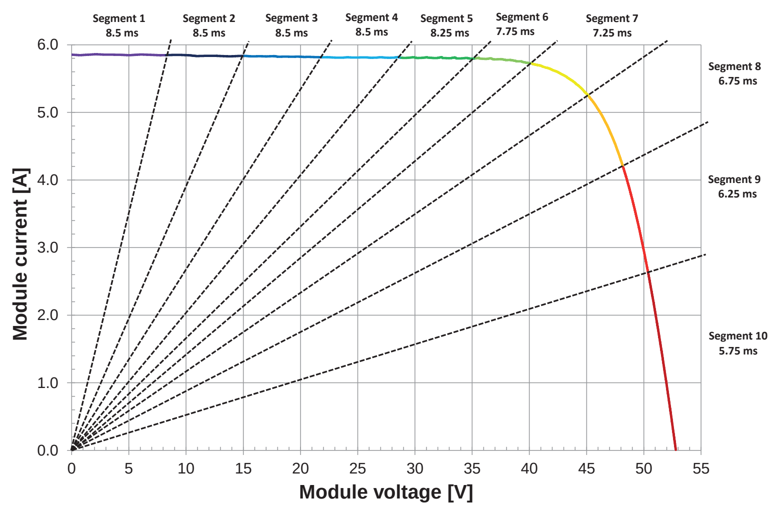

Figure 6. Sequential *I–V* curve measurement using the split-flash method (10 flashes).

PV Modules

PV Modules

5): here, the voltage is kept constant during each single light pulse, and the particular I–V data (irradiance, voltage and current) are determined at single working points in the three most important I–V curve regions of I_{sc}, V_{oc} and P_{max}. The entire I–V curve is then created using these single data points in conjunction with a mathematical interpolation of intervals. The advantage is that the working points can be measured using practically the entire light-pulse duration.

Point-by-point power measurement can be a possible solution for HE c-Si PV modules. The advantage of this measurement technique is that the temperature requires only slight correction, and the device being tested can be prepared more easily with regard to temperature. On the other hand, point-by-point measurement techniques take significantly longer, and between 15 and 20 flashes are necessary in order to achieve reliable results.

Multi-flash *I–V* curve measurement

Another power measurement procedure for PV modules with low to medium-high capacitance is the multi-flash, or so-called 'split-flash', method. Its process and outcome are similar to those of the point-by-point measurement, but with the difference that the I–V curve is measured continuously, avoiding gaps in the data acquisition; it therefore does not rely on subsequent curve fitting. During the measurement, the I–V curve is divided into several segments, which are measured consecutively using the corresponding number of flashes for different subsections (Fig. 6).

This method delivers accurate results, especially for low- and medium-capacitance PV modules, when a reasonable number of flashes are used. However, it is not so reliable in the case of HE PV modules, for which a disproportionately large number of subsections need to be investigated in order to obtain reliable data. For example, the hysteresis (difference between the direct and reverse measurements) of very high capacitance heterojunction PV modules remains at 2%, even if 50 split flashes are used.

To sum up, this procedure requires not only proper documentation but also a great deal of experience in the tuning order and position of every single subsection. In addition, the use of multi-flash pulsed solar simulators for the power measurement of high-

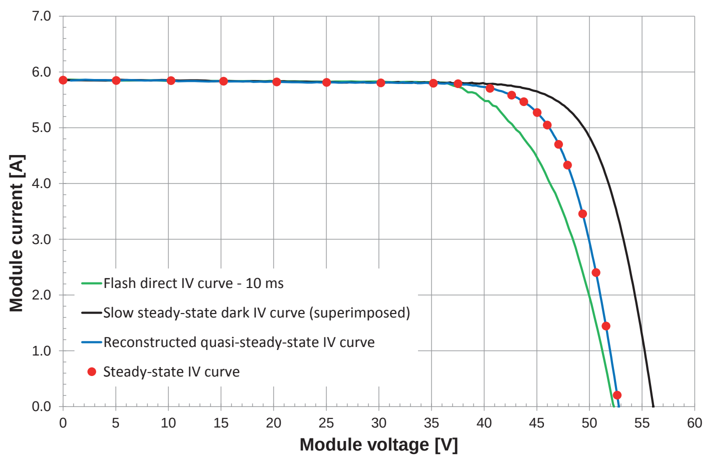

Figure 7. Functional principle of the slow dark *I–V* and reconstruction method.

TÜV Rheinland Shanghai
Measurement method: dynamic *I–V*
Test dates: 14.06.2013 onwards
Total number of projects: 28
Total number of HE modules: 61

Measurement method: multi-flash or steady-state
Total number of projects: 14
Total number of HE modules: 140

TÜV Rheinland Cologne
Measurement method: DragonBack
Test dates: 20.01.2015 onwards
Total number of projects: 5
Total number of HE modules: 16
Total number of PV modules with low-capacitance effects: 171

Measurement method: multi-flash
Test dates: 2013 onwards
Total number of projects: 70
Total number of HE modules: 264
Total number of PV modules with low-capacitance effects: 298

TÜV Rheinland Shanghai/Cologne Test Report Uncertainty
Measurement uncertainty on I_{sc}: 2.4%, k = 2
Measurement uncertainty on P_{max}: 2.5%, k = 2
Measurement uncertainty on V_{oc}: 0.7%, k = 2

Table 1. Measurement statistics.

capacitance modules is very time-consuming and should be restricted to low-capacitance modules.

> **"The use of multi-flash pulsed solar simulators for the power measurement of high-capacitance modules is very time-consuming and should be restricted to low-capacitance modules."**

Dark *I–V* and reconstruction

A method for measuring the *I–V* curve of c-Si high-capacitance PV modules that delivers accurate results has been suggested by Virtuani and Rigamonti [5] at the University of Applied Sciences and Arts of Southern Switzerland (SUPSI). This method relies on obtaining the dark *I–V* of the PV module and its short-circuit current under illumination; the complete *I–V* curve under illumination is then reconstructed by combining this information (Fig. 7). The technique is sensitive to the effect of certain factors, such as the series resistance, on the accuracy of correction. Results presented at EU PVSEC in 2013 [6] were excellent, with errors of < 0.5% in the estimation of P_{max} for one set of technologies (HJT); satisfactory results were also obtained for another set of devices (BCT), where an overestimation of P_{max} by less than 2.5% was achieved.

To achieve reliable results, this method requires that the module's dark and illuminated currents and voltages have a similar reverse saturation current. While the throughput is high, this method demands time and experience.

Dynamic *I–V* and DragonBack methods

The dynamic *I–V* method is a single-flash measurement technique that delivers reliable results for every kind of cell and module technology with a low- to high-capacitance behaviour. This novel technique was developed by the TÜV Rheinland Research and Development team [4], and TÜV Rheinland has been using it since 2013 (see Table 1).

In the dynamic *I–V* method the quasi-steady-state *I–V* curve is sampled by maintaining the voltage constant while the current stabilizes to its capacitance-free response (Fig. 8); the final *I–V* curve measurement accurately and rapidly predicts the actual *I–V* characteristic of the test device. This method allows the electrical characterization of HE devices and yields high measurement quality. The throughput is also high, but the technique is more complicated if *I–V* corrections have to be applied.

Another procedure for measuring HE PV modules is the DragonBack method (Fig. 9), developed by SUPSI-ISAAC and Pasan SA; this method allows the *I–V* characterization of low- to high-capacitance modules without suffering from measurement artefacts. The advantage of this technique is that the *I–V* curve of low-capacitance modules can be measured within one 10ms flash; in addition, it is not necessary to determine the requisite sweep time for the measurement. For medium- and high-capacitance PV modules, however, the procedure is modified to combine standard and split-flash measurements, with up to 10 flashes. TÜV Rheinland also worked with this method in January 2015 (see Table 1).

The DragonBack method is as quick as the dynamic *I–V* method for low-capacitance modules, such as those fabricated with selective emitter p-type cells. Both of these concepts use a selected number of points of the *I–V* curve and rely on interpolation. The achievable throughput is therefore high, which makes dynamic *I–V* and DragonBack promising measurement techniques, especially for HE c-Si modules with high capacitance. The use of these methods, however, requires a great deal of experience.

Conclusion

Measuring the power of HE solar cells is a challenging task that requires specific know-how. The R&D teams of TÜV Rheinland in Cologne and Shanghai have developed several measurement techniques for handling modules with high capacitance and for measuring them precisely. TÜV Rheinland suggests the multi-flash method with a continuous *I–V* curve for modules with lower capacitances,

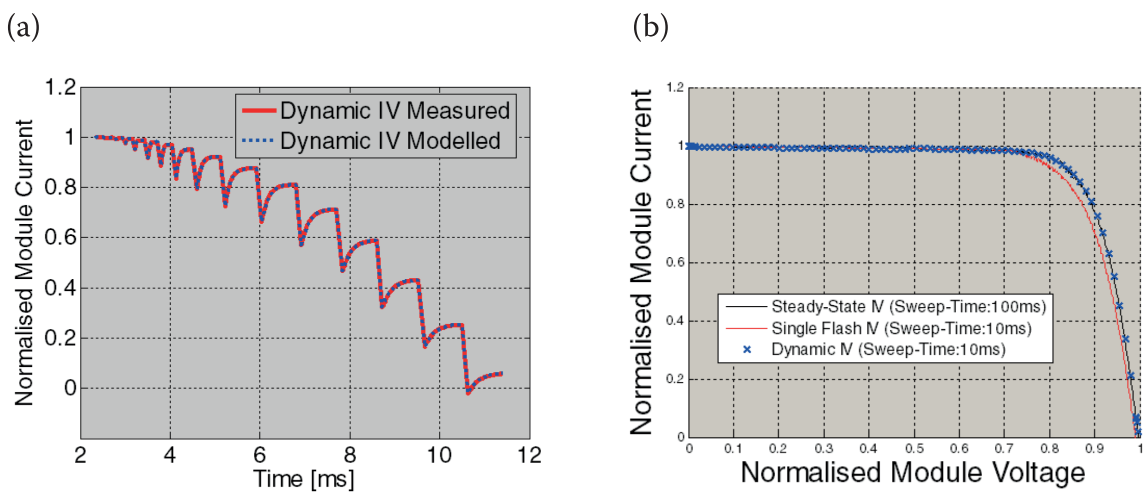

Figure 8. (a) Dynamic *I–V* method with non-linear voltage ramp and stabilized module current. (b) Perfect match of steady-state and dynamic *I–V* characteristics.

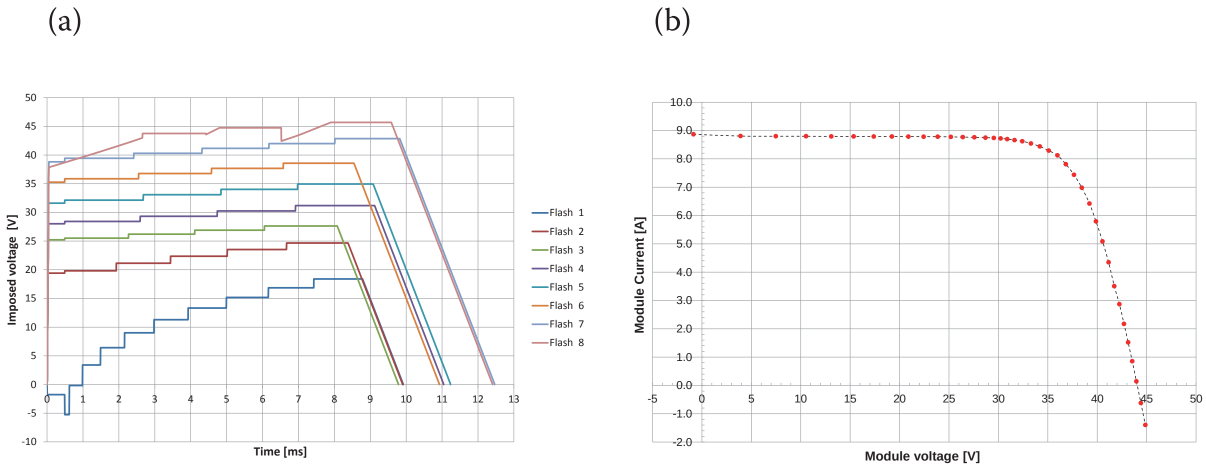

Figure 9. (a) DragonBack method with discontinuous sweep voltage for the measurement of the *I–V* curve within eight single flashes. (b) The resulting *I–V* characteristics created with interpolated data points.

such as selective emitter p-type. The dynamic *I–V* and DragonBack methods are recommended for measuring higher-capacitance PV modules.

"The dynamic *I–V* and DragonBack methods are recommended for measuring higher-capacitance PV modules."

With the use of these techniques, TÜV Rheinland has been able to achieve both high measurement throughputs and accurate measurements at the same time. Last, but not least, spectral mismatch corrections in accordance with IEC 60904-7:2008 are strongly advised, especially for HE PV modules, in order to further reduce measurement uncertainties.

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About the Authors

Christos Monokroussos is a technical expert for photovoltaics at TÜV Rheinland in Shanghai, China, where his activities focus on the characterization of solar cells and PV modules, as well as on the quality control of PV measurement systems. He received his Ph.D. in photovoltaics from the Centre of Renewable Energy Systems Technology (CREST) at Loughborough University, UK.

Johannes Stang is a project engineer for solar energy at TÜV Rheinland in Cologne, Germany, where he works in the fields of qualification, certification and reliability testing. He received a master's for project work on non-destructive spectral-response measurement of solar modules and minimizing measurement errors.

Enquiries

Dr. Christos Monokroussos
TÜV Rheinland (Shanghai) Co., Ltd.
TÜV Building III
No.177, Lane 777
West Guangzhong Road
Zhabei District
200072 Shanghai
China
Email:
Christos.Monokroussos@tuv.com

Johannes Stang
TÜV Rheinland Energie und Umwelt GmbH
Solar Energy Assessment Center Cologne
Am Grauen Stein
51105 Cologne
Germany
Email:
johannes.stang@de.tuv.com

Website: www.tuv.com/solar

Operational sustainability in the field versus the laboratory: PV modules and insulation resistance

Jim Zhu & **Jeff Wang**, Wuxi Suntech Power Co., Ltd., Wuxi, China

ABSTRACT

Poor insulation resistance in modules is one of the primary contributors to module failure. Regimes currently in place to test the insulation resistance of crystalline silicon modules have proved problematic, as the conditions found in a laboratory are not on a par with environmental conditions at installation sites. This paper explores the shortcomings of current testing standards and recommends further tests that should be introduced to prevent module failures in the field.

Introduction

PV module malfunctions can significantly impair the operational performance of solar projects, leading to decreased operating capacity and jeopardizing personnel safety. Since a PV module has no moving parts, its operating life is largely determined by the stability and resistance to corrosion of the materials from which it is constructed. Manufacturers' guarantees of up to 20 years indicate the quality of bulk silicon PV modules currently being produced. Nevertheless, there are several failure modes and degradation mechanisms which may reduce the power output or cause the module to fail. Nearly all of these mechanisms are related to water ingress or temperature stress.

As most people in the PV industry are aware, poor insulation resistance in modules is one of the primary contributors to module failure. This issue causes great concern to customers and manufacturers of PV modules. Even though the international standards for dry-insulation resistance are determined by rigorous laboratory testing procedures, extensive field failures persist. Both PV producers and customers have persistently questioned why PV modules that operate suitably in controlled laboratory settings intermittently malfunction in the field, and have contested the original testing results.

Source: Suntech.

Figure 1. Improved testing regimes are required in order to better understand module insulation resistance.

“Even though the international standards for dry-insulation resistance are determined by rigorous laboratory testing procedures, extensive field failures persist.”

PV Modules

Because of fluctuating weather conditions, PV module field installations do not operate in static, controlled conditions. Inverters very often enter into safe mode and shut down as a result of precipitation, as variations in weather conditions can stimulate energy leakages. In other instances, an inverter failure may be initiated by early morning dew. These situations suggest that PV modules have a low insulation resistance when operating in wet conditions. Nevertheless, when modules are returned to a controlled laboratory environment and retested, the modules function adequately under current testing standards.

Insulation resistance testing

Currently, the measures for internationally permitted insulation resistance tests on crystalline silicon PV modules include the following tests: IEC61215ED2 10.3 Insulation Test, IEC61730-2 mst16 Dielectric Withstand Test, and UL1703 26 Dielectric Voltage Withstand Test. This sequence of tests is performed without illumination and at room temperature and a relative humidity of ≤75%. A study conducted by Suntech scientists, however, reveals that these testing conditions prove to be problematic, as laboratory conditions are not on a par with environmental conditions at installation sites [1].

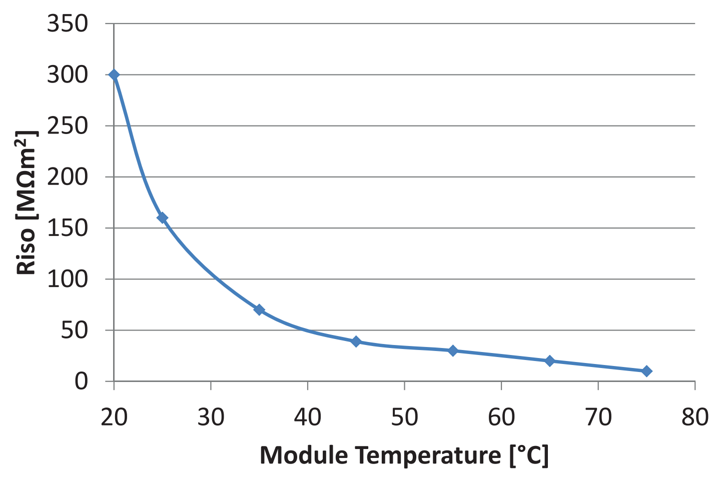

Figure 2. The effect of module temperature on insulation resistance.

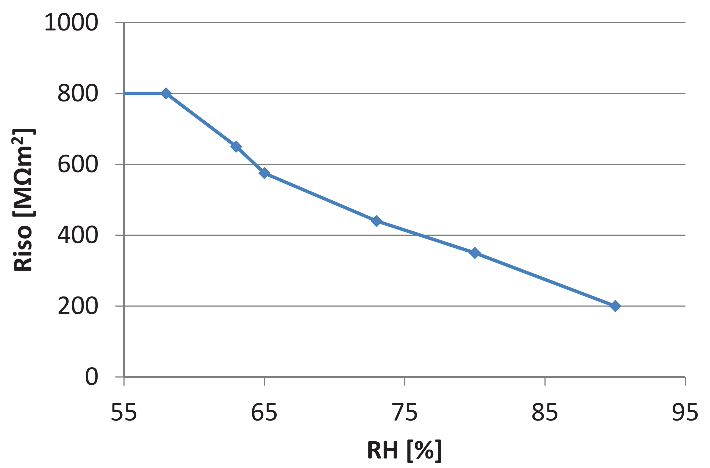

Figure 3. The effect of relative humidity on insulation resistance.

Suntech’s Quality Control team was tasked with examining the discrepancies. In an attempt to reform laboratory testing standards, and in turn reduce field malfunctions, Suntech’s scientists were charged with isolating the integral inconsistencies between international testing standards for PV modules and the actual module operational conditions in the field.

Suntech’s experiments and results

Currently, Suntech has approximately 36 million PV modules installed globally; these modules have an operational failure rate as low as 0.04%. However, within the company’s extensive corporate database, there are some reports of field module failure due to insulation performance deficiencies. Most malfunctions have occurred either in the early morning or on rainy days. The problematic PV panels exhibited a decline in insulation performance, which in turn triggered a leakage current, causing the inverter to shut down.

The team of Suntech scientists collected data for numerous elements that may affect PV module insulation performance; these included module temperature, relative humidity, illumination, and detection timing of system leakage current. The Suntech scientists conducted experiments, and results were established on the basis of each factor.

Module temperature

With regard to increased module temperature, Suntech’s tests revealed that the insulation resistance of a PV module measured at 25°C decreases by 75% when measured under field temperatures of 45°C (Fig. 2). As the field temperature rises, the decline in insulation resistance approaches 90% when the module temperature reaches 60°C.

Relative humidity

The relative humidity results of Suntech’s study confirm that an increase in relative humidity is exceedingly detrimental to the insulation resistance of PV modules. This behaviour poses a challenge, as relative humidity generally surpasses the laboratory standard of 75% in much of the world throughout the year. According to the study, the insulation resistance decreases approximately 50% when the relative humidity increases from 50% to 75%; the resistance drops again by half when the relative humidity rises to 90% (Fig.

3). Relative humidity is a distinct and vital factor impacting the installation capabilities of a PV module once removed from the laboratory and operational in the field.

Illumination

Suntech's Quality Control team also explored the influence of illumination on insulation resistance: the results revealed that illumination induces an increase in module temperature while simultaneously producing a significant decline in resistance. As a stand-alone factor, however, illumination does not have a major influence on resistance.

Leakage current detection

A final factor that interferes with insulation resistance is the inverter settings. Suntech has established that inappropriate and rudimentary inverter settings can be the source of inverter malfunctions and system shut-downs, instigated by a temporary leakage current. The study indicated that the majority of devices have a protective measure that identifies leakage currents within five seconds of system activation.

Tests have shown, however, that there is a higher level of precision and stability 20 seconds after the PV installation is activated. Consequently, by implementing a 20-second delay in shutting down low-level leakage currents, the probability of false or unnecessary errors can be reduced. This factor, coupled with early morning dew, offers the true explanation as to why a considerable number of failures occur and are detected in the morning hours, when PV module installations power up.

"Suntech recommends that current testing standards be enhanced by additional comprehensive testing measures."

Conclusions

Suntech's findings show that the current international standards which are in place for testing insulation resistance are insufficient with regard to the prevention of operational malfunctions of PV modules once installed and functional in the field; furthermore, these standards are insufficient for ensuring personnel safety. Suntech's efforts have revealed that there is a distinct difference between laboratory test conditions and actual field conditions: laboratory testing conditions fail to simulate the increased temperature and high relative humidity that are common in PV installation surroundings. In order to decrease the number of malfunctions in PV module insulation on operational sites, Suntech recommends that current testing standards be enhanced by additional comprehensive testing measures.

Additionally, Suntech strongly recommends that the following tests be added to further reduce field failures: 1) extended dry-insulation test conditions, with a module temperature of 60±2°C and a relative humidity of 85±5%; and 2) extended wet leakage current test conditions, with a test solution temperature of 60±3°C. These testing conditions reflect the environmental and operational reality of PV module installations. If international standard procedures are enhanced through the addition of these tests, manufacturers and customers can experience minimal insulation malfunctions, better quality assurance and higher performance of PV modules with respect to insulation resistance.

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PV Modules

About the Authors

Jim Zhu is the chief scientist of Wuxi Suntech. He 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 of quality management. He has been the company's chief scientist since 2013.

Jeff Wang is director of Wuxi Suntech's Photovoltaic Test Center.

Enquiries

Nickey Zhu
Marketing Specialist, Marketing
Wuxi Suntech Power Co., Ltd.
9 Xinhua Road
New District, Wuxi
Jiangsu Province
214028 China

Tel: +86 510 8531 7090
Email: chanyuan.zhu@suntech-power.com

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News

Global PV installations to surpass 50GW in 2015

Three research and consultancy firms have forecast in separate reports that global PV installations would surpass 50GW in 2015, with predictions from Mercom Capital Group (54.5GW), EnergyTrend (51GW) and IHS (57GW).

IHS also forecast 318GW of solar modules to be installed in the next five years, bringing global cumulative PV installations to 498GW by 2019, a 177% increase from around 180GW at the end of 2014. This will generate average annual installations of nearly 64GW, according to IHS' analysis.

Source: NREL

Separate market assessments have predicted global PV installations to exceed 50GW in 2015.

News

GLOBAL UPDATES

Global installed utility-scale solar jumped 65% in 2014

The total installed capacity of utility-scale solar jumped 65% in 2014, according to figures released by Wiki-Solar.org.

The website, which tracks the installation of >5MW solar installs across the globe, claims that there was a total of 35.9GW of utility-scale solar capacity at the end of 2014. The total marks a 14.2GW jump from 2013.

The UK has spearheaded a return to growth for the utility-scale solar sector in Europe, according to the figures.

Wiki-Solar states that capacity is fairly evenly split across the three leading continents: Asia, Europe and North America. However, 2014 marked the first year since 2011 that the European market for utility-scale solar experienced growth following declines in 2012 and 2013.

Philip Wolfe, founder of Wiki-Solar said: "Europe's resurgence – after the 2012 policy changes in the traditional powerhouse of Germany – has been fuelled mainly by a buoyant British market."

Study shows solar energy becoming cheapest power source

Solar power is becoming the most inexpensive source of power in many parts of the world, according to a study by the Fraunhofer Institute for Solar Energy Systems and commissioned by Agora Energiewende, an independent German think-tank.

The study, the 'Current and Future Costs of Photovoltaics', states that by 2025 the cost of producing power in central and southern Europe will be between four and six cents per kilowatt hour, and by 2050, it will be down to two to four cents.

The study used the most conservative figures, leaving out the possibilities of large breakthroughs within the time studied.

National PV market updates

China officially installed 5.04GW of new solar capacity in Q1

Figures released by China's National Energy Administration (NEA) show a combined total of 5.04GW of new solar capacity was grid connected in the first quarter of 2015.

The NEA said that the 5.04GW total included 4.38GW of utility-scale solar power plants and 660MW of distributed generation installations.

Cumulative solar capacity was said to have reached 33.12GW at the end of the first quarter of 2015, which included 27.79GW of utility-scale projects and 5.3GW of distributed generation capacity.

India hits 3.38GW of PV despite missed annual target

India now has around 3.38GW of grid-connected solar installed, according to official figures from the country's Ministry of New and Renewable Energy (MNRE).

The country has made significant strides in clean energy over the past few years. PV Tech reported almost exactly two years ago that the cumulative installed capacity of solar in India was less than half of what it is today when it stood at 1.4GW in March 2013.

The government of Narendra Modi, which came into power in May last year set the bar even higher, with the country now having in place a "100GW of solar by 2022" target.

Source: IBC Solar

India has surpassed 3.38GW of grid-connected PV power.

Source: JA Solar

China's 2015 PV target will help stabilize module prices, according to EnergyTrend.

News

US installed 6.2GW of solar PV in 2014, report confirms

The US installed 6.2GW of solar PV in 2014, according to a new report by GTM Research and the Solar Energy Industries Association (SEIA).

The figure represents a year-on-year increase of 30%. There was also 767MW of concentrated solar power capacity added. The residential sector installed 1.2GW last year, the first time it surpassed the 1GW mark. More than 500MW of this was installed without any state-level support, another first.

New US large-scale solar installations fall 84% in early 2015

The amount of new large-scale solar installations in the US in the first two months of 2015 fell 84% year on year, with just 16MW of additional capacity added in February.

Data issued on Thursday by the US Federal Energy Regulatory Commission revealed that a total of eight new units with a total capacity of 16MW were added to the US grid last month, contributing towards a total of 68MW added from 13 separate projects in the first two months of the year combined.

This represents a drastic fall on last year's total, when 44 projects with a combined capacity of 437MW were installed during the same period.

And the February 2015 total is also down 84% on February's total last year, when 97MW of solar power generation was installed.

European PV market declined by 36% in 2014 - EPIA

New PV installations were down 36% in 2014, it was announced at the 10th annual Market Workshop of the European Photovoltaic Industry Association (EPIA).

Europe installations declined from 11GW installed in 2013 to just 7GW the following year.

In other reports, Italy installed only 385MW in 2014, while Belgium installed just 65MW.

Meanwhile UK government figures showed solar PV generation almost doubled in 2014 with an increase of 93% in 2014 to 3.9TW.

The UK government also reported that US$17.6 billion has been invested in the UK's solar PV sector between 2010 and 2014.

Component trends

IHS: Commercial PV to drive BOS market up to US$19 billion by 2019

The worldwide market for balance of systems (BOS) for solar power could be worth US$21 billion by 2019, with the greatest activity expected to be seen in the commercial sector, according to a new report from analysis firm IHS.

The IHS report, 'PV Balance of System Equipment – 2015', highlighted that the sector as a whole could grow by 5% annually.

Meanwhile as much as 11.5GW of non-PV-module-related hardware costs, such as mounting systems and inverters, could be installed in the commercial sector alone. This is likely to be the case in part because many maturing markets move away from their subsidy-driven utility-scale sector build-outs.

Solar module prices set to stabilise on China's 2015 17.8GW install target – EnergyTrend

Market research firm EnergyTrend expects PV module pricing to stabilize and production and utilization rates to improve after China's National Energy Administration (NEA) raised the country's overall PV installation target from 15GW to 17.8GW in 2015.

Although module ASP declines have moderated significantly in 2014 due to continued growing global demand, overcapacity remains an issue.

China's production of PV modules totalled 35GW in 2014, with the top 10 domestic manufacturers accounting for 56% of total production with capacity utilization rates of close to 90%.

However, PV module manufacturers in China with less than 500MW of capacity were said to have average production utilization rates as low as 72%.

China's new 2015 installation target was therefore expected to provide almost immediate relief for manufacturers struggling with anti-dumping duties in the US and Europe.

Finance and support

Yieldcos and ITC sunset drive buoyant quarter for solar funding

The growth of solar yieldcos and the pending decrease in the US investment tax credit ensured a buoyant first quarter of 2015 for corporate funding of the global sector, according to clean-tech research firm, Mercom.

Mercom's latest quarterly analysis reveals global funding of solar from venture capital, debt financing, and public market financing raised by public companies hit US$6.4 billion in Q1 2015, almost double the US$3.4 billion raised in Q4 2014.

The bulk of the increased funding seen in the quarter came from debt financing, which surged from US$1.5 billion in the last quarter to almost US$5 billion in Q1 2015.

Germany and UK submit tenders for PV and other renewables

Just five solar projects totalling 72MW won contracts in a UK government auction in which PV competed with other renewable energy technologies for the first time.

The Department for Energy and Climate Change unveiled the 27 winning projects in the first contracts for difference (CfD) auction, under which the most competitive bids receive 15-year contracts at a guaranteed 'strike price'.

Solar PV was forced to compete with onshore wind for a share of the pot.

Meanwhile Germany's Federal Network Agency has announced the first tender for ground-mounted photovoltaic systems.

Germany received more than 170 submissions for its first competitive large-scale solar PV tender, leaving the round significantly oversubscribed.

Materials and advanced cell concepts under the microscope in latest PV roadmap

Ben Willis, Head of Content, *Photovoltaics International*

ABSTRACT
As the upstream PV industry enters a new phase of growth, manufacturers are seeking new strategies and technologies to enable them to continue to cut costs and remain competitive. The sixth edition of the annual International Technology Roadmap for Photovoltaic describes the key trends likely to shape the PV sector in the coming year. This paper analyses some of the most promising areas for development.

Introduction

After several difficult years for the upstream PV industry, recent months have seen positive momentum building as supply and demand have returned to some sort of equilibrium. ASPs have begun to stabilize, or at least have not declined as quickly as they had been doing, prompting market research firm IHS to predict four-year record high profits for the module manufacturers this year of US$5bn – double last year's total (see Table 1).

The extent to which manufacturers are now investing in new production capacity certainly bears this forecast out. It is equally clear, however, that not all parts of the supply chain are yet feeling the effects. The latest analysis by SEMI of PV equipment manufacturer performance, for example, shows a year-on-year decrease in both order bookings and billings, and the ratio between the two – the number of orders fulfilled – remaining below parity. This is an indicator that the headline figures do not tell the full story.

"Recent months have seen positive momentum building as supply and demand have returned to some sort of equilibrium."

That message – of a tentative upturn – is at the heart of the latest edition of the International Technology Roadmap for Photovoltaic (ITRPV) [1]. Launched at the SNEC expo in Shanghai at the end of April, the ITRPV, now in its sixth iteration, is published annually with the aim of informing the industry about anticipated technology trends in the field of crystalline silicon PV.

The roadmap acknowledges the industry's ongoing efforts to cut costs and remain competitive through ongoing innovation, highlighting the fact that in 2014 several manufacturers reported a return to profitability as a reward for their efforts.

As in previous editions, however, the roadmap is clear on the need for industry

Source: GT Advanced Technologies.

Figure 1. Polysilicon is one of the areas identified by the ITRPV as offering the most potential for further cost reductions in PV manufacturing.

to maintain its historical 'learning rate' – the rate at which ASPs decline relative to module shipments – of around 20% (Fig. 2). This will be achieved through the introduction of advanced cell concepts, improved module technologies and new production processes that significantly reduce manufacturing costs. Such ongoing innovation will be an intrinsic factor in PV's ongoing competitiveness and therefore sustainability.

Materials

Recent analysis of polysilicon prices on PV Tech, Photovoltaics International's sister website, has revealed the delicate nature of the interplay between polysilicon supply, PV module capacity expansions, and downstream demand in the coming year. The rebalancing of supply with growing demand for modules, and the consequential uptick in capacity expansions, would suggest a parallel growth demand for polysilicon. In early May, however, REC Silicon reported a sharp drop in sales as a number of factors, including weaker than expected demand from China, coincided.

This indication that business for polysilicon producers remains unpredictable is reflected in recent erratic polysilicon pricing. In 2014 a mid-year peak of US$23/kg was predicted, followed by a drop back in pricing to US$18–20/kg by the end of the year and possibly beyond. This seems borne out by the REC Silicon case, with the company revealing it had seen a 7.9% fall in prices in the first quarter of 2015.

With polysilicon remaining the most expensive individual material in a module, according to the roadmap, cutting costs in this part of the value chain would seem to be an ongoing necessity, regardless of the peaks and troughs in demand and pricing; the ITRPV acknowledges this fact, citing it as an area with significant potential for cost reductions.

With this in mind the roadmap says it expects fluidized-bed reactor (FBR) technology to increase its share in relation to silicon made using the Siemens process (Fig. 3). Other processes, such as upgraded metallurgical-grade silicon (umg-Si), are not expected to gain any significant market share at the expense of the other two processes, as they are unlikely to demonstrate any major cost advantages. Nevertheless, they will remain available on the market; for example, one US-based firm, Silicor Materials (formerly Calisolar) is pursuing plans to develop a umg-Si plant in Iceland, which it claims will offer significant cost advantages over conventionally produced polysilicon.

The roadmap cites the ongoing roll-out of diamond wire sawing in wafer production as a significant development, offering the potential to cut wafering process costs.

	PV modules 2014	2015	Y/Y change
Shipments	48GW	61GW	+27%
Revenues	$31bn	$38bn	+20%
Gross margins	7%	13%	+6%
Gross profit	$2.3bn	$5bn	+117%

Table 1. Estimate of module manufacturers' profits in 2015.

Source: IHS PV Market Integrated Tracker.

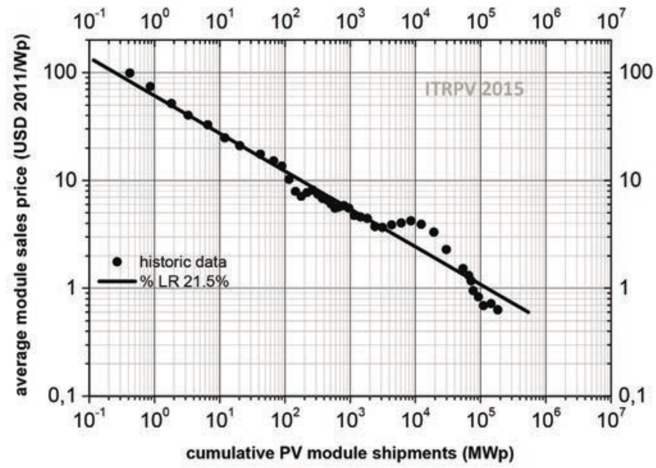


Figure 2. Learning curve for module price as a function of cumulative PV module shipments.

Source: ITRPV.

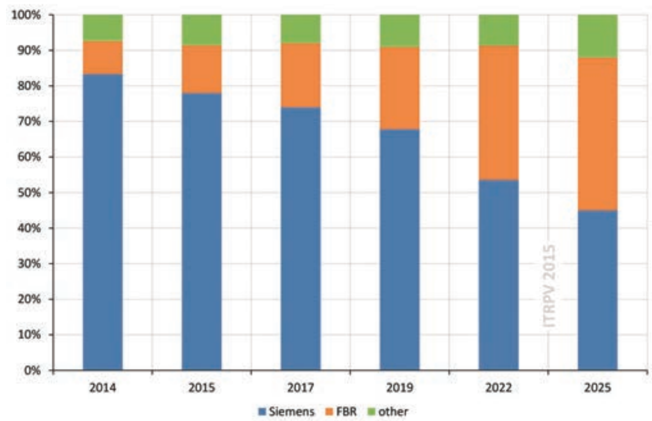


Figure 3. Expected change in the distribution of poly-Si production techniques.

Source: ITRPV.

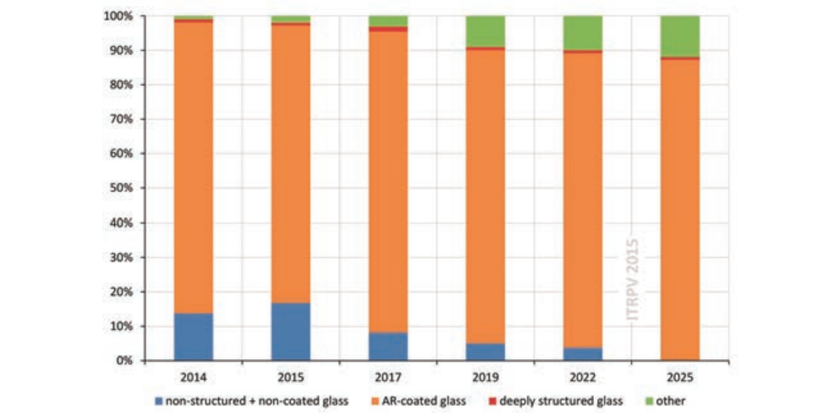
Slurry-based wafer sawing is currently the dominant technology, but diamond wire sawing is maturing in mono-Si wafering and thus becoming more widespread.

The same is expected in multicrystalline wafering, with the roadmap predicting significant market share gains for diamond wire use at the expense of slurry-based techniques over the next 10 years. Other new manufacturing technologies, particularly kerfless, are not expected to get above 5% in market share terms.

Material costs are also a consideration in the final production of modules. One of the principal materials used in module production is the glass that covers the front of a panel. The roadmap points out that anti-reflection coatings have become commonplace on the front cover glass as a means of improving optical performance. Consequently, AR-coated glass is set to remain the dominant force in c-Si modules for the next 10 years, with an expected market share of over 80% by 2025 (Fig. 4).

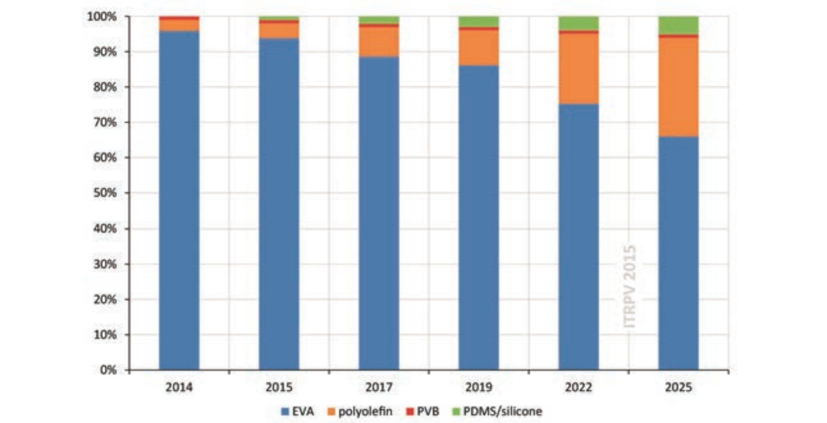
One issue highlighted by the roadmap is that not all coatings on the market

Market Watch



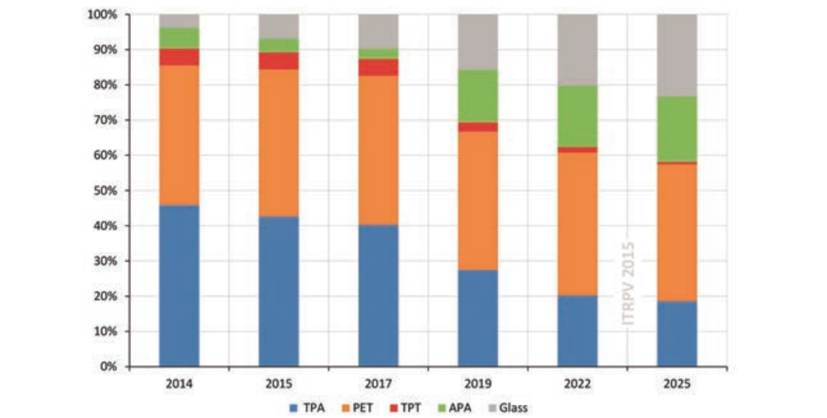
Source: ITRPV.

Figure 4. Expected relative market share of different front cover materials.



Source: ITRPV.

Figure 5. Expected market shares for different encapsulation materials.



Source: ITRPV.

Figure 6. Expected market shares for different module backsheet materials.

perform equally well under various outdoor conditions over a module's life cycle, raising questions over their stability. However, the ITRPV suggests there is a clear trend towards improved service lifetimes among coating brands, indicating that most products should be in line with expected module service lifetimes within the next five years.

Two other key components of a module – the encapsulant and backsheet materials – are also explored by the ITRPV. Encapsulants have been the subject of intensive development work aimed at reducing costs. The roadmap predicts that, although EVA will remain the dominant encapsulant type for the foreseeable future, these efforts will see polyolefin-based materials grow from a market share of 2% in 2014 to around 30% in 2025 (Fig. 5).

This trend towards alternative materials is even more pronounced where backsheets are concerned, with the market share of TPA expected to decline and that of both APA and glass to increase, reaching 25% and 20% respectively by 2025. PET backsheets are expected to retain their current share of around 40% (Fig. 6).

Processes

Another key area for reducing costs is in the development of new and more-productive manufacturing processes.

The ITRPV confirms a trend identified in previous issues towards larger ingot mass as a method for increasing throughput: 'Gen 6' and 'Gen7' ingots of 1,000kg are now being commonly manufactured on production lines today, with greater masses anticipated for casted silicon and Czochralski/Continuous Czochralski (Cz/CCz) mono-Si ingots alike. Casted silicon ingots are expected to reach 1,200kg within four years with the transition to 'Gen8' production, while the mass of mono ingots, driven by CCz technology, will double over the next 10 years, to 300kg.

Aside from the greater throughput made possible by increased ingot size, two other important manufacturing advances are the increased throughput and yield from sawing. As regards throughput, the roadmap predicts an increase of 20–25% over the next 10 years for both slurry-based and diamond wire sawing.

Where yield enhancement is concerned, the optimization of kerf loss during sawing is a key consideration, as it allows an improvement in productivity – as opposed to just throughput – in wafering. As things stand, kerf loss in diamond wire is around 20 microns less than the 150 microns lost through slurry-based sawing; for both technologies the roadmap predicts that kerf loss will decline by around 25 microns in the next decade.

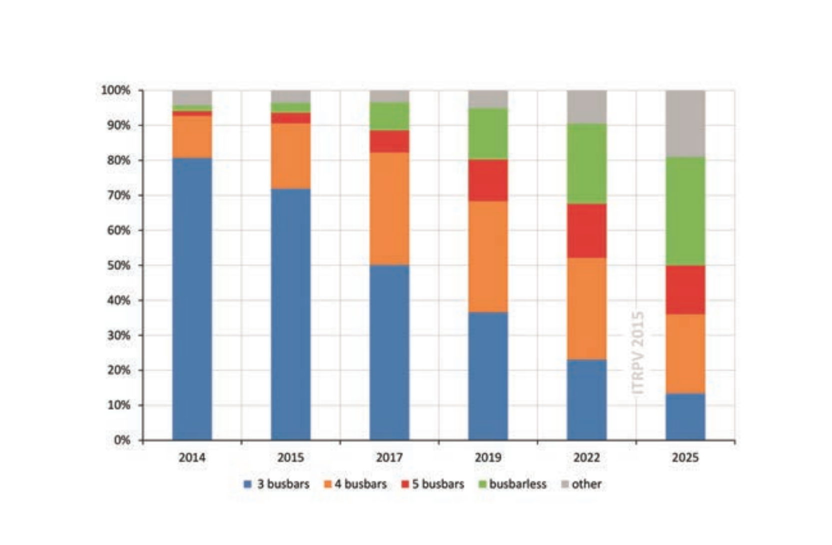
Beyond ingot and wafer production processes, the ITRPV also focuses on emerging trends in metallization. Within this area, one key development highlighted in the latest roadmap edition is the number of busbars used in cell layout. The three-busbar layout currently dominates the industry, but the roadmap envisages that this will be replaced in the next few years by four- or even five-busbar designs (Fig. 7).

That trend is already well in evidence. Prior to SNEC in April, Chinese firm Suntech said it was upgrading all its cell manufacturing capacity from three- to four-busbar layout, then during the show unveiled a new module line – dubbed 'HyPro' – incorporating the new four-busbar cells. Hanwha Q CELLS revealed a similar progression to four-busbar design during SNEC in its HSL S series modules, while shortly after SNEC, SolarWorld disclosed that some of its US production would be upgraded to five-busbar technology alongside a previously announced shift to PERC (passivated emitter rear cell) cell technology.

Products

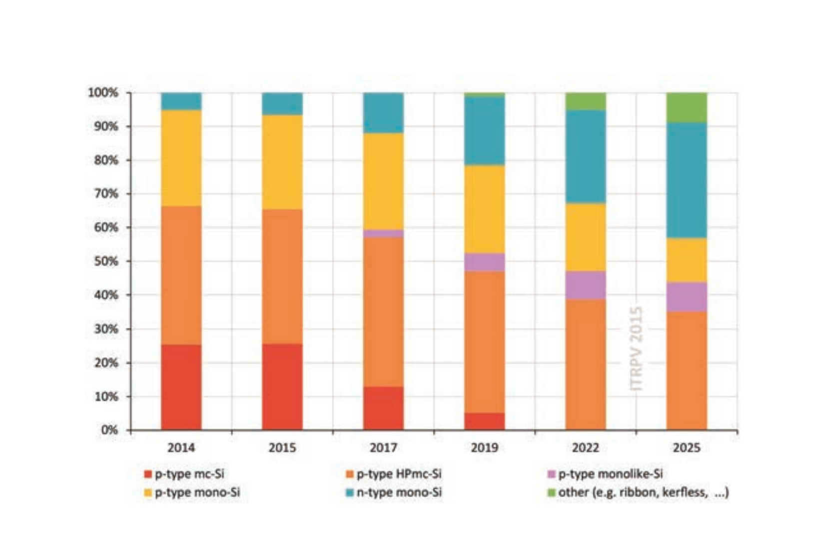
Since the emergence of the first signs of an upturn for the battered PV manufacturing industry last year, debate has been focused on which of the cell and module technologies that have been under development will emerge as the industry's workhorses as it enters a new phase of growth.

Until now that title has arguably been held by mc-Si cell-based modules, which make up for generally lower efficiencies with cheaper production processes. This year mc-Si cells are expected to achieve a market share of over 60%. However, that is set to change.



Source: ITRPV.

Figure 7. Worldwide market share for different busbar technologies.



Source: ITRPV.

Figure 8. Worldwide market share for different wafer types.

> "By 2025, according to the ITRPV, mono-Si cell technology will have developed from a minority player to one with a 47% market share."

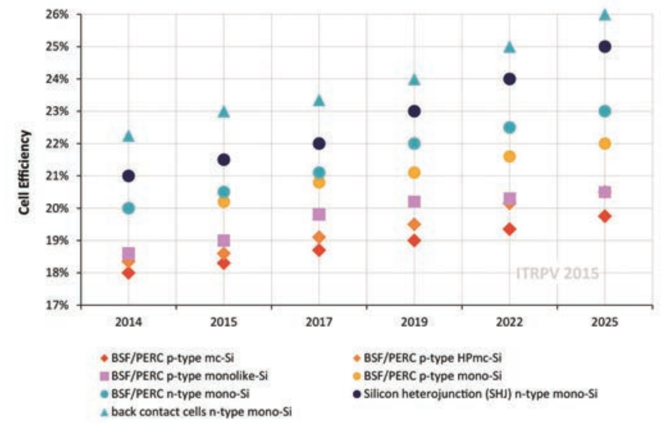
By 2025, according to the ITRPV, mono-Si cell technology will have developed from a minority player to one with a 47% market share. Within this, n-type mono, with its offer of higher efficiencies, will become the main player at the expense of p-type mono-Si, whose share will roughly halve within the next 10 years.

On the mc-Si side, while cells using this material will lose out in absolute terms, high-performance p-type mc-Si will grow in importance and replace 'conventional' mc-Si altogether by 2022. Mono-like, or quasi-mono, which has all but disappeared, is expected to make a limited comeback, with an 8% market share by 2025 (Fig. 8). ReneSola is currently the main exponent of quasi-mono technology.

Regardless of wafer material, the roadmap reveals plenty of room for improved efficiencies in most of the main crystalline silicon technologies. Perhaps unsurprisingly, the greatest scope for efficiency improvements is in the advanced n-type mono-Si family of cells; this has been extensively explored in a previous issue of this journal [2]. Broadly speaking, n-type cells offer a host of benefits, including greater resistance to degradation, not to mention the previously discussed performance advantages. The only barrier has been cost, but that has mainly been a function of economies of scale rather than any fundamental technology-related expense. Parity between p- and n-type technologies is therefore expected by around 2018, after which n-type will start to grow in dominance (Fig. 9).

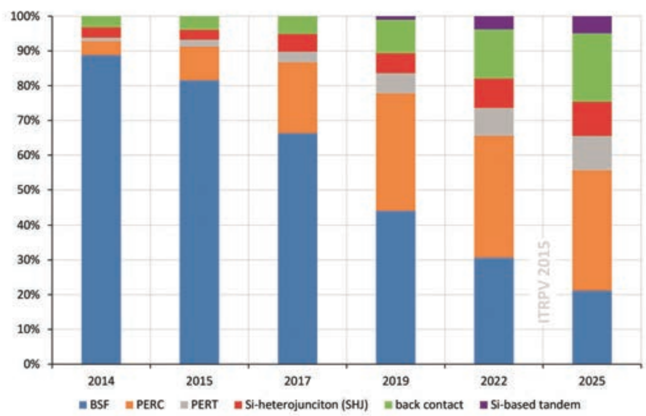
Another landmark identified in the roadmap is in the improvement in mc-Si cell efficiencies. Some of these, having loitered in the upper teens, are predicted by the ITRPV to exceed the 20% mark in mass production within the next few years, led by high-performance p-type PERC variants. The first glimpse of this came earlier this year, when China's Trina Solar revealed it had achieved a 19.14% conversion efficiency in a prototype mc-Si module using its p-type PERC technology.

On the subject of PERC, this would seem to be a cell technology whose time has well and truly come. In the first quarter and a bit of 2015, production line upgrades announced by several leading manufacturers – Suntech, SolarWorld and JinkoSolar to name a few – have included PERC technology. This is underlined by the roadmap's predictions, which foresee PERC's market share eating into that of back-surface field (BSF) cells, the current dominant player (Fig. 10).



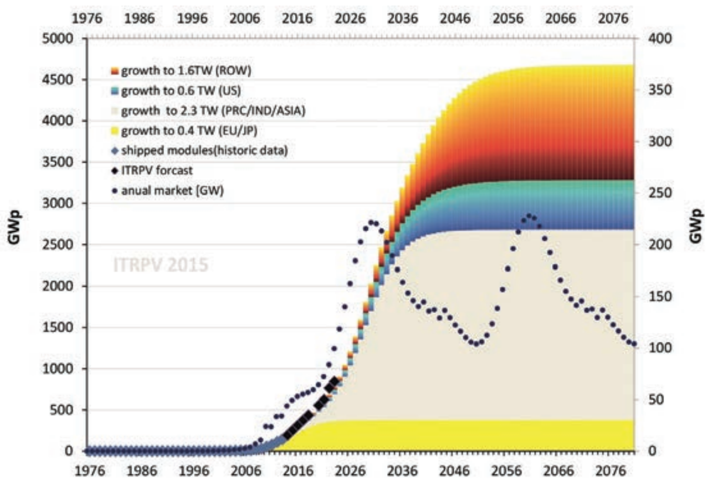
Source: ITRPV.

Figure 9. Average stabilized efficiency values for Si solar cells (156mm × 156mm).



Source: ITRPV.

Figure 10. Worldwide market shares for different cell technologies.



Source: ITRPV.

Figure 11. Cumulative installed module power calculated with a logistic growth approximation for different regions based on the IEA predictions of approximately 4.7TWp installed PV module power in 2050.

Heterojunction cells too are expected to see wider take-up, with a market share of 10% by 2025. The roadmap also predicts that an increasing number of cells will be bifacial – sensitive to light on both sides. Beginning in 2014, the ITRPV estimates that bifacial cell take-up will steadily increase to around a 20% share by 2025. This trend will not necessarily be reflected in bifacial modules, as not all bifacial cells will be integrated into bifacial modules with transparent backsheets or glass–glass construction, according to the roadmap.

> "ITRPV anticipates PV production demand peaking in 2030 at 220GW, then declining to around 100GW by 2050."

Outlook

On the basis of simple modelling of demand over the coming decades, the ITRPV anticipates PV production demand peaking in 2030 at 220GW, then declining to around 100GW by 2050. This up-and-down cycle will repeat itself as old systems are replaced (Fig. 11).

This modelling is based on International Energy Agency (IEA) figures, which are recognized for being conservative where solar and other renewables are concerned, and so should be treated with some caution. However, the ITRPV message is that there will be no 'endless' market for PV modules and that 'endless' capacity expansions will not therefore be needed.

Nevertheless, the roadmap describes the opportunities for PV manufacturing as 'considerable', with ongoing technology upgrades, the replacement of worn-out equipment, and 'modest' capacity expansions combining to constitute a considerable business segment in the coming years.

The roadmap concludes: "Current activities for increasing module power and cell efficiency, ensuring more efficient wafering and poly-Si usage, and achieving a higher utilization of production capacities as discussed in this ITRPV edition will help manufacturers with their efforts to supply the market with highly competitive and reliable c-Si PV power generation products in the years to come."

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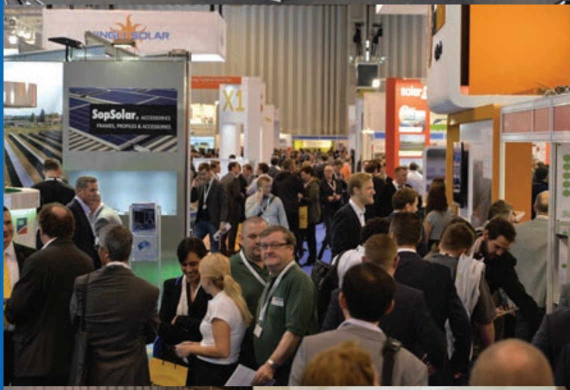
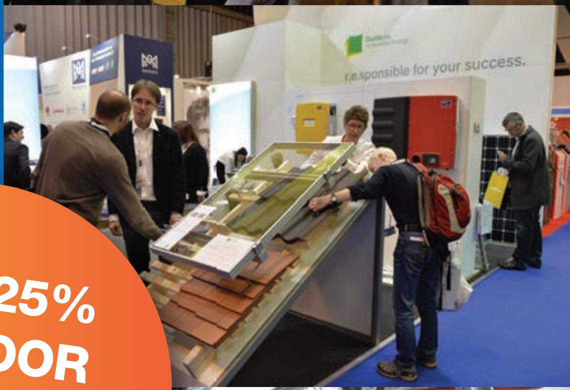


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N-type silicon solar cell technology: ready for take off?

Why are the two c-Si solar cell concepts with the highest efficiency, IBC from SunPower and HIT from Panasonic, based on n-type technology and out there for a very long time? Why is almost 90% of PV production still based on p-type c-Si technology? Will that change in the future? The latter has been one of the most-discussed questions in c-Si PV for a few years now. in March the Silicon conference and more specifically the 5th nPV workshop and HERCULES workshop addressed this topic, showing improvements in p- and n-type Si technologies.

The reason why p-type technology is dominant today has definitely mostly a historical background. The history and past status was described in the twenty-first edition of *Photovoltaics International* in 2013. So we are very confident, also in agreement with the ITRPV consortium, that n-type technology will gain more and more importance in the share of technologies, as many companies are upgrading their p-type or n-type cell lines and even investing in new capacities, as summarized at the end of this blog post. As depicted in Figure 1 the PV world in future will be divided into high-performance (HP) p-type mc-Si cells with >22% efficiencies and n-type cells with >25% efficiencies.

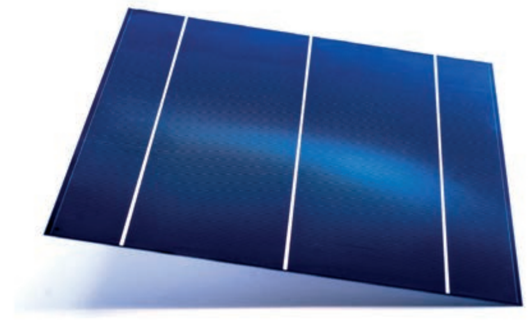
Material

The fact that the two cell technologies featuring the highest efficiencies in industrial production are based on n-type Cz-Si wafer is a striking demonstration of why n-type wafers are the most suitable material for high-efficiency solar cells. Going more into details, there are some physical reasons for the superiority of n-type versus p-type, the most important are:

- due to absence of boron, there is no light-induced degradation (LID) occurring in p-type Si wafers, due to boron-oxygen complexes
- as n-type Si is less sensitive to prominent metallic impurities, in general the minority carrier diffusion lengths in n-type Cz-Si are significantly higher compared to p-type Cz-Si
- n-type Si is less prone to degradation during high temperature processes such as B-diffusion.

Accordingly it can be assumed that, in order to guarantee an electrical quality in the wafers that is sufficiently high for the fabrication of solar cells with a cell efficiency of over 20% (in particular regarding the minority charge carrier diffusion length), 'average' to 'high' quality wafers are required for p-type, while for n-type 'low' to 'average' should be sufficient. Taking for granted that the wafer prices indicated in Figure 2 are related to the wafer quality, currently, the wafers for such solar cells should be priced in the range of US$1.08-1.22 in the case of p-type, while suitable n-type wafers have a price ranging from US$1.25-1.30.

Accordingly, depending on the individual supply situation, n-type wafers can be up to 20% more expensive than p-type wafers. However, experts in industrial Cz-Si crystal growth agree that – apart from a wider resistivity distribution over one crystal – there is no technological difference between the growths of p- and n-type crystals that would explain an increased manufacturing cost for n-type wafers. Therefore it all comes down to economy of scale: currently, more than 80% of the worldwide Cz-Si crystal production capacity for PV is dedicated to p-type. According to the expectations of the latest ITRPV (see Figure 1) parity between p- and n-type productions will be nearly achieved by 2018. Then, at the latest, all cell manufacturers should have access to n-type wafers at the same price as p-type wafers. Vertical integration into crystal growth and wafering would be a way for cell manufacturers to achieve the breakeven earlier.



Source: IMEC.

An n-type PERT solar cell.

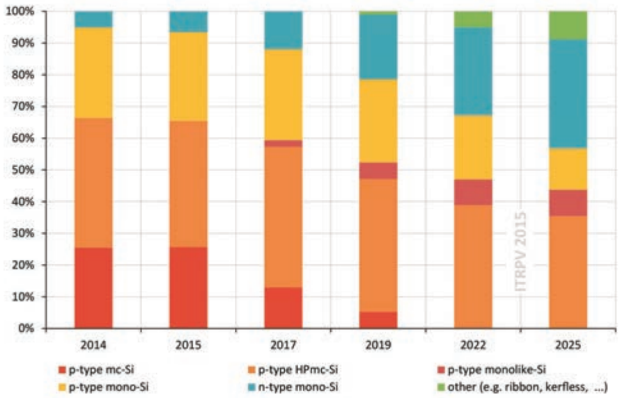
The growing market share of n-type and the availability of n-type modules at standard price levels will also result in a higher awareness among end-users regarding the LID issue of p-type modules, highlighting another benefit of n-type in terms of levelized cost of energy (LCOE).

One of the possible solutions for avoiding LID in p-type, apart from using more costly Cz-Si with low oxygen content, is the permanent deactivation of the B-O-complexes by a combined heat-illumination treatment. Equipment that is capable of performing this treatment in a reliable way with industrial throughput is currently under development at some equipment suppliers, such as Centrotherm.

In conclusion, considering that cell concepts enabling efficiencies significantly exceeding 21% will require boron diffusion, the lower degradation of n-type Si during high temperature processes will make it the predominant wafer material for industrial solar cell manufacturing in the mid-term future.

Processes

The advantages and drawbacks of different diffusion technologies were already discussed in our last article for *Photovoltaics International*, cited above. Nothing much has changed since then – the B-diffusion has to be performed fast, cost-effectively and



Source: http://www.itrpv.net

Figure 1: Relative market shares of casted and mono c-Si.

Item	Low	Average	High
156 mm Mono PV Wafer	1.04	1.080	1.22
156 mm N-Mono PV Wafer	1.25	1.300	1.55

Source: http://www.pvinsights.com

Figure 2: Updated market prices (USD/wafer) for p- and n-type Cz-Si wafers

homogeneously which is not that easy. Centrotherm is focusing on low-pressure BBr3 diffusions and Sandvik has designed a BBr3 boron deposition process which has a unique gas flow configuration. Tempress and Semco also have solutions for tube furnace BBr3 and BCl3 diffusions respectively, while Schmid has also been very successful with its APCVD B-diffusion equipment where the diffusions are done from one-sided deposition of doped oxides. AMAT, Kingstone, Intevac and others are offering solutions for ion-implantation, however not all of them for boron.

The challenge after the process of a good B-diffused surface is to clean it properly, passivate it effectively and metallize without high losses in Voc. There are many solutions for special applications which are provided by RENA (cleaning, metallization), Schmid (cleaning, metallization), SINGULUS (cleaning, passivation, metallization) centrotherm (passivation), R&R (passivation), Levitech (passivation), Solaytech (passivation), Dupont (metallization), Hareaus (metallization) and many others. In order to reach efficiencies in production exceeding 21-22%, the Al spiking has to be eliminated in future which leads to limited Voc of about 655mV. Also the edge isolation is not trivial on n-type solar cell processing and has to be implemented thoroughly into the cell process.

Costs

Increasing significantly the cell efficiencies compared to standard Al-BSF cell technology requires the introduction of additional process steps as discussed before. Consequently, advanced cell concepts such as PERC, MWT and PERT come with a higher cost of ownership (COO) in US$/cell. HIT and today's industrially implemented IBC-cell concepts feature in addition more complex (i.e. more expensive) process technologies.

As mentioned above, n-type concepts (n-PERT, HIT, IBC) have been – up to now – also disadvantaged by a higher wafer price. However, depending on the achievable module power and on the module manufacturing cost, the COO in US$/Wp at module level can still be economically interesting. This applies even more, if one considers the parameter that determines the return on investment of each PV system, irrespective of its exact type and size: the LCOE in US$/kWh. When building a PV system with high efficiency modules, less cabling, mounting structures, land, labour and other elements are required – in short: the related balance of system (BOS) cost, and consequently the total cost of the installed system, is reduced. A lower cost of the PV system (US$/Wp) results in a lower LCOE (US$/kWh).

In this respect, many advanced c-Si solar cell technologies with boron back surface field or emitter are inherently bifacial or can be easily made bifacial. Bifaciality reduces the LCOE even further, as it acts just like an "efficiency booster": as illustrated in Figure 3, assuming a moderate 15% bifacial gain (increase in kWh/kWp(front)), a bifacial BiSoN module with 280Wp (front Pmpp) features the same energy yield as a 320Wp monofacial module while featuring a COO that is in the range of standard mc-Si modules with a Pmpp of 250 Wp.

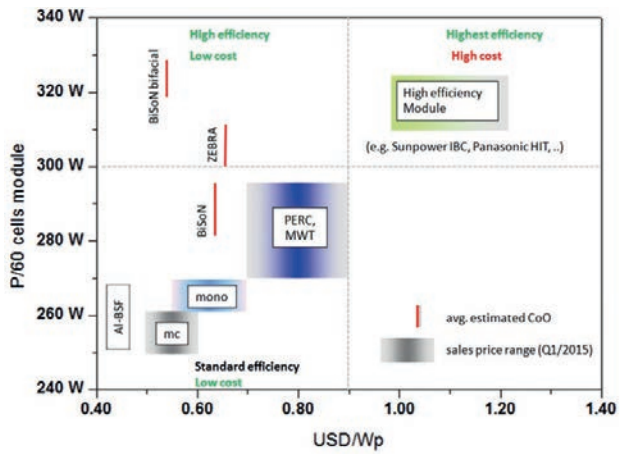


Figure 3: Market price vs. Pmpp of 60-cells modules for various industrially implemented cell technologies compared to the calculated Coo for BiSoN (n-PERT) and ZEBRA (n-IBC) technology. Coo calculation based on 1.0 USD/wafer for p-type Cz-Si and 1.3 USD/wafer for n-type Cz-Si.

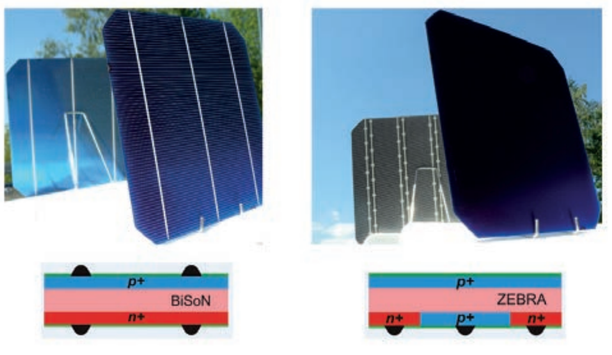


Figure 4: PERT (BiSoN) solar cell and IBC (ZEBRA) solar cell of ISC Konstanz.

Newcomer companies and new R&D Highlights

Many companies have been involved in n-type cell and module production for many years such as SunPower, Panasonic, Yingli, PVGS, Neosolarpower and LG. Newcomers such as First Solar, Silevo, Mission Solar (Nexolon), SSNED, Motech and MegaCell are following quickly. Many of them presented their progress at the nPV workshop, showing >20% efficient n-type cell concepts that can be also used in glass-glass or glass-transparent foil modules, benefiting from the bifacial character of the cells.

Many institutes are developing similar cell concepts on large six-inch wafers (some still having some processes which are hard to transfer to production) and reaching efficiencies >22% for a simple n-type PERT structure (IMEC) or >22% for an IBC structure (ISFH). Results from IMEC´s, FhG's, ISE´s and ISFH´s n-type developments are summarized in the 27th edition of *Photovoltaics International*. All these results were also shown in presentations at the nPV workshop. In addition, ISC Konstanz together with MegaCell showed BiSoN (BIfacial Solar cell On N-type) cells in production and the newest improvements to the ZEBRA (diffused n-type IBC) technology with >21.5% efficiency (both concepts depicted in Figure 4). ECN presented its upgrade of nPASHA – the n-type MWT cell with >21% efficiency. Last but not least INES and EPFL/CSEM summarized their excellent results on heterojunction cell and module concepts.

In summary we can say that n-type is on its way to rapidly taking off. The cell concepts have been out there for a long time, the wafers are constantly getting cheaper, the paste manufacturers are improving their n-type products quickly and the awareness of kWh thinking instead of Wp mentality is growing. So the ramp for take-off is prepared - and the n-type rocket is now starting its engines.

This is an edited version of a blog that first appeared on www.pv-tech.org.

Dr Radovan Kopecek and **Dr Joris Libal** are both solar cell scientists at ISC Konstanz in Germany.