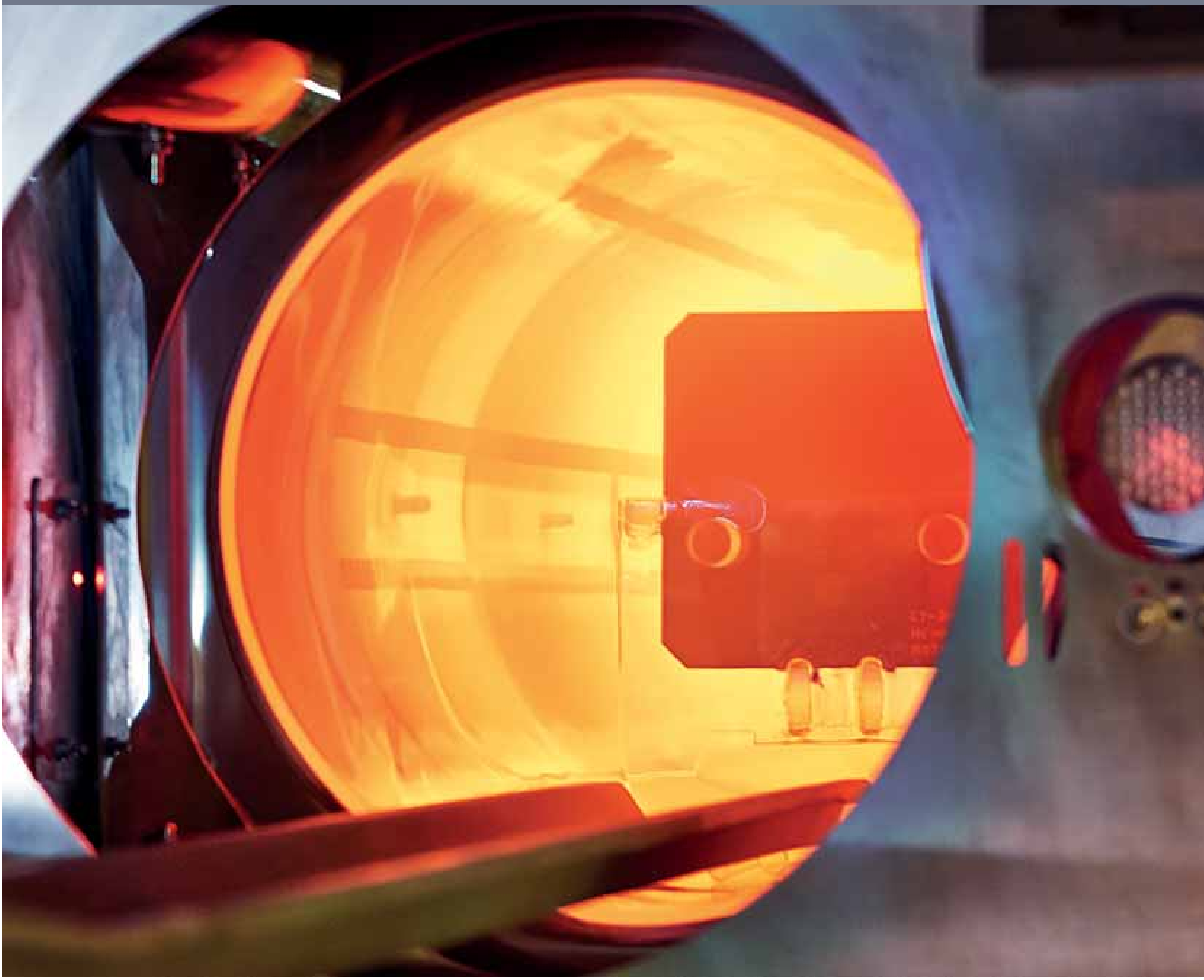
Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS



Edition 40

Power rating and qualification of bifacial PV modules

TÜV Rheinland looks at the power rating issue for bifacial devices

The opportunity for wafer-based reduction in LCOE

1366 Technologies on the cost and performance advantages of its wafering process as it moves into commercialization

Towards industrial manufacturing of TOPCon

Fraunhofer ISE on a possible follow-up technology to PERC

Challenges for the interconnection of crystalline silicon heterojunction solar cells

Fraunhofer ISE researchers look at different approaches and focuses on ribbon-based interconnection technologies

Four-terminal perovskite/c-Si tandem PV technology

Progress and analysis of four-terminal perovskite/c-Si tandem technology by ECN/TNO and Solliance

www.pv-tech.org

PVTECH .ORG

Photovoltaics International

Published by:
Solar Media Ltd.,
3rd Floor, America House, 2 America Square
London EC3N 2LU, UK
T: +44 (0) 207 871 0122
E info@pv-tech.org
www.pv-tech.org

Publisher: **David Owen**

Head of Content: **John Parnell**
Managing Editor: **Ben Willis**
Commissioning Editor: **Adam Morrison**
Sub-Editor: **Steve D. Brierley**
Senior News Editor: **Mark Osborne**
Reporters: **Tom Kenning, Andy Colthorpe**
Design: **Tina Davidian**
Production: **Daniel H Brown, Sarah-Jane Lee**
Sales Director: **David Evans**
Account Managers: **Adam Morrison, Graham Davie, Lili Zhu**

Cover image: BiSoN bifacial solar cells under production

Image courtesy of Megacall

Printed by Buxton Press

Photovoltaics International
Fortieth Edition
Second Quarter, May 2018
Photovoltaics International is a quarterly journal published in February, May, September and December.

Distributed in the USA by Mail Right International, 1637 Stelton Road B4, Piscataway, NJ 08854.

ISSN: 1757-1197

USPS Information
USPS Periodical Code: 025 313

Periodicals Postage Paid at
New Brunswick, NJ
Postmaster: Send changes to:
Photovoltaics International,
Solar Media Ltd., C/o 1637 Stelton Road,
B-4, Piscataway, NJ 08854, USA

Foreword

Welcome to the tenth anniversary edition of *Photovoltaics International*. Over the past decade this journal has documented the latest developments in the fast-changing of world PV technology, bringing you exclusive insights from researchers working at the industry's cutting edge.

Over that time the pace of change has been astonishing, so much so that it scarcely seems as though one new technology is accepted before the next arrives on the scene. So seems to be the case with the passivated emitter and rear cell (PERC), which having become the technology upgrade of choice across the industry now appears to have a successor in waiting.

In this edition researchers at Fraunhofer ISE look at so-called tunnel oxide passivated contact (TOPCon) technology as a follow-up to PERC. First introduced in 2013, TOPCon overcomes some of the limitations of PERC in mitigating recombination losses while offering the promise a more straightforward route to back-end processing than some of the other alternatives to PERC. Their paper (p.46) examines some of the possible routes to future commercialization of the TOPCon concept.

Meanwhile, a team from TÜV Rheinland takes a deep dive into the vexed question of how the industry can most usefully define the benefits of bifacial technology (p.90). Although bifaciality is well on the route to mainstream acceptance, the question of how the extra energy gain from bifacial modules can be measured and rated has still not been settled. The TÜV authors look at some of the steps being taken to standardise the testing and rating of bifacial devices.

At the other end of the value chain, US-based 1366 Technologies gives an account of its contribution to reducing costs in wafer manufacturing, a significant ongoing expense in industrial PV cell production and thus a key focus for efforts to drive down the levelized cost of solar-generated electricity. 1366 Technologies offers an exclusive insight into its 'DirectWafer' technology, which it says achieves the long-sought cost and performance advantages over current ingot-based production methods.

Elsewhere in this edition, Canadian Solar outlines some of the solutions it has developed for tackling light-induced degradation in multi-PERC cells and modules (p.57), a persistent challenge with PERC technology. We also feature an update from TNO in the Netherlands on efforts to combine perovskite and crystalline silicon technologies, and analysis of the possible cost advantages of such tandem devices (p.66).

No issue of *Photovoltaics International* would be complete without some exploration of the wider picture in which many of the innovations described in this journal are framed. In this edition our deputy editor Tom Kenning reports from the recent PV CellTech event in Malaysia, where the 'Who's Who' of the PV manufacturing world gathered to debate the current state of play in solar technology. Turn to p.13 for his account of what some of the industry's leading figures are talking about.

We hope you find this edition as informative and indispensable as always. Thank you for your ongoing support. Here's to the next ten years!

John Parnell
Head of content
Solar Media Ltd

Editorial Advisory Board

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.

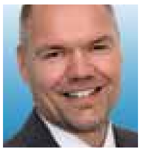
Our editorial advisory board is made up of senior engineers from PV manufacturers worldwide. Meet some of our board members below:

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 $Cu(In,Ga)Se_2$ thin-film solar cells.

Dr. Wei Shan, Chief Scientist, JA Solar

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

Chen Rulong, Chief Technology Officer, Solar Cell R&D Department, Wuxi Suntech

Chen Rulong graduated from Changchun Institute of Optics and Fine Mechanics, majoring in applied optics. He began working in the field of R&D on solar cells from 2001. He is a visiting fellow at the University of New South Wales in Australia and an expert on the IEC Technical Committee 82, which prepares international standards on PV energy systems.

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.

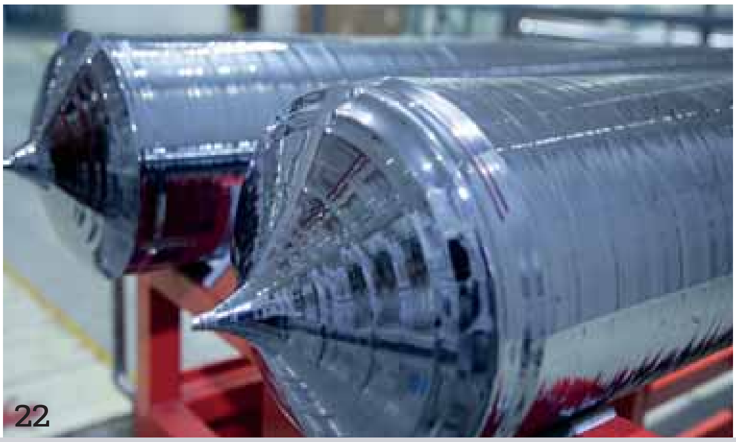
Matt Campbell, Senior Director, Power Plant Products, SunPower

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.


MEYER BURGER
Intersolar Europe:
Hall A2, Stand 260
June 20 – 22, 2018



Contents

Product reviews

Cell Processing: Aurora

Aurora Solar's 'Veritas Insight' provides fully integrated quality control system for advanced solar cells

Product Outline: Aurora Solar Technologies has introduced the 'Veritas Insight', designed to provide a fully integrated quality control system for high-efficiency solar cells such as PERC.

Problem: There are a number of challenges facing cell manufacturers in characterizing and controlling production variation of high-efficiency solar cells. These variations cause yield limitations and profit loss, and can introduce excess warranty liabilities, due to poor electrical performance and other variances in finished cells. The effects can also be seen in the often-lengthy time it takes to bring new high-efficiency production lines up to speed, resulting in many weeks of suboptimal performance. Manufacturers therefore need to make use of the powerful information embedded within the enormous quantity of production data being generated as the industry scales to hundreds of gigawatts of annual production and make actionable information to boost manufacturing yield and detect hidden process behaviour that affects product quality.

Solution: Veritas Insight detects and interprets complex process deviations or faults that cannot be directly discerned, but cause protracted declines in average efficiency or costly quality issues in the field. It reveals causal relationships between finished cell electrical variations and controllable upstream fabrication process variations in real-time. This allows production personnel to see, understand and manage trade-offs and fluctuations as these occur in production. Veritas Insight provides these benefits with end-of-line cell performance alone or in combination with other production line measurements.

Applications: Fully integrated quality control system for high-efficiency solar cells such as PERC, bifacial, heterojunction and other cell technologies.

Platform: Veritas Insight provides end-of-line cell analysis or in combination with other production line measurements.

Availability: Available since April 2018.

PV Modules: Bischof + Klein

Bischof + Klein offers polypropylene-based backsheet for extreme solar cell protection

Product Outline: Bischof + Klein has introduced a new generation of PV module backsheets, B+K 'BackFlex' PP, to provide greater stability when exposed to UV radiation and increased protection against moisture ingress.

Problem: The backsheet plays an important role in the lifespan of PV modules. It has to protect the inner parts against corrosion and hydrolysis over a period of 20 years and more. It additionally has to withstand the harsh climates to which PV modules are exposed. Electrical safety in terms of insulation also plays an important role. Finally, special requirements such as low shrinkage during vacuum lamination have to be met by the manufacturer.

Solution: Polyester (PET), in particular, is prone to hydrolysis due to its polymeric structure. The ingress of water vapour into PV modules can cause corrosion of the metallic components but also hydrolysis of the encapsulant EVA, leading to the formation of acetic acid. B+K BackFlex PP is said to reduce water ingress by more than 50% compared to market standards as it is based on polypropylene and is therefore naturally resistant to hydrolysis. The BackFlex PP is certified for a system voltage of 1,500V DC. The 360μm DuroFlex PP offers a dielectric strength of 60kV. During PV module production, the module stack is vacuum laminated. In this process, backsheet shrinkage is minimized to reduce mechanical stress inside the module stack; the B+K BackFlex PP undergoes shrinkage of no more than 0.3% in both dimensions, according to the company.

Applications: PV module backsheet.

Platform: The B+K BackFlex PP backsheet can withstand more than 5,000 hours of damp heat testing (85°C/85% r.h.). It is manufactured in a one-step co-extrusion process that requires no glue or solvents.

Availability: Available from May 2018.

PV Modules: Henkel

Henkel's novel electrically conductive adhesive is designed for next-gen solar device assembly

Product Outline: Henkel Adhesive Electronics has developed a series of electrically conductive adhesives (ECAs) to facilitate lower-cost, improved reliability and process-friendly assembly of solar devices. The LOCTITE ABLESTIK ICP 8000 series ECAs have been designed to elevate module performance and accommodate various assembly processes including cell interconnect ribbon bonding and shingled solar modules.

Problem: More challenging solar cell processing due to thinner wafers and emerging new cell designs has illuminated the need for an evolution in electrical interconnect materials. This in combination with the cost pressures facing solar technology manufacturers, as well as the requirement for increased module power output, has driven the development of Henkel's latest line of next-generation electrically conductive adhesives.

Solution: LOCTITE ABLESTIK ICP 8000 is a series of ECAs designed specifically for the demands of solar cell interconnect and in-use module performance. The formulations also offer processing and performance characteristics such as compatibility with wafer thicknesses of less than 160μm, fast printing and dispensing capability at speeds of greater than 200mm per second and full curing in less than 20 seconds at low temperatures between 110°C and 150°C, allowing maximum UPH and improving in-line inspection and yields.

Applications: LOCTITE ABLESTIK ICP 8000 series materials are compatible with all cell architectures including PERC, n-PERT, HJT and third-generation photovoltaic cells, and are available in all regions globally.

Platform: LOCTITE ABLESTIK ICP 8000 series materials offer reliable tabbing with wafer thicknesses below 160μm and are designed for both Ag, Sn and SnPb ribbon. It has 1.2 N/mm+ peel strength on all common ribbon types and 200+ mm/sec. print speeds and <30 sec. cure at 120°C, <10 sec. cure at 150°C. For shingled solar modules the 8000 series offers 200+ mm/sec. dispense and print speeds and <30 sec. cure at 120°C, <10 sec. cure at 150°C.

Availability: Available in all regions for sampling and high-volume production.

Product reviews

Fab & Facilities: **CamLine**

CamLine provides faster navigation through R&D experiment data

Product Outline: camLine has launched XperiDesk (XD) 5.4 that streamlines existing and adds diverse functions for Process Development Execution Systems. The XperiDesk Suite applies the principles of Enterprise Information Management (EIM) and Manufacturing Intelligence (MI) to the field of R&D for high-tech manufacturing processes such as wafers, solar cells and modules.

Problem: With search result-based relation searching, it has become much easier to iteratively sift through the experiment data. The user can now easily navigate through the cloud of experiment results. Previously, this was only possible for a single item in the relation graph view. Another improvement is the extended functionality of sorting parameters into directories. This requested feature improves the oversight in the previously flat parameter maintenance views and even allows to sort one parameter into multiple directories. The manufacturability check has been extended as well. During the check in previous versions of the software, only the already flat numeric parameters were considered.

Solution: Various enhancements to the XperiDesk platform have been made to provide a faster and more cost-effective development through structuring and optimizing the complete R&D workflow. The highlights of XD 5.4 enhancements immediately respond to current demands in the field: users can use previous search results as selector for semantic relation searches, parameters can now be sorted into (multiple) directories and the manufacturability check evaluates calculated parameters.

Applications: High-tech manufacturing processes such as wafers, solar cells and modules.

Platform: Other improvements in XperiDesk (XD) 5.4 are the seamless synchronization of Runs currently in production between the full and the operator client and the more versatile handling of regular expression handling in the MS Excel import client. Finally, it comes with various improvements with respect to performance and streamlining the user guidance and multi-organization usage.

Availability: Currently available.

Materials: **Singulus**

The LINEX inline wafer texturing system from Singulus reduces costs and boosts cell efficiencies

Product Outline: Singulus Technologies has introduced a new two-step multicrystalline wafer texturing process on its inline 'LINEX' platform, said to reduce manufacturing costs and improve cell conversion efficiencies.

Problem: Multicrystalline solar wafers are increasingly cut with diamond wire, which permits a markedly higher yield of wafers per block. The market for multicrystalline solar wafers is expected to continue to rise next year, with a growing proportion of wafers processed using diamond wire saws. This technology means the cost per wafer can be significantly reduced. Using this sawing technique is more environmentally friendly than the conventional slurry process, which involves a mixture of oil and silicon carbide but the sawing process damages the surface of the solar wafers.

Solution: Singulus' LINEX' wafer texturing platform texturing removes saw marks and produces a uniform, homogeneous structure, according to the company. The manufacturing process incorporates two distinct steps developed in-house: the use of new additives and the use of ozone for post-cleaning, which provides a complete automated dry-in/dry-out solutions for wet-chemical treatment in standard and high-efficiency lines

Applications: Texturing of multicrystalline wafers are being cut with diamond wire saws.

Platform: The LINEX inline processing system features a newly developed conveyor system that guarantees extra-gentle handling of the solar wafers throughout the entire process and markedly reduces the breakage rate, according to the company.

Availability: Already available.

Fab & Facilities: **NOS Microsystems**

NOS Microsystems electronic software delivery system supports transition to industry 4.0

Product Outline: NOS Microsystems has developed getPlus, an electronic software delivery (ESD) ecosystem that bridges the gap between automation provider and end user. The user-friendly tool helps factories make the transition to industry 4.0, as is happening among many PV manufacturers.

Problem: System integration becomes complicated when hundreds or thousands of different systems of various ages have to cooperate with each other and at multiple locations in multiple countries.

Solution: getPlus provides production-line maintenance monitoring through guaranteeing safe online delivery of entitled software and updates to clients. Quick and secure updates support security, performance and the overall lifespan of production machines, and lets clients act before a defect causes costly downtime. getPlus links clients with their customer by connecting to suppliers' current web interfaces. There, it provides an easy to use platform that automates the updating process for customers.

Applications: getPlus works seamlessly with all database systems, existing delivery system or cloud service.

Platform: The software delivery manager is lightweight at just 200kB (<1MB) on the client side, so small that it does not even require installation. It integrates into clients' existing databases—SAP, Oracle and any others—to establish ESD or enhance the ratio of existing ESD with easy, self-service access to software updates.

Availability: Available since April 2018.

News

GTM Research highlights regional solar demand shifts expected in 2018

Global solar PV installations are expected to surpass 104GW in 2018, despite the top four markets, including China, forecasted to decline collectively by 7%, according to GTM Research.

The market research firm is forecasting that PV installations in China will not reach the record 53GW plus reached in 2017. Instead the demand will fall to 48GW in 2018. However, China would still account for around 47% of global demand this year.

According to GTM's latest market report, the US market is expected to be flat in 2018, adding a forecasted 10.6GW.

In contrast, India is expected to regain momentum and is forecasted to install 7.1GW in 2018. Global growth is also being supported by rapidly expanding markets in Latin America, the Middle East and Africa.

Credit: Huawei

China is among four leading solar markets forecast to decline in 2018.

GTM noted that Latin America, driven by Brazil and Mexico would reach 5.6GW of installations in 2018, while the Middle East and Africa would reach installations totalling around 4.7GW.

After several years of decline, Europe is also expected to rebound as Spain is expected to install over 1GW in 2018, as well as France.

TRADE DISPUTES

US rejects EU's call for less punitive measure on solar imports

The US has rejected the European Union's request for an alternative to the US safeguard measure on imports of crystalline silicon solar cells that would be less penalising on imports from the EU, according to a joint communication filed with the WTO on 19 March.

The two parties held consultations in February after the EU submitted a complaint at the WTO calling for the discussions over the 30% import tariffs enacted by the Trump administration.

The filing stated: "In particular, the European Union asserted that EU imports were not causing any serious injury due to their volume and higher prices. Thus, it suggested a form of measure that would be less penalizing for European Union imports such as a quota allocated by country or a minimum import price. The United States did not agree with this."

Moreover, no agreement was reached on compensation for the EU.

A total of eight countries or unions have filed complaints at the WTO over the US safeguard measures - the latest to do so being Vietnam - but this is the first case where an outcome of consultations has been announced.

India drops solar anti-dumping probe, fresh petition expected

The Directorate General of Anti Dumping and Allied Duties (DGAD) has terminated its anti-dumping investigation regarding imports of solar cells from China, Malaysia and Taiwan, but a fresh filing from the petitioners covering a new period of injury is still expected.

The Indian Solar Manufacturers Association (ISMA) withdrew its petition at the beginning of March aiming to "contemporize" the investigation to show what it claimed to be a period of even greater injury to domestic manufacturers between July and December 2017. A key member of the ISMA told PV Tech that the intention to file a fresh petition is still very much alive.

As expected, DGAD has now dropped the original investigation, but it raised concerns about ISMA's actions, noting that the investigation which lasted several months, had just reached its conclusive stage with everything finalised and a disclosure statement ready to be issued, when the ISMA requested for its termination.

Nonetheless, under Anti-Dumping rules, DGAD is obliged to terminate any investigation once the domestic industry files a written request for termination.

India sets oral hearing date for Malaysian solar glass anti-dumping investigation

India's Directorate General of Anti-Dumping and Allied Duties (DGAD) will hold an oral hearing for its anti-dumping investigation into imports of textured, tempered glass from Malaysia on 11 June in New Delhi.

DGAD launched the investigation at the start of February.

The sole petitioner was India's largest solar glass firm Gujarat Borosil, who was also the lone petitioner for a similar successful case against imports of tempered glass from China last year.

Credit: Tata Power Solar

Indian authorities have dropped an anti-dumping investigation into Chines, Malaysian and Taiwanese solar imports.

Borosil is the only Indian supplier that produces its own annealed (raw) glass instead of relying on imports.

In April, India launched an anti-dumping investigation into imports of EVA encapsulant material for solar modules from China, Malaysia, South Korea, Thailand and Saudi Arabia.

Meanwhile, in March, DGAD terminated its anti-dumping investigation regarding imports of solar cells from China, Malaysia and Taiwan, but a fresh filing from the petitioners covering a new period of injury is still expected.

India launches anti-dumping investigation into imports of EVA sheets for PV modules

India has launched an anti-dumping investigation into imports of EVA (ethylene vinyl acetate) encapsulant material for solar modules from China, Malaysia, South Korea, Thailand and Saudi Arabia.

The action from the Directorate General of Anti-Dumping and Allied Duties (DGAD) came in response to a petition filed by India-based integrated PV manufacturer Renewsys India, the renewable energy arm of conglomerate, Enpee Group.

DGAD noted that Renewsys is the largest producer of EVA sheets in India and the petition was backed by two other domestic producers, Vishakha Renewables and Allied Glasses.

The period of investigation is from 1 October 2016 to 30 September 2017. However, the financial years 2014/15, 2015/16 and 2016/17 will also be considered in order to analyse whether there has been injury to the domestic industry.

According to DGAD, Renewsys has claimed that it can produce all the widths and all the thicknesses of EVA sheets required by India's module manufacturers. It also claimed there are no known differences between its products and the imports from the five listed countries.

Indian manufacturers have now filed three anti-dumping petitions that affect solar in the last year.

LOBAL MARKET UPDATES

China's PV installations 22% higher in first quarter 2018

China installed a total of 9.65GW of solar PV capacity in the first quarter of 2018, a 22% increase over the prior year period, according to China's National Energy Administration (NEA).

The official breakdown of installations included 7.68GW of distributed solar capacity, which increased by 217%, compared to the prior year period.

In contrast, utility-scale installed capacity declined 64% to only 1.95GW in the first quarter of 2018, compared to the prior year period.

Asia Europe Clean Energy (Solar) Advisory Co, (AECEA), which issued a statement on the NEA released figures at a NEA press conference on April 24, had previously forecasted around 7.5GW of installations in China in the first quarter of 2018.

AECEA also noted that further improvements had been made on grid curtailment issues, notably in the autonomous region of Xinjiang and province of Gansu, where the curtailment levels had been above 20% throughout 2017.

Solar notches up clean sweep in German renewable tender

All 200MW of Germany's latest wind and solar tender has been awarded to PV projects.

The Bundesnetzagentur, the Federal Network Agency, said on Thursday that it had received bids for a total of 395MW of capacity.

The average successful tariff for projects was 4.67 euro cents per kWh (US$0.0467/kWh). Successful bids ranged from 3.96-5.76 euro cents. The average is slightly higher than the 4.33 euro cents recorded in the country's previous solar-only tender.

Onshore wind prices in the dual tender average 7.23 euro cents per kWh.

Jochen Homann, president of the Federal Network Agency said the lowest bids had been successful but indicated that there would continue to be support for other generators.

"For the success of the energy transition, however, a mix of different technologies is required," said Homann.

The next solar-only tender is on 1 June.

Brazil to reach 2GW of solar by December

Brazil is expected to hit 2GW of installed solar PV capacity by December 2018, according to the country's solar association Absolar.

Brazil crossed the 1GW milestone at the beginning of this year. Absolar said there are more than 27 thousand distributed generation units in operation, which together total more than 320MW of capacity. This sector in 2016 saw growth of 270%. Then in 2017, it grew by 304% and it is projected to grow another 358% this year.

Brazil's latest 'A-4' power auction saw energy agency EPE allocate 806.6MW AC of solar at the

Solar projects scooped all the available capacity in a recent tender in Germany.

Credit: Belectric

lowest ever price in the country.

The capacity was dispersed among 29 PV projects at an average price of BRL118.07/MWh (US$35.25), offering a discount of 62.2% in relation to the ceiling price. The previous auction saw average prices reach BRL145.68/MWh.

South Africa's delayed PPAs finally signed

The South African government has signed 27 power purchase agreements (PPAs) after resolving the latest twist in the long-running saga.

Utility firm Eskom had delayed the contracts claiming that they were no longer in the interest of the company. Last month the impasse appeared to be resolved until two labour unions intervened at the courts, claiming the projects would cost jobs at existing, fossil fuel power plants.

At that time, energy minister Jeff Radebe said that despite the court being unable to raise a legal reason why the contracts could not be signed on 13 March, the signing would be postponed until the legal process had run its course. The court chose not to uphold the complaint on 29 March.

The 27 contracts represent ZAR56 billion (US$4.7 billion) of investment and, according to the department of energy, will create more than 58,000 jobs for South Africans.

A number of developers were caught up in the delays including Scatec Solar, which was awarded 258MW of solar capacity in the fourth round of the country's tender process.

California to make solar mandatory on new homes from 2020

California has become the first state in the US to mandate for solar on new build homes.

The California Energy Commission approved new Building Energy Efficiency Standards on Wednesday, including the requirement for a PV array on new build homes.

The proposal has been in the works for two years and will require builders to use "smart inverters" and offer optional energy storage.

"The combination of rooftop solar and the option to add energy storage systems as an efficiency compliance credit provides builders with an attractive, cost-effective option to fully electrify homes," said Abigail Ross Hopper, president and CEO, Solar Energy Industries Association (SEIA).

"Other states may not be ready for this step yet, but this is a precedent-setting policy – one that will bring enormous benefits and cost savings to consumers. It is my hope and belief that when other states, many of which are developing rapidly growing solar markets of their own, see the benefits of this policy, they will develop similarly aggressive policies."

The Commission estimates that homes built under the 2019 standards will be 53% more energy efficient than those built to the 2016 rules.

US climbs to second in renewables attractiveness index despite solar tariffs - EY

The US has overtaken India in EY's latest renewable energy country attractiveness index report, despite the US imposition of a 30% tariff on imports of cells and modules earlier this year.

The American market climbed from third to second place in the index, since the solar tariffs are mostly absorbed and wind projects are not subject to subsidy cuts under the recently passed US tax reform bill, said EY.

India's attractiveness has itself been hampered by the looming threat of Safeguard Duties on imports, which could be set as high as a recommended 70%. Investors are also concerned by low prices in Indian procurement. This also helped Germany overtake India to reach third place in the index.

For the third time in a row, China topped the index. Other significant changes included the UK and the Netherlands climbing to seventh and ninth respectively, while Taiwan has re-entered the top 40 ranking.

Despite a large fall in renewables investment in 2017, the UK saw its market adapting to subsidy-free solar PV, onshore wind projects and moves to repower old wind farms, while the Netherlands had recent offers for unsubsidized offshore wind and has a growing solar PV market.

Mono vs multi, n-type vs p-type: outlooks from PV CellTech 2018

Tom Kenning, deputy editor, PV Tech

Abstract

PV CellTech has become the upstream PV industry's foremost annual event. This year, a key topic for discussion was whether n-type silicon would trump p-type as manufacturers look to drive up efficiencies, as well as the inevitable debate over the relative fortunes of multi and mono technologies. Tom Kenning reports from the event.

Solar Media's Finlay Colville highlighted the slowdown in Chinese PV investment as a key issue for the industry.

PV CellTech 2018 in March saw chief technology officers and senior executives from the world's top solar cell manufacturers and equipment suppliers give key indications of which cell technologies will be driving the industry in the coming years.

This article covers some of the hunches and opinions gathered from delegates over the two days in Penang, Malaysia. The newest and highest efficiency cell technologies are on the rise, but we also heard of stalwart multicrystalline silicon technologies managing to scrape back the efficiency gaps with their own innovations. Timing will be critical in terms of which technologies will take off over the next two years.

Most delegates were cautious in their responses and when it came to certain technology comparisons they felt that it was just too soon to predict, even in an industry that has started moving at pace.

Kicking off the conference, Finlay Colville, head of market research for PV Tech and parent company Solar Media, said that the US import tariffs resulting from Section 201 were far from the main global issue today for the solar industry.

"Everything is about signs over the next few years of there being a slowdown in investment going into manufacturing in China; that is literally the single biggest, most important thing for the whole solar industry," he said. "Also the ability of the downstream channels to actually install all these modules."

Despite the formidable rise of monocrystalline cell technology, changes and developments in multicrystalline technology have allowed it to continue prevailing in the last two years, while also keeping manufacturing capacity at the necessary levels to reach the major industry milestone of 100GW in a year, said Colville.

The mono vs multi debate

A question the whole industry still wants to know is which of mono or multi will dominate over the next three to five years.

"It's not going to be as clear cut," said Gordon Deans, founder and COO, Aurora Solar Technologies. "There are advantages to both technologies and what you can see from people talking this year at CellTech and also last year is that sometimes you'll get somebody saying multi is the clear winner for them and other people will say mono is the clear winner for them.

"It depends what you are trying to achieve and what your cost factors are in your sourcing of materials and your supply chain and your production as well. There's not one single answer; it's how does your particular situation drive what your decisions are – that's what matters."

This balanced view was echoed by Guangyao Jin, chief scientist at DuPont Photovoltaic & Advanced Materials, who said: "We believe both multi and mono have their own advantages. The cost of mono wafer has trended down while multi has tried very hard to increase efficiency and power output. They will coexist for quite a long period of time."

Closing gaps

The mono/multi question can't be properly considered without hearing from the heavyweights in mono technology, LONGi Green Energy Technology. Xie Tian, the firm's director of wafer quality management said that there was a very big wafer price gap between multi and mono last year, mostly due to the mono wafer shortage, but the price gap between multi and mono is consistently becoming smaller and smaller.

Pierre Verlinden, who until recently was the long-standing chief scientist of Silicon Module Super League (SMSL) member, Trina Solar, said that, historically, multi has clearly dominated. However, despite its being able to regain some interest back from the mono surge due to the conversion of the technology from Al-BSF to PERC, there is still a greater interest in mono because "the best benefits" come from mono. Nonetheless, the industry has often demonstrated new efficiencies with mono technology only for the developments to be transferred back to multi to reduce cost, and Verlinden believes this trend will continue.

He said: "Today we make high performance multi wafers that are almost as good as Cz wafers. […] If you focus on impurities you can improve the lifetime of your multi-crystalline wafers and then get roughly about the same performance as you get in mono-crystalline Cz technology."

Finlay Colville introduced GCL-Poly, which has been one of the biggest drivers of multi on the wafer side in the last three to four years, along with Canadian Solar, one of the biggest proponents of multi cell manufacturing – a unique company that has its arm in every part of the value chain from cell manufacturing all the way to project development and EPC activities. Colville said together, both firms had been key to keeping multi competitive and retaining its market share.

Guoqiang Xing, senior vice-president and CTO at Canadian Solar, said the cost of multi-PERC technology is reducing along with the inception of high-performance multi technologies. More importantly he said his firm had taken multi-PERC into mass production at the gigawatt level last year – adding: "We have a long way to go but I think multi will stay competitive for a long time to come."

Meanwhile, Yuepeng Wan, CTO at GCL-Poly, said that for multi to keep its market dominance it was "very critical" that it is able to offer higher output modules so that the end consumer has a choice of level of output.

Breaking even

However, PV Tech heard one executive suggest that the multi-crystalline business case has no shortage of challenges to remain competitive. Efficiency gains are increasing much faster for mono than multi, combined with decreasing manufacturing step costs for mono wafers, and there are some markets where mono-PERC modules are now slightly cheaper than Al-BSF modules. Although, this is not the case in markets with high costs of capital, such as Turkey and India, the executive said.

Indeed, Basma Amezian, business developer, Singapore Solar Exchange, looking at manufacturing break-even price/cost boundaries, said: "Taking as a reference absolute best-in-class processing costs in the industry, which would be relevant for the multi-gigawatt China-based factories, we can see that multi cell makers struggle to make profits. On the other hand, for mono we consider that there is a more or less good margin between the processing costs and the break-even boundaries.

"Of course it will depend on each company, processing costs and strategies and a lot of different variables, but if the assumptions are correct we can see here that the multi cell makers made loses in the first quarter and the fourth quarter of 2017, they barely broke even in Q3 and they only made a one-digit profit in Q2.

"For mono cell makers, however, we consider their margins were between 8 and 15% and even on their lowest price level in Q1 2018, their margin was the lowest of the year but also the maximum that the multi cell makers made."

Pierre Verlinden, until recently Trina Solar's chief scientist, said the outcome of the multi/mono debate was not clear cut.

The p-type versus n-type debate

N-type technology is on most people's radar today and the industry is watching closely for any hints as to whether it will come to trump p-type technology or co-exist happily over the next decade should the industry reach terawatt production levels.

It's worth nothing that another of the major questions at CellTech was, 'What happens after PERC?', particularly as we heard several times that

PERC is set to become dominant in the market as early as this year. This question is certainly partly tied up in the n versus p-type debate going forward.

Super Top Runner

China's 'Super Top Runner' programme, which targets the highest efficiency technologies, is seen as a key enabler for technologies using n-type and heterojunction, but Finlay Colvile said the 1.5GW put aside for this – in a market that can do 65GW – is still very small, allowing more traditional cell technologies to continue to prosper.

Canadian Solar's Guoqiang Xing said that for the Super Top Runner programme, players only have to score on the technology rather than the levelized cost of Electricity (LCOE), which is driving the production in newer technologies.

As a side note, Xing said that he had expected diamond wire sawing (DWS) to have a 70% market share in 2019, but instead it is likely to reach 100% already this year. "It's like a tornado," he said.

One wonders if any specific cell architectures could also become tornados in their own right.

DuPont's Jin said that due to the Super Top Runner programme driven by China, his firm expects significant growth of n-type passivated contact technology in the coming few years. However, he said the question of whether it will become mainstream to replace p-type position in the market today, will be "highly subject to the total cost of ownership improvement throughout the whole value chain engagement".

Omid Shojaei, CEO, INDEOTec, said he could not see much limitation in terms of people switching between p-type and n-type, assuming there is enough supply of mono wafers.

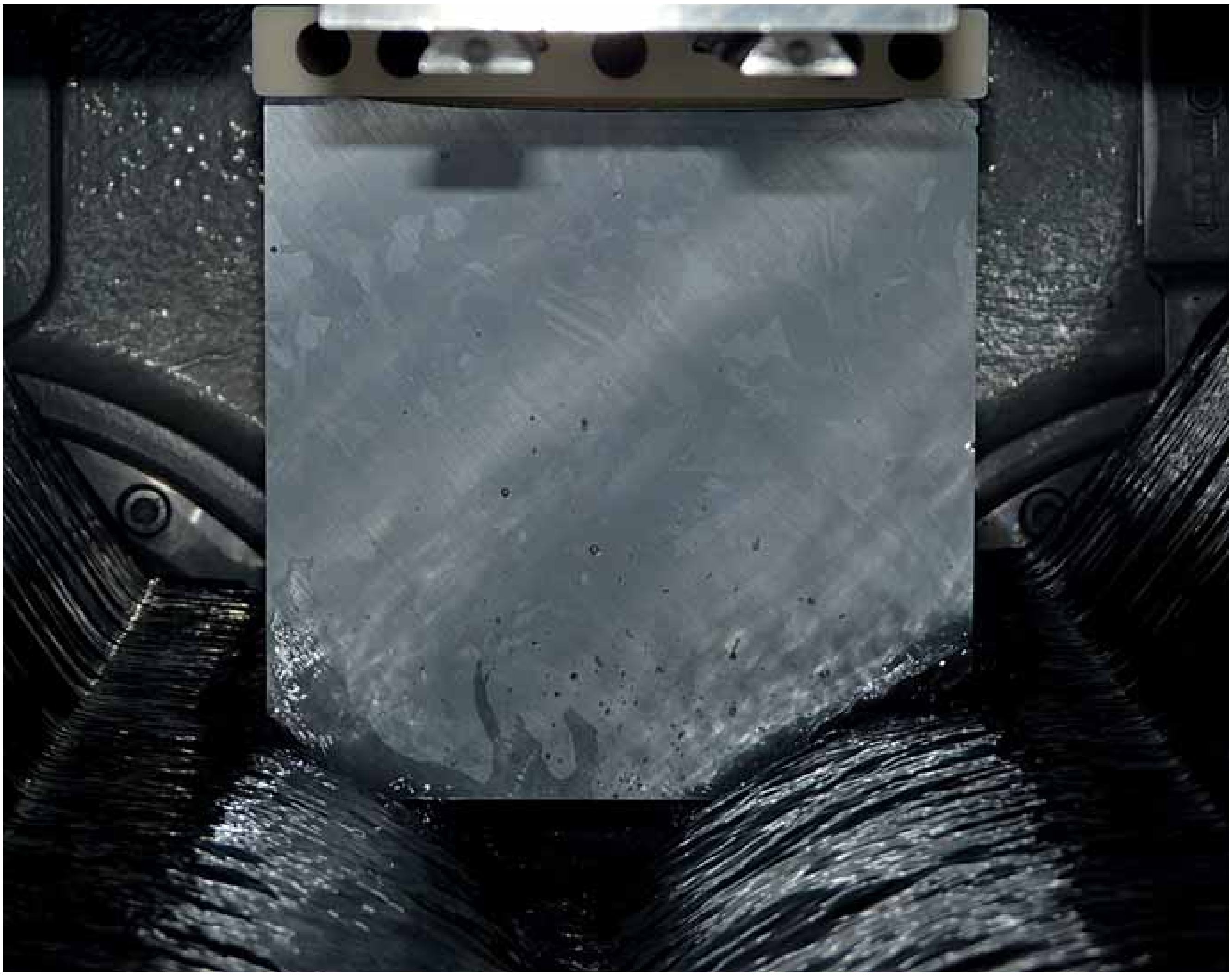
HJT

Shojaei added: "If we talk about heterojunction – of course we can do it with both p-mono and n-mono. The results are better with the n-mono so there is probably something like 1% absolute efficiency that are better with the n-types so I would say that if heterojunction picks up, this will also increase the share of n-type versus p-type mono but it's not an easy question."

He said there are a lot of new players in heterojunction, with more than 30 labs just working on its next generation, adding that he sees the HJT market rising from 2GW to 22GW in the next three years.

He said Japan remains the best market for the moment led by Kaneka and Panasonic, but there are no specific plans to expand. So to reach that 22GW, there will be roughly 2GW in Korea, 5GW in the rest of the world and the rest made up by China, which is clearly the biggest investor today in the HJT market.

Shojaei had said that PERC can get to around 21-22% maximum on the industrial level, but this



Credit: CEA-Tech INES

The growth of diamond-wire sawing was described as a "tornado".

was an area of contention at the conference.

Holger Neuhaus, director of innovation and technology, SolarWorld Industries, later claimed that PERC would reach >24% in industrial production. While Martin Green of the University of New South Wales said PERC should see 23.6% in production in the next two to three years.

Is n-type really 'better'?

Pierre Verlinden said that n-type is a "wonderful material" because it's less sensitive to iron impurities than p-type. However, he noted that if such metallic impurities were removed from the equation in wafers – if the iron concentration is reduced – then theoretically p-type efficiency would be better than n-type.

He added: "So there is no reason technically why we should go switching to n-type if we stay with the standard PERC technology."

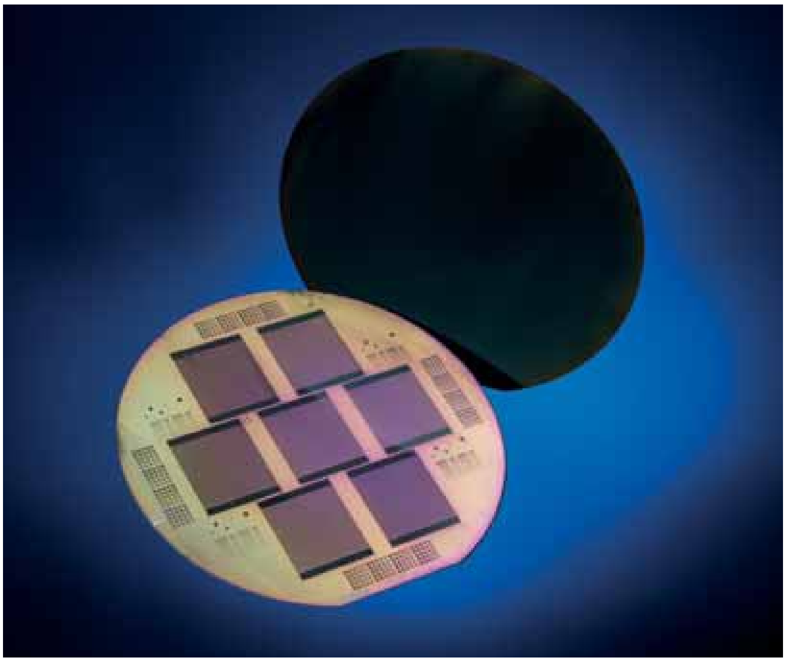
P-type multi still dominates manufacturing, he claimed, but n-type is the preferred choice with passivated contact technology.

Gunter Erfurt, CTO, Meyer Burger, said: "This is too early to say. When you look at the highest efficiency cells so far for PERC, these were p-type. It started with the initial Martin Green [UNSW] cell – this was a p-type above 24.6 or 25% and now with the p-PERC cells that ISFH presented one month back it's another proof that it is a false statement when people say n is by definition better than p. This is not true; it's all about managing the silicon bulk quality to get it to a level where it's allowing for higher efficiencies.

"Next year, I think 2019/20, the two dominating gallium doping patent families are expiring after 20 years – Shin-Etsu and Kyocera. I believe this will be the moment when people are getting rid of boron and putting in gallium because all the highly efficient PERC cells were all gallium-doped. You get very nice lifetimes, very little degradation and there are more tricks and other ideas to use other doping instead of boron so I would say for the time being this is an open question.

"At the end of the day it's all about balancing the cost structure and if n is unable to reach the yields to make it a profitable business, it will not make the breakthrough."

Hyun Jung Park, research fellow, Solar R&D Laboratory, LG Electronics, said the cell efficiency gap between both technologies had been reducing, but LG has been developing n-PERT, TOPcon and HJT cells to maintain the gap between p- and n-type. However, she noted that cost is still the weakness for n-type as it has higher wafer material



Credit: ISFH

ISFH's recent 26.1% record is a reminder that p-type silicon still has room for efficiency improvements.

costs than p-type wafers.

Nevertheless, LONGi's Tian said he expects the n-type market to become bigger and bigger, which will make the cost difference between p and n smaller.

Wei Shan, CTO of JA Solar on the other hand, said that p-type PERC would remain the prevailing technology for the next few years and said it was "a tall ask" to challenge that in terms of cost-effective mass production of alternatives. Nevertheless, he said issues such as cost and yield would gradually be resolved and eventually n-type will take off.

Further reading on the n-versus-p debate

Commenting shortly after PV CellTech 2018, Finlay Colville added that the growth of the solar industry, driven by China in 2016 and 2017, had opened the door for a wide range of high-efficiency platforms across both n-type and p-type cell technologies.

"In many cases, especially in China, the technologies are not in direct competition with one another. And often, deployment in China is coming from secondary factors, such as parent company involvement in project development and EPC activities, or carve-outs for cell or module efficiency levels. This is hiding a genuine comparison based on operating costs and energy yields."

"But it is clear that the n-type landscape is moving fast, and the technical success of LG Electronics has ushered in a new wave of companies seeking to make modules where the key differentiation today is based on cell efficiency, with these companies yet to fully address the issues yet to come when operating factories profitably at the multi-gigawatt level."

News

First Solar building new 1.2GW CdTe thin-film manufacturing plant in Perrysburg, Ohio


Credit: First Solar

First Solar is building a new US-based production line for its Series 6 module.

Leading CdTe thin-film PV module manufacturer First Solar has announced the building of a new 1.2GW manufacturing plant near its existing flagship facility in Perrysburg, Ohio.

The company said that the new production plant for its large-area Series 6 modules would require around US$400 million in capital expenditure and create around 500 new jobs.

The capacity expansion plan includes a 1 million square foot facility located in Lake Township, Ohio, a short distance from the Perrysburg facility, which is expected to start construction in mid-2018 and enter full production ramp in late 2019.

As a result, First Solar will have a nameplate capacity in the US of 1.8GW of Series 6 modules and clearly be the largest PV manufacturer in the US.

"Strong demand in the U.S. for advanced solar technology, along with recent changes in U.S. corporate tax policies, have encouraged our decision to grow First Solar's US production operations," said Mike Koralewski, First Solar's senior vice president of global manufacturing. "State and local officials and Jobs Ohio have also worked with us to create a business-friendly environment that supported our objectives. These factors, combined with our own economies of scale in high tech manufacturing, make expanding US operations an attractive, win-win opportunity."

With two new Series 6 module manufacturing plants in Vietnam, First Solar is projecting around 6.6GW of nameplate capacity in the next 3 years.

The recent imposition of Section 201 trade case tariffs on c-Si cells and modules imported into the US from the majority of countries capable of shipping to the US was intended to revitalise US manufacturing.

Secretary Ross of the US Department of Commerce added: "This is exactly the result we had hoped for, and are delighted that First Solar reacted so quickly."

MANUFACTURING EXPANSION PLANS

JinkoSolar continues with wafer, cell and module capacity expansions in 2018

Leading 'Silicon Module Super League' (SMSL) member JinkoSolar is planning further capacity expansions across wafer, cell and module assembly in 2018, including a module assembly plant in the US, after strong capital expenditures in 2017 that totalled US$480 million.

The company reported that in-house wafer capacity went from 5GW in 2016 to 8GW in 2017, a 3GW year-on-year increase.

Solar cell capacity increased by 1GW in 2017, reaching 5GW. Module assembly capacity increased from 6.5GW in 2016 to 8GW in 2017, a 1.5GW year-on-year increase.

In 2018, JinkoSolar has set plans to add 1GW of in-house wafer capacity in the first quarter, bringing total nameplate capacity to 9GW. By the end of the year a further 500MW expansion of wafer capacity is expected.

The SMSL is also adding a further 1GW of solar cell capacity through the year, bringing in-house nameplate capacity to 6GW by year-end.

In-house module assembly capacity is being expanded by a further 1.5GW in 2018. This includes a 500MW increase in the first quarter of 2018 and therefore a further 1GW by year-end. Total module capacity is therefore expected to reach 10GW in 2018.

The difference between 2017 and 2018 expansions, apart from a slowdown in wafer capacity expansion plans, is the establishment of a module assembly plant in Florida, US.

Although capacity details of the US plant remain undisclosed, JinkoSolar has reported that in its recent stock offering that was expected to net the company US$71.1 million, would be used for the new assembly plant as well as for other capital expenditure requirements for the capacity expansion and upgrade of other facilities.

Canadian Solar lowers capacity expansion plans for 2018 as shipment guidance stalls

Canadian Solar has lowered nameplate capacity expansion plans in 2018 for both in-house solar cell production and module assembly as total module shipment guidance for 2018 indicates marginal growth.

The company reported that total solar module shipments in 2017 reached a new record high of 6,828MW, compared to 5,232MW in 2016.

However, initial guidance given for 2018, which includes a wide range for module shipments to be between 6.6GW to 7.1GW, suggests less than 300MW of shipment growth year-on-year, or less than 4% annual growth.

Having adjusted manufacturing capacity expansions throughout 2017, Canadian Solar continued to tweak plans for 2018, a second time.

In reporting fourth quarter and full-year 2017

Credit: Canadian Solar

Canadian Solar has lowered capacity expansion plans for 2018 on the back of stalled shipment guidance.

financial results, Canadian Solar noted that its wafer manufacturing capacity at the end of 2017 stood at 5.0GW, a 3GW increase from 2016. The company also noted that all wafer capacity had been migrated to diamond-wire saw technology in 2017, which goes in tandem with its proprietary 'black silicon' texturing process required with diamond wire-saw for p-Type multicrystalline wafers.

However, the company has not announced new wafer capacity expansions for 2018, keeping capacity as 5GW.

Solar cell manufacturing capacity stood at 5.45 GW at the end of 2017, up from 2.44GW in 2016, in-line with previous upwardly revised guidance.

China's CETC breaks ground on 200MW solar cell facility in India

Chinese firm CETC Renewable Energy Technology (India) has carried out a groundbreaking ceremony for its first phase 200MW solar cell manufacturing facility in the Indian state of Andhra Pradesh.

The firm, whose parent company is Beijing-headquartered state-run company China Electronics Technology Group Corporation (CETC), signed a memorandum of understanding (MoU) with the Andhra Pradesh Economic Development Board (APEDB) for the plant back in January. The facility is located in Sri City, Chittoor district. Around 300 jobs are expected to be generated in the first phase, followed by 1,500 for the entire project.

Many MoUs are signed in India to no avail, so the Indian government, which has been trying to attract foreign PV manufacturers into the country, will be encouraged by what CETC described as a "giant step forward".

After being contacted by PV Tech, CETC declined to provide further information on when the first phase would be completed or what capacity is planned for the second phase.

CETC claims on its website to already have an annual production capacity of 1.5GW of solar cells and PV modules.

TOOL SUPPLIERS

Meyer Burger expects strong order intake to continue in 2018

Leading PV manufacturing equipment supplier Meyer Burger has guided another strong year of order intake and annual revenue as the industry continues a major technology migration.

Meyer Burger reported total incoming orders of CHF560.7 million (US$592 million) in 2017, an increase of 23% compared to the previous year and represented the highest level of incoming orders for the past six years.

The company noted that in its Photovoltaics segment, a number of large orders had been placed especially for PERC (Passivated Emitter Rear Cell) technologies using its 'MAiA' in-line system based on its proprietary PECVD technology as well as its heterojunction technology and diamond wire wafer technology.

The migration to PERC technology was noted to have been at a faster pace than previously expected with almost all standard mono-Si cell capacity expected to be switched to PERC by the end of 2018. Meyer Burger said that it its MAiA 2.1 platform was estimated to have taken around a 70% market share.

However, the migration of multi-Si cells to PERC was going at a slower pace due to degradation issues.

Meyer Burger also noted that although incoming orders in the first two months of 2018 were around CHF36.2 million (US$38.2 million), order momentum was expected to pick up again during the course of the year as second tier cell producers would upgrade to PERC.

As a result, the company is targeting net sales of between CHF450-500 million and an EBITDA margin of about 10% in 2018.

Meyer Burger to outsource 'SmartWire' connection equipment manufacturing to Mondragon Assembly

Leading PV manufacturing equipment supplier Meyer Burger is to outsource the manufacturing of its 'SmartWire' connection equipment to PV module assembly and automation specialist, Mondragon Assembly.

Meyer Burger said that Mondragon would start production of its 'SWCT' equipment no later than by end of the fourth quarter 2018, which would coincide with production of the equipment stopping at its production site in Thun. The company would then continue to focus R&D and marketing activities of the SWCT technology.

Luis Mari Imaz, CEO of Mondragon Assembly said: "We strongly believe that our partnership with Meyer Burger will be of mutual benefit to both companies. We are excited about the working together with such a recognized solar technology leader."

Daniel Lippuner, COO of Meyer Burger, added: "Collaboration with Mondragon with their strong experience in contract manufacturing and automation ideally complements our in-depth PV module equipment expertise. By outsourcing the production of our SWCT equipment to Mondragon, we are able to benefit from their flexible, cost-competitive manufacturing structure. This will help us to expedite the industrialization of our innovative SmartWire Connection Technology."

InnoLas Solutions acquired by Swiss industrial investment firm CGS

PV laser technology equipment specialist InnoLas Solutions has been sold to Swiss industrial investment and management firm CGS for an undisclosed sum.

CGS has taken an undisclosed majority stake in InnoLas, while current owner Richard Grundmüller was said to have retained an undisclosed shareholding.

The aim is to leverage InnoLas Solutions laser technology and expertise to become the core of future add-on acquisitions to build a larger business within an industrial sector, dubbed a 'Buy & Build' strategy by CGS.

The investment firm has made over 20 individual acquisitions and exited five industrial clusters since starting business in 1999.

InnoLas will be at the centre of a new industrial group for laser technology.

The laser specialist works in the solar, semiconductor and related electronics sectors.

Intevac's 12 ion implanters for Chinese solar customer still in order backlog

Specialist semiconductor and PV equipment supplier Intevac reiterated that its 12 unit 'ENERGi' solar ion implant tool order valued at around US$23 million that was booked in March 2017 remained in its order backlog at the end of the first quarter of 2018.

Delays associated with the customer's manufacturing plant construction of a 2GW-plus n-type monocrystalline IBC (Interdigitated Back Contact) solar cell plant were previously cited for tool shipment delays.

Credit: Meyer Burger

Meyer Burger is expecting orders in its PV segment to remain strong in 2018.

Intervac had shipped an initial three ion implanters the third quarter of 2017, with installation expected by the end of the first quarter of 2018, while revenue recognition was expected sometime late in the second quarter of 2018 or early in the third quarter. However, this remained dependent on the customer completing plant construction and initiating tool install.

In reporting first quarter 2018 financial results, Wendell Blonigan, president and chief executive officer of Intevac said in its latest earnings call that three initial ion implant tools were waiting installation, although other production tools were being installed ahead of the ion implanters.

"The tools that we have out there right now that are waiting for installation is an n-type ramp, so we're seeing that come back to life," noted Blonigan in the call. "We're seeing some tools installed there and we anticipate getting the installed, the first tools in a reasonable period once they move in some other equipment. So we see that moving."

However, Blonigan also noted that more recent installation delays had been primarily due to the customer shifting some of the new production lines installed at the new facility to n-PERT production.

"While the schedule and timing are not finalized, at this time we continue to expect three more tools will ship mid-year [2018] with six in revenue for 2018 and the other six in 2019," added Blonigan.

Interest in next-generation solar cell technologies remain high in China as policies in place for 'Top Runner' and 'Poverty Alleviation' programmes dictate the deployment of high-efficiency solar modules and provide multi-gigawatt markets annually.

US-headquartered IBC pioneer SunPower has under 1.2GW of IBC cell production capacity at facilities in Malaysia and the Philippines. However, Intervac's Chinese client has yet to enter volume production of IBC solar cells and has yet to install enough lines to fully ramp to over 2GW. At that point SunPower will have a direct cell technology competitor in the market.

PV manufacturing capacity expansion announcements in Q1 2018

By Mark Osborne, senior news editor, Photovoltaics International

Abstract
PV manufacturing capacity expansion announcements in the first quarter of 2018 continued to mirror those of the previous two years, highlighting the recent trend of the last quarter and the first quarter of each year (since the end of 2015) being the most active. The quarter being discussed also represents a revival in thin-film expansion plans, the return of PV module assembly outpacing solar cell announcements and the return of India and the US as major destinations for new capacity plans.

January review
Total expansion announcements were 11,450MW, down from 16,100MW in December 2017 and down from 20,800MW in November 2017. However, January 2018 was responsible for setting a new 'mini' record for capacity expansion announcements, compared to other January months, since the beginning of 2014.

The majority of expansion plans came from the PV module assembly segment, which topped 8,600MW. Only one month (November 2015) had exceeded this figure when 11,180MW of module assembly plans were announced.

Solar cell expansion plans in January 2018 were 2,850MW, down significantly from 7,350MW in the previous month and down substantially from 20,000MW announced in November 2017, which set a new record for monthly solar cell expansion announcements.

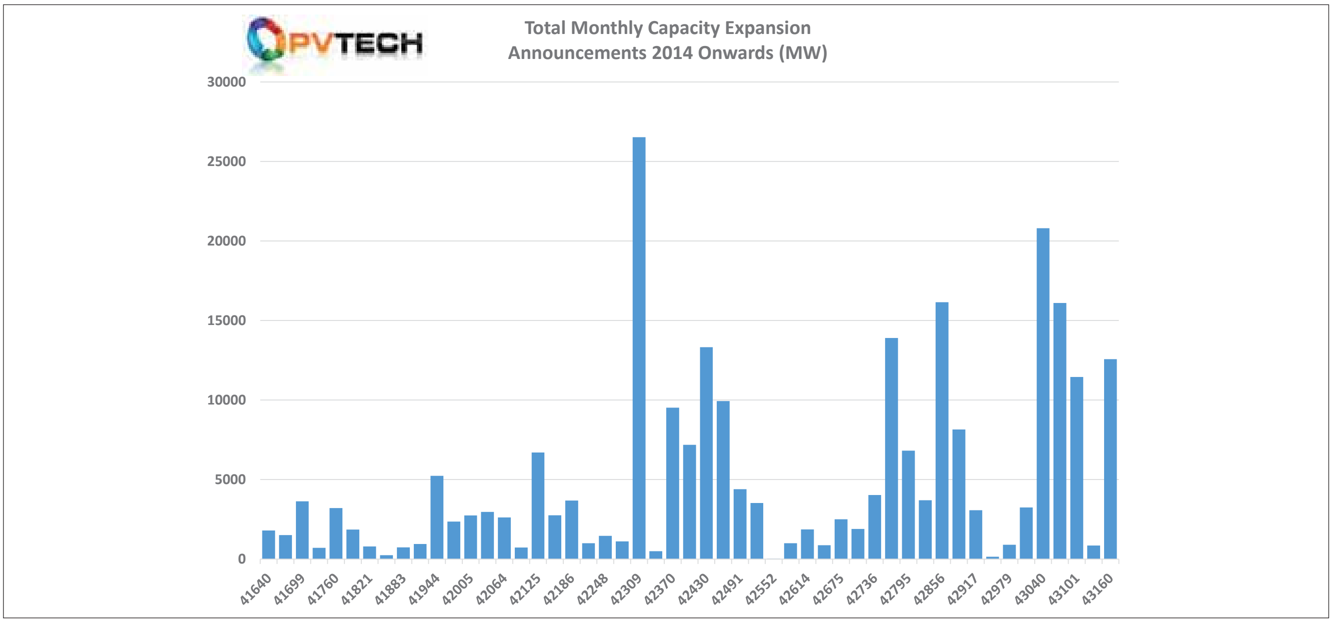
Therefore it should be a surprise that after just two months when a total of 27,000MW of new cell capacity plans had been announced, January would experience further declines. In fact, 2017 stands out for breaking the trend since 2014 that solar cell expansion plans closely tracked those of module assembly. However, solar cell expansion in 2017 accounted for more than 65% of the total.

Notable announcements included LONGi Green Energy Technology and newly created UREC, a joint venture consolidation of Taiawan-based PV manufacturers Gintech Energy, Solartech Energy, Neo Solar Power.

As LONGi is a 'Silicon Module Super League' (SMSL) member, we will cover it later in the SMSL review section but the company accounted for

LONGi was a key player in the quarter with 6GW of capacity expansion announcements.

Credit LONGi Green Energy Technology



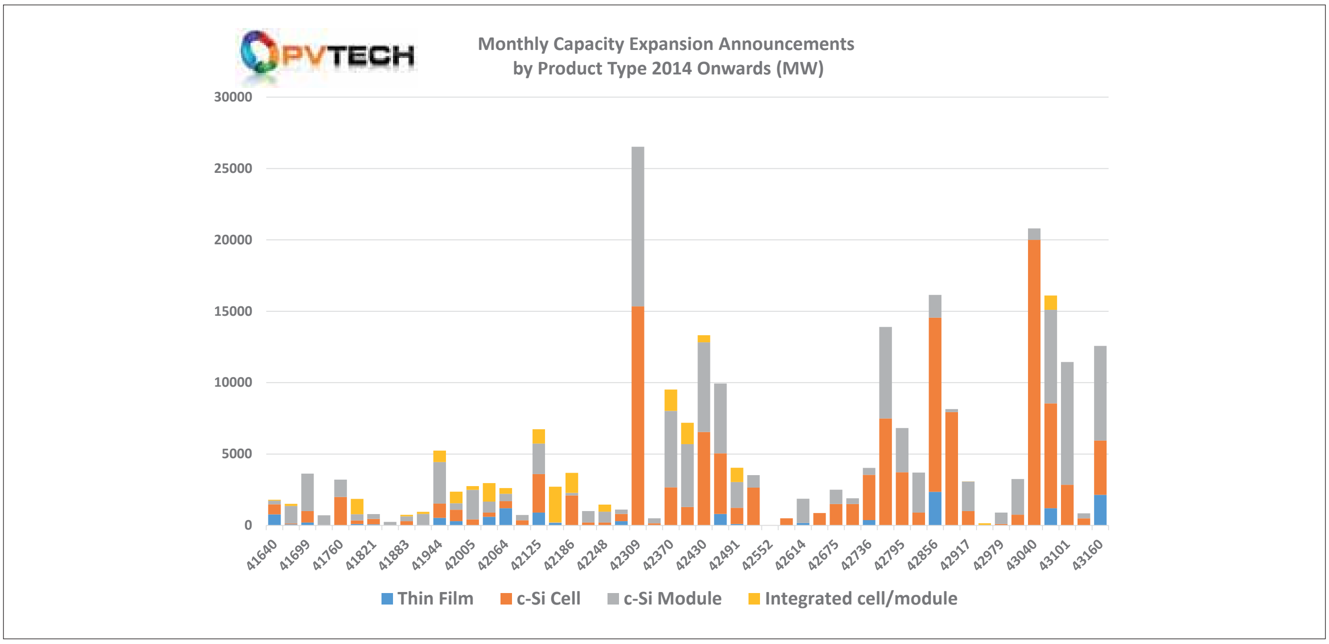


Figure 1(top). Total monthly capacity expansion announcements 2014 onwards (MW).

Figure 2 (bottom). Monthly capacity expansion announcements by product type 2014 onwards (MW).

5,000MW of module assembly expansion plans in January in China and a further 1,000MW of cell and module plans in India.

Soon after its formation, UREC was cited in media reports for its interest in establishing cell and module manufacturing operations in the US, after the Section 201 trade case as high tariffs were imposed. Some reports indicated a 500MW to 1,000MW nameplate capacity that could be implemented in phases.

Other notable plans included the possible expansion at Photowatt, a subsidiary of EDF Energies Nouvelles in France, to meet the growing French government tenders and in-house projects with effectively a 450MW module assembly expansion using mono-cast wafers and possibly a JV involvement from SMSL member, Canadian Solar.

Leading SMSL JinkoSolar also confirmed plans to build a highly automated module assembly plant in Jacksonville, Florida, USA post Section 201 trade case.

February review

The month of February was in total contrast to the previous month as only a combined total of 850MW of new expansion plans were announced.

Only 500MW of solar cell expansions were announced coupled to only 350MW of module assembly.

Notable was a proposed 150MW module assembly expansion at Recom-Sillia in France and plans by Mission Solar in San Antonio, Texas, USA to double module assembly capacity to 400MW, which was after the Section 201 trade case tariff decision.

Although February announcements did not top 1,000MW, 2017 was notable for having two months (August and September) when announcements did not reach 1,000MW.

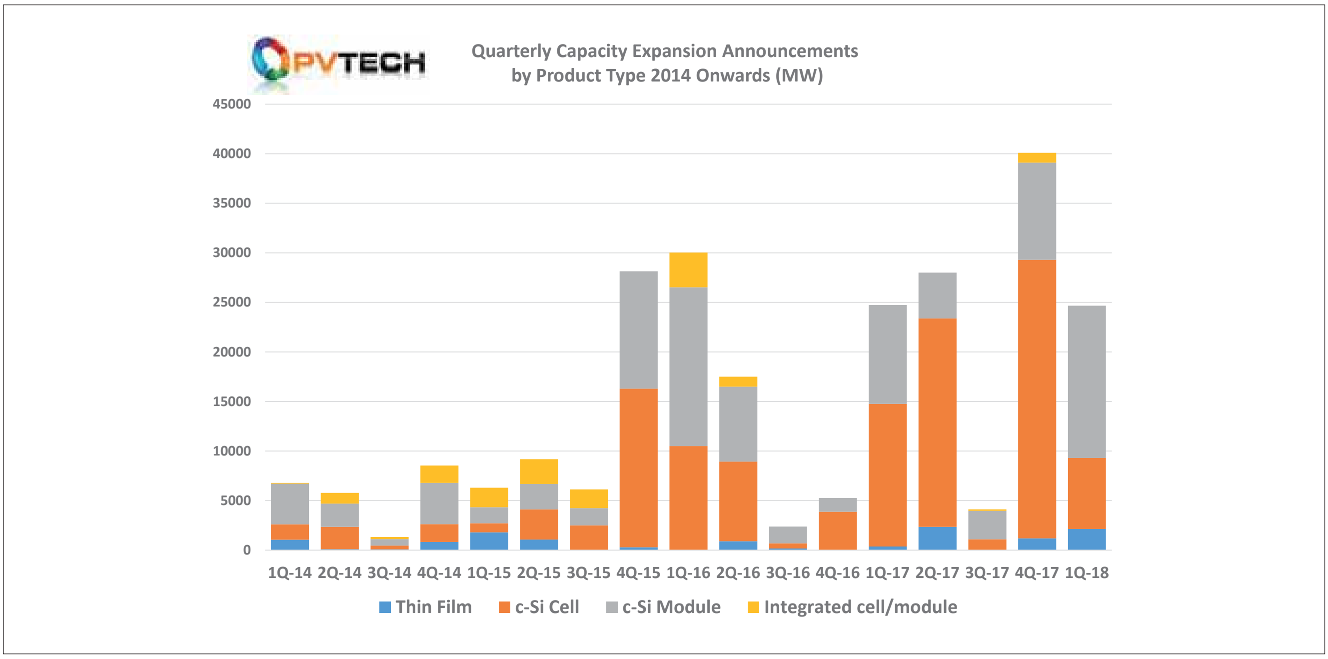


Figure 3 (top). Quarterly capacity expansion announcements by product type 2014 onwards (MW).

March review

After the collapse in announcements in February, March bounced back stronger than January, accounting for a combined total of 12,570MW of new cell, module assembly and thin-film expansion plans.

Indeed, March 2018 was the second highest for announcements since 2014; the highest March so far recorded was in 2016 (13,325MW).

Once again module assembly announcements led the way, totalling 6,620MW, compared to 3,810MW of solar cell expansion plans. However, thin film module expansions, primarily CIGS (Copper-Indium-Gallium-Selenide) from Hanergy Thin film Power Group, totalled 2,140MW.

Hanergy would seem to have created a completely new business model in 2017 that provides new industrial parks with a portfolio of a-Si, CIGS, GaAs and c-Si heterojunction (HJ) turnkey production lines to provide local government bodies access to solar technology and attract other hi-tech companies to new industrial parks.

The company announced for the first time in its 2017 annual report, issued at the end of March, that it had already secured contracts from three newly formed industrial park project companies in Mianyang Sichuan, Datong Shanxi and Zibo Shandong, which had purchased thin-film production lines from the company valued at approximately CNY11.3 billion (US$1.79 billion).

Unrelated to the industrial park business model, Hanergy also highlighted a contract signed in October 2017 with Huafengyuan (Chengdu) New Energy Technology Co.,Ltd., for the purchase of 600MW of nameplate capacity of automated and integrated 'High Efficiency Silicon heterojunction (SHJ) solar cell' production lines and technology

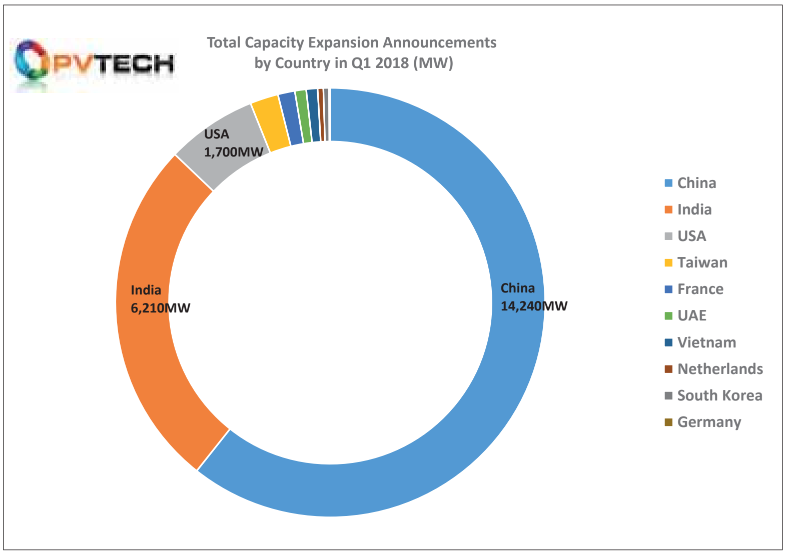


Figure 4 (bottom). Total capacity expansion announcements by country in Q1 2018 (MW).

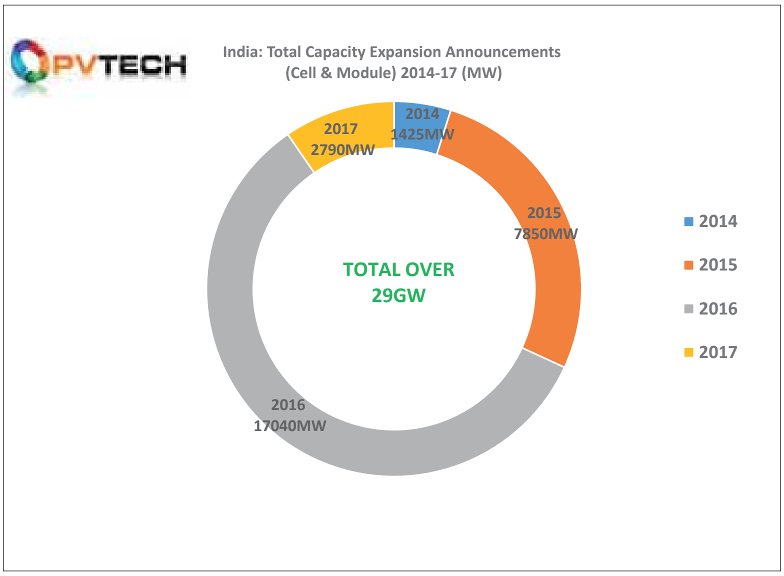


Figure 5. India: total capacity expansion announcements (cell & module) 2014-17 (MW).

transfer, valued at CNY1.39 billion (US$222.5 million) and CNY175.9 million (US$27.9 million), respectively.

Hanergy TF noted that it had delivered the equipment for the first 120MW production line during 2017, with an advance from the customer of US$4.05 million. Total equipment orders outlined in its annual reported reached 2,740MW.

India was also notable for around 28 dedicated PV module assembly firms planning small-scale expansions that reached around 4,000MW, while several cell and module producers planned a total of over 200MW of cell expansions.

Leading SMSL member JinkoSolar also provided expansion plan updates totalling 2,500MW in March on top of the 400MW module assembly plans for the US, which were announced in January 2018.

Quarterly review

The first quarter of 2018 is almost identical to the first quarter of 2017. Combined capacity expansion announcements reached 24,879MW, compared to 24,745MW in the first quarter of 2017.

However, the Q1 2018 breakout by segment is more biased to module assembly expansion plans, while the Q1 2017 bias was towards solar cell expansions.

A key trend consistent from the beginning of 2014 has been that the first quarter of each year has been strong for expansion plans and in the last three years exceeded or come close to reaching total combined announcements of 25,000MW.

In Q1 2018, module assembly capacity expansion plans topped 15,570MW, the second highest on record, only exceeded in the first quarter of 2016 when plans announced topped 16,000MW.

Thin-film activity increased quarter-on-quarter, due solely to Hanergy and totalled 2,140MW in the quarter, up from 1,200MW in Q4 2017.

Geographical review

On a geographical basis, Q1 2018 replicated the return of China as the number one destination for new capacity expansion announcements seen in 2017. China accounted for a combined segment total of 14,240MW in Q1 2018, or 61% of the total. China accounted for over 71,000MW in 2017, or 73% of the combined segment total.

However, Q1 2018 saw the re-emergence of India as the second largest destination for planned expansions. India accounted for 6,210MW in the quarter, or 27% of the combined segment total.

As already noted, plans from domestic module assembly companies totalling around 4,000MW were a key driver, while China-based LONGi announced 1,000MW of both solar cell and module assembly plants to be built in the country.

The resurgence of India is believed to be driven by threats of anti-dumping duties in India as well as momentum building, despite challenges in the downstream utility-scale sector. Indeed, with the US imposing further anti-dumping duties in early 2018, India becomes even more important to PV manufacturers located in China.

As previously noted in these reports, PV manufacturing capacity expansion announcements in India have proved significantly difficult to translate into 'effective' capacity.

In 2014, expansion plans totalling over 1,400MW were announced for India, which increased significantly in 2015 to 7,850MW, peaking at just over 17,000MW in 2016. Planned expansions in India collapsed to only 2,790MW in 2017.

In total, planned expansions in India since 2014 to the end of 2017 had reached over 29,000MW.

In contrast, the total planned expansions in India that have translated to effective new capacity since the beginning of 2014 are around 4,500MW, which includes around 1,700MW of new effective cell capacity and around 2,750MW of new effective module assembly capacity.

However, adding to the challenges in developing effective new capacity in India are the low utilization rates of existing manufacturing facilities.

SMSL update

Typically, in the first quarter the majority of SMSL members (JinkoSolar, Trina Solar, Canadian Solar, JA Solar, Hanwha Q CELLS, LONGi Group, GCL Group), provide capacity expansion updates when releasing fourth quarter and full-year financial results.

However, at the time of this report only JinkoSolar, Canadian Solar, Hanwha Q CELLS and LONGi Group had provided updates. Since going private, Trina Solar has not provided updated information on capacity expansion plans.

JinkoSolar

Leading SMSL member, JinkoSolar, is planning further capacity expansions across wafer, cell and module assembly in 2018, including a module assembly plant in the US, after strong capital expenditures in 2017 that totalled US$480 million.

JinkoSolar reported that in-house wafer capacity went from 5GW in 2016 to 8GW in 2017, a 3GW increase year on year, while solar cell capacity increased by 1GW in 2017, reaching 5GW.

Module assembly capacity was said to have increased from 6.5GW in 2016 to 8GW in 2017, a 1.5GW increase year on year.

In 2018, JinkoSolar has set plans to add 1GW of in-house wafer capacity in the first quarter, bringing total nameplate capacity to 9GW. By the end of the year a further 500MW expansion of wafer capacity is expected.

The company is also adding a further 1GW of solar cell capacity through the year, bringing in-house nameplate capacity to 6GW by year-end, while in-house module assembly capacity is being expanded by a further 1.5GW in 2018. This includes a 500MW increase in the first quarter of 2018 and therefore a further 1GW by year-end. Total module capacity is therefore expected to reach 10GW in 2018.

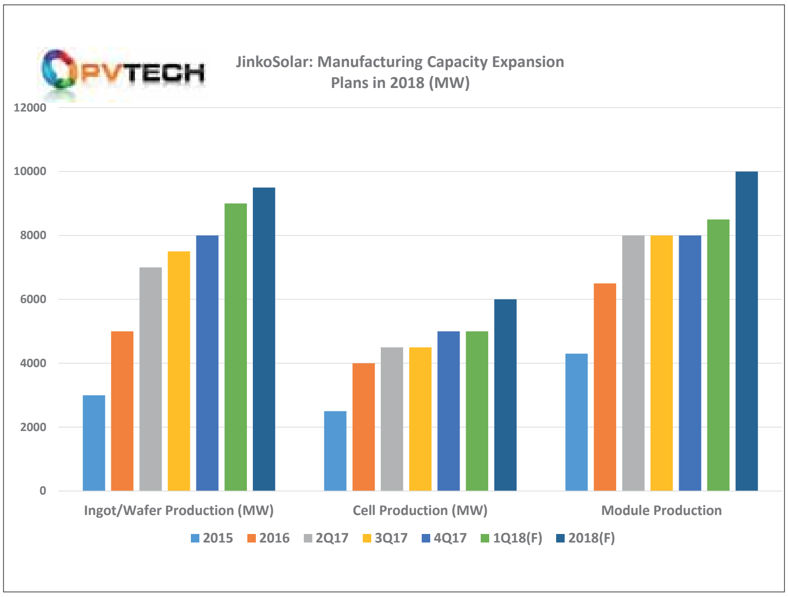
The difference between 2017 and 2018 expansions, apart from a slowdown in wafer capacity expansion plans, is the establishment of a 400MW module assembly plant in Florida.

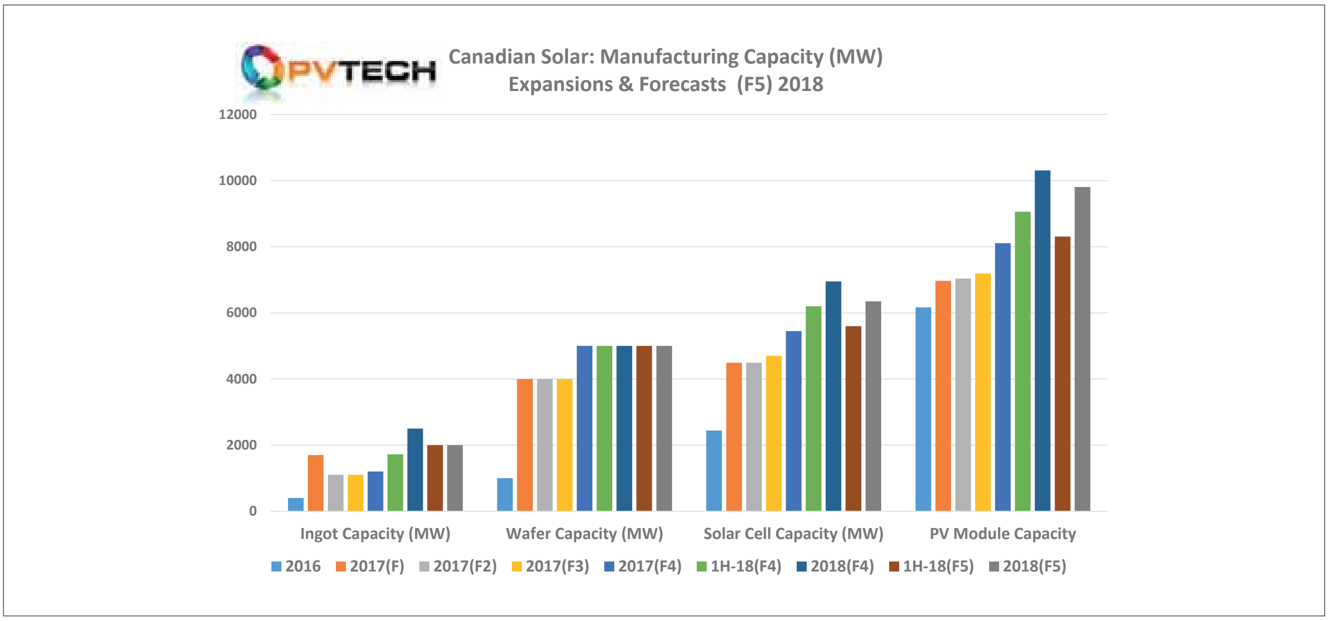
Canadian Solar

Third-ranked SMSL, Canadian Solar, surprised by announcing a slowdown in capacity expansions and lower nameplate capacity plans than given in

Figure 6 (top). JinkoSolar: manufacturing capacity expansion plans in 2018 (MW).

Figure 7 (bottom). Canadian Solar: manufacturing capacity (MW) expansions & forecasts (F5) 2018





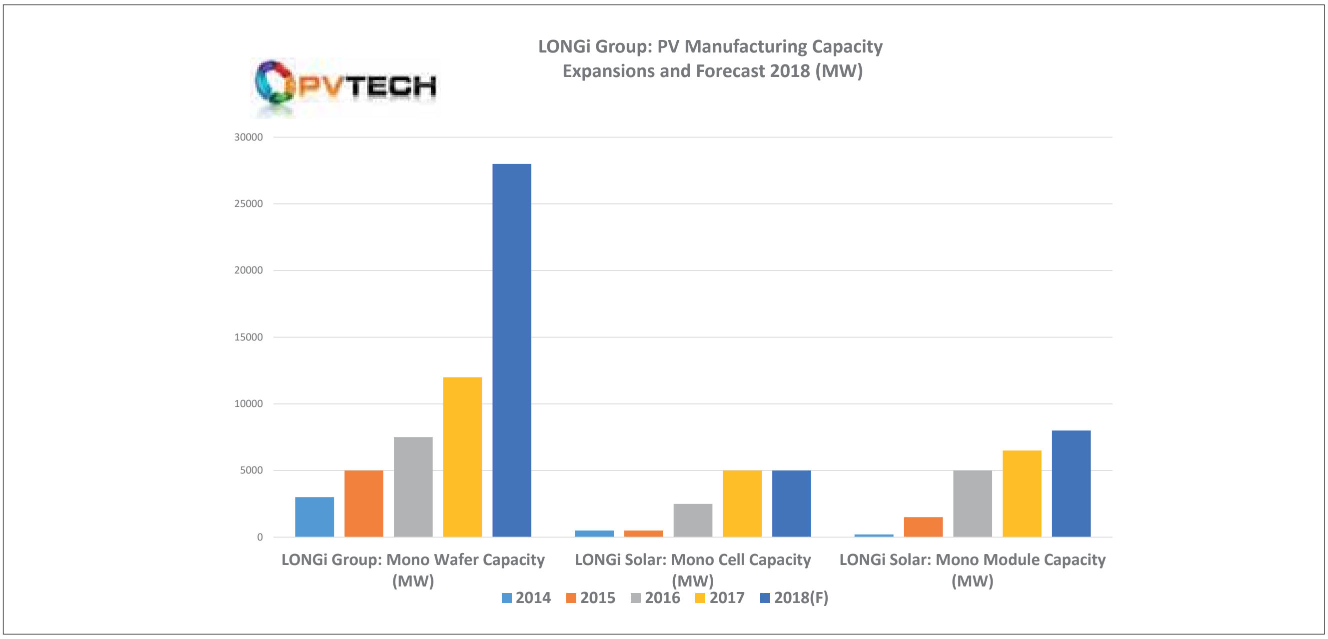


Figure 8. LONGi Group: PV manufacturing capacity expansions and forecast 2018 (MW).

late 2017. Having adjusted manufacturing capacity expansions throughout 2017, Canadian Solar continued to tweak plans for 2018.

The SMSL noted that its wafer manufacturing capacity at the end of 2017 stood at 5.0GW, a 3GW increase from 2016. However, the company has not announced new wafer capacity expansions for 2018, keeping capacity as 5GW.

Solar cell manufacturing capacity stood at 5.45GW at the end of 2017, up from 2.44GW in 2016, in line with previous upwardly revised guidance.

However, Canadian Solar has revised its cell capacity expansion plans again, noting that it expected nameplate cell capacity to reach 5.6GW by mid-2018, compared to 6.20GW in its previous update. The SMSL also noted that cell capacity at the end of 2018 was expected to reach 6.35GW, compared to previous guidance of reaching 6.95GW.

A similar adjustment has been made to in-house module assembly capacity expansion plans. The SMSL noted module capacity reached 8.11GW by the end of 2017, up from 6.17GW in 2016. The company said that module nameplate capacity was expected to reach 8.31GW by mid-2018, compared to its last update of reaching 9.06GW in that time frame.

Total module assembly capacity by the end of 2018 is targeted at 9.81GW, compared to 10.31GW guidance, previously given. Canadian Solar has not issued its annual report and therefore has yet to disclose capex figures for 2017.

Canadian Solar's management noted that it had recently experienced under-utilization rates at its module assembly plant in Canada and its manufacturing plant in Southeast Asia, due to the Section 201 tariff decisions by the US government.

Hanwha Q CELLS

The fifth-ranked SMSL, Hanwha Q CELLS had already restricted capital expenditure throughout 2017, all except for a the JV manufacturing plant in Turkey planned in response to building a 1.3GW (DC) PV power plant in the country which is expected to be operational in 2021.

The company had previously guided capital expenditures in 2017 to be around US$50 million, which would be allocated to manufacturing technology upgrades and certain R&D-related expenditures. However, the SMSL'S capex in 2017 was US$66.1 million, while R&D expenditure was down 51.2% to US$24 million, compared to US$49.2 million in 2016.

The SMSL had had an in-house nameplate capacity of 4,300MW for solar cells and modules at the end of 2017, unchanged from the previous year.

In 2018, Hanwha Q CELLS expects a slight increase in capex, due to initial spending on its new integrated manufacturing operations in Turkey. The company guided capex of US$90 million in 2018 and an allocation of around US$37 million to the new plant in Turkey.

In early April, so technically outside the scope of this report, the SMSL reported a fourth quarter loss of US$50.5 million, primarily attributed to the asset write down of its entire wafering operations, which were based at dedicated facilities in Lianyungang, Jiangsu Province, China.

The company had multicrystalline ingot nameplate capacity of 1,550MW and 950MW of multicrystalline wafer capacity. The SMSL cited that the wafering operations were unprofitable as well being impacted by a downward trend in wafer prices.

However, the JV in Turkey requires Hanwha Q CELLS to establish wafering operations not just solar cell and module assembly to comply with the downstream project tender win.

LONGi Group

Leading integrated high-efficiency monocrystalline module manufacturer and seventh ranked SMSL member LONGi Green Energy Technology via is subsidiary LONGi Solar (cell/module) manufacturer had executed on an aggressive capacity expansion strategy in 2017.

Mono wafer capacity went from 7,500MW in 2016 to 12,000MW by the end of 2017, a 60% increase, year-on-year. Mono solar cell capacity went from 2,500MW in 2016 to 5,000MW by the end of 2017, a 100% increase, compared to the prior year.

However, module assembly capacity increased at a relatively lower pace, going from 5,000MW to 6,500MW by the end of 2017, a 30% increase year-on-year.

The company announced in Q1 2018 that mono wafer capacity would be expanded to 28,000MW by the end of 2018, more than a 133% increase over the previous year.

Although solar cell capacity is expected to remain at 5,000MW, LONGi will expand mono module assembly to 8,000MW by the end of 2018, a 60% increase, year-on-year.

However, separate to the expansion cited, LONGi Group announced in the first quarter of 2018 that it would invest US$309 million, including around US$240 million in constructing a new facility in Andhra Pradesh, India, with an initial nameplate capacity of 1,000MW of monocrystalline solar cells and expand its mothballed 500MW module assembly plant (previously announced) to 1GW.

The new solar cell facility is expected to be operational in January 2020, while the expanded module assembly plant plans are expected to be completed and production ramp occur by the end of August 2019.

Conclusion

As discussed, capacity expansion announcements in the first quarter of 2018 remained strong, driven primarily by China and India on the back of domestic downstream demand. The US benefited from Section 201 tariffs, but only in respect to module assembly expansions and relatively small new assembly plant plans from the leading SMSL.

A significant increase in thin-film expansion plans, specifically in China, driven by one company, Hanergy, which provided a surprise revival, notably for CIGS technology.

The return of module assembly announcements that far outpaced those of dedicated solar cell expansion plans was a key highlight.

News

GCL-Poly building 20GW mono ingot manufacturing facility in China

Leading polysilicon and multicrystalline wafer producer GCL-Poly Energy Holdings is planning to build a 20GW monocrystalline silicon ingot manufacturing facility in Qujing, China.

GCL-Poly's wafering subsidiary GCL-Poly (Suzhou) New Energy Co has entered into an agreement with the Qujing Municipal Government with plans for a joint venture with unspecified strategic partners for the required facilities said to cost around CNY9 billion (US$1.4 billion).

The new mono ingot product plant would be built in two 10GW phases and use the firm's CCZ (Constant Czochralski Monosilicon) technology.

GCL-Poly had increased nameplate wafer capacity to 30GW at the end of 2017, a 62.2% increase over the previous year.

Actual wafer production in 2017 was approximately 23,902MW an increase of 37.9% from 17,327MW produced in 2016.

GCL-Poly had around 2GW of mono wafer capacity at the end of 2017.

In early 2018, leading fully-integrated high-efficiency monocrystalline manufacturer LONGi Green Energy Technology planned to triple monocrystalline ingot and wafer capacity to 45GW in 2020.

The planned expansions by the key rivals is a response to the industry transition to high-efficiency monocrystalline wafers and away from multicrystalline

GCL-Poly is building a new mono-Si manufacturing facility in China.

FINANCIAL RESULTS

GCL-Poly's wafer subsidiary reports increased revenue in Q1 2018

GCL-Poly Suzhou reported revenue in the first quarter of 2018 of around US$675.3 million, up from around US$562 million in the fourth quarter of 2017, up from US$634 million in the prior year period.

GCL-Poly Suzhou had also increased nameplate wafer capacity in 2017, going from 18.5GW in 2016 to 30GW at the end of 2017, a 62.2% rise.

However, wafer ASP declines have continued to weigh on profitability.

GCL-Poly Suzhou reported a net profit of approximately US$14.46 million in the first quarter of 2018, compared to a net profit of around US$13.9 million in the prior year period, despite the capacity increases.

GCL-Poly is planning to build a 20GW monocrystalline silicon ingot manufacturing facility in Qujing, China. GCL-Poly Suzhou had entered into an agreement with the Qujing Municipal Government with plans for a JV with unspecified strategic partners for the required facilities said to cost around RMB9 billion (US$1.4 billion).

Daqo breaks quarterly polysilicon shipment record but wafer sales slump in Q1

Daqo has produced a record high 5,657MT of polysilicon in the first quarter of 2018, as well as breaking its previous record of external sales volume, which reached 5,411MT.

However, multicrystalline wafer sales volume plummeted to only 13.3 million pieces, compared to 22.3 million pieces in the fourth quarter of 2017 and 22.4 million pieces in the first quarter of 2017.

Daqo reported first quarter 2018 revenue of US$103.3 million, compared to US$103.7 million in the fourth quarter of 2017 and US$83.8 million in the first quarter of 2017.

Revenues from polysilicon sales to external customers were US$95.6 million, compared to US$89.8 million in the fourth quarter of 2017 and US$70.4 million in the first quarter of 2017.

The sequential increase in revenues from polysilicon was primarily due to higher polysilicon sales volumes, which were partially offset by lower ASPs.

Revenues from wafer sales were only US$7.6 million, compared to US$13.9 million in the fourth quarter of 2017 and US$13.4 million in the first quarter of 2017.

The company guided 5,600MT to 5,800MT of polysilicon production in the second quarter of 2018 with sales of approximately 5,300MT to 5,500MT.

LEGAL

Yingli Green forced into court arbitration over US$897.5 million polysilicon contract claim

Struggling Chinese PV manufacturer Yingli Green Energy is being forced into arbitration at the London Court of International Arbitration (LCIA) by a major polysilicon producer over a long-term 'take or pay' supply contract with damages claimed to be US$897.5 million.

Yingli Green recently reported a 2017 annual net loss of US$510 million and a cash position of only US$58.1 million. The company was forced to raise warnings over its 'going concern' position.

Around 2007, shortages of polysilicon led to many PV manufacturers locking in fixed-price long-term supply contracts based on 'take or pay' agreements.

By 2011, polysilicon supply had increased significantly and spot market prices had collapsed, leaving companies paying higher prices than the open market.

Some major cell producers such as Q Cells, Suntech and last year, SolarWorld, primarily went bankrupt over these 'take or pay' supply contracts.

Adding to the recent woes was the decision by China's Ministry of Industry (MOFCOM) to impose high import duties on overseas polysilicon producers, notably the US at the beginning of 2014, as part of a solar trade war with the US.

Meyer Burger appealing dismissal of diamond wire patent infringement case in China

PV manufacturing equipment supplier Meyer Burger will appeal an initial judgment made in a Chinese court that dismissed its patent infringement lawsuit against Wuxi Shangji Automation Co over its Diamond Wire Management System (DWMS).

The decision by the Nanjing Intermediate Court to reject its patent infringement lawsuit regarding Chinese patent number CN 104411434B comes quickly after filing the case in February,2018.

At that time Hans Brändle, chief executive of Meyer Burger Technology, had said: "Meyer Burger invests substantial amounts in R&D each year to create cutting-edge technologies that deliver significant value to our customers. We are determined that our customers will exclusively benefit from our industry leading technology as we push the limits of photovoltaic innovation. Our intellectual property serves as the foundation of our technologies and market leadership."

Diamond wire technology has been at the centre of a major migration to monocrystalline wafer technology as well as production cost cutting to help multicrystalline wafers to remain competitive. Adoption of diamond wire sawing and wafer texturing processes also boosts cell conversion efficiencies.

OPERATIONS AND EXPANSIONS

Daqo further expanding ultra-high purity mono-crystalline-grade polysilicon production

China-based polysilicon producer Daqo New Energy is accelerating the pace of its Phase 3B capacity expansion project as well as starting Phase 4A that will increase annual polysilicon capacity by 35,000MT.

Credit: Yingli Solar

Yingli faces legal proceedings over a polysilicon contract.

In February 2018 Daqo said it planned expanding polysilicon production by at least 12,000MT in less than 18-months, which would be dedicated to supplying high-efficiency monocrystalline wafers due to continued strong demand.

Daqo had then said that its Phase 3B expansion at its Xinjiang, China, facility had completed ground foundation and initial ground preparation work in the fourth quarter of 2017 and was expected to start pilot production in the first half of 2019.

The expansion would lead to a total annual nameplate capacity of over 30,000MT by the end of the second quarter of 2019.

The company has quickly revised those plans by accelerating the pace of expansion to include the complete construction and installation of equipment, as well as pilot production starting by the end of 2018. The ramp to full production capacity of 30,000MT is therefore expected to occur during the first quarter of 2019.

Daqo also said that it was kick-starting its Phase 4A polysilicon expansion, which was intended to increase annual polysilicon capacity by 35,000MT.

Wacker expects to restart polysilicon production at US plant in Q2

Polysilicon producer Wacker Chemie plans to restart production at its Charleston, US, facility in the second quarter of 2018, after an explosion on 7 September 2017.

Although the explosion and fire were relatively small, the long delay in restarting production was said to be due to difficulties in identifying the exact cause of the explosion, which was eventually traced to a new chlorosilane pump design that failed. The company also received US$100 million in an insurance claim for damages but is awaiting for the insurance payout for loss of production.

With the Charleston facility out of action, Wacker has been running its two polysilicon plants in Germany at full-capacity but the overall lower production continued to impact revenue in the first quarter of 2018.

Wacker reported polysilicon sales of €219.3 million (US$265.5 million) in the first quarter of 2018, 18%

less than in the prior year period.

EBITDA came in at €48.2 million (US$58.3 million), a 32% decline, due to ongoing costs at the Charleston facility.

Hanwha Q CELLS shuts wafering operations

Hanwha Q CELLS has discontinued its ingot and wafer manufacturing operations in the fourth quarter of 2017, due to the wafer operations being unprofitable.

The company reported a fourth quarter loss of US$50.5 million, primarily attributed to the asset write down of the wafering operations, which were based at dedicated facilities in Lianyungang, Jiangsu Province, China. Hanwha Q CELLS had multicrystalline ingot nameplate capacity of 1,550MW and 950MW of multicrystalline wafer capacity.

The company's bottom line had been negatively affected by the recognition of a one-time loss associated with the discontinuation of its wafer manufacturing operations and bad debt expenses, without which it would have seen an improvement in its profitability due to elimination of losses resulting from unprofitable operations as well as a downward trend in wafer prices.

The company reported a net loss attributable to ordinary shareholders of US$9.2 million in 2017, while gross margin in the fourth quarter of 2017 was 8.5%, compared with 11.6% in the third quarter of 2017, primarily due to the write-off of wafer production assets.

However, the company said that its gross margin would have been 14.8%, up 3.2% points quarter-on-quarter and up 7.8% points compared to the fourth quarter of 2016, when excluding the asset write-off.

REC Silicon starting volume FBR polysilicon production at Yulin plant in China

Polysilicon producer REC Silicon achieved 800MT of Fluidized Bed Reactor (FBR) granular polysilicon production at its joint venture plant in Yulin, China, in the first quarter of 2018.

The Yulin plant JV was announced back in February 2014, with a planned 18,000MT of granular polysilicon and 1,000MT of Siemens-based polysilicon and 500MT of silane gas loading capability.

Full capacity utilization is expected during the second half of 2018, making it the first FBR plant to operate in China. The company expects the plant to produce 8,000MT in 2018. The facility was completed within the budget of US$1.25 billion.

However, due to the solar trade war between the US and China, REC Silicon has been operating its US polysilicon plants below half production capacity rates. The company has been locked out of supplying to China due to high import tariffs.

The challenging business conditions caused by the trade war also limited REC Silicon's ability to invest in the JV plant, resulting in its 49% shareholding being reduced to just 15%. The company has an option in three years to take a 34% equity interest in the plant.

REC Silicon reported first quarter 2018 revenues of US$69.6 million, down from US$78.0 million in the previous quarter. EBITDA was US$14.6 million compared to US$10.3 million in the previous quarter.

CEO Tore Torvund said: "I am very encouraged by the strong results this quarter. The US$14.6 million EBITDA is the strongest EBITDA we have reported in three years. The solar market continues to expand at a strong rate and REC Silicon will be part of that growth as demand for our FBR material increases."

Polysilicon production in the reporting quarter was higher than guided at 3,523MT.

LONGi taps Daqo for major ultra-high-quality polysilicon supply

High-efficiency monocrystalline module manufacturer LONGi Green Energy Technology has secured an ultra-high-quality polysilicon supply agreement with China-based polysilicon producer Daqo New Energy Corp.

Daqo said that the polysilicon supply agreement with LONGi amounted to 39,600MT over a 32-month period. Financial details were not disclosed.

Baoshen Zhong, Chairman of LONGi, commented: "Daqo New Energy's ultra-high-quality polysilicon and reliability make them the ideal strategic supplier, and we look forward building a deeper partnership with them."

Daqo has also recently announced plans for expanding production by at least 12,000MT in less than 18-months that will be dedicated to supplying high-efficiency monocrystalline wafers producers, due to continued strong demand.

Daqo had said that the Phase 3B expansion at its Xinjiang, China facility was expected to start pilot production in the first half of 2019. The expansion would lead to a total annual nameplate capacity of over 30,000 MT by the end of the second quarter of 2019.

Credit: Wacker

Wacker hopes to restart production at its Charleston facility in Q2 2018.

The opportunity for wafer-based reduction in LCOE

Adam Lorenz[1], Jochen Rentsch[2], Sebastian Nold[2], Todd Templeton[1] & Laureen Sanderson[1]
[1]1366 Technologies, Bedford, Massachusetts, USA; [2]Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

Abstract
As the PV industry strives to reach terawatt scale, addressing the last remaining cost centres of the crystalline silicon value chain will play a critical role in ensuring that the industry can continue to achieve lower systems costs, and provide the extremely low levelized cost of electricity (LCOE) required to drive the adoption of this form of energy. Wafer manufacturing remains the single largest cost driver in industrial cell production. While incremental improvements, such as diamond wire (DW) sawing, have helped to lower silicon consumption, wafer manufacturing has lacked the significant step change necessary for achieving dramatic cost reduction. Creating silicon wafers directly from the melt, without sawing, has long been recognized as a potential breakthrough technology for PV, as it would: 1) allow more effective silicon utilization; 2) eliminate ingot cropping, squaring and blocking and associated consumables costs; and 3) eliminate the most wasteful, high-cost step in wafer manufacturing – the sawing. This paper discusses Direct Wafer® technology, which achieves the long-sought cost and performance advantages compared with current ingot-based production methods; also discussed are the current technical achievements of this wafering process as it moves into commercialization. Wafers produced directly from the melt have been shown to deliver equal or better solar cell efficiency and module stability. Moreover, the ability to operate at the melt level provides significant opportunity for additional R&D achievements, opening a clear path for future industrial importance.

Background
The concept of manufacturing wafers without kerf – the sawdust-like by-product of slicing ingots – is not new. For decades the solar industry has consistently sought ways to eliminate waste and strip cost from the conventional process. Numerous early attempts were made to work at the melt level, but the resulting technical achievements could not compete with the incumbent approaches. While the traditional methods continued to make incremental improvements, the knowledge gained from the earlier work towards kerfless wafer manufacture provided the foundation for what has since emerged: a disruptive wafer production process that pulls silicon wafers directly from a molten bath, simultaneously achieving low cost, high throughput and superior performance.

Fundamentally, the *Direct Wafer process* is a furnace invention, a machine that allows a standard-sized wafer to be created in a single step. At an industry level, this method represents the first major advancement in furnace technology in nearly 50 years, the last being the development of the directional solidification (D-S) system in the early 1970s. That has since gone on to become the standard for multicrystalline ingot casting, while the Czochralski growth method, developed in 1916 and adopted for silicon by Bell Labs in the 1950s, has remained the dominant process for monocrystalline ingot pulling [1]. Both ingot casting and ingot pulling incur manufacturing costs associated with multiple steps, beginning with polysilicon purification and crystallization, then bricking, grinding and chamfering, and finally cropping, wire sawing and cleaning of the wafers. From a production-cost perspective, silicon usage, crystallization and wire slicing represent the three dominant parts of the traditional wafer-processing chain.

Polysilicon to wafer approaches
For half a century there have been two approaches to converting polysilicon into wafers. While these technologies have adequately met the needs of the PV industry, they endure as significant cost centres, limited by an inability to dramatically reduce the amount of input material required during fabrication.

Today the majority of silicon wafers for solar cells are produced by the directional solidification technique, also known as *ingot casting*. The standard process for the production of multicrystalline silicon consists of multiple steps:

- Heating up
- Melting of feedstock
- Crystallization phase and cooldown with reduced pressure
- Argon purging

The resulting ingots, with a total mass of 950kg, typically yield 36 bricks from a 6 × 6 sawing template. Typical crystal growth rates are in the range 10–15mm/h. The total cycle time – depending on the crucible size/loaded mass, the crystal growth velocity and the general furnace layout – is in the range 65 to 70 hours for current Gen6 furnace technology.

The silicon waste associated with the multicrystalline approach is significant, as opportunities for recycling are limited because of the high levels of impurities – such as iron, nickel, copper and carbon – at the top of the ingot, a result of the segregation coefficient (segregation coefficient = the difference in solubility of impurity atoms in liquid from that in solid). This top layer must be removed and scrapped, and the remaining ingot must still contend with impurities from the crucible and coating which have diffused into the cast material and lead to poor quality at the bottom and sides of the ingot (the 'red zone').

It is possible for ingot casting to produce higher-quality mc-Si material (called *high-performance (HP) mc-Si* or *high-efficiency (HE) mc-Si*) through the 'half melt approach' [2–4]. This process maintains a temperature below 1,400°C at the bottom of the crucible to keep the lower portion of the Si feedstock from melting. This unmelted Si acts as a seed to initiate a multicrystalline grain structure with homogeneously distributed small grains. While this process has led to the production of mc-Si ingots with fewer dislocations, resulting in a higher-quality material, the process time is lengthened and the overall yield is reduced, given that the seed region cannot be used for cell production.

The monocrystalline silicon wafer material for the PV market is currently produced by the Czochralski technique (also called *Cz pulling*), which also consists of several steps [5,6]:

- Heating up
- Melting of feedstock and melt stabilization
- Dipping of the seed crystal and necking process
- Initial crystal growth to the desired diameter ('shoulder growth')
- Crystallization of the ingot with constant diameter ('body')
- Growth of the end cone before the crystal is pulled and the furnace is cooled down

Standard Cz pullers for silicon PV wafer production utilize crucibles of up to 22" in diameter, with up to 210kg of Si mass and a crystal length of up to 2.8m. It has been reported recently, however, that machine developments (especially in China) will lead to larger machines which use crucibles of 28" or 30" in diameter. These furnaces would have additional feeding systems to add Si feedstock into the melting process, yielding crystal masses of 325kg and crystal lengths of up to 4.0m. It is expected that these crystal pullers will also have the configuration for multi-pulling or continuous Cz (to potentially increase crystal growth throughput).

Ingot processing

The processing of ingots into wafers is shown in Fig. 1, together with a complete loss-and-recycle analysis throughout the wafer production chain. The bricking of D-S ingots currently uses a diamond wire (DW) cutting machine with a water-based fluid in a grid-like configuration. Each of the parallel cutting lines is as long as the side length of the final wafer, and the ingot, including its side slabs, is cut in one process. While the side slabs can be recycled, sawing itself accounts for approximately 6kg of kerf loss.

The raw-side faces of the newly sawn bricks reach final size and surface quality during a two-step process involving grinding and polishing; this results in an additional kerf loss of approximately 20kg. The inclusion-rich top and bottom sections of the bricks are cropped using a band saw or an inner diameter (ID) saw, and the top section (42kg) is discarded because of metal contaminants and materials with low segregation coefficients, carbide or carbon particles. The bottom section is recycled and used for the next growth run. The bricks are then ready for wafering (wire slicing).

Today, the preferred technique for wafering is the DW cutting technique. In contrast to the former slurry technique, the abrasive particles are diamond fragments which are bonded to the steel core wire, either by resin gluing or by electroplating.

The cost of diamond wire is a magnitude higher than that of standard wire, and the higher-speed cutting process operates so as to make the most use of the wire by regularly reversing the wire movement direction ('pilgrim mode'). The fluid used during the process to cool the cutting channels and to transport the cut material (kerf) is water based with additives. Whereas the DW

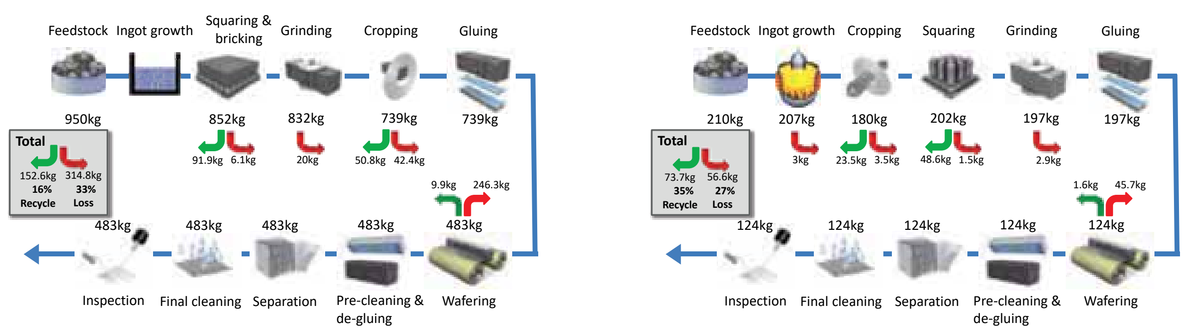


Figure 1. Silicon loss-and-recycle analysis throughout the D-S HP mc-Si (left) and Cz-Si (right) wafer process chains.

technique has been the predominant method for the cutting of monocrystalline silicon for many years, the major shift to DW cutting for multicrystalline silicon only began in 2017, but it has already become the main technique in 2018.

The final step, wafer cleaning, requires two processes. In the first of these, the cut wafers – still glued to the glass carrier beam – are cleansed to remove the cooling fluid. They are then de-glued in a mild acid bath, demounted from the carrier beam, machine separated and fed into the final cleaning system, which consists of spraying and rinsing in a hot ultrasonic or megasonic bath to wash the wafer surfaces. As a last step, the wafers are dried and transported to another area for a final quality check, sorting and packaging.

Direct Wafer approach

The Direct Wafer process, developed by 1366 Technologies, to make 156mm wafers [7] directly from a silicon melt eliminates the high-cost ingot-production steps described earlier. The key enabler of the Direct Wafer technology is a method for freezing a thin sheet of silicon on the surface of the melt, removing the sheet from the molten bath, and subsequently extracting the free-standing sheet. Within the same equipment, the sheet is then trimmed with a laser to form the final wafer geometry, and the clean trimmings are collected to be reused. The process, which uses heat removal perpendicular to the plane of the wafer, enables a high production rate of low-stress silicon within an extremely pure growth environment.

> "The Direct Wafer process to make 156mm wafers directly from a silicon melt eliminates the high-cost ingot-production steps."

The Direct Wafer platform was designed to produce industry-standard wafer geometry, to leverage cell and module manufacturers' existing investments, and to deliver a product that both drops into the current infrastructure and could benefit from the industry's collective performance and cost improvements.

In early 2009, 1366 first explored a proof of concept and several embodiments of the Direct Wafer method using molten tin as a model material at hot plate temperatures for rapid design iterations. Once a baseline was achieved with tin, a small-scale prototype silicon wafer furnace was built by the 1366 team. The initial wafers were transformed into small solar cells, measuring 2cm × 2cm, with an efficiency of 10%. In 2011 the first full-scale furnace was built to produce industry-standard-size 156mm wafers.

Table 1. Resulting net silicon utilization from a recycle-and-loss analysis for all considered manufacturing methods.

Manufacturing method	Net silicon utilization per wafer [g/wafer]
Cz-Si reference process at 10GWp (160μm)	15.65
HP mc-Si reference process at 10GWp (180μm)	17.07
Direct Wafer baseline process at 1GWp (180μm)	10.79
Direct Wafer roadmap process at 10GWp (130μm)	7.00

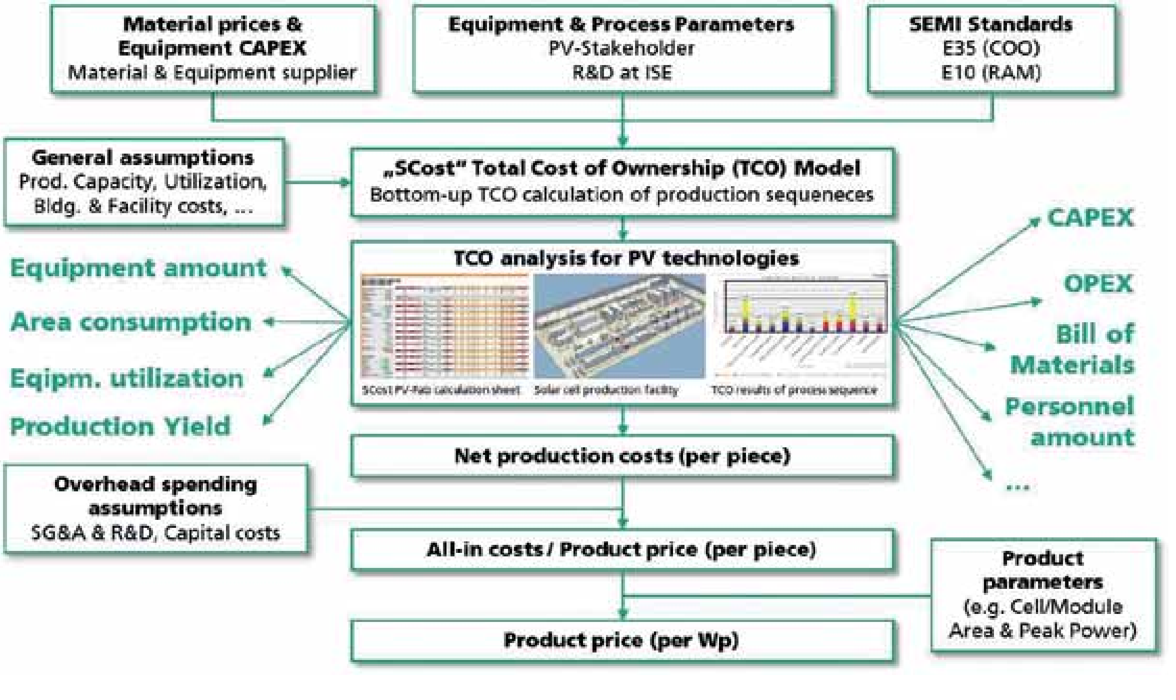


Figure 2. Methodology for the cost calculation using the SCost tool, developed at Fraunhofer ISE.

Having achieved reasonable electrical performance from the cells, 1366 opened a demonstration factory in 2013 to begin building full-scale manufacturing machines and continued to improve the furnace design. Three full-size production Direct Wafer machines currently operate in the demonstration factory, with each of these latest generation tools capable of producing 240 wafers per hour (15 sec cycle time, ~10MW per year). These demonstration machines provide the platform that is being reproduced for the first mass-production facility currently under way.

Total cost of ownership methodology

To provide an informed calculation of the cost-reduction capability of the Direct Wafer process, an economic analysis featuring a bottom-up calculation of the industrial PV value chain was conducted and adapted for individual production technologies. The underlying cost model is aligned with the SEMI standard E35 for the calculation of the cost of ownership (COO) for semiconductor and PV production equipment, as well as the SEMI standard E10 for reliability, availability and maintainability (RAM) [8,9]. The equipment- and process-related input parameters (e.g. process throughput or material consumption), as well as equipment capital expenditure (CAPEX), are gathered from various PV stakeholders, mainly directly from the equipment manufacturers, but also from PV companies using the equipment in actual production. Material input prices are primarily collected directly from the suppliers of the material. With the bottom-up total cost of ownership (TCO) model 'SCost', the process information from the individual process steps is put into complete process sequences, in combination with general production assumptions, such as the envisioned capacity and planned utilization of the production facility (as shown in Fig. 2).

The result of the TCO analysis of the process sequence is the net production costs per manufactured production item. The net production costs include all costs of production, and are divided into categories with the following cost components:

- **Equipment:** Production equipment and automation, including delivery, installation and qualification.
- **Building and facilities:** CAPEX, capital costs and operational expenditure (OPEX) related to fab building and facilities – HVAC, gas farm, DI water production, chemical supply, waste disposal, warehouse, offices, infrastructure personnel, canteen, etc.
- **Utilities:** Power, cooling, CDA, exhaust, DI water, water, N_2, etc.
- **Parts:** Spare parts and wear and tear.
- **Process consumables:** Solids, liquids, gases, etc.
- **Waste disposal:** Materials for fab internal disposal, costs for external disposal.
- **Labour in production:** Operators, technicians, supervisors, engineers, scientists.
- **Cost of yield loss (CYL):** Breakage and pieces not meeting quality requirements.

For capital cost, the weighted average cost of

Table 2. General model assumptions and calculation parameters.

Parameter	Value	Unit
Production output[a]	10,000	MWp/annum
Factory capacity utilization (320 days/annum, 24 hours/day)	7,680	hours/annum (87.7%)
Shift-dependent staff deployment to the production line[b]	4.0	FTE/position
Building[c] and facility[d] CAPEX: ingot and wafer production (building/facility)	200/950	$/m^2
Depreciation period (equipment/facility/building)	10/10/20	years
Silicon price	14.67	$/kg
Electricity price	6	¢/kWh
Capital costs (WACC after tax) for all stages	5.00	%
Equity/debt share	20/80	%
Cost of equity/debt (pre-tax)	10/5	%
Average tax rate	25	%

[a] Output with respect to assumed capacity utilization (higher utilization → higher output).
[b] Average number of employees per position to cover the total labour needs (including vacation and illness) with respect to the factory's capacity utilization (FTE = 'full-time equivalent').
[c] CAPEX calculated on total building area. Includes all costs for land, site preparation and building.
[d] CAPEX calculated on gross manufacturing area. Includes all required production facilities, such as HVAC, gas farm, DI water, chemical supply, waste disposal → facilities are ready for equipment hook-up.

capital (WACC) approach is used, including debt payments but also an assumed equity return for the company. Capital costs are calculated on the average employed capital of the company, including the fixed capital for production equipment, building and facilities, as well as for tied-up inventory capital in incoming and outgoing products, parts and process consumables and waste materials. Not included in the net production costs are overhead costs for selling, general and administrative (SG&A) expenses and for R&D, as well as capital costs associated with the corporate unit. For SG&A and R&D, market benchmark values are taken (as the share of revenues from annual reports from PV manufacturers); these are included in the 'all-in costs' component.

Finally, the main product-quality parameter included is the conversion efficiency of the cell or module; this is calculated from the peak power output (the power output under standard testing conditions – STC) and the area of the device.

The SCost methodology for the techno-economic assessment of PV technologies along the PV value chain is described in more detail in Nold et al. [10].

Table 2 gives an overview of the general model assumptions and the calculation parameters used in the TCO analysis.

Fig. 3 presents the results of the economic assessment of ingot and wafer production for a monocrystalline (Cz-Si) wafer and a high-performance multicrystalline wafer (HP mc-Si), as well as for the Direct Wafer baseline and roadmap approaches. Given today's capacities, the calculations were conducted on the basis of an annual output of 10GWp, with the exception of the Direct Wafer baseline, which assumed an annual output of 1GWp only, to represent initial scaling of the existing platform.

The poly-Si input material alone accounts for approximately half of the net wafer production cost for both of the reference technologies. Less poly-Si material is consumed for the Cz-Si wafer production, given that its internal silicon recycling rate is higher than that of mc-Si wafer production, and that more-aggressive thickness reduction is under way for Cz-Si wafers (also reflected by the lower net silicon utilization per wafer shown

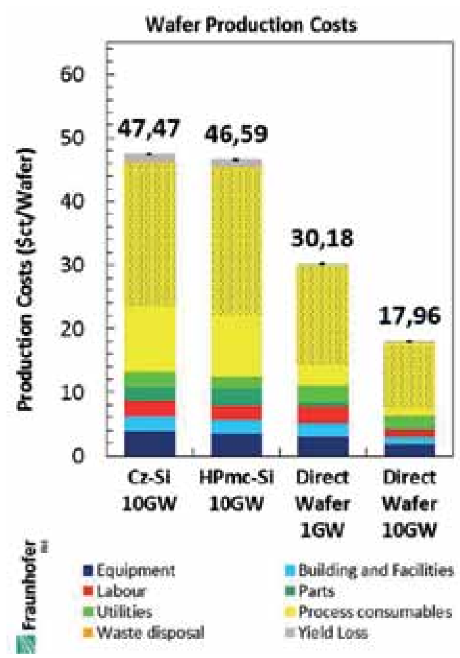


Figure 3. Results of the economic assessment of ingot and wafer production for Cz-Si and HP mc-Si wafers, and of the innovative Direct Wafer approaches (the poly-Si share of process consumables is indicated by the shaded area).

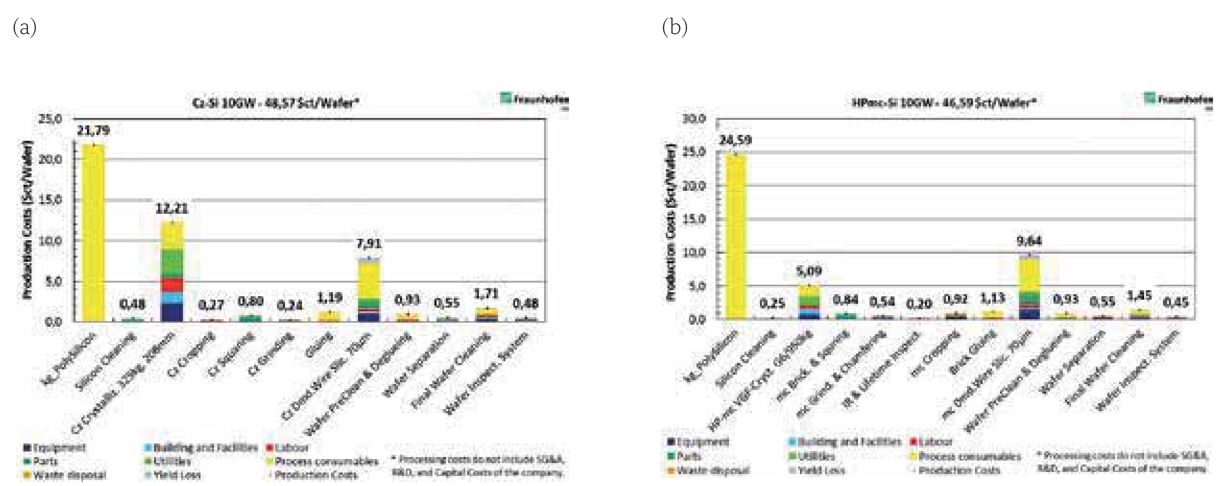


Figure 4. Cz-Si (a) and HP mc-Si (b) wafer net production costs (stepwise from left to right) for an ingot and wafer production with an annual output of 10GWp.

"The significant progress represented by the Direct Wafer process is particularly compelling with respect to the impact on the levelized cost of electricity (LCOE)."

in Table 1). Even though the crystallization equipment throughput for Cz-Si has increased, the equipment output for Cz-Si is still lower than for mc-Si. Thus, for the production of a Cz-Si wafer of the same size as an mc-Si wafer by D-S, more crystallization tools are required, resulting in higher Cz-Si ingot crystallization costs of 10.18¢/wafer, compared with 5.09¢/wafer for the HP mc-Si ingot (see Fig. 4). The slicing of mc-Si wafers is more expensive than for Cz-Si because cutting speeds must be decreased in order to cut through multiple different grain orientations.

Fig. 6 shows a comparison of the cost-assessment results with current wafer market prices according to the market analyst PVinsights. The red boxes indicate low, average and high wafer spot market prices in April 2018. As the Cz-Si wafers allow higher solar cell and module efficiencies than HP mc-Si wafers, higher wafer prices are achievable in the market, independently of the production costs.

Levelized cost of electricity

The significant progress represented by the Direct Wafer process is particularly compelling with respect to the impact on the levelized cost of electricity (LCOE). An analysis was performed (Fig. 7) using a combination of:

- the annual 10GWp all-in wafer costs established in this paper;
- the current PVinsights pricing to determine the cell and module conversion estimates for passivated emitter rear cells (PERCs) of 46¢/wafer and 60¢/wafer respectively for ingot-based manufacturing processes;
- the balance of system (BOS) data established by 'Bridge to India' [11].

The higher-efficiency mono (+1.6%$_{abs.}$ Ncell; −3%$_{rel.}$ cell to module) enables a system cost advantage of 3¢/Wp compared with HP mc-Si because of the near parity of wafer cost. This advantage is outweighed by the dramatic wafer cost reduction provided by innovation using Direct Wafer technology.

Quality and efficiency

The electrical quality and the subsequent efficiency potential of silicon wafers are determined by interactions between grain

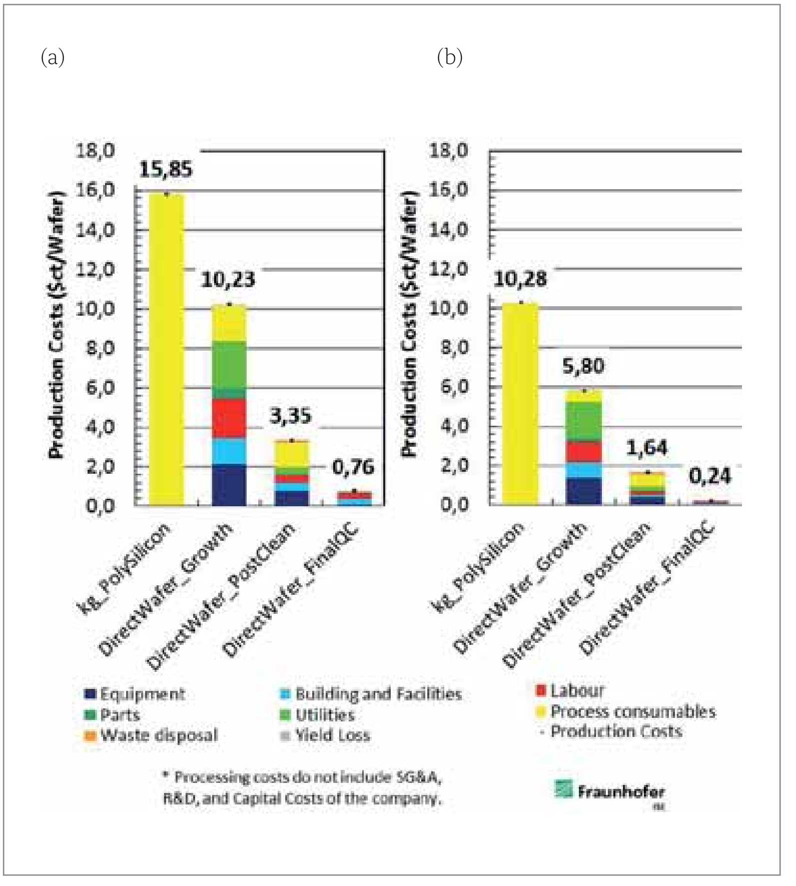


Figure 5. Direct Wafer net production costs (stepwise from left to right) for production with an annual output of (a) 1GWp (baseline), and (b) 10GWp (roadmap).

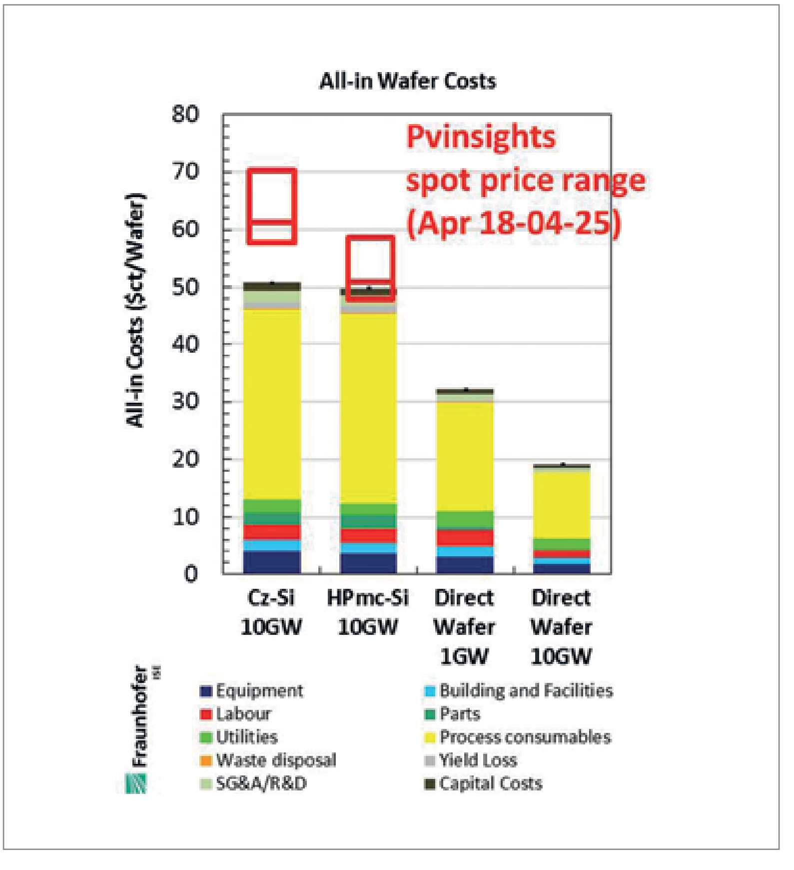


Figure 6. Comparison of the cost assessment results with current wafer market prices according to the market analyst PVinsights. The red boxes indicate low, average and high wafer spot market prices in April 2018 (DW-cut mono and mc-Si wafers outside of China).

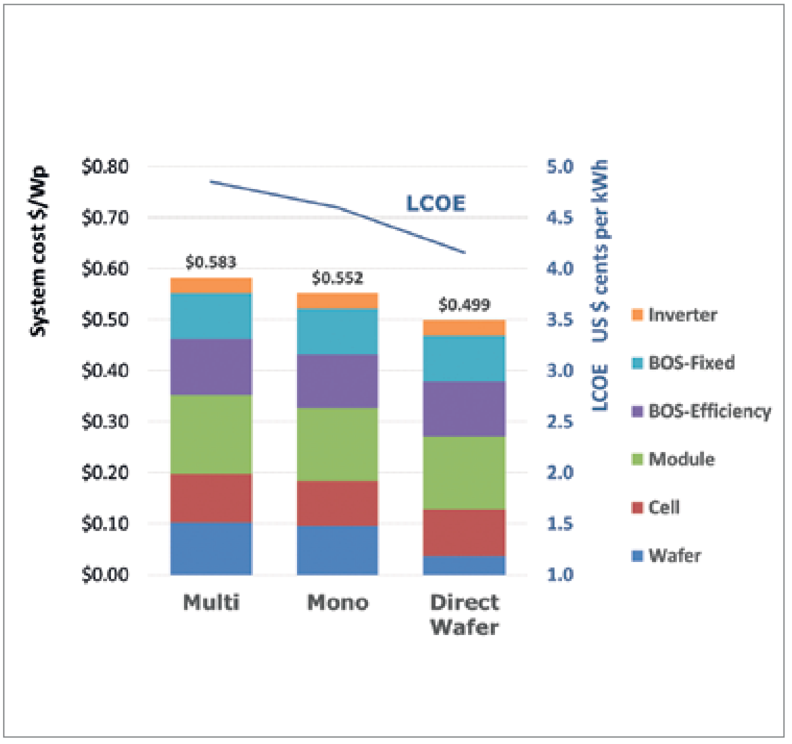


Figure 7. Comparison of LCOE assessment results using the all-in wafer costs established in this paper, PVinsights pricing and 'Bridge to India' BOS data.

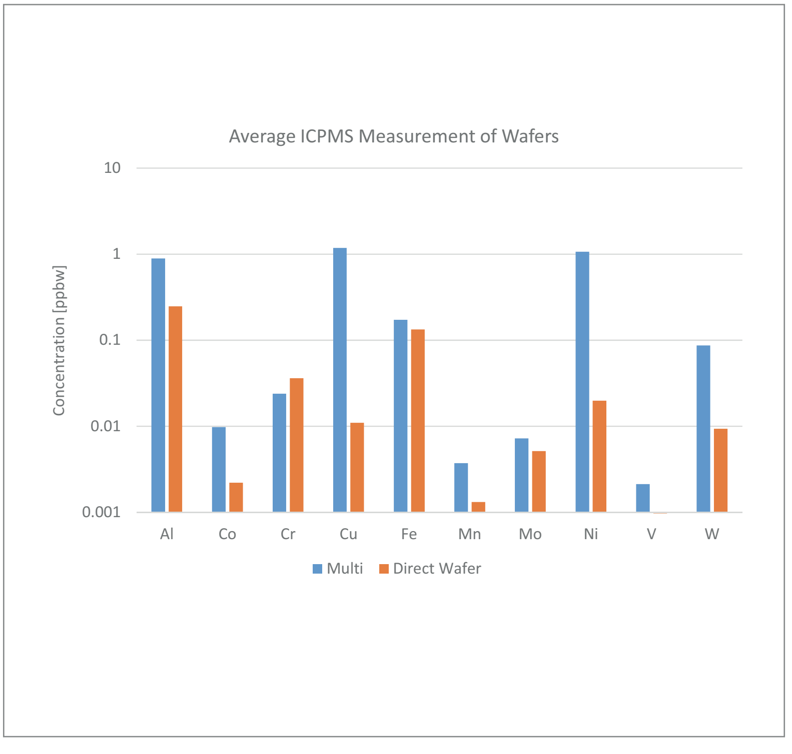


Figure 8. Comparison of impurity concentrations of wafers produced by mc-Si and Direct Wafer processing. Wacker Chemie AG provided hyperpure polysilicon as raw material, analytical services and technical consulting in the framework of its partnership with 1366 Technologies.

"Wafers formed directly from the melt have been shown to deliver solar cell performance the same as (or better than) that of ingot-based wafers in customer trials."

structure, dislocations and impurities. Contrary to the situation several years ago when the industry was focused on seeding mono D-S ingots, which struggled with dislocations, it has recently been shown that small grains in the D-S of seeded HP mc-Si actually help to lower dislocation density and produce higher-bulk-lifetime wafers. This is also true for the Direct Wafer method, which enables consistent control of the nucleation and growth for every wafer, so that the crystal structure is currently tuned for optimal performance with a uniform grain size between 0.5 and 1.0mm. These grain boundaries are perpendicular to the wafer surface and are well passivated by hydrogen during standard cell processing, which means that they do not play a significant role in bulk recombination of the finished cell. The beneficial effect of horizontal sheet growth, where the removal of heat is normal to the plane of the wafer, eliminates large thermal gradients in the wafer which would give rise to thermal stress and or high-density dislocations.

The interaction between the crucible and the silicon during an ingot's growth is known to be detrimental to performance. This interaction leads to the degradation of electrical properties along the ingot border, a layer referred to as the *red zone*. This layer is too poor in quality to be processed into wafers and must be discarded. Moreover, it is understood that because the ingots are held near their melting point for more than one day, significant in-diffusion from dirty materials occurs, impacting wafer quality, performance and passivation. The Direct Wafer growth process, however, occurs in a higher-purity environment, limits in-diffusion to just a few seconds, and delivers stable efficiency over growth periods exceeding six weeks. This long-term stability is made possible by a mechanism that prevents the build-up of impurities in the melt; this is in contrast to Cz growth, in which impurity build-up in the melt during ingot growth limits the number of ingots or the cumulative volume of silicon grown before impurities degrade performance.

In Fig. 8, inductively coupled plasma mass spectrometry (ICPMS) results demonstrate the various metals and levels detected on the basis of an average of the measurements of ten different wafers of each type. The purity advantages of the Direct Wafer growth environment are clearly visible.

The role of purity directly translates to wafer quality. The uniformity of wafer quality is visible in the module electroluminescence (EL) images in Fig. 9; the high-defect density areas found in standard multi wafers can be seen in contrast to the more uniform Direct Wafer module. A tighter cell efficiency distribution is also achieved in the case of Direct Wafer, demonstrated by a recent cell processing run of 24,000 wafers, which achieved 90% of all cells within three Ncell bins using 0.1%

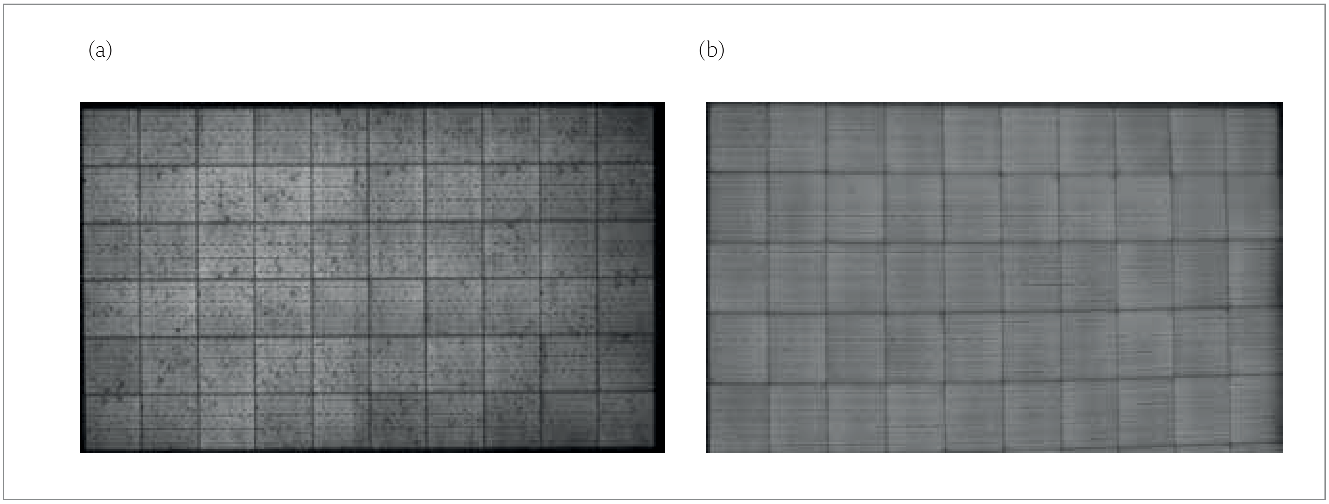


Figure 9. EL images of PV modules made with (a) HP mc-Si wafers, and (b) Direct Wafer products. The impact of dislocation tangles is evident in multi.

steps. The elimination of the low-efficiency tail common in ingot-based manufacturing reduces the sales and inventory challenges that result from the need to discard defective cells or the selling of lower-quality products at a discount.

Wafers formed directly from the melt have been shown to deliver solar cell performance the same as (or better than) that of ingot-based wafers in customer trials. With the demonstrations conducted on standard production equipment, these achievements are rapidly translatable to high-volume, day-to-day production. Direct Wafer products using a PERC cell architecture allow efficiencies well above 20%, and lot averages above 20.5% have recently been demonstrated using Hanwha Q CELLS' Q.ANTUM PERC process. This same combination of technologies has consistently demonstrated gains of more than 0.8% per year (Fig. 10), an improvement rate nearly double that for the average cell efficiencies obtained in mass production [12].

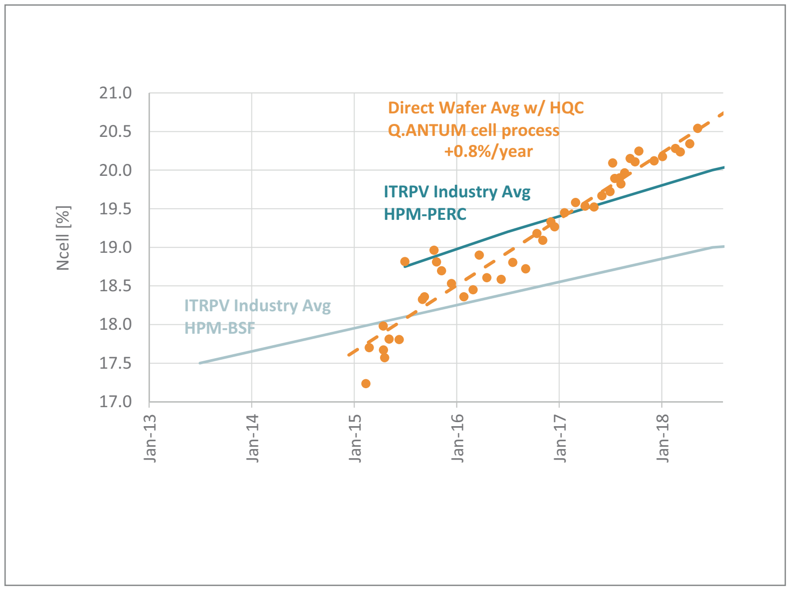


Figure 10. Evolution of the efficiency gains of Direct Wafer products in combination with Hanwha Q CELLS Q.ANTUM PERC process. Gains exceeding 0.8% per year have consistently been demonstrated.

In May 2017 a 500kW commercial installation at Tatsuno Ikariiwa in Hyōgo Prefecture, Japan, was completed. The array features Direct Wafer products in 500kW of modules manufactured at a Tier 1 cell and module manufacturer. The modules' field performance has been compared against a similar array of modules using standard HP mc-Si wafers and a similar module bill of materials (BOM) from the same manufacturer. The array has demonstrated good stability in terms of performance for the first 12 months since installation, with a specific power ratio calculated using the highest-performing sub-array of HP mc-Si modules as references. Comparative monthly performance is summarized in Figure 11.

Figure 11. Module performance of Direct Wafer modules at a commercial installation in Japan compared with HP mc-Si reference modules. Data was collected from the installation of more than 1,700 modules of each type.

Direct Wafer technology roadmap

The eventual migration to thinner wafers and the maturity of the Direct Wafer process will undoubtedly bring additional optimization. The technology has the potential to help the wafer industry break free from its commodity standing to one of strategic importance and advantage through

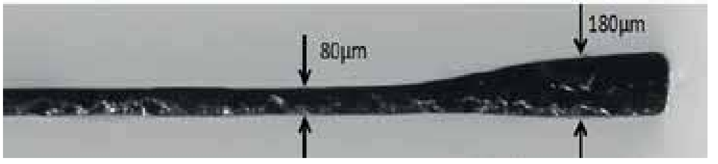


Figure 12. Example of locally controlled wafer thickness.

"Addressing the significant cost centre represented by the wafer is the key to achieving the LCOE reduction for terawatt solar."

the introduction of new wafer features impossible to achieve with conventional manufacturing.

To reduce the amount of silicon used and increase the efficiency achievable by PV wafers, manufacturers have pursued various methods of reducing wafer thickness. While wire sawing can be used to produce wafers thinner than the standard 180µm thickness, these thin wafers have lower mechanical integrity and break during cell fabrication, electrical interconnection and encapsulation in modules. Through the production of 3D wafers, the Direct Wafer process can meet the industry's anticipated need for thinner wafers without compromising wafer strength [13]. This is directly tied to the ability to work at the melt level, which allows local control of wafer thickness; local control can create a thick border where the perimeter of each wafer is of greater thickness than the remainder of the wafer, resulting in a strong, thin wafer that is able to withstand typical manufacturing stresses (Fig. 12). It provides manufacturers with a solution to reducing silicon usage without comprising existing standards or quality, and makes it possible to realize industry advancements in cell architecture or module features. Because the Direct Wafer process avoids the waste associated with sawing, the silicon usage can be less than 1.5g/W, and the crystalline silicon PV supply chain can achieve a wafer cost below 20¢.

The manipulation of dopant concentration has several potential advantages for cell performance, but it is impossible to alter dopant concentration when working with ingot-based silicon wafers. This is not the case when you are able to access the wafer during growth, allowing the introduction of a doping gradient through the wafer thickness. The Direct Wafer process has demonstrated that it is possible to grow wafers with a concentration of dopant six times higher at the wafer back side than at the front. This concentration characteristic has several important advantages [14]: higher voltages are achieved because of the higher concentration of dopant at the rear of the cell, and the higher lateral conductivity between the local contacts of a PERC cell can reduce the series resistance. The gradient in dopant can also provide a field effect, pushing the electrons to the front of the cell, for more efficient collection at the p-n junction. Simulations of the Direct Wafer approach have predicted an increase in cell efficiency of up to +0.7%, and initial tests have already demonstrated +0.3%.

Because of the continuous nature of the Direct Wafer growth method, it is also possible to grow wafers at constant resistivity over time through the use of strongly segregating dopants such as gallium. The process features a short time constant to reach a steady-state concentration in the melt in less than one hour, and is able to grow wafers at a constant bulk resistivity for 1,000 hours without the solute build-up that affects batch ingot processes, as described by the Scheil equation. The production of n-type wafers with a tight distribution of bulk resistivity has been demonstrated.

While the current equipment platform developed for Direct Wafer will support cost advantages over traditional processes, further improvements are already envisioned to increase the throughput of each Direct Wafer furnace; this will be possible without any changes to the physics associated with wafer growth. Equipment design changes can enable the growth of several wafers at a time for additional throughput and CAPEX reduction. An implementation of these design changes will allow 10GW production levels to be realized from a smaller number of furnaces, compared with even the relatively high throughput of next-generation G8 D-S furnaces. Direct Wafer production has a significantly smaller factory footprint because of the fewer steps involved, the inherent simplicity of the process, and the efficient use of materials and energy; it is a platform suitable for scaling to terawatt-level PV.

Conclusion

The concept of a wafer grown directly from molten silicon is not new, but its success had proved elusive. As a result, manufacturers focused instead on streamlining the supply chain to reduce costs, foregoing innovation and relegating the wafer to commodity status. Kerfless wafer technology, specifically the invention of the Direct Wafer process, introduces differentiation to the market, and allows cell and module manufacturers to break free from the constraints that have defined ingot-based manufacturing. Most importantly, operating at the melt level provides significant opportunity for additional R&D achievements, and provides a clear path for future industrial importance. Addressing the significant cost centre represented by the wafer is the key to achieving the LCOE reduction for terawatt solar.

References

[1] Dold, P. 2015, "Silicon crystallization technologies", in *Advances in Photovoltaics: Part 4*, Willeke, G.P. & Weber, E.R., Eds., Waltham, MA, USA: Academic Press, pp. 1–62.

[2] Ciftja, A. & Stokkan, G. 2014, "Growth of high performance multicrystalline silicon: A literature review", SINTEF, Trondheim, Norway.

[3] Yang, Y.M.et al. 2015, "Development of high performance multicrystalline silicon for photovoltaic industry", *Prog. Photovolt: Res. Appl.*, Vol. 23, pp. 340–351.

[4] Huang, X. et al. 2013, "Seed-assisted growth for high-quality multi-crystalline silicon ingots", *Proc. CSSC-7*, Fukuoka, Japan, pp. 91–96.

[5] Czochralski, J. 1918, "Ein neues Verfahren zur Messung der Kristallisationsgeschwindigkeit der Metalle", *Z. Phys. Chem.*, Vol. 92, pp. 219–221.

[6] Zulehner, W. 1999, "Historical overview of silicon crystal pulling development", *Proc. E-MRS Spr. Meet.* (Symposium E – Adv. si. substr.), Strasbourg, France.

[7] Sachs, E.M. et al. 2013, "Direct Wafer – High performance 156mm silicon wafers at half the cost of sawn", *Proc. 28th EU PVSEC*, Paris, France, pp. 907–910.

[8] SEMI 2007, "Guide to calculate cost of ownership (COO) metrics for semiconductor manufacturing equipment", SEMI E35-0312.

[9] SEMI 2014, "Specification for definition and measurement of equipment reliability, availability, and maintainability (RAM) and utilization", SEMI E10-0814E.

[10] Nold, S. et al. 2012, "Cost modeling of silicon solar cell production innovation along the PV value chain", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 1084–1090.

[11] Bridge to India 2017, "India solar compass 2017", Report [http://www.bridgetoindia.com/reports/].

[12] ITRPV 2013–2018, International technology roadmaps for photovoltaic [http://www.itrpv.net/Reports/Downloads/].

[13] Lorenz, A. et al. 2016, "3 dimensional Direct Wafer product with locally-controlled thickness", *Proc. 32th EU PVSEC*, Munich, Germany, pp. 310–312.

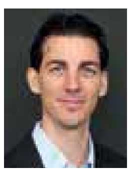
[14] Jonczyk, R. et al. 2016, "Low-cost kerfless wafers with gradient dopant concentration exceeding 19% cell efficiency in PERC production line", *Energy Procedia*, Vol. 92, pp. 822–827.

About the Authors

Dr. Adam Lorenz is the CTO at 1366 Technologies, where he leads the Direct Wafer technical team and has migrated the technology from proof of concept to commercially ready machines. He oversees the company's co-development activities with key global partners, as well as its large-scale commercial trials. He has a Ph.D. from MIT and has spent several years in the PV industry developing silicon crystal growth equipment, before joining 1366 as its first employee.

Dr. Jochen Rentsch is the head of the production technologies – surfaces and interfaces department at Fraunhofer ISE. He studied physics at the Technical University of Braunschweig, obtaining his Diploma degree in 2002. He then received his Ph.D. in physics in 2005 from the Albert Ludwig University of Freiburg, Germany. His research at Fraunhofer ISE focuses on the development of rear-passivated solar cells, new wet- and dry-chemical processing technologies, and the coordination of cell technology transfer projects.

Sebastian Nold studied industrial engineering at the University of Karlsruhe, Germany, and at the University of Dunedin, New Zealand, earning his diploma in industrial engineering at Karlsruhe in 2009. He has worked at Fraunhofer ISE since 2008 in the field of cost calculation, technology assessment and economic evaluation of new concepts in the production of silicon solar wafers, cells and modules. He is currently completing his doctoral thesis at Fraunhofer ISE on the economic assessment of silicon solar cell production technologies along the PV value chain.



Todd Templeton is responsible for 1366 Technologies' commercial strategy and development. Prior to joining 1366, he spent 10+ years in different supply chain management roles for large corporations, such as GE and Celanese. He holds a bachelor's from Texas A&M and a master's from MIT.

Laureen Sanderson is the chief communications officer at 1366 Technologies, prior to which she held senior leadership roles at communications agencies, where she spent nearly ten years advising energy technology companies. She received her bachelor's from Syracuse University's S.I. Newhouse School.

Enquiries

1366 Technologies
6 Preston Court
Bedford, MA USA
Tel: 781 861 1611
Email: info@1366tech.com

News

ISC Konstanz agrees n-type bifacial and IBC cell technology transfer to Valoe for commercialization


Credit: Megacell

ISC Konstanz has agreed a technology transfer with Valoe for commercialization of its BiSoN and ZEBRA cell technologies.

The International Solar Energy Research Center Konstanz (ISC Konstanz) has signed a technology transfer agreement with a PV module assembly equipment supplier based in Finland for the R&D centre's advanced 'BiSoN' (Bifacial Solar cell On N-type) and ZEBRA (diffused n-type IBC) solar cell technology.

Valoe noted that it had acquired a solar cell production line from Megacell, a producer of bifacial n-PERT solar cells in Italy based on the ISC Konstanz technology, which is in liquidation.

Dr. Radovan Kopecek, CTO at ISC Konstanz and managing director of advanced cell concepts, said: "We are very pleased to continue assisting you in developing ZEBRA further. Together with Valoe´s back contact module technology such a module using ZEBRA is very powerful at low costs. Valoe has, as one of the first companies in the world, developed a mass scale module manufacturing technology which makes the implementation of back contact solar cells into the module extremely simple, cost effective and with high yield. Further, Valoe's technology makes it possible to use thinner solar cells. The PV market is now ready for such modules build on IBC cell technology for many new applications."

ZEBRA based IBC cells have reach conversion efficiencies of more than 23% and module efficiencies would be supported Valoe's unique back contact module technology that can also handle ultra-thin n-type mono wafers, lowering production costs.

EFFICIENCY MILESTONES

Sharp hits 25.09% conversion efficiency for 6-inch HBC solar cell

Sharp Solar, a subsidiary of Taiwan-based contract electronics giant Foxconn, has reported a verified heterojunction back contact (HBC) solar cell on a large-area (6-inch) n-type monocrystalline wafer with a conversion efficiency of 25.09%.

Sharp Solar said the cell was validated by the Japan Electrical safety & Environment Technology laboratories (JET) and the R&D partially funded by Japan's New Energy and Industrial Technology Development Organization (NEDO) under the theme of "Development of Cost Reduction Technology of High Performance, High Reliability Solar Power Generation".

Back in 2014, Sharp reported a small-area wafer size conversion efficiency for its HBC cells of 25.1%

The HBC cell on a 6-inch (full-area) wafer is claimed by Sharp to be the highest efficiency reported to date.

JinkoSolar resets p-type monocrystalline cell efficiency at 23.95%

JinkoSolar has reset the p-type monocrystalline cell conversion efficiency record at 23.95%, through a range of wafer to cell optimisation measures.

JinkoSolar said it had used a combination of enhancements and optimization, including highly doped and low defect mono wafers, which improves the bulk quality. Certification testing of the record cell efficiency was undertaken by the Photovoltaic and Wind Power Systems Quality Test Center at the Chinese Academy of Sciences (CAS).

Further optimization of the cells selective emitter formation as well as silicon oxide passivation and the rear side passivation added to conversion efficiency gains. JinkoSolar also used its proprietary light-capturing technology, which employs black silicon and multi-layer anti-reflective coating technology that reduces the front side reflectivity of cells, said to be lower than 0.5%, boosting the short-circuit current.

Additionally, JinkoSolar said it deployed an advanced grid design and a new type of screen-printing paste to reduce the series resistance and the metal/silicon interface compound, enabling improved cell fill factor.

Kangping Chen, CEO of JinkoSolar, commented: "This recent technical breakthrough is a combination of several our latest technologies. In particular, the introduction of novel passivation and selective contact technology have successfully broken the technical bottleneck created by traditional PERC technology and represents a significant step forward for our p-type solar cells with their previous efficiency record of 23.45% in 2017. We will continue to allocate resources towards innovating new and high efficiency solar technologies and their application to the market as we continue to provide the most reliable and highest efficiency products."

According to PV Tech's annual PV manufacturers

Credit: REC

REC is installing an n-type cell line at its Singapore plant.

R&D spending analysis, JinkoSolar has significantly increase investment in R&D activities since 2015, when annual spending crossed the US$20 million mark.

CELL PRODUCTION AND TOOLS

REC Group to install n-type mono solar cell line at Singapore production plant

Norway-headquartered PV manufacturer REC Group is to install an n-type monocrystalline solar cell production line at its manufacturing facility in Singapore.

REC has over 1.4GW of dedicated p-type multicrystalline cell and module assembly capacity at its single manufacturing facility in Singapore, which has been dedicated to its PERC and half-cut cell technology.

The installation of the high-efficiency n-type mono cell line was said to be part of an expanded module product portfolio in 2018 that will use its half-cut cell technology to provide step-function increase in module performance.

The company also reported that PV module shipments in 2017, topped 1,344MW, an increase of 6%, compared to the prior year.

REC also noted that fourth quarter module shipments hit a new quarterly record of 413MW.

Steve O'Neil, CEO at REC Group said: "The increase in shipments was driven by growth in all the regions we serve, and in many markets REC outperformed average market growth. We attribute this success to the quality of our products, technology leadership, and our balanced sales across regions and market segments, residential, utility and commercial & industrial."

REC expects volume shipment growth of 7-9% in 2018.

Meyer Burger supplying advanced PERC solar cell tools to Asia-based customer

Leading PV manufacturing equipment supplier Meyer Burger has secured a large order from a major PV manufacturer with solar cell production plants in China and Malaysia.

The existing customer was said to have ordered Meyer Burgers 'MAiA' 4.1 platform for rear-side cell passivation coating of PERC solar cells for its Malaysian manufacturing plant, which was expanding production capacity, while the same customer ordered its new FABiA 4.1 platform that does passivation of the front- and rear-side of PERC cells in a single process for the customers production plant in China.

Meyer Burger noted that the order was valued at around CHF16 million (US$16.3 million) with equipment delivery scheduled to start in the third quarter of 2018 and revenue recognition expected in the fourth quarter of 2018.

R&D

SERIS develops nano-scale low-cost texturing process for mc-Si diamond-wire cut wafers

Researchers at the Solar Energy Research Institute of Singapore (SERIS) have announced the development of a significantly low-cost technique to texture nano-scale features on multicrystalline silicon (mc-Si) wafers after diamond-wire wafer cutting.

SERIS noted that the wide adoption of mc-Si wafer diamond-wire wafer cutting has been limited by existing etching processes being expensive and degrading conversion efficiencies. Reactive ion etching (RIE) is not deemed a low-cost process, while metal-catalysed chemical etching (MCCE) techniques can add metallic particle contaminants.

"Our technology is simpler, cheaper, metal-free and can achieve cell efficiencies of more than 20%. For these reasons, I strongly believe that our technology can become a mainstream texturing technology used by mc-Si solar cell manufacturers," said Dr Huang Ying, the lead inventor of SERIS' DWS Wafer Texturing Technology.

The SERIS wet-chemical technique uses proprietary chemicals to etch the mc-Si wafer surface that creates nano-scale features with dimensions smaller than the incident light wavelength, which enhance light capture with the potential for mc-Si solar cells achieving conversion efficiencies of 20%.

SERIS noted that such cell conversion efficiencies are about 0.5% (absolute) higher than those currently mass produced by leading PV manufacturers.

Dr Joel Li, Head of the Multicrystalline Silicon Wafer Solar Cell Group at SERIS added: "We have addressed a long-standing challenge faced by the PV industry with our technology, and it has been proven to be an effective method for texturing DWS multicrystalline silicon wafers at low cost. The PV industry can leverage our technology to enable the switch from slurry-cut to cheaper DWS multicrystalline silicon wafers, which are 5-15% cheaper. For a gigawatt factory, this translates to cost savings in the order of US$10 million per year. In a cost-sensitive industry like PV, this level of cost savings is highly attractive."

SERIS CEO Professor Armin Aberle said the institute planned to license the technology to manufacturers, with several tier-one suppliers already showing an interest.

Aurora Solar Technologies extends advanced cell R&D collaboration with SERIS in Singapore

Inline solar cell measurement equipment specialist Aurora Solar Technologies (AST) has secured a new collaborative research agreement with the Solar Energy Research Institute of Singapore (SERIS), which includes the previous work planned on heterojunction (HJ) cells but also creates opportunities in the growing R&D market for solar cell design and qualification.

AST will also supply SERIS with its latest 'Decima' infrared measurement system, which will be used to characterize the advanced solar cells developed at the Singapore-based R&D facility.

Dr. Armin Aberle, SERIS' CEO said: "In our work to advance the state of the art in the solar energy industry, SERIS works closely with numerous manufacturers and production equipment vendors. We expect that our work with Aurora will make a strong contribution to this industry development."

AST noted that the its ongoing HJ cell collaboration with SERIS has meant that several solar cell manufacturers have already expressed interest in evaluating Aurora's HJ capabilities.

The newly signed agreement with SERIS means AST will be joining major cell manufacturers and production equipment makers collaborating with the R&D centre on the next generation of solar cells, modules and manufacturing technologies.

Towards industrial manufacturing of TOPCon

Frank Feldmann, Sebastian Mack, Bernd Steinhauser, Leonard Tutsch, Jana-Isabelle Polzin, Jan Temmler, Anamaria Moldovan, Andreas Wolf, Jochen Rentsch, Martin Hermle & Stefan W. Glunz, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

Abstract

TOPCon is regarded as a possible follow-up technology to the passivated emitter and rear cell (PERC) concept. This paper presents the latest results for high-efficiency solar cells, and the progress made on migrating layer deposition to high-throughput tools, which are already in use in industry. Possible metallization approaches, and three different industrially relevant solar cell structures featuring TOPCon, are also discussed.

Introduction

In the last five years, the PV industry has witnessed a rally towards ever-increasing conversion efficiencies. For a long time, the industry's workhorse has been the Al back-surface field (BSF) solar cell, but this is now being replaced by the passivated emitter and rear cell (PERC), which enables conversion efficiencies above 21% in production and up to 23.6% in a production-near environment [1]. A detailed loss analysis of these solar cells reveals that minority-charge carrier recombination at the metal/semiconductor contacts is the dominant loss mechanism [2].

Two strategies to mitigate recombination losses have usually been employed: (1) the formation of a heavily doped c-Si region underneath the metal contact by diffusion or alloying (e.g. selective emitter or Al back-surface field) in order to reduce minority-charge carriers at the interface; and (2) the reduction of the metallized area fraction. A prime example of the latter strategy is the PERC structure, which features a dielectric rear passivation with local Al contacts, thereby increasing not only the open-circuit voltage (V_{oc}) but also the short-circuit current density (J_{sc}) (because of improved rear reflection of IR light). V_{oc} gains and fill factor (*FF*) losses, however, have to be carefully balanced by adapting both the pitch of the rear contact lines (or dots) and the base resistivity. Hence, a superior strategy that overcomes this limitation is a passivating contact that suppresses minority-charge carrier recombination and enables an efficient majority-charge carrier transport. The most well-known example is the a-Si:H/c-Si heterojunction (commonly referred to as HIT, HJT, SHJ) solar cell, with which open-circuit voltages as high as 750mV, as well as the world-record efficiency of 26.7%, were demonstrated. Despite these very impressive results, there are technological and economic reasons (e.g. high equipment cost) why the PV industry has not yet adopted this technology on a larger scale. One technological drawback is the low thermal stability of the a-Si:H passivation, which restricts the back-end process temperatures to about 200°C, thereby creating the need for low-temperature metallization, such as silver pastes, which are less conductive and more expensive than their high-temperature counterparts.

Tunnel oxide passivated contact (TOPCon) technology [3,4] was introduced in 2013; this technology tolerates higher back-end processing temperatures than conventional a-Si:H technology, and therefore holds the promise of a facilitated back-end processing. While low recombination current densities (J_o) are similarly possible, the contact resistivity (ρ_c) is much lower for TOPCon contacts than for a-Si:H/c-Si heterojunctions. Although different acronyms have been used for this kind of contact system, for the sake of simplicity TOPCon is used throughout this article.

TOPCon is based on the poly-Si emitter technology which was originally pioneered by the integrated circuit (IC) industry and which led to appreciable current–gain enhancement factors of high-speed bipolar junction transistors (BJTs). An excellent overview of the scientific contributions relevant to BJTs can be found in Post et al. [5]. The success of poly-Si emitter technology has inspired researchers to apply it to silicon solar cells, with the aim of boosting V_{oc}: for instance, Kwark et al. [6] demonstrated that poly-Si contacts benefited from a chemical oxide, and reported J_o values down to 10fA/cm^2 for the electron contact. In 1990 Gan and Swanson [7] introduced thermally grown interfacial oxide layers, which required very high annealing temperatures (~1,050°C) in order to break up the interfacial oxide layer.

The novelty of Fraunhofer ISE's approach was twofold: first, the TOPCon layer was realized by plasma-enhanced chemical vapour deposition (PECVD) instead of low-pressure chemical vapour deposition (LPCVD); second, its potential was demonstrated through the use of an n-type cell featuring a boron-diffused emitter and TOPCon as a full-area passivating rear contact (see Fig. 1). The

"TOPCon technology tolerates higher back-end processing temperatures than conventional a-Si:H technology."

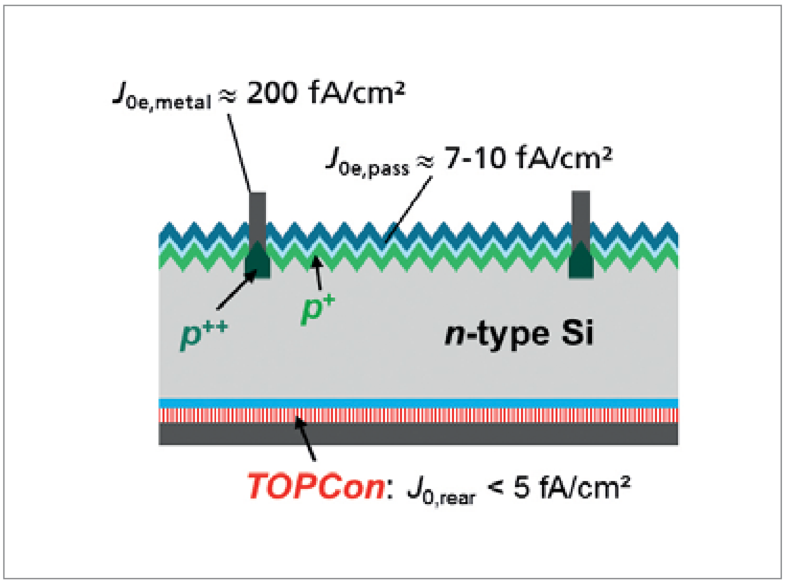


Figure 1. Schematic of an n-type solar cell featuring a boron-diffused emitter and a passivating rear contact (TOPCon).

first prototype achieved a conversion efficiency of 21.7%; by improving the light trapping and front metallization, however, a 23.7%-efficient solar cell has been demonstrated and was reported at the EU PVSEC conference in 2013 [3]. The implementation of a selective emitter further reduced front-side recombination losses, enabling an efficiency of 24.4% to be obtained half a year later [8]. Further improvements at the front and the rear have resulted in an efficiency of 25.8% [9,10], which is currently the world record for a two-side-contacted solar cell. The learning curve for Fraunhofer ISE's lab-type TOPCon solar cells is shown in Fig. 2.

Since that report of the 25.8% efficiency, numerous papers (e.g. [11–14]) have contributed to improving this passivating contact technology and promoting the understanding of the underlying physics of the contacting system. A detailed review of these activities will be published soon [15].

As shown above, outstanding conversion efficiencies have been demonstrated at the laboratory level, and so the next step needs to be the transfer of this technology to high-throughput tools in a pilot-line environment. Consequently, in the second part of the paper the following research topics will be addressed:

- The development of deposition processes on industrial production equipment.
- Metallization aspects.
- The integration into solar cell structures.

Working principle and fabrication steps

Fig. 3 shows schematically the process flow for the fabrication of a symmetrical lifetime sample

"TOPCon with the thermally grown oxide did not degrade at 900°C, but yielded excellent surface passivation quality."

featuring TOPCon on both sides. The fabrication of TOPCon requires the following three process steps:

1. The growth of an interfacial oxide layer.
2. The deposition of an amorphous (or polycrystalline) Si-based layer.
3. A high-temperature anneal.

After wafer cleaning, a thin interfacial oxide layer, typically 1.2 to 2nm thick, is grown. Such oxides can be wet-chemically grown in, for example, hot nitric acid (HNO_3) [4] or an O_3/H_2O bath [14], or they can be dry grown using a tube furnace [7,11] or a UV excimer or halogen lamp system [14]. The purpose of the interfacial oxide is to reduce dangling bonds, and thus interface-trapped charge density. It is worth noting that the as-grown oxides do not provide any surface passivation, but improve upon the high-temperature anneal.

Next, a Si-based layer is deposited either by LPCVD or by PECVD. These layers are usually a-Si or poly-Si based, but carbon or oxygen can also be added to the matrix. In most approaches the Si layer is doped during deposition; however, doping by (for example) ion implantation or $POCl_3$/BBr_3 diffusion, carried out ex situ, is feasible as well.

Provided that the Si layer is doped, the third process step is a furnace anneal in nitrogen, using process temperatures in the range 800–1,050°C. At these temperatures, the a-Si layer crystallizes, and dopants are electrically activated and partly diffuse through the oxide into the c-Si wafer. Optimum annealing temperatures supposedly have a beneficial impact on the stoichiometry of the SiO_x layer as well as of the c-Si/SiO_x interface. In addition, annealing in an oxygen-free atmosphere brings about the reaction $SiO_2 + Si \rightarrow SiO(g)$; this leads to the breakup of the oxide layer, which was investigated in great depth by Wolstenholme et al. [16]. This reaction mechanism can be used advantageously in order to facilitate transport through thicker (>1.5nm) oxides, which would otherwise pose a substantial tunnelling barrier. Feldmann et al. [17] demonstrated, by means of temperature-dependent *J–V* measurements, that tunnelling is the dominant transport path for thinner oxides.

A fourth process step, hydrogenation, is typically used in order to further enhance the passivation quality. Hydrogenation, with the use of atomic hydrogen (which can be sourced from H-containing films, such as Al_2O_3 or SiN_x, or from hydrogen plasma), reduces the interface-trapped charge density at the c-Si/SiO_x interface.

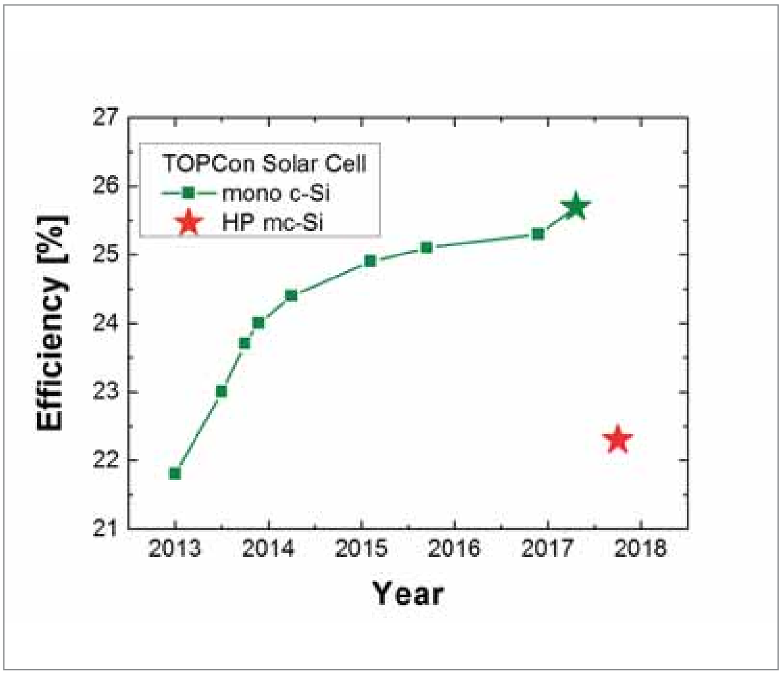


Figure 2. Evolution of the conversion efficiency of lab-type TOPCon solar cells.

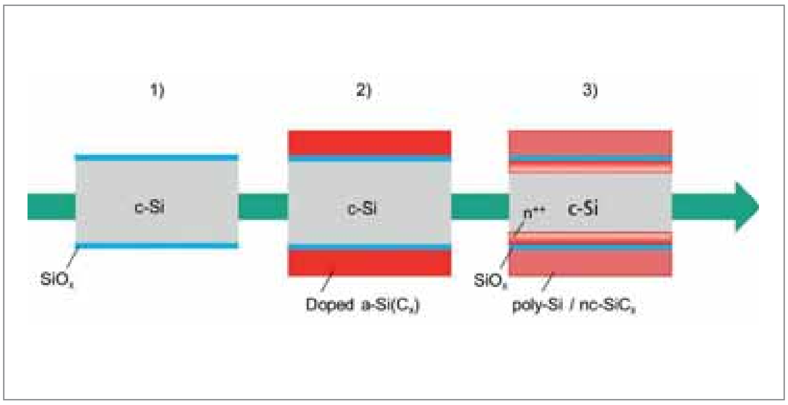


Figure 3. Steps involved in TOPCon fabrication: 1) interfacial oxide layer growth; 2) a-Si (or poly-Si) layer deposition; 3) high-temperature anneal.

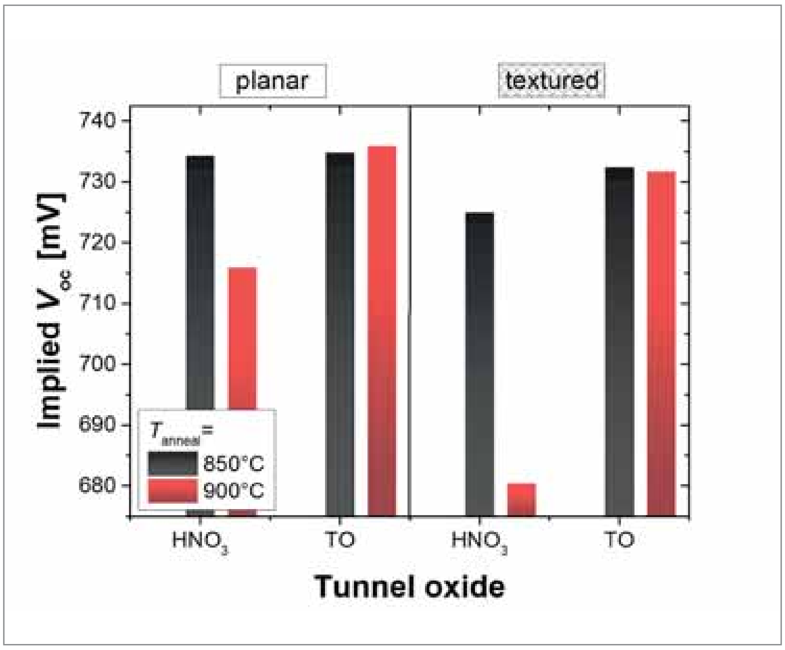


Figure 4. iV_{oc} achieved by n-TOPCon on planar and textured surfaces respectively. Two different interfacial oxides are compared.

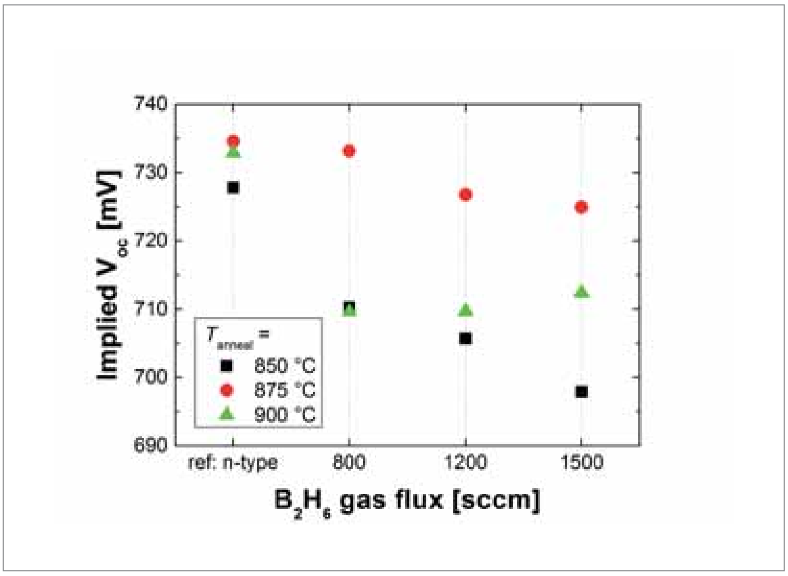


Figure 5. Measured iV_{oc} for asymmetrical samples featuring n-TOPCon on the front side and p-TOPCon on the rear [21].

Figure 6. A side view of the PECVD carrier, listing the average iV_{oc} measured for each wafer [19].

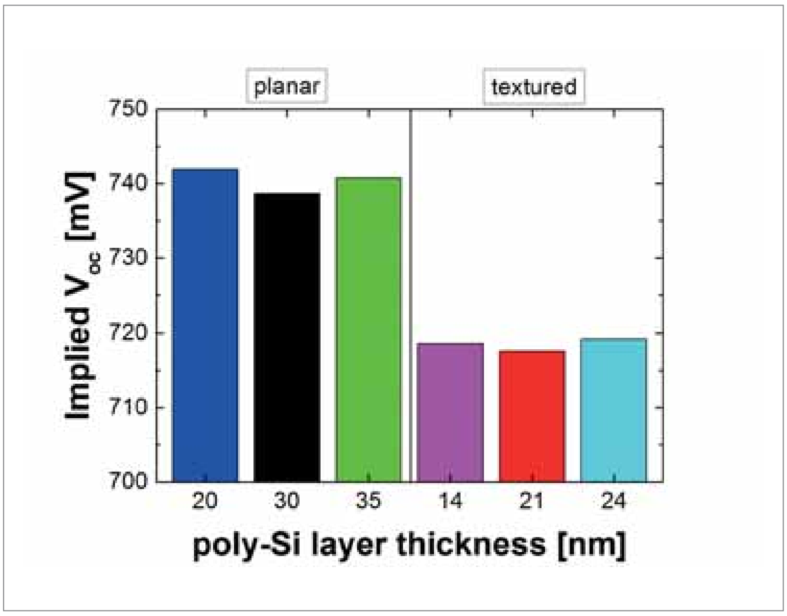


Figure 7. iV_{oc} achieved by n-TOPCon on planar and textured surfaces.

Industrial-scale deposition technologies

LPCVD is a state-of-the-art technology in the microelectronics industry for the deposition of amorphous or polycrystalline Si films. The crystallinity of the film is controlled by the deposition temperature, which also controls the deposition rate. The advantages of this technique are the high homogeneity of the layers, the good step coverage, the high reproducibility and the possibility of growing the required interfacial oxide layer in situ. The drawbacks of this technique are the inherently double-sided deposition and the relatively low deposition rates (e.g. 2.8nm/min at 550°C and 8.3nm/min at 615°C [18]). The former of these drawbacks always requires additional process steps, such as masking and/or single-side layer removal, if the poly-Si layer is to be applied only to one side of the cell.

An alternative method for depositing doped Si films is PECVD, which is a well-established process in the PV industry for the deposition of thin films, such as Al_2O_3 or SiN_x. It is usually regarded as a single-sided deposition technique, but a minimal wrap-around at the cell edges can occur, which can be addressed by inline wet-chemical etching. Moreover, Si alloys with oxygen or carbon can be easily realized by PECVD, and the process can be adapted to the needs of the particular surface of the solar cell. One challenge with PECVD films is the risk of blistering due to the usually large amounts of hydrogen incorporated within the Si layer; this puts restrictions on the maximum film thickness, but this issue is generally mitigated by using higher deposition temperatures (300–450°C) than those used for HJT cells. Another concern can be ion bombardment during deposition, which might inflict damage on the thin interfacial oxide layer.

In the following sections, the latest results achieved using either PECVD or LPCVD tools will be presented. (More details can be found in the authors' recent publications [19–22].)

Low-frequency direct plasma PECVD

The authors recently demonstrated that a centrotherm cPLASMA 2000 PECVD tool is capable of gently depositing doped a-Si layers onto a thin tunnel oxide [19]. The resulting surface passivation quality achieved with n-TOPCon (electron-selective contact) was excellent on both shiny-etched and textured surfaces. Fig. 4 shows the implied V_{oc} (iV_{oc}) measured on symmetrical structures incorporating n-TOPCon on both sides; in the experiment, a wet-chemical oxidation process (hot nitric acid – HNO_3) was compared with a thermally grown oxide (TO).

The authors' investigations of the stoichiometry of differently grown oxides have been reported in previous publications; the results hinted at a correlation between stoichiometry and improved thermal stability as well as improved surface passivation quality [14]. Fig. 4 clearly shows that TOPCon featuring the wet-chemical oxide yields very high iV_{oc} values of ~730mV on planar surfaces, and up to 725mV on textured surfaces; however, the annealing process at 900°C led to a significant degradation, especially on textured surfaces. On the other hand, TOPCon with the thermally grown oxide did not degrade at 900°C, but yielded excellent surface passivation quality (iV_{oc} ~ 730mV on textured surfaces). Hence, there is only a subtle difference between the passivation quality on planar and textured surfaces, which is in agreement with other reports in the literature [23].

Fig. 5 shows Fraunhofer ISE's latest results for p-TOPCon, the hole-selective contact [21]. The influence of the diborane (B_2H_6) gas flux on the surface passivation quality provided by p-TOPCon was studied in a similar way to that for the electron-selective contacts. To this end, p-TOPCon was applied to the rear of solar cell precursors having n-TOPCon on the front side. The reference device, which is a symmetrical structure comprising n-TOPCon on both sides, achieved iV_{oc} values in the range 727 to 735mV for all three annealing temperatures; thus, the J_o contribution from n-TOPCon was less than 2fA/cm². The asymmetrical samples showed somewhat lower iV_{oc} values because of increased recombination at the hole-selective junction. For the optimum annealing temperature of 875°C, iV_{oc} decreased from 733mV to 725mV with increasing B_2H_6 gas flux; these values correspond to a J_o of about 2–6fA/cm², which is an excellent value for p-TOPCon. Furthermore, by means of surface photovoltage (SPV) and Suns-V_{oc} testing, it was verified that these layers not only serve as excellent surface passivation layers but also form a well-functioning pn junction with c-Si.

Building on these excellent results, a study of the homogeneity of the passivation over an entire wafer load has been carried out. To demonstrate the process, a horizontal wafer boat with 20 slots for 6" Cz wafers was used. The wafers were saw-damage etched and cleaned, and a thin interfacial oxide was grown in hot nitric acid. After the deposition of a ~35nm-thick a-Si(n) layer on both sides, the film thickness was checked: a mean layer thickness of 34.5±1.4nm (deviation 4%$_{rel.}$) was measured by spectroscopic ellipsometry. A high-temperature anneal was performed at 850°C, as was an additional forming-gas anneal (5% H_2, 95% N_2), which slightly enhanced the initial surface passivation quality.

Fig. 6 shows a schematic of the wafer carrier; the corresponding iV_{oc} and implied fill factor (*iFF*) values are listed for each wafer. The average iV_{oc} is 719±2mV and demonstrates the good homogeneity of Fraunhofer ISE's process. Moreover, photoluminescence (PL) imaging revealed a very good level of homogeneity of surface passivation over each wafer.

Since the horizontal configuration of the wafer carrier is only used for research applications, whereas vertical boats are used exclusively in production, the process will be performed with a larger vertical boat in a next step. Besides uniformity over the process boat, the current work being done addresses process time and process gas utilization rate, both of which need to be improved to meet industrial requirements.

Radio-frequency PECVD

A modified MAiA tool from Meyer & Burger for TOPCon is also currently being evaluated; instead of microwave sources, the tool is equipped with radio-frequency plasma sources. In a previous study it was already shown that stacks of intrinsic and P-doped a-Si:H providing good surface passivation quality on textured surfaces can be realized with this system. Such processes have now been adapted to the needs of TOPCon (i.e. lower H content in order to avoid blistering); very encouraging iV_{oc} values of 740mV and 720mV have been achieved for planar and textured surfaces respectively (see Fig. 7). The work is still in the preliminary stages, and further evaluation and development of this process is planned.

"Industrial tools for both LPCVD and PECVD can be used to deposit the doped Si layer for TOPCon with high passivation quality."

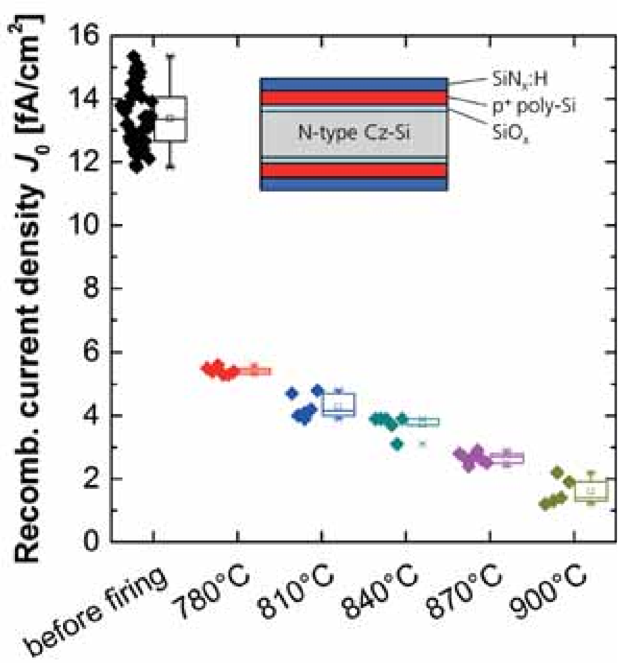


Figure 8. J_0 for each side of symmetrical test structures with interfacial oxide, boron-doped poly-Si layer and SiN_x capping, determined after contact firing for different set temperatures [20].

LPCVD

In an initial experiment, a Tempress Spectrum system was used to deposit boron-doped poly-Si layers with a thickness of 300nm by LPCVD onto an interfacial oxide layer grown in situ. After thermal annealing at 900°C in a N_2 atmosphere, SiN_x layers were deposited on both sides by PECVD to yield symmetrical samples. The impact of different set firing temperatures on the resulting J_o for each side is shown in Fig. 8.

Apparently, higher set firing temperatures lead to a decrease in J_o, presumably because of a more efficient hydrogen release from the SiN_x capping layer. In addition, the extraordinary quality of TOPCon is highlighted by the very low J_o, with values down to 1fA/cm²; including the n-type wafer, this corresponds to an iV_{oc} of up to 732mV for the symmetrical structure. In view of the applied oxide thickness, a low-resistive majority-carrier transport is expected for this structure. Future work will focus on decreasing the poly-Si layer thickness in order to improve throughput, and on further development of the process to allow full loads of more than 1,000 wafers.

To summarize, it has been demonstrated that industrial tools for both deposition techniques – LPCVD and PECVD – can be used to deposit the doped Si layer for TOPCon with high passivation quality.

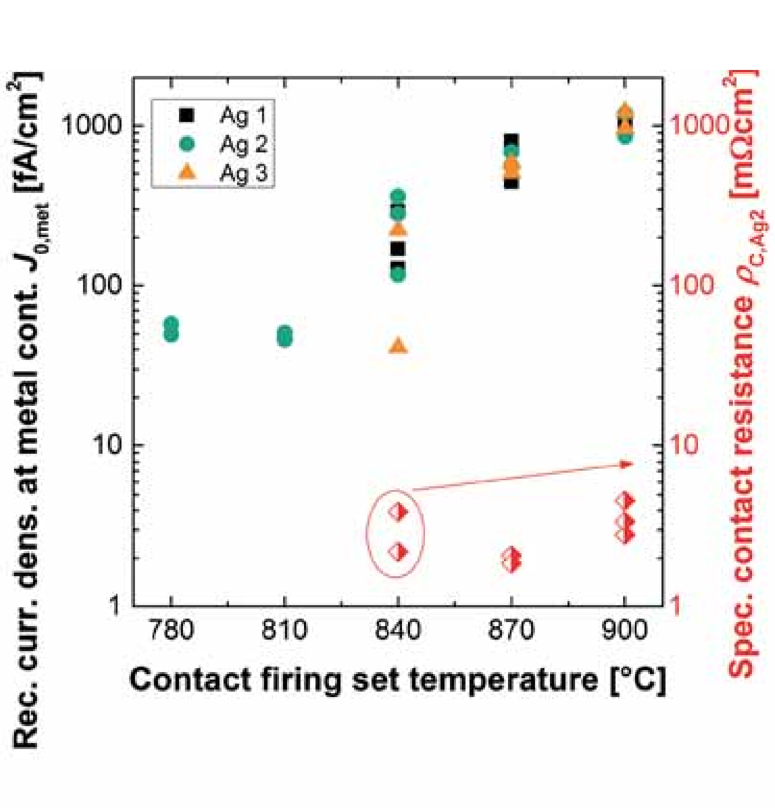


Figure 9. $J_{0,met}$ **determined by PL imaging at the metallized sites, and** ρ_c **of screen-printed silver pastes (Ag 2) on boron-doped poly-Si layers, for different set firing temperatures (Adapted from Mack et al. [20].).**

Metallization for TOPCon

To date, most of the solar cells incorporating TOPCon feature external contacts formed by the physical vapour deposition (PVD) of metals such as silver or aluminium. However, PVD is not yet a technology widely used in the Si PV industry today, and is mostly employed for contacting SHJ or interdigitated back contact (IBC) solar cells. Various solutions, such as silicides/polycides, have

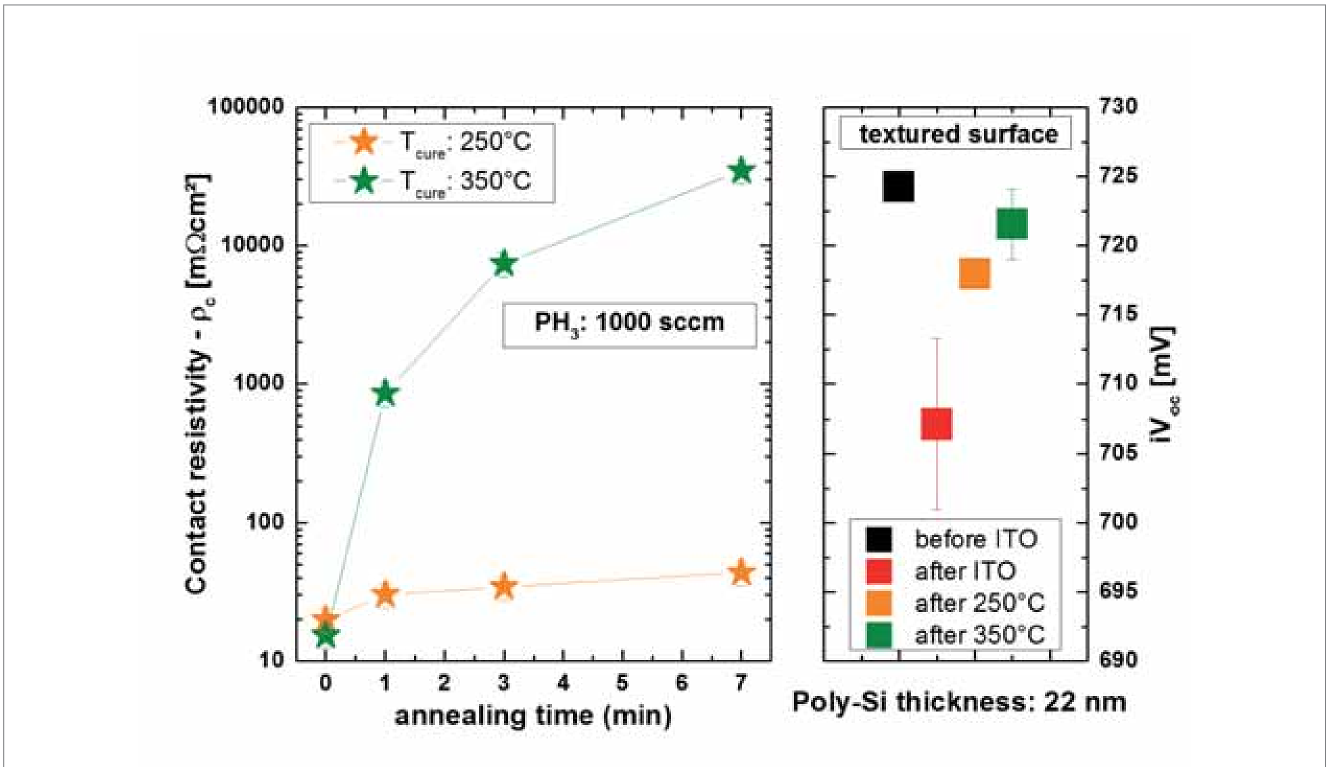


Figure 10. Contact resistivity (left) and iV_{oc} **(right) of n-TOPCon/ITO stacks [22].**

been developed by the microelectronics industry, but these are rather complex, and therefore not economically attractive for solar cell production. As an alternative option, the following metallization schemes can be envisioned: (1) screen-printed metallization, (2) a transparent conductive oxide (TCO)/metal stack, and (3) electrochemical solutions (plating). Since the third possibility is still at a very early development stage, the focus will be on the results obtained for approaches (1) and (2).

Screen-printed metallization

Screen printing is the standard metallization technique for solar cells and is therefore the preferred choice for cell manufacturers. In this approach, SiN_x is deposited onto TOPCon, a silver paste is then screen-printed, and the cells are finally subjected to a fast-firing step. The advantages are:

- Possibly high compatibility with front-side metallization (co-firing).
- Cost-effective and well-established process.
- Hydrogenation of TOPCon is without cost.

Mack et al. [20] reported on the contacting of 300nm p-type poly-Si films by SP-FT pastes. For this, commercially available silver pastes were used; these were originally developed for contacting

"The use of a TCO/metal stack instead of screen-printed metallization avoids the local depassivation of TOPCon."

diffused phosphorus emitters. The results of transfer length method (TLM) measurements are shown in Fig. 9. Two of the silver pastes allow the contacting of the poly-Si layer, with low ρ_c values of 2 to 4mΩcm^2, for set firing temperatures of 840 to 900°C. Apart from the low ρ_c values, these set temperatures are in the same range as the required temperatures for the front-side firing of solar cells, which indicates that there appears to be a process window for co-firing.

The results, however, also show a significant interaction between the paste and the poly-Si, which is in line with the work of other authors [24]. First of all, the Ag paste partly consumes the underlying poly-Si film, and forms a highly recombination-active contact with the c-Si base. Significantly higher J_0 values at the metallized areas have therefore been reported [20] (see Fig. 9), compared with non-metallized sites in Fig. 8. One strategy to reduce minority-carrier recombination at the metal contacts is an enhanced drive-in of dopants; however, this adversely affects the

Company/Institute	Area [cm^2]	Cell type	TOPCon layer/ Deposition method	Metallization	η [%]	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]
ISE [9,10]	4	Hybrid	n-SiC_x / PECVD	PVD Ag	25.8*	724	42.9	83.1
ISE [9,28]	4	Hybrid (mc-Si)	n-SiC_x / PECVD	PVD Ag	22.3*	674	41.1	80.5
ISE	100	Hybrid	n-SiC_x / PECVD	PVD Ag	23.4*	697	41.4	81.1
ANU [34]	4	Hybrid	n-poly-Si / PECVD + $POCl_3$ diffusion	PVD Ag	24.7	705	42.4	82.6
EPFL [35]	4	Hybrid	p-SiC_x / PECVD	PVD ITO/Ag	21.9	698	39.4	79.5
TU Delft [36]	7.84	Hybrid	p-poly-Si / LPCVD + B implantation	PVD Ag	20.8	656	40.7	75.2
ECN [25]	239	Hybrid	n-poly-Si / LPCVD	SP-FT Ag	21.5	676	39.7	80.4
Tempress [37]	239	Hybrid	n-poly-Si / LPCVD	SP-FT Ag	21.6	666	41.0	79.0
Meyer Burger [38]	239	Hybrid	n-poly-Si / PECVD	SP-FT Ag	21.2	676	40.3	79.3
GIT [39]	239	Hybrid	n-poly-Si / PECVD	PVD Ag	21.2	683	39.7	78.1
Jolywood [40]	239	Hybrid	n-poly-Si / n/a	SP Ag	22.4	688	40.8	81.4
ISFH [41]	4	IBC	poly-Si / LPCVD + implantation	PVD Al	26.1*	727	42.6	84.3
ISE [42]	4	IBC	poly-Si / LPCVD + implantation	PVD Al	23.7*	720	41.3	79.6
SunPower [29]	153	IBC	n/a	n/a	25.2	737	41.3	82.7
Trina Solar [30]	239	IBC	n-poly-Si / LPCVD	SP Ag	25.0	716	42.3	82.8
EPFL [43]	4	Top/rear	SiC_x / PECVD	PVD ITO SP Ag	22.6	720	38.8	81.0
ISFH [44]	244	Top/rear	poly-Si / LPCVD + implantation	PVD ITO SP Ag	22.3	714	38.5	81.1

**independently confirmed efficiency*

Table 1. Efficiency table, highlighting the results from different companies and institutes.

recombination current at the non-metallized sites [25]. As of today, TOPCon in combination with SP-FT paste cannot be considered to be a passivating contact, but rather a conductive surface passivation layer featuring local contacts. Significant improvement of this technology is expected from paste development rather than from an adaptation of TOPCon. Work is currently being carried out on integrating these layers and metal pastes as a rear contact in bifacial p-type solar cells, as well as on the development of lean process sequences.

TCO/metal stacks

TCOs, such as tin-doped indium oxide (ITO), are commonly used as electrodes for HJT solar cells. These particular oxides enable low-resistive contacts to be made to doped a-Si:H, provide a low sheet resistance required for lateral charge-carrier conduction to the metal grid, and serve as an anti-reflection coating at the front and as an optical spacer at the rear. TCOs can therefore be considered an attractive multifunctional contact material for TOPCon. The combination of TCO and TOPCon is also highly attractive because TOPCon's higher thermal stability potentially widens the process windows or facilitates the use of other deposition techniques, such as PECVD. The results obtained for sputtered ITO will be outlined next.

When sputtering TCO on TOPCon, a similar issue arises as with HJT cells: sputter-induced damage of the passivation quality. In a series of experiments, the influence of sputter deposition conditions (e.g. power, pressure) on differently prepared TOPCon structures (with respect to layer thickness, doping level and drive-in of dopants) was investigated. One decisive parameter for controlling the sputter damage is the TOPCon layer thickness, since very thin films are highly sensitive to sputter conditions, whereas thicker films seem not be affected by various sputter processes. In the case of very thin TOPCon layers, sputter damage will occur, which has to be cured by a thermal treatment.

Fig. 10 shows the impact of sputter deposition and subsequent thermal annealing [22]. In contrast to HJT cells, the issue of sputter damage is not completely resolved at T = 250°C; in fact, temperatures in the vicinity of 350°C are required to bring about an almost complete recovery of the initial surface passivation quality. Depending on the TCO material, such high annealing temperatures can either improve or degrade its bulk properties. For instance, at such high temperatures, ITO becomes less transparent (because of increasing free-carrier density) and exhibits a lower mobility; on the other hand, ZTO or AZO become *more* transparent and exhibit *higher* mobilities after annealing [26,27].

One thing that all materials screened so far have in common, however, is that a contact barrier between TOPCon and TCO appears at 350°C, which results in a dramatic increase in contact resistivity (see Fig. 10). This issue can be elegantly circumvented by adapting the TOPCon contact as well as the sputter process, so that lower curing temperatures can be used. At a temperature of 250°C, for instance, contact resistivities below 40mΩcm² were measured, which is only about one-fifth of the values reported for HJT cells.

TOPCon integration into solar cells

Research in the PV community focuses mainly on three cell concepts:

1. Hybrid cell structures featuring a homojunction at the front and a TOPCon rear contact.
2. IBC cells with TOPCon contacts.
3. HJT-like solar cells with TOPCon top/rear contacts.

Table 1 summarizes the solar cell efficiencies achieved by different institutes and companies. Most papers currently report on the hybrid solar cell structure, because it can be a drop-in replacement for current PERT/PERC cells. On the laboratory scale, the best two-side-contacted cell is Fraunhofer ISE's n-type cell with a boron-diffused front emitter and a TOPCon rear contact. By transferring this solar cell concept to n-type high-performance mc-Si wafers, a world-record efficiency of 22.3% has been achieved [9,28].

The first large-area solar cell processed on industrial equipment was announced by Stodolny et al. [23] from the Energy Research Centre of the Netherlands (ECN), and reached an efficiency of 20.7%. While these cells feature screen-printed contacts, work on n-type cells with plated front metallization and a TCO/metal stack at the rear is currently under way at Fraunhofer ISE. As mentioned earlier, the use of a TCO/metal stack instead of screen-printed metallization avoids the local depassivation of TOPCon; moreover, thinner poly-Si layers can be used and mitigate the negative effect of free-carrier absorption on the short-circuit density. In consequence, this particular metallization strategy has a higher efficiency potential. In a first step, an n-type solar cell featuring a homogeneous boron-diffused front emitter and TOPCon rear contact was created on an area of 100mm × 100mm, with an independently confirmed efficiency of 23.4% being achieved. Future work is dedicated to reducing recombination at the front metal contacts by addressing the issue of laser-induced damage to the silicon crystal and implementing a selective emitter.

The IBC cell concept has the potential for very high efficiencies, as demonstrated by Kaneka's world-record solar cell. In early 2018, the Institute for Solar Energy Research in Hamelin (ISFH) demonstrated a 26.1%-efficient IBC cell (4cm²) featuring both polarities of the poly-Si contact at the rear [41]. Being several steps ahead of the PV community, SunPower already produces IBC cells and modules featuring passivating contacts (technology not disclosed), with efficiencies of up to 25.2% and 24.1% respectively [29]. By the beginning of 2018, Trina Solar announced an efficiency improvement from 24% to 25% [30]; one notable change to their IBC cell was the replacement of the phosphorus-diffused BSF by a phosphorus-doped poly-Si contact.

The third concept is quite similar to a HJT cell, but uses TOPCon contacts of both polarities. This configuration enables very high V_{oc} values similar to an IBC cell and has the potential for very high *FF*: for instance, Nogay et al. [31] demonstrated an *FF* of 84.0% on a planar solar cell, which confirms the excellent surface passivation and low contact resistivity values of TOPCon/TCO stacks. The drawback of this approach, however, is related to the significant parasitic absorption in the poly-Si layers. From simple solar cells, a J_{sc} loss of about 0.4mA/cm² per 10nm poly-Si layer thickness has been determined [32]; this is in agreement with optical calculations using the optical constants of poly-Si as input parameters [33]. Another challenge is sputter damage, which is more pronounced for the very thin films required for front-side application.

Conclusion

Progress towards the upscaling of TOPCon technology has been reported in this paper. It has been shown that TOPCon can be realized by both industrial-scale PECVD and LPCVD deposition systems, and that there is no difference in terms of passivation quality. The single-sided nature of PECVD is one strong advantage of this technique; on the other hand, LPCVD facilitates the growth of thicker poly-Si layers, which can presumably be more easily contacted using SP-FT pastes. Each technique therefore has its merits and drawbacks. It is difficult to determine at this stage the throughput of the different tools and perform reliable cost calculations, as process development is ongoing; the authors will therefore refrain from advocating the use of one technology over another.

The summary of the solar cell results obtained nicely underlines the potential of TOPCon to be a key enabling technology for high-efficiency solar cells; as a result, TOPCon is regarded by many as a follow-up technology to PERC. The next steps to be taken are the development of a cost-effective and non-damaging metallization scheme, and the integration into a lean and industry-feasible process flow.

Acknowledgements

The authors would like to thank all co-workers at Fraunhofer ISE who contributed to this study. The work was funded by the German Federal Ministry for Economic Affairs and Energy under contract number 0325877D (Project PEPPER), 0324086A (Project HIPPO) and 0324125 (Project PV-BAT 400).

References

[1] Kenning, T. 2018, PV-Tech news report (Feb. 28) [https://www.pv-tech.org/news/longi-hits-record-23.6-conversion-efficiency-for-mono-perc-solar-cells].
[2] Saint-Cast, P. et al. 2017, *physica status solidi (a)*, Vol. 214, DOI: 10.1002/pssa.201600708.
[3] Feldmann, F. et al. 2013, *Proc. 28th EU PVSEC*, Paris, France, p. 988.
[4] Feldmann, F. et al. 2014, *Sol. Energy Mater. Sol. Cells*, Vol. 120, p. 270.
[5] Post, I.R.C., Ashburn, P. & Wolstenholme, G.R. 1992, *IEEE Trans. Electron Dev*., Vol. 39, p. 1717.
[6] Kwark, Y.H. & Swanson, R.M. 1987, *Solid State Electron*., Vol. 30, p. 1121.
[7] Gan, J.Y. & Swanson, R.M. 1990, *Proc. 21st IEEE PVSC*, Kissimmee, Florida, USA, Vols. 1 and 2, p. 245.
[8] Feldmann, F. et al. 2014, *Sol. Energy Mater. Sol. Cells*, Vol. 120, p. 270.
[9] Green, M.A. et al. 2018, *Prog. Photovolt: Res. Appl.*, Vol. 26, p. 3.
[10] Richter, A. et al. 2017, *Sol. Energy Mater. Sol. Cells*, Vol. 173, p. 96
[11] Römer, U. et al. 2014, *Sol. Energy Mater. Sol. Cells*, Vol. 131, p. 85.
[12] Peibst, R. et al. 2016, *Sol. Energy Mater. Sol. Cells*, Vol. 158, p. 60.
[13] Yan, D. et al. 2015, *Sol. Energy Mater. Sol. Cells*, Vol. 142, p. 75.
[14] Moldovan, A. et al. 2015, *Sol. Energy Mater. Sol. Cells*, Vol. 142, p. 123.
[15] Glunz, S.W. & Feldmann, F. 2018 [submitted], *Sol. Energy Mater. Sol. Cells*.
[16] Wolstenholme, G.R. et al. 1987, *J. Appl. Phys.*, Vol. 61, p. 225.
[17] Feldmann, F. et al. 2018, *Sol. Energy Mater. Sol. Cells*, Vol. 178, p. 15.
[18] Yang, J. et al. 2000, *J. Microelectromech. Sys.*, Vol. 9, p. 485.
[19] Steinhauser, B. et al., *Solar RRL*, DOI: 10.1002/solr.201800068.
[20] Mack, S. et al. 2017, *physica status solidi (RRL)*, Vol. 11, p. 1700334.
[21] Polzin, J.-I. et al. 2018, *Proc. SiliconPV 2018*, Lausanne, Switzerland.
[22] Tutsch et al. 2018, *Proc. SiliconPV 2018*, Lausanne, Switzerland.
[23] Stodolny, M.K. et al. 2016, *Sol. Energy Mater. Sol. Cells*, Vol. 158, p. 24.
[24] Çiftpınar, H.E. et al. 2017, *Energy Procedia*, Vol. 124, p. 851.
[25] Stodolny, M.K. et al. 2017, SiliconPV 2017, Freiburg, Germany, *Energy Procedia*, Vol. 124, p. 635.
[26] Rucavado, E. et al. 2017, *Phys. Rev. B*, Vol. 95.
[27] Peibst, R. et al. 2018 [submitted], *IEEE J. Photovolt*.
[28] Benick, J. et al. 2017, *IEEE J. Photovolt*., Vol. 7, p. 1171.
[29] Smith, D.D. et al. 2016, *Proc. 43rd IEEE PVSC*, Portland, Oregon, USA, p. 3351.
[30] Yang, Y. 2018, nPV Workshop, Lausanne, Switzerland.
[31] Nogay, G. et al. 2017, *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.
[32] Feldmann, F. et al. 2017, SiliconPV 2017, Freiburg, Germany, *Energy Procedia*.
[33] Reiter, S. et al. 2016, *Energy Procedia*, Vol. 92, p. 199.
[34] Yan, D. 2018, *Proc. SiliconPV 2018*, Lausanne, Switzerland.
[35] Ingenito, A. et al. 2018, *Proc. SiliconPV 2018*, Lausanne, Switzerland.
[36] Ingenito, A. et al. 2017, *Solar RRL*, Vol. 1, No. 7, DOI: 10.1002/solr.201700040.
[37] Naber, R.C.G. et al. 2016, *Proc. 32nd EU PVSEC*, Munich, Germany.
[38] Koenig, M. et al. 2017, *Proc. 27th Intl. PVSEC*, Otsu, Japan.
[39] Tao, Y. et al. 2016, *Prog. Photovolt: Res. Appl.*, Vol. 24, p. 830.
[40] Liu, Y. 2018, nPV Workshop, Lausanne, Switzerland.
[41] ISFH 2018, News (Feb. 6) [https://isfh.de/en/26-1-record-efficiency-for-p-type-crystalline-si-solar-cells/].
[42] Reichel, C. et al. 2017, *J. Appl. Phys*., Vol. 122.
[43] Nogay, G. et al. 2018, *Proc. SiliconPV 2018*, Lausanne, Switzerland.
[44] Peibst, R. et al. 2017, *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.

About the Authors

Frank Feldmann studied electrical engineering and information technology at the Technical University of Aachen (RWTH) in Germany from 2005 to 2010, during which he was awarded the Henry Ford II prize. In 2015 he received his Ph.D. from the Albert Ludwig University of Freiburg for his work on TOPCon technology. He received the Junior Einstein Award sponsored by SolarWorld AG in 2016, and is currently a postdoctoral researcher at Fraunhofer ISE.

Sebastian Mack received a physics Diploma degree from Friedrich Schiller University, Jena, Germany, and a Ph.D. from the University of Konstanz, Germany. For his doctorate research, conducted at Fraunhofer ISE, he investigated thermal oxidation processes for industrial high-efficiency solar cells. Since 2012 he has been a scientist at Fraunhofer ISE, where his current interests lie in solar cells with passivated contacts.

Bernd Steinhauser studied physics at the Albert Ludwig University of Freiburg. In 2017 he received his Ph.D. from the University of Konstanz on the topic of multifunctional doped passivation layers for solar cell applications. Since 2009 he has been working at Fraunhofer ISE, where is now a postdoctoral researcher. His research topics include surface passivation, dielectric layer deposition, laser ablation and plating for both p-type and n-type silicon solar cells.

Leonard Tutsch completed his master´s in physics under the Elite Graduate Program at the University of Regensburg, Germany, in 2016. He is currently working towards his Ph.D. within the selective contacts team at Fraunhofer ISE, where his research focus is on both transparent conductive and charge-carrier-selective metal oxides for the contacting of solar cells with passivating contacts.

Jana-Isabelle Polzin studied physics at Goethe University, Frankfurt am Main, Germany, and earned her master's in 2017. She then joined Fraunhofer ISE and is currently a doctoral candidate at the Albert Ludwig University of Freiburg. She works on poly-Si-based passivating contacts for silicon solar cells.

Jan Temmler studied physics at the University of Potsdam, Germany, and received his Diploma degree in 2015 for his work at Fraunhofer ISE on the analysis of amorphous silicon (a-Si:H) for use in silicon heterojunction (SHJ) solar cells. He is currently a Ph.D. candidate at Fraunhofer ISE, where his main area of research is the development of PECVD-deposited a-Si:H for its application to SHJ solar cells on an industrial scale.

Anamaria Moldovan studied chemistry at the Universities of Zurich, Switzerland, and Freiburg, Germany. She received her Diploma degree in 2011 for her work on wet-chemical cleaning, and her Ph.D. from the University of Freiburg in 2016 for her work on cleaning and conditioning for high-efficiency silicon solar cells. She then focused on postdoctoral research into solar cells with passivated contacts, and has been head of the selective contacts team at Fraunhofer ISE since 2018.

Andreas Wolf studied physics at the Technical University of Darmstadt, Germany, and the Royal Institute of Technology, Stockholm, Sweden. In 2007 he received his Ph.D. from the Leibniz University of Hanover, Germany, for his work on sintered porous silicon and layer transfer silicon solar cells, which he carried out at the Institute for Solar Energy Research Hamelin (ISFH), Germany. Since 2008 he has been with Fraunhofer ISE, where he currently heads the thermal processes group in the photovoltaics division.

Jochen Rentsch is the head of the production technologies – surfaces and interfaces department at Fraunhofer ISE. He studied physics at the Technical University of Braunschweig, Germany, obtaining his Diploma degree in 2002. He then received his Ph.D. in physics in 2005 from the Albert Ludwig University of Freiburg, Germany. His research at Fraunhofer ISE focuses on the development of rear-passivated solar cells, new wet- and dry-chemical processing technologies, and the coordination of cell technology transfer projects.

Martin Hermle received his Ph.D. in physics from the University of Konstanz, Germany, in 2008. He joined Fraunhofer ISE in 2002, where he has been the head of the advanced development of high-efficiency silicon solar cells department since 2008. His research interests include the development of solar cell technologies for high-efficiency silicon-based solar cells, and the analysis, characterization and modelling of silicon and silicon-based tandem solar cells.

Stefan W. Glunz received his Ph.D. from the University of Freiburg, Germany, in 1995. He is the director of the photovoltaics – research division at Fraunhofer ISE, and a professor of photovoltaic energy conversion at the Albert Ludwig University in Freiburg. His research interests include the design, fabrication and analysis of high-efficiency solar cells. He received the Eni Award in 2008 and the Becquerel Award for Outstanding Merits in Photovoltaics in 2014.

Enquiries
Dr. Frank Feldmann
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstr. 2
79110 Freiburg, Germany
Tel: +49 761 4588-5287
Email: frank.feldmann@ise.fraunhofer.de

Solutions to realizing LID-controlled multi-PERC cells and modules

Fangdan Jiang, Jan-Nicolas Jaubert, Daqi Zhang, Zheng Yao, Guangyong Xiong, Jian Wu & Guoqiang Xing, Canadian Solar Inc., Suzhou, Jiangsu, China

Abstract

State-of-the-art black-silicon texturing technology has been successfully implemented in all of the 4.5GW multi-Si cell production lines at Canadian Solar (CSI). With a combination of black-silicon texturing and diamond-wire-sawn wafers, it has been possible to increase cell efficiency and wattage, while significantly reducing the cost. To further improve CSI's multi-Si product performance and cost, multi-Si passivated emitter rear contact (multi-PERC) technology has been developed to achieve a mass production cell efficiency of more than 20% on average, and a module power exceeding 300W. By the end of 2017, a production capacity of over 1GW had been established, and CSI's majority multi-Si cell capacity will be upgraded to PERC in 2018. This paper will introduce the solutions to realizing light-induced degradation (LID)-controlled multi-PERC cells and modules, as well as offering a discussion of the degradation performance. In addition, the technology evolution of CSI's high-efficiency multi-Si products and a roadmap for 22%-efficiency multi-Si cells are presented.

Background

For the past few years, multi-Si has been the mainstream technology, holding a majority market share. However, multi-Si's leadership of the market is facing a serious challenge from mono-Si, which is demonstrating inherently higher efficiencies and whose wafer costs are rapidly decreasing. It is therefore critically important to implement promising technologies such as diamond-wire sawing, black-silicon texturing and PERC in the mass production of multi-Si cells in order to improve efficiencies and further reduce costs.

By Q3 of 2017, CSI had successfully implemented diamond-wire sawing and state-of-the-art black-silicon texturing in all its multi-Si cell production lines, with a total capacity of 4.5GW and a mass production efficiency exceeding 19.2% [1]. The integration of PERC technology in multi-Si cells, however, is much more challenging, particularly because of light-induced degradation (LID) and light- and elevated-temperature-induced degradation (LeTID) issues [2–6]. It has been reported by UNSW and other institutes that two degradation modes exist in multi-PERC: 1) the fast degradation mode, which occurs within 100 hours and is caused by Type 1 defects; and 2) the slow degradation mode, which occurs over a period of up to one thousand hours and is caused by Type 2 defects [3]. Nevertheless, the LeTID effect reported by Hanwha Q-CELLS in multi-PERC is a cause of great concern for this technology [5,6].

By combining technical innovations throughout ingot material control, cell process optimization, advanced regeneration and intensified inline process control, CSI realized a mass production of LID-controlled multi-PERC cells and modules with a total capacity of over 1GW by the end of 2017; this capacity will be ramped up to more than 4GW by the end of 2018. In this paper, the performance of CSI's multi-PERC cells and modules will be presented, and the solutions to realizing LID-controlled multi-PERC cells and modules will be introduced.

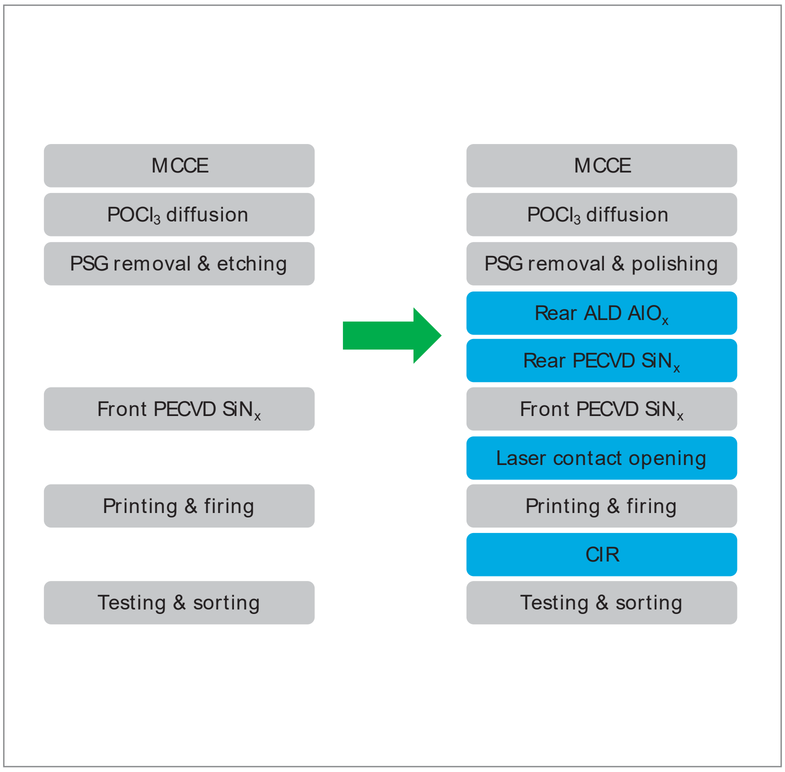


Figure 1. Process flows for conventional multi-Si cells (left), and CSI's high-efficiency multi-PERC cells (right).

Performance of multi-PERC cells and modules

Fig. 1 shows the process flow for CSI's high-efficiency multi-PERC cells; the process flow for non-PERC cells is also shown for comparison purposes. After CSI's proprietary state-of-the-art black-silicon texturing (metal-catalysed chemical etching – MCCE), an n^+-Si emitter is formed by

> "The integration of PERC technology in multi-Si cells is much more challenging, particularly because of LID and LeTID issues."

low-pressure $POCl_3$ diffusion in the tube furnace. The next step is phosphosilicate glass (PSG) removal and rear-side polishing.

Al_2O_3 layers deposited by the atomic layer deposition (ALD) technique are used to passivate the rear surfaces. The post-deposition annealing of as-deposited Al_2O_3 layers is integrated in the subsequent rear-side SiN_x anti-reflection coating (ARC) deposition by a tube plasma-enhanced chemical vapour deposition (PECVD) process. The front-side SiN_x ARC is also deposited by the tube PECVD process.

Following laser contact opening, the metallization is performed by screen printing and a co-firing process. All the as-fired multi-PERC cells then go through a current-induced regeneration (CIR) process, before the final testing and sorting.

The efficiency distribution of CSI's multi-PERC cells is shown in Fig. 2; the average efficiency of the cells exceeds 20%, which equates to a 0.9% efficiency gain compared with conventional multi-Si cells based on diamond-wire-sawn (DWS) wafers.

A comparison of the *I*–*V* parameters for multi-PERC and conventional black-silicon multi-Si cells is given in Table 1. The open-circuit voltage V_{oc} is boosted by 13.6mV, and the short-circuit current I_{sc} is increased by 320mA, by employing multi-PERC technology.

As regards module performance, as shown in Fig. 2(a), the average wattage of standard 60-cell multi-PERC modules exceeds 287W, which is comparable to that achieved by mono-Si modules. In combination with the use of module technologies such as half-cut and multi-busbar, the average wattage of 120-cell multi-PERC modules exceeds 300W, as shown in Fig. 2(b); this is again comparable to that for mono-PERC modules. Clearly, the implementation of multi-PERC enhances the competitiveness in terms of performance of multi-Si compared with mono-Si, but at a lower cost.

Solutions to controlling LID

LID issues are much more challenging for multi-PERC than for mono-PERC. Direct evidence of this is that there are many manufacturers who can produce quality reliable mono-PERC modules, but only a few who are able to produce multi-PERC modules [7].

UNSW and other research institutes have proposed the existence of both a fast degradation mode, occurring within 100 hours and caused by so-called *Type 1 defects*, and a slow degradation mode, lasting up to one thousand hours and caused by so-called *Type 2 defects*. The Type 1 defects have been identified as being B–O defect complexes, whereas the Type 2 defects are not yet fully explained. Hydrogen [8] or metal impurities such as Fe, Co and Ni [9] are the most likely suspects for Type 2 defects. UNSW recently

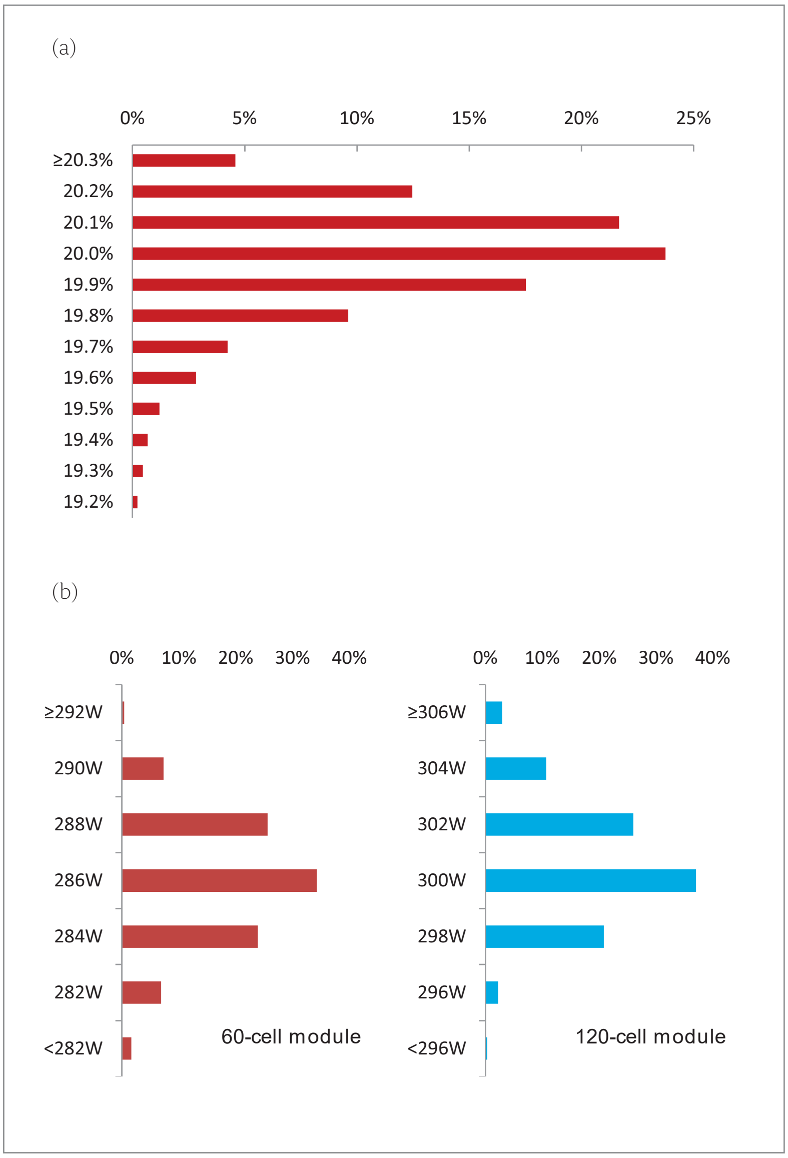


Figure 2. (a) Efficiency distribution of multi-PERC cells. (b) Wattage distribution of 60-cell and 120-cell multi-PERC modules.

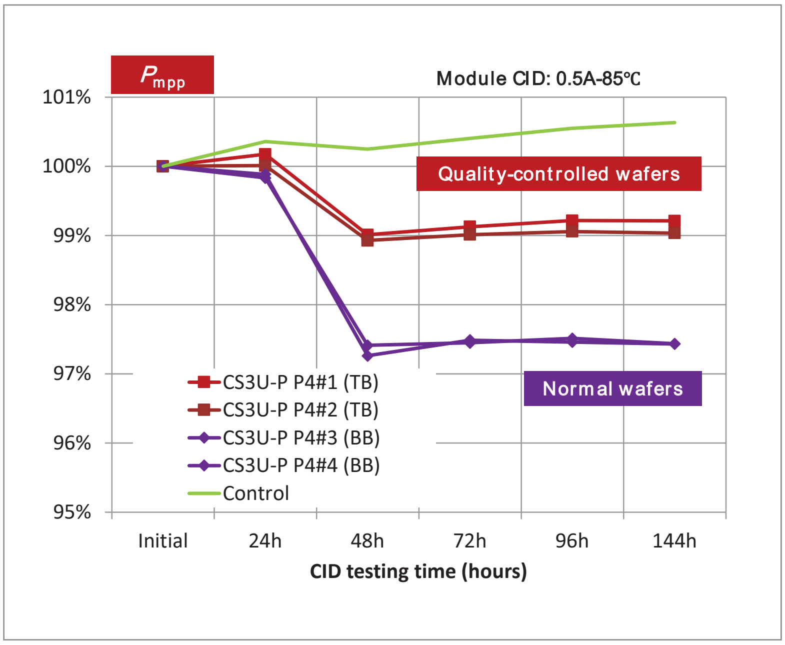


Figure 3. Effect of wafer quality on degradation performance of multi-PERC modules.

ΔV_{oc} [mV]	ΔI_{sc} [mA]	ΔFF [%]	$\Delta\eta$ [%]
+13.6	+320	−0.77	+0.90

Table 1. *I–V* parameter differences between multi-PERC cells and conventional black-silicon multi-Si cells.

"To solve the most challenging LID issues for multi-PERC, CSI has implemented several technical innovations."

reported that these Type 1 and Type 2 defects are also present in p-type mono-Si and n-type mono-Si [10].

To solve the most challenging LID issues for multi-PERC, CSI has implemented several technical innovations:

1. A unique ingot-casting process to control the impurity content within multi-Si wafer materials.

2. An optimized cell process, especially with regard to the metallization, in order to suppress defect-complex formation and to enhance hydrogen passivation of the multi-Si bulk.

3. An advanced regeneration process to deactivate the defects that cause LID.

4. An intensified inline process control to create reliable LID-controlled multi-Si PERC cells and modules.

The degradation rate for multi-PERC is dependent on the ingot and wafer material quality. For multi-Si ingots, the trend generally seen is that the degradation rate increases from the top part of the ingot to the bottom part. Additionally, there are various effects on the degradation rate arising from resistivity or doping concentration, oxygen content and structural defect density. The degradation rate is also sensitive to the dopant – B or Ga or a mixture of B and Ga; the beneficial effect of Ga doping, or partial Ga doping, is widely accepted. Fig. 3 shows the notable differences in multi-PERC module degradation, tested by current-induced degradation (CID), between quality-controlled and normal multi-Si wafers.

The significant impact of the firing temperature on degradation has been widely investigated [11,12]. Either lowering the peak temperature or lowering the cooling rate in the firing process will help to reduce the degradation rate considerably. Many theories to explain these findings have been proposed [11–14]; possible explanations are that a reduced firing temperature will suppress defect formation and/or change the hydrogen content in the multi-Si bulk.

The key to reducing the degradation rate of multi-PERC is the advanced regeneration process. The regeneration process to address the defect complexes causing LID consists of excess carrier injection, and adequate temperature and duration time [15]. Generally, for mono-PERC a light-induced regeneration (LIR) process using a halogen lamp, LED or laser is used [15]; however, the industrial LIR process is not adequate for use with multi-PERC. CSI uses a proprietary CIR process; compared with LIR, there are many advantages of CIR, such as a broader process window, higher throughput, lower electricity consumption and lower cost. By using the CIR process, the degradation rate can be reduced by up to 80%.

Fig. 4 shows the correlation between the reduced degradation rate after CIR treatment and the degradation rate without CIR treatment, tested by CID. It can be seen that the higher the degradation rate for multi-PERC cells without CIR treatment $CID_{w/o\ CIR}$, the greater the mitigation coefficient $CID_{w/o\ CIR}$-CID_{CIR} reflected in the reduced degradation rate. Interestingly, there is a quasi-linear correlation between $CID_{w/o\ CIR}$-CID_{CIR} and $CID_{w/o\ CIR}$, indicating that the CIR process effectively passivates the defect complexes causing LID. Moreover, it can be seen that the quality of the wafers from some suppliers (suppliers 1 to 4) is not satisfactory, showing a very high degradation rate without CIR treatment. This again reflects the importance of controlling the quality of the ingot and wafer materials in order to produce multi-PERC cells with controlled LID.

The reason why it is much more challenging to control the LID with multi-PERC than with mono-PERC is primarily the wide variation in quality of multi-Si wafers [6]. Even though innovative steps have been taken to control the impurity concentration of multi-Si ingots, it is still essential to reinforce the inline process control; in particular, a more exhaustive monitoring of degradation rate at the cell level is necessary, in addition to prompt process optimization in response to fluctuations.

Normally the LID of Si solar cells is tested by light-soaking; however, this technique has some drawbacks, such as a test time that is too long (typically 24–72 hours), imprecise control of the wafer temperature, and limited sample volume. To test the LID performance of multi-PERC cells, CSI uses the CID method, which offers several advantages, as listed in Table 2.

The set-up of the CID method is also illustrated in Table 2. The parameters for the CID method are forward-biased injection current, wafer temperature and duration. These parameters are

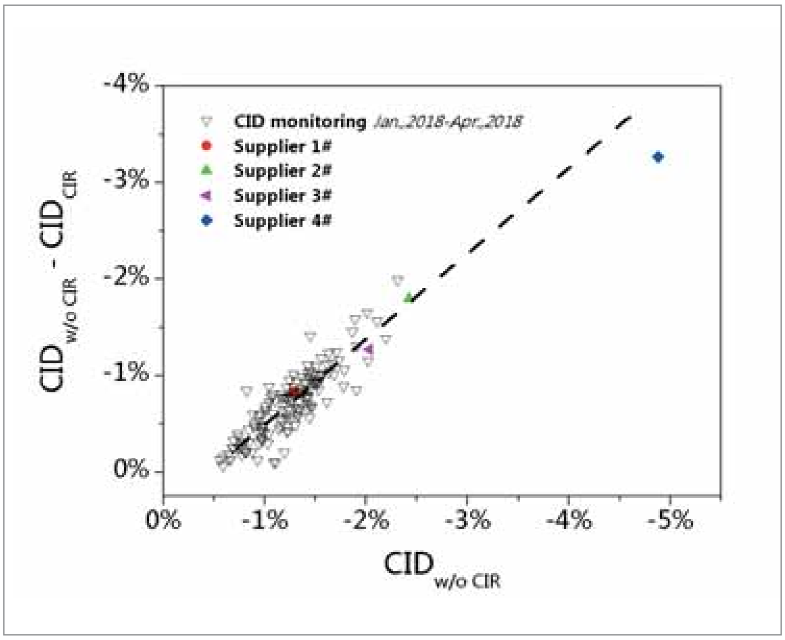


Figure 4. LID mitigation coefficient of the CIR process, reflected in the reduced degradation rate.

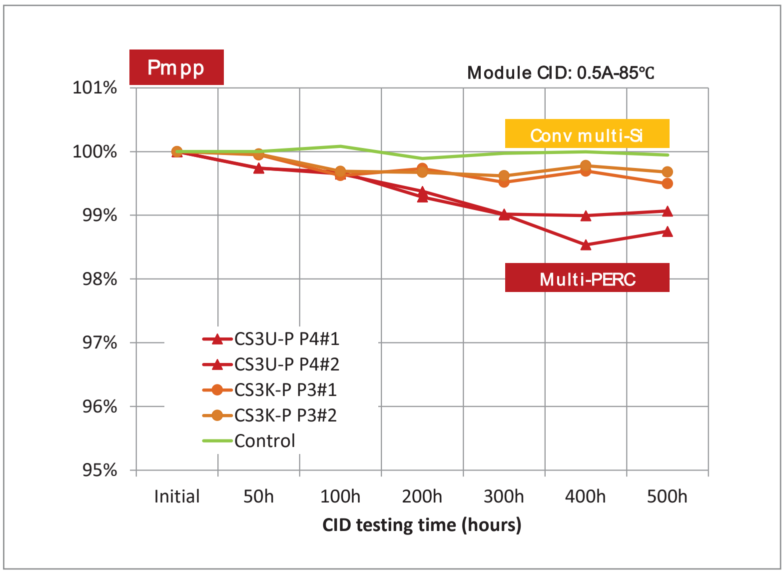


Figure 5. Module performance of CSI's multi-PERC modules undergoing CID testing.

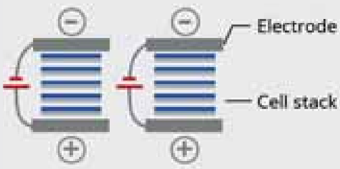
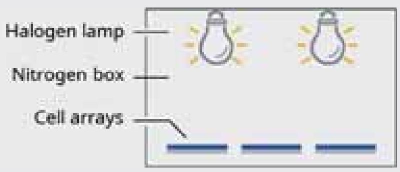
	CID (typical conditions: 3.5A-105°C-4h)	LID (typical conditions: 1,000W/m²-65°C-24h)
Injection intensity	Controlled by forward-biased current (0–10A)	Controlled by light intensity (0–1 sun)
Cell temperature control	50–150°C adjustable, accuracy <5°C	Not easy to control, sensitive to light intensity
Batch capacity	Up to 80 cells per stack, with small footprint	10–100 cells per tiled array, with large footprint
LeTID correlation	Higher temperature higher correlation	Not easy to control temperature above 75°C
Schematic set-up		

Table 2. Advantages of CID over LID in testing the degradation behaviour of multi-PERC cells.

> "The next step will be an integration of advanced technologies to upgrade to P4+, with an efficiency of up to 20.6%."

carefully selected after extensive experimental studies to reflect the degradation rate of multi-PERC cells as much as possible. In fact, if setting the injection current and wafer temperature parameters to certain values results in a regeneration-dominant effect, it is a CIR process; on the other hand, if lower values for the injection current and wafer temperature result in a degradation-dominant effect, it is a CID process. The chosen CID parameters are 3.5A, 105℃ and 4 hours, which is equivalent to testing LID by light-soaking with the parameters 1,000W/m^2, 65℃ and 24 hours; in addition, the sampling rate used is 0.08% of the total number of cells produced for each cell line. The use of this strategy results in excellent control of the CID of multi-PERC cells, to less than 1%.

For the module degradation test, the CID method is also used instead of indoor or outdoor light-soaking methods, with the set-up and parameters suggested by Hanwha Q-CELLS. Fig. 5 shows the comparison of CID degradation between multi-PERC modules and conventional multi-Si modules. The figure highlights that there is an increase in the module degradation rate of multi-PERC modules, as compared to conventional multi-Si modules. After 300 hours, however, the degradation rate of multi-PERC modules stabilizes, and proves to be less than 1.5% for up to 500 hours of testing; this is equivalent to two years of hot climate outdoor exposure, as proposed by Hanwha Q-CELLS [16].

All the cell and module degradation results demonstrate that, after taking several technical innovative steps, the LID of CSI's multi-PERC cells and modules can be successfully controlled.

Future roadmap

CSI specializes in producing high-efficiency multi-Si cell and modules. In 2017 there was a rapid evolution of technology and products, and this is expected to continue in 2018, as shown in Fig. 6. By Q3 of 2017, conventional P2 (slurry wafer and acid texturing) was phased out and fully upgraded to P3 (DWS wafer and black-silicon texturing), in a total capacity of 4.5GW. Additionally, starting from Q3 of 2017, P4 (DWS wafer, black-silicon texturing and multi-PERC) was phased in, and the capacity will be more than 4GW by the end of 2018. The next-generation high-efficiency multi-Si product P5 will begin to be phased in from Q3 of 2018 and will gradually gain more share.

On the basis of the current P4 product with an efficiency of greater than 20%, the next step will be an integration of advanced technologies (including bifacial, selective emitter, multi-busbar, paste optimization) to upgrade to P4+, with an efficiency of up to 20.6%. Further down the line, the goal is to upgrade to the next-generation wafer technology P5, with an efficiency of up to 21.5%, and eventually to P5+, approaching an efficiency of 22%.

Figure 6. Technology evolution of CSI's high-efficiency multi-Si product: P2 (conventional slurry), P3 (MCCE+DWS), P4 (multi-PERC), P5 (next-generation multi-Si).

Conclusion

Through innovations in materials, cell processing, advanced regeneration and enhanced inline process control, CSI has successfully demonstrated LID-controlled multi-PERC cells and modules in GW capacity. Multi-PERC technology is a must for high-efficiency multi-Si products to compete with upcoming high-volume mono-Si products. In order to further improve competitiveness, the fabrication of bifacial multi-PERC and an integration of advanced technologies to push efficiencies even higher will be essential.

References

[1] Wang, X. et al. 2017, *Photovoltaics International*, 35th edn, pp. 67–72.

[2] Ramspeck, K. et al. 2012, *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 861–865.

[3] Hallam, B. et al. 2016, *physica status solidi (RRL)*, Vol. 10, No. 7, pp. 520–524.

[4] Luka, T. et al. 2016, *Photovoltaics International*, 32nd edn, pp. 43–48.

[5] Fertig, F. et al. 2015, *physica status solidi (RRL)*, Vol. 9, No. 1, pp. 41–46.

[6] Kersten, F. et al. 2015, *Sol. Energy Mater. Sol. Cells*, Vol. 142, pp. 83–86.

[7] Fertig, F. et al. 2017, *Energy Procedia*, Vol. 124, pp. 338–345.

[8] Wilking, S. et al. 2014, *Sol. Energy Mater. Sol. Cells*, Vol. 131, pp. 2–8.

[9] Luka, T. et al. 2017, *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands, pp. 413–417.

[10] Niewelt, T. et al. 2017, *J. Appl. Phys.*, Vol. 121, p. 185702.

[11] Glunz, S. et al. 2001, *J. Appl. Phys.*, Vol. 90, pp. 2397–2404.

[12] Bothe, K. et al. 2002, *Proc. 29th IEEE PVSC*, New Orleans, Louisiana, USA, pp. 194–197.

[13] Unsur, V. et al. 2016, *Proc. 43rd IEEE PVSC*, Portland, Oregon, USA, pp. 717–719.

[14] Kouhlane, Y. et al. 2016, *J. Electron. Mater.*, Vol. 45, pp. 5621–5625.

[15] Herguth, A. et al. 2009, *Proc. 24th EU PVSEC*, Hamburg, Germany, pp. 974–976.

[16] Kersten, F. et al. 2017, *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands, pp. 1418–1421.

Enquiries

Fangdan Jiang
Canadian Solar Inc.
1099 Xiangjiang Road, SND
Suzhou, Jiangsu
China, 215129
Email: fangdan.jiang@canadiansolar.com

News

Manz reports first quarter revenue record as CIGS thin-film pre-payments total €43 million

Credit: Manz

Manz has reported a spike in revenue for Q1 2018.

PV and electronics equipment manufacturing and automation specialist Manz AG has reported first quarter 2018 revenue 80.8% higher than the prior year period, and a new first quarter revenue record for the company.

First quarter revenue was €86.1 million (US$102.3 million), an 80.8% increase over the prior year period, primarily due to around €43 million (US$51.1 million) received in new CIGS (Copper, Indium, Gallium, DiSelenide) tool order pre-payments from China-based customers.

However, Earnings before interest, taxes, depreciation and amortization (EBITDA) in the 2018 reporting period was negative €0.9 million, compared to €23.2 million in the prior year period.

New orders in the first quarter of 2018 were €87.6 million compared to €292.7 million in the prior year period, which included record (€263 million) CIGS order placements from China. Manz has received around 50% of the major order in payments to date.

Manz reiterated revenue growth for 2018 to be in the range of 10 to 14 % over 2017 (€325 million) with a slightly positive EBIT excluding one-time effects.

BUSINESS

First Solar benefiting from increased European demand as Series 6 bookings increase

Leading CdTe thin-film PV manufacturer First Solar may be benefiting from increased demand for its modules from utility-scale customers in the US, which has resulted in the announcement of a new 1.2GW Series 6 module production plant, yet bookings in Europe are fast approaching 1GW.

The company had booked 580MW of module supply orders across Europe, notably Turkey and France in the last 12 months and more than 350MW was booked in the first quarter of 2018.

First solar is benefiting from its low-carbon manufacturing footprint which is a stipulation in French Government tenders.

However, it was the continued increase in bookings for the firm's new large-area Series 6 modules that stood out in the first quarter of 2018, although so did the recognition that it was suffering from module assembly bottlenecks and so Series 6 supply in 2018 could be at the low end of its expected range. The first volume manufacturing of the modules occurred in early April 2018 from its 600MW Ohio fab, although certification was taking longer than expected.

First Solar reported first quarter 2018 sales of US$567 million, an increase of US$228 million from the prior quarter. This was primarily due to the sale of international projects in India and Japan and the sale of its Rosamond project in the US.

5N Plus secures new material supply deals with First Solar

Canada-based specialty metals firm 5N Plus has secured a series of multi-year contracts for the supply of semiconductor materials (CdTe) and an ancillary services deal with leading CdTe thin-film PV module manufacturer, First Solar. The new material supply deals would last through early 2021.

Nicholas Audet, executive vice president, Electronic Materials at 5N Plus, commented: "The specialty semiconductor market is a natural growth space for the future development of 5N Plus with the segment Electronic Materials' range of advanced semiconductor products ideally positioned to enable our customers across a spectrum of applications to competitively serve their end markets."

5N Plus has been a major and longstanding supplier of recycled and purified CdTe to First Solar.

The thin-film manufacturer is expanding production capacity to meet demand for its large-area Series 6 modules both at new facilities in the US and Vietnam.

First Solar is projecting around 6.6GW of nameplate capacity in the next three years.

Singulus books over US$48 million in new CIGS thin-film production tool orders

Specialist PV manufacturing equipment supplier Singulus Technologies has booked over €40 million (US$48.5 million) in new CIGS (Copper-Indium-Gallium-Diselenide) thin-film manufacturing equipment orders in 2018.

Stefan Rinck, chief executive, said: "Our company has received in the first months of 2018 already prepayment with a order volume over €40 million for CIGS production equipment. We are thus able to further expand our leading position for the delivery of production machines for CIGS solar modules. Our order backlog currently exceeds €130 million."

Major customer China National Building Materials

(CNBM) had signed a contract in late December 2017 for the delivery of five 'CISARIS' selenization machines for its plant in Bengbu, Anhui province, to expand capacity from 150MW to 300MW. CNBM has plans to expand production to 1,500MW in the future.

Singulus has also signed an agreement as well as payment from a subsidiary of a large, stock-listed energy company that also manufacturers PV modules in China for its TENUIS II, CIGS & CdTe wet-chemical coating process tools, valued at €10 million (US$12.1 million).

FUNDING AND FINANCE

Oxford PV taps key investors for £8.02 million in new funding

Perovskite solar cell developer Oxford Photovoltaics (PV) has undertaken a new funding round, led by key investors, Statoil and Legal & General Capital.

The £8.02 million (US$11.18 million) investment was to support Oxford PV's ongoing commercialization programme, which takes its perovskite-on-silicon tandem solar cell technology from the company's new lab in Oxford, UK, to industrial-scale processes and equipment at the company's process demonstration line in Brandenburg an der Havel, Germany.

Frank P. Averdung, chief executive of Oxford PV, said: "Over the last few years Oxford PV has built significant momentum and has now scaled up the necessary infrastructure such as R&D competencies, industrial capabilities, and a joint development partnership with a large photovoltaic player, enabling the company to maintain its leadership position in this area and bring a commercial perovskite PV solution to the silicon solar market in the near future."

GreatCell Solar gets perovskite funding from EU Horizon 2020 programme

Australia-based perovskite solar cell developer GreatCell Solar, formerly Dyesol, has recently secured European Union funding of €500,000 through the Horizon 2020 project.

The company qualified for the H2020-SGA-FET-GRAPHENE project funding via its small R&D operations in Rome, Italy. The project is focused on the development and the installation of a Perovskite Solar Cell (PSC) Photovoltaic (PV) 10m2 solar array in the Greek island of Crete.

This is designed to test and evaluate degradation rates of perovskite solar cells and modules in real-world conditions that could lead to improved encapsulation of perovskite solar cell-enabled glass substrates, while investigating, in particular, the usage of graphene in PSC solar cells.

GreatCell Solar noted that its commercialisation plans included targeting PSC modules that generate electricity for as low as US$3.5 cents per kWh or US$0.20 cents to US$0.25 cents per watt-peak (Wp).

The company will indirectly benefit from another EU-funded R&D programme on perovskite solar cells that brings together a number of European research and commercial partners, including Ecole Polytechnique Federale de Lausanne (EPFL) in Switzerland. EPFL has been the key long-standing R&D partner of GreatCell Solar.

Oxford PV has secured fresh investment for its ongoing move towards commercialization.

Credit: Oxford PV

R&D

Imec tasked with leading EU funded perovskite solar cell R&D programme

Nanoelectronics R&D organisation imec has been appointed as the lead to a three-year €5 million EU-funded R&D programme on perovskite solar cells that brings together a number of European research and commercial partners.

The Efficient Structures and Processes for Reliable Perovskite Solar Modules (ESPResSo) consortium will focus R&D on alternative cost-effective materials, novel cell concepts and architectures, and advanced processing know-how and equipment to overcome the current numerous limitations of developing commercial perovskite technology.

The consortium aims to bring perovskite cell performance close to its theoretical limit by demonstrating cell efficiency of more than 24% (on $1cm^2$) and less than 10% degradation in cell efficiency.

It will also work on commercial-scale cells and modules that are expected to use slot-die coating and laser processing that are intended to enable modules with more than 17% efficiency showing long-term (>20 years) reliable performance as deduced from IEC-compliant test conditions.

SERIS sets sights on tandem solar cell R&D to achieve 30% conversion efficiencies

The Solar Energy Research Institute of Singapore (SERIS) has set a new R&D goal to develop a commercially viable thin-film-on-silicon tandem solar cell with 30% conversion efficiencies.

SERIS researchers will collaborate with Nanyang Technological University (NTU) and Campus for Research Excellence and Technological Enterprise (CREATE) of NRF on both III-V and perovskite materials, while SERIS will develop optimized silicon bottom cells.

SERIS is also initiating R&D efforts to develop low-cost, high-efficiency building-integrated PV

(BIPV) modules and systems, including facades to support adoption in cities. SERIS noted that it would be working on high-efficiency, light-weight solar technologies that are aesthetically pleasing and yet economically viable.

Solliance and ECN tout 26.3% conversion efficiencies of tandem perovskite solar cell

Researchers at Solliance and ECN have fabricated a 6-inch industrially processed c-Si cell with a perovskite top layer that is mechanically stacked using ECN's MWT-SHJ (metal-wrap-through silicon heterojunction) design that has achieved conversion efficiencies of 26.3%.

The tandem perovskite solar cell combines good cell efficiency with a very high near infrared transparency of 93%, an increase of 3.6 percentage points over the efficiency of the directly illuminated silicon cell laminate.

The semi-transparent top cell was combined with a 6-inch size MWT-SHJ c-Si cell of 22.7% encapsulated cell efficiency and was processed by Choshu Industry Co in collaboration with ECN. This bottom cell contributes 9.9 percentage points to the tandem cell efficiency, according to ECN.

COMPANY NEWS

Hanergy's new business model is selling thin-film production lines to industrial parks in China

China headquartered PV thin-film equipment and module producer Hanergy Thin Film Power Group (Hanergy TF) has created a completely new business model in 2017 that provides new industrial parks a selection from a portfolio of a-Si, CIGS, GaAs and c-Si heterojunction (HJ) turnkey production lines to provide local governments access to solar technology and attract other hi-tech companies to new industrial parks.

Hanergy TF said of its new business, dubbed 'Industrial Parks Projects', that a company subsidiary, Hanergy Mobile Energy Holdings Co., Ltd., took a 20% stake in local governments' planned industrial parks, which were also owned by the local government and various third party investors.

Hanergy claims to have created a new business model providing equipment to new industrial parks.

Credit: Ben Willis

The shareholders of the industrial park project become the ultimate purchaser of Hanegy TF equipment and technology as the Hanergy subsidiary limits its shareholding below the 30% equity interest rules when Hanergy would be deemed an associate of a connected party.

The local governments then have solar manufacturing plants that can promote and deploy solar systems using the local plant from a priority perspective for distributed photovoltaic power generation and agricultural facilities, urban lights, public buses, electric vehicles, highways, and government funded poverty alleviation and other similar local projects.

Manz sacks CFO on opposition to strategic direction of company

PV and electronics equipment manufacturing and automation specialist Manz AG has dismissed its CFO, Gunnar Voss von Dahlen with immediate effect.

The company said that von Dahlen's dismissal was due to "divergent opinions about the company's strategic direction in the future".

After several years of losses and restructuring activities, Manz returned to profitability in 2017 and reported highest revenue volume in the company's history, which amounted to around €325 million.

Until the CFO position has been filled, the duties and responsibilities of the CFO will be assumed by the chief executive, Eckhard Hörner-Marass and the chief operating officer, Martin Drasch.

Von Dahlen had been responsible for finance and controlling, human resources, IT, organization, administration, investor relations and legal affairs since June 2017.

German CdTe thin-film solar manufacturer enters insolvency administration

German CdTe thin-film module manufacturer Calyxo GmbH has entered insolvency proceedings in Thalheim, Germany.

The provisional insolvency administrator Lucas Flöther of law firm Flöther & Wissing issued a statement highlighting that Calyxo would continue to operate during the proceedings.

Calyxo was said to be employing 155 employees at its manufacturing operations in Thalheim. Workers wages and salaries are secured by the bankruptcy funds for three months until the end of June, according to the administrator.

"The application for insolvency has no impact on the day-to-day business operations," noted Flöther, "All services will continue to be of the usual quality. The goal is to maintain business operations and as many jobs as possible.

"Calyxo is a core competitive company, but in a very difficult market environment. Whether a refurbishment is possible, will show in the context of a closer examination in the next few months," added Flöther.

Four-terminal perovskite/c-Si tandem PV technology

Dong Zhang[1], Stefan Luxembourg[2], Gianluca Coletti[2], Sjoerd Veenstra[1] & Bart Geerligs[2]
[1]ECN part of TNO – Solliance, Eindhoven; [2]ECN part of TNO, Petten, The Netherlands

Abstract

Two factors have coincided to stimulate the recent spur in interest for hybrid tandem PV technology based on crystalline silicon – the fact that balance-of-system (BOS) costs are increasingly dominating turnkey system costs, which strengthens the effect of high efficiency in reducing Wp costs, and the discovery of perovskite solar cells as a promising low-cost wide-band-gap partner for crystalline silicon (c-Si). This paper presents the progress and analysis of four-terminal (4T) perovskite/c-Si tandem technology at ECN part of TNO, with perovskite technology development carried out within the Solliance research organization. Tandem cell optimization and optical loss analysis are presented, with the combination of high efficiency and high near-infrared (NIR) transmittance of the perovskite cell resulting in an experimental tandem efficiency of 26.3%. An outlook is offered for loss reduction and efficiency increase. Upscaling and interconnection of the perovskite cell are crucial aspects for industrialization, and the status at Solliance is briefly described. High-end c-Si bottom cells are then compared with mainstream industrial cells; how industrial PERC and nPERT cells can be optimized for tandem application is described, as well as even making them suitable for two-terminal tandem application, through the application of polysilicon (polySi) passivated contacts. Finally, this paper looks at the cost of tandem versus single-junction (SJ) c-Si systems, and shows that the recent literature on perovskite module manufacturing cost is consistent with a potential cost advantage of tandem devices.

Introduction

As the balance-of-system (BOS) costs begin overtaking the solar module cost in the turnkey PV system cost [1], the role of the efficiency of the PV module becomes increasingly important in reducing the levelized cost of electricity (LCOE) from PV. Additionally, the ambition for strong further growth in PV generation capacity, and the controversy this already causes in more densely populated regions (e.g. large parts of Europe) with regard to making land area available for PV system deployment, favour the development of higher-efficiency PV modules. *Tandem PV technology* which combines bottom crystalline silicon (c-Si) cells with low-cost wide-band-gap thin-film top cells is expected to enable major increases in efficiency to be made and could therefore contribute significantly in these respects.

Of the thin-film PV technologies, the perovskite solar cell is considered a promising candidate for the top cell. Modelling has shown that an optimized perovskite/c-Si tandem configuration can result in a large efficiency increase over single-junction (SJ) c-Si cells [2]. In fact, several researchers have calculated that it should be possible for the efficiency of perovskite/c-Si tandem cells to exceed 30%, which is definitely out of reach for SJ c-Si cells [3,4]. Over the last three years, much progress has been made in the field of perovskite/c-Si tandem cells (Fig. 1) [5]. A cell efficiency as high as 26.9% has been demonstrated for a four-terminal (4T) tandem cell [6], and 25.0% has been announced for a monolithic two-terminal (2T) perovskite/c-Si tandem cell [7].

Compared with the 2T configuration, the use of a 4T tandem cell configuration (Fig. 1) has certain advantages: for example, the absence of a current matching constraint, and the possibility for module construction from separately manufactured and tested submodules or submodule strings. On

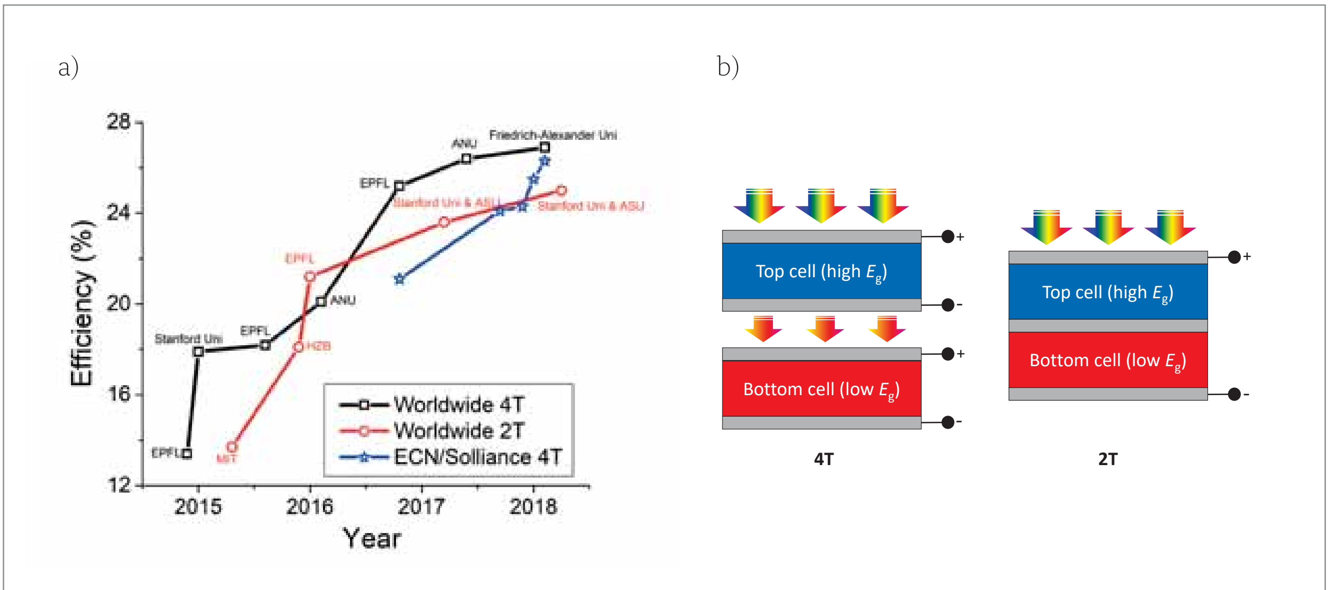


Figure 1. (a) Evolution of perovskite/c-Si tandem record efficiencies. (b) Schematic layout of 2T and 4T tandem cell configurations.

"Tandem PV technology is expected to enable major increases in efficiency to be made."

the other hand, the electrical wiring and system integration of the 4T module will be more complex, and the required transparent conductive layer with low sheet resistance on the rear side of the perovskite top cell (PTC) may result in significantly increased near-infrared (NIR) absorption loss. It seems that the R&D community and industry have not yet reached a consensus on a preference for 2T or 4T configurations, with both being actively investigated. This paper presents the progress made by Solliance and by ECN part of TNO on the development of 4T perovskite/c-Si tandems. In the research organization Solliance, of which ECN part of TNO is one of the partners, the semi-transparent perovskite device is under development, while ECN part of TNO is focusing on the c-Si cell aspects and the integration of both components in hybrid tandem modules.

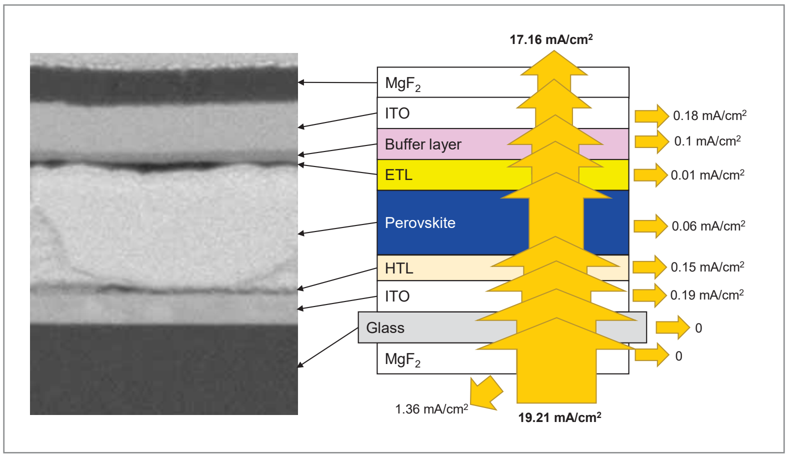


Figure 2. Cross-sectional scanning electron microscope (SEM) image of perovskite solar cell (left) developed at Solliance for use in 4T tandem cells, and its optical loss analysis (right) for the NIR region (800–1,200nm) of the AM1.5 spectrum (ETL = electron transport layer, HTL = hole transport layer) [9–11].

Perovskite/c-Si tandem cell results

One of the biggest challenges in achieving high tandem cell efficiency is the NIR transmission of the PTC. Considering the state-of-the-art c-Si cells with an external quantum efficiency (EQE) that can approach 100% [8], a limited NIR transmittance of the PTC inevitably induces large optical losses in the c-Si bottom cell. This limitation is especially relevant for 4T tandems, in which the PTC has to utilize two semi-transparent electrode layers, as these are the main causes of NIR parasitic absorption losses.

A transparent perovskite cell with a very high average NIR transmittance of 93%, developed with laboratory processes at Solliance, is shown in Fig. 2; the development of this cell has been described in detail in several publications [9–11]. The perovskite absorber layer, the organic selective contact layers, and the metal oxide charge transport layers are deposited by spin coating. The ZnO buffer layer to protect the perovskite from sputter damage is deposited by spatial atomic layer deposition (ALD), and the tin-doped indium oxide (ITO) layers are deposited by sputter coating. Thermally evaporated MgF_2 layers are added to reduce the front reflection, and also the internal reflection at the back side of the cell (in mass production, the front of the cell would have a regular anti-reflection (AR) coating, and the internal reflection at the rear would be reduced by the presence of an encapsulant).

The optical loss analysis for the 800–1,200nm NIR wavelength range is shown on the right in Fig. 2; this analysis uses the optical constants of the individual layers as determined by reflection/transmission measurements and spectroscopic ellipsometry. A key aspect of the development of this highly NIR-transparent PTC was the precise tuning of the oxygen partial pressure during the deposition of the

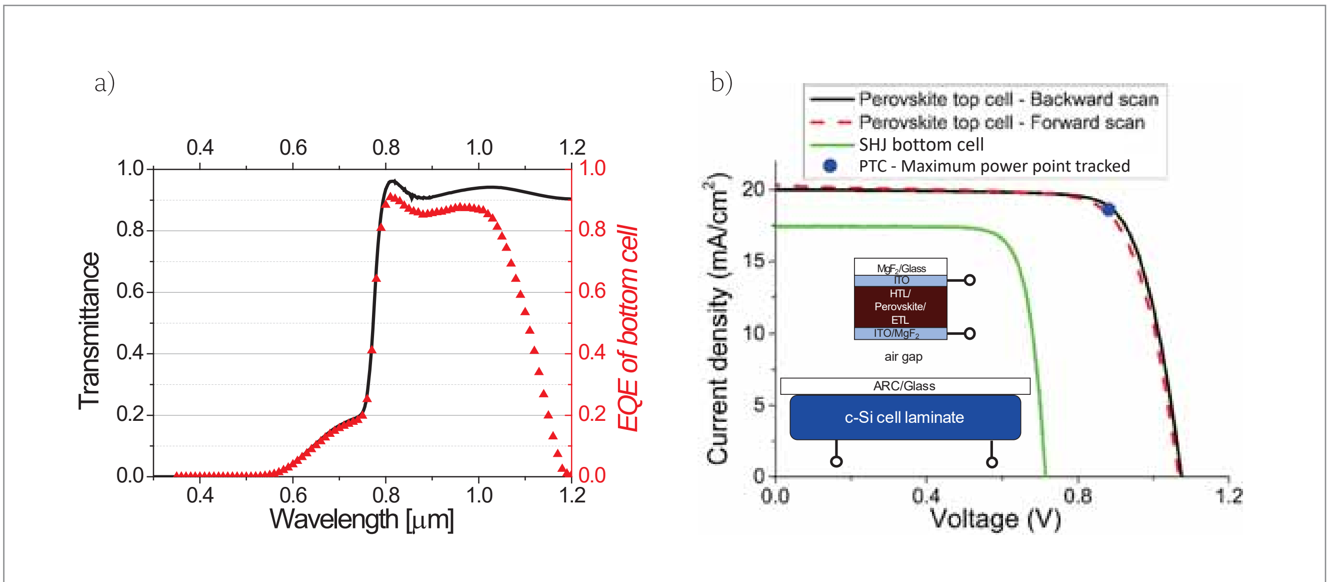


Figure 3. Best 4T tandem result obtained at ECN/Solliance: (a) transmittance of the PTC (black), and the filtered EQE of the c-Si SHJ cell (red) [12]; (b) *I–V* characteristics of the top and bottom cells (the inset shows schematically the configuration of this 4T tandem device).

Cell type		V_{oc} [V]	J_{sc} [mA/cm^2]	*FF*	η [%]
Perovskite top cell (Fig. 2)	Backward scan	1.075	20.0	0.772	16.6
	Forward scan	1.067	20.3	0.746	16.2
	MPPT 5 min.				16.4
C-Si silicon heterojunction (SHJ) cell [12]	Single-junction	0.731	39.8	0.781	22.7
	Bottom cell	0.714	17.3	0.796	9.9
Tandem cell					26.3

Table 1. Efficiency measurement of the 4T perovskite/c-Si tandem cell in Fig. 3 (MPPT = maximum-power-point tracked). (In-house measurements, taken according to the procedure outlined in Werner et al. [13].)

ITO layers, in order to control the concentration and type of defects. This allowed a high value for the product of mobility and carrier density, at relatively low carrier density, resulting in the very high NIR transmittance (Fig. 3).

The PTC described above was combined with a laminated high-efficiency silicon heterojunction (SHJ) cell [12]. Because of the difference in size of the PTC (3×3mm^2 aperture area) and the c-Si cell (243cm^2), the 4T tandem efficiency was determined on the basis of the filtered EQE measurement of the c-Si cell, as described by Werner et al. [13]. The results are shown in Fig. 3 and Table 1.

The optical analysis shows that the major remaining optical losses in this tandem stack consist of:

- Reflection: ~3.7mA/cm^2
- Absorption in the HTL and ETL of the perovskite cell stack: ~0.9mA/cm^2
- UV (inter-band) absorption in the front ITO: ~0.8mA/cm^2
- Free-carrier absorption (FCA) in the ITO: ~0.4mA/cm^2

There is a lot of room for improvement in the 4T tandem cell efficiency by further development and optimization. Fig. 4 shows how a significant increase in efficiency is possible through various enhancements, such as reductions in reflection and parasitic absorption losses, and tuning of the perovskite band gap. It is expected to be possible to achieve in practice a tandem cell efficiency of over 30% with the same c-Si cell as in Table 1.

Scalability of the perovskite process technology, and device stability

The prospect of perovskite/c-Si tandem solar cells enabling mainstream PV technology (c-Si) to enter a new efficiency regime is appealing, given the efficiency results and the outlook described above. To turn this prospect into reality, high efficiency in itself is not sufficient; it is equally important for tandem devices to be as stable as c-Si modules. In addition, industrial processes need to be in place for producing efficient and stable hybrid tandem devices on a large scale and at a low cost, leading to a competitive levelized cost of electricity (LCOE).

It is important to note the typical difference in cell dimensions between the perovskite top cell and the c-Si bottom cell in the current laboratory 4T tandem cells, a factor already touched upon in the previous section. The cell area of highly efficient perovskite top cells is often between 0.1 and 1cm^2, whereas the cell area of industrial c-Si cells is typically (6")^2, which is two to three orders of magnitude larger. Importantly, when the cell dimensions increase, the generated photocurrent increases, leading to ohmic losses in the semi-transparent electrodes. This issue can be mitigated by introducing a current-collecting metal grid, or by dividing the cell area into a number of smaller sub-cells and electrically interconnecting these sub-cells in series. In the latter case, the current flowing through the PV device is reduced and the voltage concurrently increased. Almost all commercial thin-film PV modules are based on this concept of monolithically serially interconnected cells. The optimized width of a unit cell in a serially interconnected perovskite module for a 4T tandem configuration is between 3 and 5mm, depending on the applied semi-transparent electrodes, the photocurrent density and the required area for the serial interconnection [14,15]. The area taken up by the serial interconnection, while not contributing to power generation in the perovskite module, can be as transparent as the other areas of the PTC stack, and

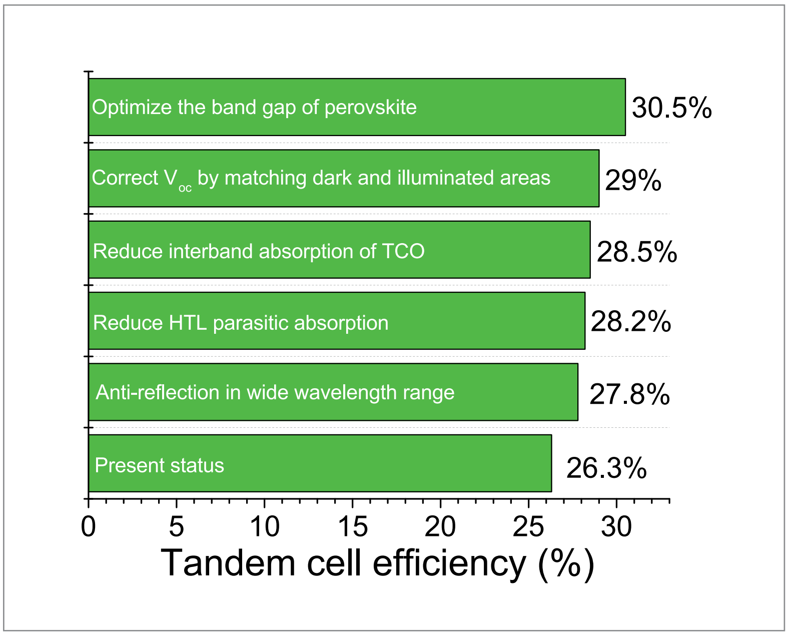


Figure 4. Outlook for improvements in the optical properties of the PTC, and thus in the perovskite/c-Si tandem cell efficiency, and for a further efficiency increase by optimizing the perovskite band gap. The V_{oc} improvement by matching dark and illuminated areas refers to avoiding the V_{oc} loss that is observed in the PTC due to the measurement aperture being smaller than the cell area. The cell V_{oc} was demonstrated to be higher at the module level [9–11].

> "High efficiency in itself is not sufficient; it is equally important for tandem devices to be as stable as c-Si modules."

can therefore contribute to power generation in the bottom c-Si module.

Consequently, by using small perovskite cells in R&D, the cell width of an optimized sub-cell in a monolithically interconnected module can be represented, without the need for already introducing an interconnection scheme in the device. As a next step, efficient 'area-matched' 4T tandem devices have now recently also been reported; these are based on stacking a perovskite module on a small c-Si cell, with a device area exceeding $1cm^2$ [16].

In order to prepare semi-transparent perovskite modules matching the size of commercially relevant 6" c-Si cells or even standard ~$1.6m^2$ c-Si modules, scalable industrial deposition methods – such as slot die coating, spray deposition, inkjet printing or physical vapour phase deposition – should be employed. An initial challenge is to reproduce with the scalable deposition method the efficiency of the non-scalable deposition method on small-size cells. Fig. 5 proves the feasibility of replacing spin coating by slot die coating to deposit the perovskite layer or selective charge transport layer, without significant loss in performance [17].

Another aspect of identifying suitable scalable processes for large-area deposition of perovskite layers is the use of solvents which can be employed in an industrial setting [18]. Although several laboratory-scale deposition processes have been developed for perovskite solar cells, the most frequently used wet-chemical method involves the deposition of the perovskite precursors by spin coating in a single step, followed by the application of a second solvent [19]. The second solvent (also called *anti-solvent*) causes rapid supersaturation in the drying, but still wet, film, resulting in a uniform, smooth, high-quality perovskite layer. The accurate timing of the application of the second solvent (after the deposition of the perovskite precursor solution) is crucial. This procedure, however, is not by any means easily transferable to an industrial setting.

Several research groups have developed more industrially relevant processes by engineering the solvent system [20], or by using a strong air flow to quench the crystallization process [21]. At Solliance, the development of these processes has recently led to the realization of 6" SJ perovskite modules prepared with scalable deposition methods, with efficiencies of 13.8% on the aperture area and 14.5% on the active area (Fig. 6) [22].

The typical absorber materials used in perovskite solar cells are not as resistant to external stress factors as silicon. Nevertheless, by the application of stable layers contacting the perovskite layer, and by preventing ingress and even egress of chemical components by the application of gas barrier layers, several groups have now reported stable device performance under prolonged illumination (1,000h, 1 sun equivalent) or with exposure to elevated temperatures (1,000h, 85°C), without suffering more than a 10% drop in performance. These results show that if the perovskite solar cell is well packaged, it can be stable when exposed to light and elevated temperatures and can pass the IEC damp-heat test [23].

Choosing and optimizing c-Si bottom cells for tandem application

The c-Si bottom cells most often used in studies of perovskite/c-Si tandem cells are high-performance cells, in particular interdigitated back contact (IBC) and amorphous-silicon/c-Si heterojunction (SHJ) cells. For the large-scale production of perovskite/c-Si tandem PV, it could make more economic sense to use lower-cost bottom cells; the reason for this is that increasing the efficiency of the bottom cell will not translate directly to the same efficiency gain in the full tandem stack. As a result, the process

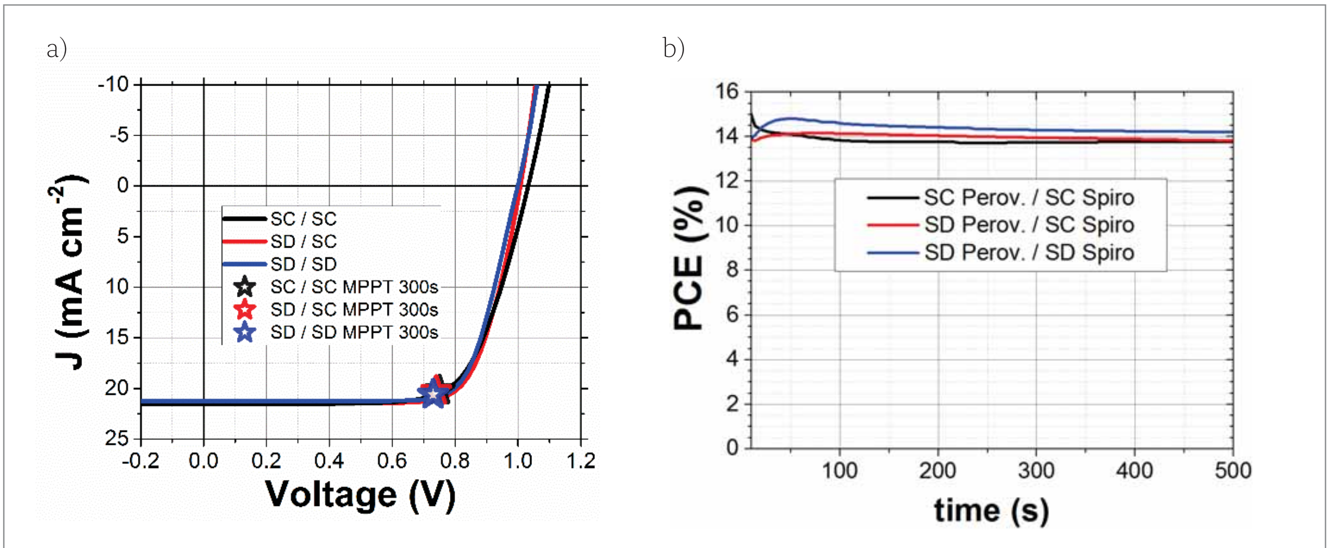


Figure 5. Illustration of the feasibility of replacing spin coating (SC) by scalable slot die (SD) coating technology in perovskite cell processing: (a) typical *J–V* curve of the perovskite cells; (b) typical maximum-power-point tracking (MPPT) curves for the devices, measured under maximum-power-point voltage bias, from Di Giacomo et al. [17]. (Perov. = perovskite absorber layer; Spiro = spiro-OMeTAD charge contact layer.) Reprinted with permission from Di Giacomo et al. [17].

costs for a higher-efficiency c-Si bottom cell will be greater in terms of added $/W for the tandem stack than those for the c-Si cell alone.

The filtered performance of c-Si cells (i.e. the performance in a tandem stack) depends on the transmittance of the perovskite stack, as well as on the c-Si cell properties, such as EQE, V_{oc} loss under reduced irradiation, and shunt and series resistances. Fig. 7 and Table 2 show a comparison of the performance of several c-Si cells, relevant to industrial mass production, for tandem application.

Fig. 7 shows the spectral efficiency [4] of various industrial and industrially relevant c-Si cells. The spectral efficiency incorporates the V_{oc} and fill factor (*FF*) determined under reduced irradiation to correspond to the filtered J_{sc}. Typically, it is found that V_{oc} scales with irradiation according to the diode equation with an ideality factor close to unity (i.e. about 22mV loss under the ~1.6eV perovskite stack), and that *FF* increases because of the reduction in series resistance loss. The contribution to tandem cell efficiency can be estimated from the product of the spectral efficiency, the transmittance of the perovskite stack, and the photon power density in the AM1.5 spectrum, integrated over the photon wavelength. The resulting *I–V* parameters of the filtered c-Si cells are given in Table 2.

Table 2 shows that the efficiency benefit under AM1.5 of the SHJ over the nPERT cell is halved in tandem application. The Al-BSF cell has significantly worse spectral efficiency for NIR wavelengths, and therefore shows a comparatively large reduction in efficiency in filtered operation (e.g. filtered efficiency 1.0% lower than a PERC cell, compared with 1.6% lower efficiency under AM1.5). In addition to the more established industrial cells, Fig. 7 shows the results for an nPERT cell employing polysilicon (polySi) passivated contacts on the front and rear sides, instead of a diffused emitter and back-surface field (BSF); this use of polySi passivated contacts is discussed in detail in the next section. In the context of selecting the bottom cells, it should be noted that in a 4T tandem cell design, the J_{sc}s of the top and bottom cells do not need to be matched as in the case of the 2T design; as a result, a 4T design based on bifacial c-Si cells will enable bifacial modules with the associated energy yield benefit.

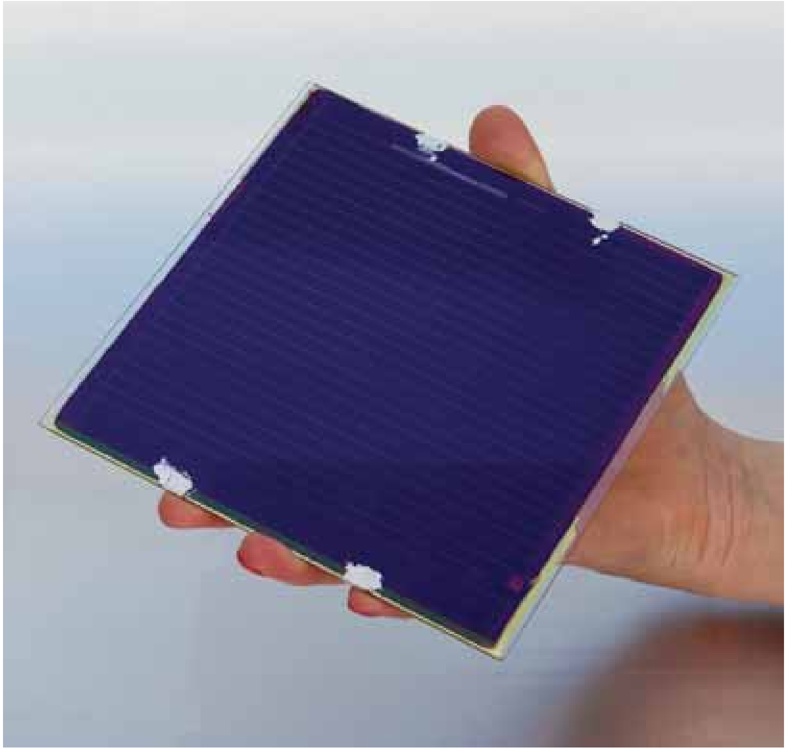


Figure 6. A 6" × 6" perovskite module processed by slot die coating, laser interconnection and encapsulation with a barrier film [17].

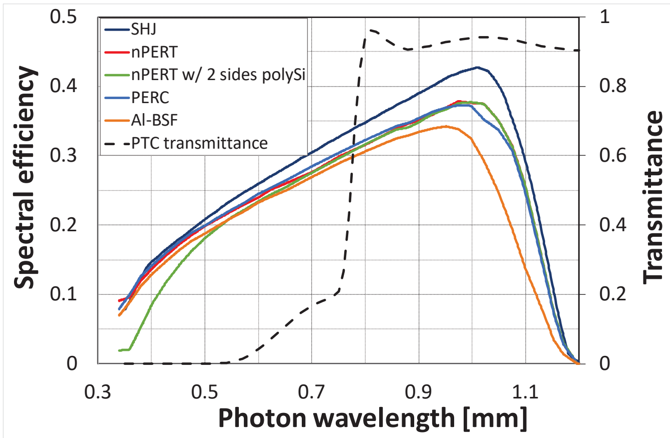


Figure 7. Spectral efficiencies of several types of industrial or industrially processed c-Si cells (solid lines). The transmittance of the perovskite cell stack described in the perovskite/c-Si tandem cell results section is indicated by the dashed line.

Cell type	AM1.5				Filtered				
	V_{oc} [V]	J_{sc} [mA/cm^2]	*FF*	η [%]	V_{oc} [V]	J_{sc} [mA/cm^2]	*FF*	η [%]	J_{sc} ratio
SHJ	0.731	39.8	0.781	22.7	0.714	17.3	0.796	9.9	0.436
nPERT	0.664	39.4	0.793	20.7	0.642	16.8	0.813	8.8	0.426
PERC	0.670	39.6	0.807	21.4	0.647	16.7	0.813	8.8	0.422
nPERT with polySi both sides	0.685	38.2	0.765	20.0	0.656	17.0	0.785*	8.8	0.445
Al-BSF	0.640	38.2	0.810	19.8	0.615	15.6	0.812	7.8	0.407

*estimated

Table 2. Single-junction efficiency and contribution to tandem cell efficiency for different types of c-Si cell. The SHJ cell is laminated with AR-coated glass; the other cells are unlaminated.

"The implementation of a polySi contact can be achieved with only a minor addition to the regular process flow."

PolySi passivated contacts on the bottom cell

In SJ c-Si solar cells, much attention has recently been directed at the implementation of extremely carrier-selective contacts, which, because of their low contact recombination, enhance the voltage and efficiency of the solar cell. In particular, a stack of thin oxide and a doped polySi layer is considered a practical and useful carrier-selective contact, which has enabled the realization of a cell efficiency higher than 25% [24,25]. Recombination current pre-factors (J_o) of less than 1fA/cm^2 have been achieved for n-type polySi; moreover, even fire-through metal paste contacts, while not fully passivated, can result in relatively low recombination current pre-factors of well below 500fA/cm^2 for the metallized area.

When aimed at SJ c-Si cell use, polySi is applied onto the back of the solar cell, since the significant number of carriers which are generated in a front-side polySi layer by short wavelength photons are generally not collected in the wafer, but instead lost to recombination. NIR wavelengths are, however, mainly transmitted through a front polySi layer to the c-Si wafer. A front polySi contact therefore shows less parasitic absorption when applied onto a c-Si bottom cell in tandem application, while it enhances cell performance through its low recombination. This phenomenon is illustrated in Table 2 by a comparison of the regular nPERT and the nPERT with a polySi contact layer on both sides; the two devices have similar J_{sc}s, but the V_{oc} is significantly boosted in the case of the nPERT with polySi passivated contacts.

A particular benefit of a polySi front contact is that it is expected to be suitable for 2T tandems, since the polySi passivating layer is conductive, in contrast to traditional passivating layers which are dielectric. In this respect, c-Si cells with a polySi front contact are an attractive alternative to SHJ cells, enabling high-temperature processed mainstream industrial cells to be adapted for use in 2T tandems.

Apart from nPERT cells with front and rear polySi contacts [26], the development of PERC cells with a front polySi contact (poly PERC, Fig. 8, [27]) has also begun. In both cases, the implementation of a polySi contact can be achieved with only a minor addition to the regular process flow (primarily the deposition of the oxide/polySi stack), and therefore with minor, if any, additional cost to the c-Si cell process.

Two types of parasitic absorption are of importance for bottom cells using a front polySi contact layer: 1) parasitic band-to-band absorption of the short wavelengths transmitted through the top cell; and 2) parasitic FCA of the long wavelengths. The parasitic band-to-band absorption is determined by the thickness of the polySi, the band gap of the perovskite, and the transmission shoulder at the absorption edge due to the finite thickness of the perovskite. The FCA is determined by the doping level and optical properties (effective path length) of the bottom cell. Qualitatively, the effect of the band-to-band absorption is clearly observable in the EQE and spectral efficiency (see, for example, Fig. 7). A ray-tracing model analysis was used to quantify the losses, on the basis of the optical properties of the perovskite stack described in the perovskite/c-Si tandem cell results section, with a shift of the refractive index and extinction coefficient curves of the perovskite layer over 0.15 and 0.35eV to model the wider band gap perovskites. The results are shown in Fig. 9.

The band-to-band absorption loss shown in Fig. 9 will decrease if the transmission shoulder of the perovskite is reduced (for example, if a thicker perovskite layer is used). In addition, for a 2T tandem cell application, the polySi layer thickness can be reduced, since the polySi does not need to provide lateral current transport.

The FCA loss depends on the doping level, which, for a certain required sheet resistance, depends on the mobility in the polySi. In practice, the mobility in n-type polySi is around half to one-third that in equally doped crystalline silicon, depending on the

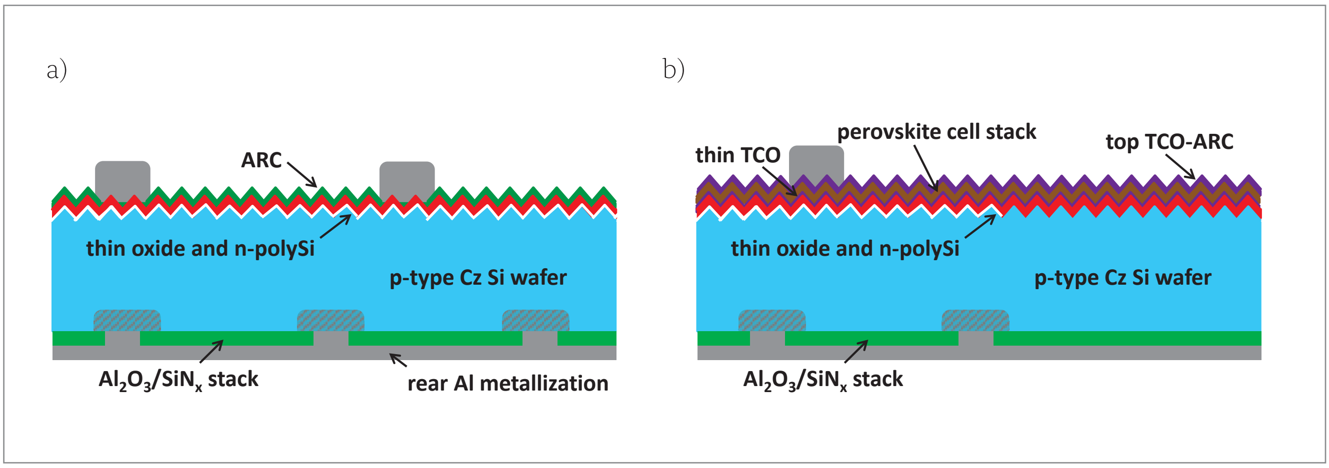


Figure 8. Schematic of the application of a polySi passivated contact in a bottom cell for a tandem stack in: (a) a PERC cell for 4T tandem application; (b) a possible 2T tandem layout based on the same cell concept.

exact process conditions [28]. Compared with a poly PERC cell, for an nPERT cell additional FCA is caused by the presence of a p-type polySi layer. While this seems to favour a PERC cell design (unless bifacial operation is required), the experimental results in Table 2 do not bear out the significantly large differences in the modelled FCA between PERC and nPERT. Further experimental and model analysis may be required in order to clarify this.

Cost

One of the principal arguments for tandem PV is the increase in efficiency, which will reduce the contribution of area-related module and system costs to the cost per Wp and the cost per kWh (LCOE). By virtue of this effect, tandem PV can potentially become more cost-effective than SJ PV, despite the additional cell process costs.

If the reference SJ (c-Si) turnkey system cost is \$1/Wp, a one percentage point efficiency gain for a tandem module over the c-Si bottom submodule will have a value of roughly \$10/m², when neglecting the increase in Wp-related BOS costs. If the best laboratory results for the efficiency gain of around 4–5% (see the perovskite/c-Si tandem cell results section) of tandem cells over mainstream industrial cells can be maintained at the module level, this would then represent a value of about \$40–50/m².
This estimate for cost-effectiveness, and the cost reduction that can be achieved at the system level, are illustrated in a more generalized way in Fig. 10. Details of the model, sensitivities, etc. are given in Geerligs [29]; the work reported in this reference also considers the relation between system cost comparison and LCOE comparison, noting the possible changes in thermal effects (operating temperature, temperature coefficient), and in degradation (a relative efficiency degradation of 1%/year would increase the LCOE by more than 10%, the same order of magnitude as the potential system cost advantage in Fig. 10).

Several studies on the anticipated cost of perovskite module production have recently been published. The cost estimates in these studies vary widely: for example, the estimates of the manufacturing cost of the transparent conducting oxide (TCO) layers vary between \$3/m² [30] and more than \$9/m² [31]. Some published manufacturing cost estimates are listed in Table 3, in which the cost of a metal electrode, if assumed to be in the stack, has been replaced by the cost of a second TCO electrode.

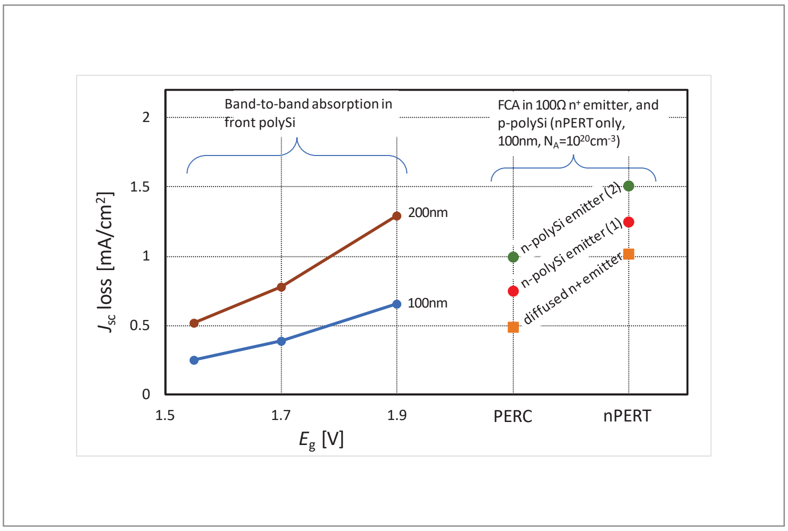


Figure 9. Ray-tracing model results of the parasitic absorption in c-Si bottom cells. Left graph: band-to-band absorption in a polySi passivating contact on the front of a c-Si bottom cell, as a function of the perovskite band gap. Right graph: FCA in PERC and nPERT cells with a 100Ω/sq. front emitter – a diffused emitter, a polySi emitter with half the mobility of crystalline silicon (1) or a polySi emitter with one-third the mobility (2). For example, the polySi emitter (1) has an n-type doping concentration of 1.6×10^{20}cm^{-3} over a thickness of 100nm.

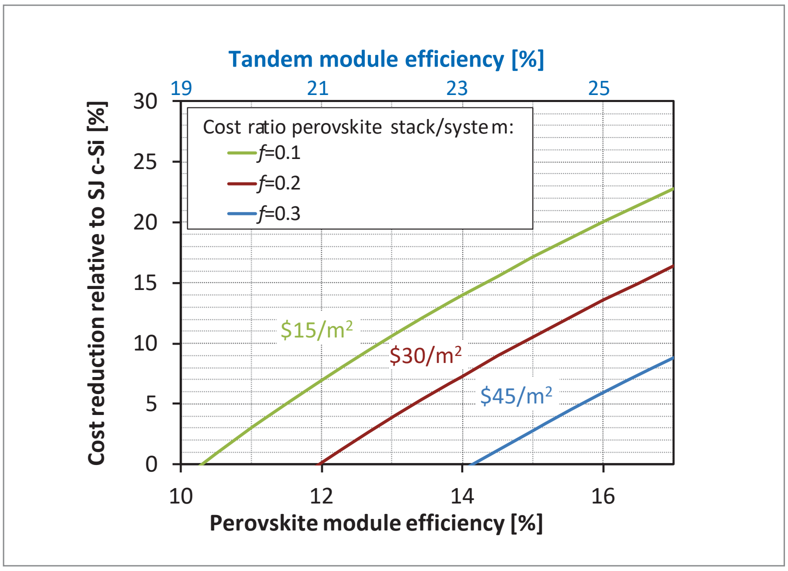


Figure 10. Illustration of the system cost reduction for a perovskite/c-Si tandem PV system, relative to a c-Si SJ PV system with 18% module efficiency, as a function of the cost for adding the perovskite stack (including, if relevant, changes in module materials, system cabling, power electronics, etc.). The parameter *f* is the ratio of this perovskite stack cost to the total SJ system cost, and the coloured labels show the approximate translation to a stack cost in \$/m² in the case of a SJ system cost of \$1/Wp. A filtered c-Si module efficiency of 9% in a tandem configuration is assumed in this calculation, roughly appropriate for a perovskite band gap of 1.7eV. Model details are given in Geerligs [29].

Reference/year	Perovskite stack [\$/m²] [a]	Complete module [\$/m²]	Stack structure
[32]/2015	25.5	55	ITO/TiO_2 scaffold/perovskite/Spiro/ITO
[31]/2017	Not specified separately	≥50[b]	ITO/PEDOT:PSS/perovskite/PCBM/Ca/Al
[30]/2017	9±1[b]	34±5[b]	ITO/NiO/perovskite/ZnO/Al

[a]Including monolithic interconnection and busbar contacts.
[b]The cell stack includes a rear metal electrode; the cost of this metal electrode was therefore replaced by the cost of the front ITO electrode in that particular study.

Table 3. Manufacturing cost estimates for a perovskite stack and module, sourced from the literature.

The perovskite cell stack structure reported in the most recent study, by Song et al. [30], is closest to the stack described earlier, in the perovskite/c-Si tandem cell results section; the stack has a manufacturing cost estimate, including the monolithic interconnected semi-transparent stack with busbars, of about $9±1/m². However, that study assumes a stack of unproven simplicity, without the use of organic charge transfer materials. The same study notes that the current cost of several often-used organic layers (e.g. PCBM) is excessive. Thus, in principle a perovskite stack cost consistent with a significant cost/Wp reduction (see Fig. 10) is feasible, although a challenge may still present itself in relation to other additional tandem costs, such as for barriers to ensure the stability of the perovskite cell stack, or an increase in cost/Wp associated with the junction box, system cabling or electronics.

Conclusions

The perovskite/c-Si tandem concept is considered to be very promising for significantly enhancing the mainstream module efficiency. The increased energy yield versus the nominal increase in manufacturing cost per m² is expected to result in a decrease in LCOE. Besides the high potential suggested by the calculations, a few research groups, including ECN/Solliance, have made significant progress in experimental demonstrations of high-efficiency tandem cells in recent years.

In terms of efficiency results, the perovskite/c-Si tandem has caught up with the world record of the SJ c-Si cells after just a few years of development. To further increase the tandem cell efficiency, to beyond 30%, special attention must be paid to the reduction of optical losses and to the optimization of the perovskite band gap.

In order to actually commercialize the perovskite/c-Si tandem technology, reliability and scalability of perovskite technologies are extremely important aspects. With optimized cell architecture and encapsulation, perovskite cells have demonstrated considerable progress in stability under continuous illumination and thermal stress. Furthermore, it was found that perovskite cells processed by scalable technologies, such as slot die coating, can perform just as well as those processed by lab-scale spin coating.

"Reliability and scalability of perovskite technologies are extremely important aspects."

Acknowledgements

Part of this work was performed within the framework of the projects TEZ0214010 (Hi-Eff) and TEUE116193 (Hiper), which receive funding from the Topsector Energie of the Dutch Ministry of Economic Affairs. We would like to thank Tempress Systems, Vaassen, The Netherlands, and in particular Dr. R. Naber, for providing the front-and-rear polySi solar cell, Choshu Industry Co. for the metal-wrap-through SHJ cell, and Dr. Qi Wang of Jinko Solar for the commercial PERC and Al-BSF cells for performance analysis in the tandem stack.

References

[1] ITRPV 2018, "International technology roadmap for photovoltaic (ITRPV): 2017 results", 9th edn (Mar.) [http://www.itrpv.net/Reports/Downloads/].
[2] Zhang, E.D. et al. 2016, "Combination of advanced optical modelling with electrical simulation for performance evaluation of practical 4-terminal perovskite/c-Si tandem modules", *Energy Procedia*, Vol. 92, pp. 669–677.
[3] Löper, P. et al. 2015, "Organic–inorganic halide perovskite/crystalline silicon four-terminal tandem solar cells", *Phys. Chem. Chem. Phys.*, Vol. 17, pp. 1619–1629.
[4] Yu, Z. (Jason), Leilaeioun, M. & Holman, Z. 2016, "Selecting tandem partners for silicon solar cells", *Nat. Energy*, Vol. 1, p. 16137.
[5] Eperon, G.E., Hörantner, M.T. & Snaith, H.J. 2017, "Metal halide perovskite tandem and multiple-junction photovoltaics", *Nat. Rev. Chem.*, Vol. 1, p. 95.
[6] Omar Ramirez Quiroz, C. et al. 2018, "Balancing electrical and optical losses for efficient 4-terminal Si-perovskite solar cells with solution processed percolation electrodes", *J. Mater. Chem. A*, Vol. 6, pp. 2583–3592.
[7] McGehee, M. & Holman, Z. 2018, Announcement at the MRS Spring Meeting.
[8] Green, M.A. et al. 2017, "Solar cell efficiency tables (version 50)", *Prog. Photovolt: Res. Appl.,* Vol. 25, pp. 668–676.
[9] Najafi, M. et al. 2018, "Highly efficient and stable flexible perovskite solar cells with metal oxides nanoparticle charge extraction layers", *Small*, Vol. 14, 1702775.
[10] Zhang, D. et al. 2018 [submitted], "High efficiency 4-terminal perovskite/c-Si tandem cells", *Sol. Energy Mater. Sol. Cells.*
[11] Najafi, M. et al. 2018 [forthcoming], "Stable and highly transparent perovskite cell and module for high efficiency perovskite/c-Si 4-terminal tandems", 35th EU PVSEC, Brussels, Belgium.
[12] Coletti, G. et al. 2016, "23% metal wrap through silicon heterojunction solar cells – A simple technology integrating high performance cell and module technologies", *Proc. 32nd EU PVSEC*, Munich, Germany, pp. 715–717.
[13] Werner, J. et al. 2016, "Efficient near-infrared-transparent perovskite solar cells enabling direct comparison of 4-terminal and monolithic perovskite/silicon tandem cells", *ACS Energy Lett.,* Vol. 1, pp. 474–480.
[14] Rakocevic, L. et al. 2017, "Interconnection optimization for highly efficient perovskite

modules", *IEEE J. Photovolt.*, Vol. 7, No. 1, pp. 404–408.
[15] Galagan, Y. et al. 2016, "Towards the scaling up of perovskite solar cells and modules", *J. Mater. Chem. A*, Vol. 4, No. 15, pp. 5700–5705.
[16] Jaysankar, M. et al. 2018, "Perovskite-silicon tandem solar modules with optimised light harvesting", *Energy Environ. Sci.*
[17] Di Giacomo, F. et al. 2018, "Up-scalable sheet-to-sheet production of high efficiency perovskite module and solar cells on 6-in. substrate using slot die coating", *Sol. Energy Mater. Sol. Cells*, Vol. 181, pp. 53–59.
[18] Wang, J. et al. 2017, "Highly efficient perovskite solar cells using non-toxic industry compatible solvent system", *Sol. RRL,* Vol. 1, 1700091.
[19] Jeon, N.J. et al. 2014, "Solvent engineering for high-performance inorganic–organic hybrid perovskite solar cells", *Nat. Mater.*, Vol. 13, pp. 897–903.
[20] Yanget, M. et al. 2017, "Perovskite ink with wide processing window for scalable high-efficiency solar cells", *Nat. Energy,* Vol. 2, 17038.
[21] Conings, B. et al. 2016, "A universal deposition protocol for planar heterojunction solar cells with high efficiency based on hybrid lead halide perovskite families", *Adv. Mater.,* Vol. 28, No. 48, pp. 10701–10709.
[22] Solliance 2018, Press release (Apr.) [https://solliance.eu/nl/solliance-sets-14-5-cell-performance-record-on-large-perovskite-modules/].
[23] Bush, K.A. et al. 2017, "23.6%-efficient monolithic perovskite/silicon tandem solar cells with improved stability", *Nat. Energy,* Vol. 2, 17009.
[24] Richter, A. et al. 2017, "n-Type Si solar cells with passivating electron contact: Identifying sources for efficiency limitations by wafer thickness and resistivity variation", *Sol. Energy Mater. Sol. Cells,* Vol. 173, pp. 96–105.
[25] Haase, F. et al. 2017, "Interdigitated back contact solar cells with polycrystalline silicon on oxide passivating contacts for both polarities", *Jpn. J. Appl. Phys.,* Vol. 56 [https://isfh.de/en/26-1-record-efficiency-for-p-type-crystalline-si-solar-cells/]
[26] Luxembourg, S.L. et al. 2017, "Perovskite/crystalline silicon tandems: impact of perovskite band gap and crystalline silicon cell architecture", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands, pp. 1176–1180.
[27] Geerligs, L.J. et al. 2018 [forthcoming], "PERC and nPERT industrial low-cost cells provided with front polysilicon passivated contact for tandem application", 35th EU PVSEC, Brussels, Belgium.
[28] Stodolny, M.K. et al. 2017, "Material properties of LPCVD processed n-type polysilicon passivating contacts and its application in PERPoly industrial bifacial solar cells", *Energy Procedia,* Vol. 124, pp. 635–642.
[29] Geerligs, L.J. 2017, "On cost-effectiveness of perovskite/c-Si tandem PV systems", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands, pp. 1171–1175.
[30] Song, Z. et al. 2017, "A techno economic analysis of perovskite solar module manufacturing with low-cost materials and techniques", *Energy Env. Sci.*, Vol. 10, pp. 1297–1305.
[31] Cai, M. et al. 2017, "Cost-performance analysis of perovskite solar modules", *Adv. Sci.,* Vol. 4, 1600269.
[32] Tinker, L. 2015, "Challenges and opportunities for organic-inorganic halide perovskite solar cells", Presentation, USA DOE Sunshot Initiative.

About the authors

Dong Zhang received his Ph.D. from Delft University of Technology, studying silicon heterojunction solar cells. In 2013 he joined ECN and Solliance as a researcher, working on thin-film solar cells. Currently, his main research interest is the tandem PV concept, combining perovskite and silicon technologies.

Stefan L. Luxembourg received his Ph.D. from AMOLF in the field of biophysics. After a postdoctorate on thin-film silicon at the Delft University of Technology, he joined ECN in 2009, initially in the field of policy studies. In 2013 he joined the ECN solar department, where he has been working on topics related to light management, down-conversion, colour generation and perovskite/silicon tandems.

S.C. (Sjoerd) Veenstra received his Ph.D. from the University of Groningen, The Netherlands. In 2002 he joined ECN to work on organic photovoltaics; this work then became part of Solliance in 2011, when the thin-film PV activities of imec, ECN and TNO were amalgamated in a 'solar alliance'. Since 2018 he has been the manager of Solliance's perovskite solar cell programme.

L.J. (Bart) Geerligs has been with ECN (now 'ECN part of TNO') since 2000, where he has since set up several research programmes. From 2004 to 2011 he was in charge of n-type cell technology projects, including the transfer to industrial pilot production of nPERT and nMWT technologies. Beginning in 2014 and for several years after, he led research on polySi passivating contacts, and is currently the programme manager for hybrid tandem solar cells and modules.

Enquiries

Bart Geerligs
Tel: +31 650 009 558
Email: bart.geerligs@tno.nl

News

SunPower buys SolarWorld Americas

US-headquartered high-efficiency solar module manufacturer SunPower Corp has acquired Hillsboro, Oregon-based PV manufacturer, SolarWorld Americas. Financial details were not disclosed.

SunPower will invest capital into the manufacturing operations in Oregon to convert the production to its P-Series modules, which use monocrystalline PERC cells fabricated in China under a JV arrangement.

Tom Werner, SunPower CEO and chairman, said: "The time is right for SunPower to invest in US manufacturing, and SolarWorld Americas provides a great platform for us to implement our advanced P-Series solar panel manufacturing technology right here in our home market. P-Series technology was invented and perfected in Silicon Valley, and will now be built in SolarWorld Americas' factory, helping to reshape solar manufacturing in America."

Credit: SolarWorld Americas

SunPower has acquired SolarWorld Americas for an undisclosed sum.

SunPower's move to acquire SolarWorld Americas, which had a nameplate module capacity of around 500MW comes after the Section 201 trade case that imposed anti-dumping duties on almost all countries that have module production capacity.

SunPower's solar cell production plants are based in the Philippines and Malaysia, while the vast majority of module assembly production is undertaken in Mexico.

Upon completion of the deal, SunPower would become the largest silicon solar module manufacturer in the US.

FINANCIAL RESULTS

SunPower's Q1 losses exceed guidance as asset sales and more restructuring starts

SunPower Corp has reported a larger than guided first quarter 2018 loss, posting its eleventh sequential quarterly deficit and a program of asset sales.

SunPower reported a GAAP net loss of US$116 million in the first quarter of 2018, significantly lower than the US$572 million loss reported in the fourth quarter of 2017.

SunPower had cash and cash equivalents at the end of the quarter of US$260.6 million, down from US$435.1 million at the end of the previous quarter.

Profitability remains elusive, as SunPower also guided an expected GAAP net loss to be in the range of US$125 million to US$100 million in the second quarter of 2018.

In response, SunPower will be selling its roughly 2GW portfolio of PV power plant projects in Mexico after selling a 126MW development project, at Guajiro, in the first quarter. The company also sold several smaller completed projects in the US and its Boulder Solar project.

Yingli Green Energy posts net loss of US$510 million in 2017

Struggling major China-based PV manufacturer Yingli Green Energy has reported a 2017 annual loss of US$510 million and a cash position of only US$58.1 million as going concern issues return.

Yingli Green reported total revenue of US$1,285.5 million in 2017, compared to US$1,206.4 million in 2016 on the back of PV module shipments of 2,953MW, compared to 2,170.4MW in 2016.

Although PV module shipments in the fourth quarter of 2017 increased by 40% compared to the third quarter and total PV module shipments in 2017 increased by 36% compared to 2016, the company was impacted by a major decline in ASPs.

The company reported an operating loss of US$452.3 million in 2017, and a net loss of US$510 million, compared to an operating loss of US$251.1 million and a net loss of US$293.6 million in 2016.

SHIPMENTS

Risen Energy targeting over 800MW of overseas module shipments in 2018

Major China-based PV module manufacturer Risen Energy, which entered PV Tech's Top 10 module manufacturer's rankings for the first time in 2017, expects to ship at least 800MW of PV modules outside China in 2017.

Risen shipped around 2.5GW to 3GW of PV modules in 2017 and had total product revenue of approximately US$1.8 billion, up from around US$1.1 billion in 2016, a 63% increase, year-on-year.

Risen noted that it had around 1,000 projects either under development or being delivered across the globe so far this year.

The company is following the Chinese government's One Belt, One Road initiative by exporting products, brands and technologies abroad and has announced it is undertaking EPC work on a 25MW PV power plant in Nuwakot, Nepal, which is using Risen's 275W modules.

JA Solar's solar module shipments reach record 7,143.1MW in 2017

'Silicon Module Super League' (SMSL) member JA Solar has reported record module shipments in 2017, increasing over 55%, while revenue increased over 25%.

The company reported total shipments of 7.6GW, including 127.4MW of modules to its downstream projects business. External shipments were 7.5GW, which represented an increase of 52.4% from 4.9GW in 2016. Module shipments were 7,143.1MW, up from 4,606MW, a 55% increase.

JA Solar's external product shipments (cells and modules) were led by China, accounting for 48.4% of total shipments in 2017, although down almost 5% from the previous year.

JA Solar reported net revenue in 2017 US$3.0 billion, an increase of 25.5% from US$2.4 billion in the previous year.

Total gross profit was US370.3 million), or 12.3% of net revenue, compared with US$352.5 million, or 14.6% of net revenue, in 2016.

Operating profit was US$110.0 million, compared to US$138.8 million in 2016.

Hanwha Q CELLS shipped 5,438MW of modules in 2017

Hanwha Q CELLS reported 5,438MW of modules recognised as revenue in 2017, up 18.7% from 2016. However, revenue was US$2,177.4 million, a decrease of 10.2% from 2016.

The company had previously guided PV module shipments of 5,500MW to 5,700 MW in 2017, while guiding 2018 module shipments to be in the range of 6,000MW to 6,200MW.

Hanwha Q CELLS had an in-house nameplate capacity of 4,300MW for solar cells and modules at the end of 2017, unchanged from the previous year.

The company's fourth quarter 2017 sales increased due to stockpiling in US, specifically for the utility-scale market prior to Section 201 tariffs.

The company reported a full year 2017 gross profit of US$243.6 million, compared with US$440.3 million for the full year 2016. Gross margin was 11.2%, compared with 18.1% for the full year 2016.

NEW TECHNOLOGY

LONGi Solar takes half-cut mono PERC solar module to record 360 watts

LONGi Solar, subsidiary of LONGi Green Energy, the leading integrated monocrystalline PV manufacturer, has said its 120-cell half-cut monocrystalline PERC solar module has exceeded 360W, a new record that was certified by TÜV-SÜD.

Dr. Jun Lv, vice president of LONGi Solar, said: "LONGi Solar's 120-cell half-cut monocrystalline PERC module applies our leading PERC technology. Average cell efficiency reached 22%; degradation in the first year is less than 2%, and stabilizing at less than 0.55% per year. PERC has been proven to increase power generation performance in low-light conditions and has excellent resistance to hot spots."

LONGi Solar is in the process of accelerating the upgrade of its solar cell production lines to completely migrate to PERC production in 2018. The company had 5GW of in-house mono c-Si solar cell capacity at the end of 2017.

Credit: Hanwha Q CELLS

Hanwha Q CELLS shipped almost 5.5GW of modules in 2017.

3SUN outlines transition to heterojunction bifacial module production

Enel's PV module manufacturing subsidiary 3SUN has outlined its '2.0 innovation project,' which includes the installation of a new assembly line to enable the manufacture of bifacial panels.

3SUN is kicking-off plans to install a new 80MW annual nameplate capacity crystalline silicon cell line to then assemble bifacial panels starting in the second quarter of 2018.

In the first quarter of 2019, 3SUN expects to be operational with a 110MW heterojunction (HJ) solar cell line and to almost double the HJ nameplate production capacity to 200MW in the third quarter of 2019.

Based on productivity and optimisation strategies, nameplate capacity could eventually reach 250MW.

The retooling from a-Si thin-film modules to HJ technology is expected to see the manufacturing plant produce 1,400 modules per day and approximately 500,000 modules per annum when fully ramped.

The transition to crystalline cells is expected to produce modules with 18% efficiencies in 2018 and over 20% for bifacial HJ modules from 2019 onwards.

Fraunhofer ISE teams with SCHMID on lower cost BIPV modules

The Fraunhofer Institute for Solar Energy Systems ISE has teamed with PV manufacturing equipment specialist, SCHMID Group, on lower cost BIPV modules that could reduce production costs by as much as 35%.

Within the 'BIPV-Fab' project, which was partially funded by the German Federal Ministry for Economic Affairs and Energy, the development partners looked at modifications needed for building integration of PV modules for facades, such as the module format, glass colour's and encapsulation material, through to the different thicknesses of glass and variations in the solar cell matrix that can best be applied to buildings.

During the one-year project that focused on industrial applicability, cost calculations were carried out for all of the developed product solutions, which concluded that there were significant cost savings to be made.

DuPont Photovoltaic collaborating with Envision on solar module degradation analytics

PV materials specialist DuPont Photovoltaic Solutions is collaborating with China-based wind turbine manufacturer, Envision, using its Energy IoT platform, EnOS, for analytical investigations into PV module degradation and failures across a number of real world field studies.

Stephan Padlewski, regional marketing leader, DuPont Photovoltaic Solutions, Europe, Middle East and Africa, said: "By combining our material science capabilities and knowledge with Envision's expertise in big data analytics, we can help provide asset owners with a quantitative and predictive analysis of ageing for preventive maintenance of solar panels and their components in the field."

The field studies on module reliability will include module backsheet failure mechanisms to improve the analytics for ageing solar assets.

PERSONNEL CHANGES

JA Solar's long-standing CFO leaves

JA Solar has announced that its long-serving CFO, Herman Zhao has left the company, effective 27 March 2018.

Zhao was re-appointed CFO in December 2013 after previously serving in the role from July 2006 to May 2008. Zhao left to pursue other interests.

Baofang Jin, chairman and CEO of JA Solar, commented: "We thank Herman for his many years of service to JA Solar. We respect his decision and wish him the very best in his future endeavours."

JA Solar is currently planning to withdraw its public listing on NASDAQ.

SunPower's CFO leaving July 1 and hires former SunEdison deputy CFO

SunPower's long-term executive vice president and CFO, Charles D. Boynton is to leave the company on 1 July for other career opportunities, the company has announced.

SunPower has hired Manavendra S. Sial, a former MEMC/SunEdison finance and operations manager that has in the past been in the CFO role at several companies unrelated to the PV industry.

While at SunEdison from March 2010 to December 2015, Sial held various global finance and operations leadership roles, according to SunPower.

Before SunEdison's spectacular bankruptcy, Sial became the senior vice president of finance and deputy chief financial officer. SunEdison filed for bankruptcy April, 2016.

Sial was said to have spent more than half of his career with General Electric in a variety of roles, from FP&A leader for the Energy Services unit to CFO of Power Delivery for GE's Transmission and Distribution group.

Challenges for the interconnection of crystalline silicon heterojunction solar cells

Angela De Rose, Torsten Geipel, Denis Erath, Achim Kraft & Ulrich Eitner, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

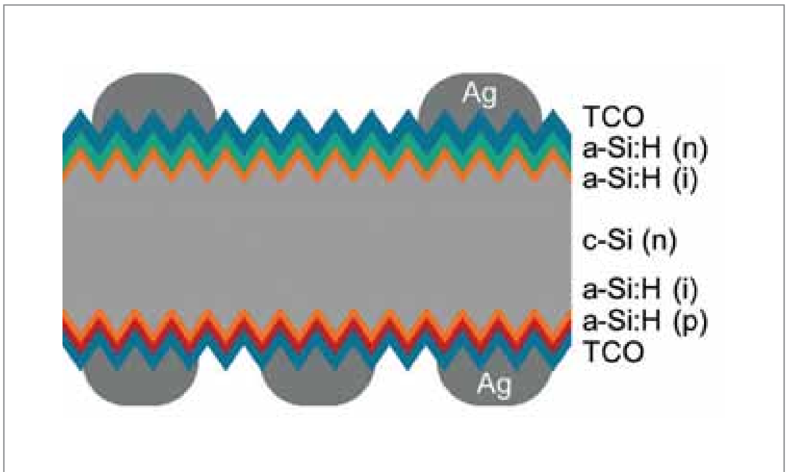
Abstract

Crystalline silicon heterojunction (HJT) solar cells and modules based on amorphous silicon on monocrystalline wafers offer advantages over established wafer-based technologies in terms of efficiency potential, complexity of the manufacturing process, and energy yield of the modules. The temperature sensitivity of these solar cells, however, poses considerable challenges for their integration in modules. Currently, there exist three approaches for the interconnection of HJT solar cells, each with its own strengths and weaknesses: 1) ribbon soldering with low-melting-point alloys; 2) gluing of ribbons by using electrically conductive adhesives (ECAs); 3) SmartWire Connection Technology (SWCT). This paper provides an overview of the different approaches and focuses on ribbon-based interconnection technologies. Soldering at process temperatures below 200°C enables standard stringing equipment to be used, but this method is known to result in weak adhesion of the low-temperature metallization pastes on the cell surface. This study focuses on the microstructure of the solder joints for such pastes, and an indication of the origin of the associated low peel strength is given. The dependence of the quality of ECA-based interconnections on curing conditions is analysed with regard to printability, electrical properties and peel strength. Recent results for different ECAs processed using a mass-production stringer are presented, and a 60-cell HJT module exceeding 320Wp is demonstrated.

Silicon heterojunction cell technology

There is a growing interest in semiconducting hetero-structures in PV fabrication lines for silicon solar cells. Within the last few years, several impressive photoconversion efficiencies for heterojunction (HJT) solar cells on n-type wafers have been reported. The highest efficiencies have been achieved in combination with an interdigitated back-contact (IBC) design, as in 2017 by Kaneka with 26.7% (designated area, da: 79cm^2) and 26.3% (da: 180.4cm^2) [1,2], or in 2014 by Panasonic with 25.6% (da: 143.7cm^2) [3]. For two-side-contacted HJT cells, Kaneka achieved 25.1% (aperture area: 151.9cm^2) in 2015 [4], and Panasonic showed 24.7% with a wafer thickness <100μm (total area: 101.8cm^2) in 2014 [5].

Figure 1. Schematic of a bifacial silicon HJT solar cell with an n-type c-Si wafer, rear emitter and a-Si:H layer for excellent passivation. (Not drawn to scale.)



A major advantage of HJT solar cells over homojunction cells is the optimized quality of the interface between the c-Si wafer and the a-Si layer; this enables a high passivation quality and leads to the suppression of recombination at the surface of the wafer, and therefore to a higher open-circuit voltage (730–750mV). Additionally, thinner Si wafers (<165μm), the high quality of the deposited amorphous thin film layers and the improved fill factor (>82%) allow one to get close to the theoretical conversion efficiency limit of Si solar cells. The HJT technology facilitates a lower temperature coefficient of power, enabling superior module performance compared with homojunction cells [2,6]. One of the possible structures of an HJT solar cell that requires an interconnection of both sides is shown in Fig. 1.

Besides the high performance of HJT solar cells, the corresponding production chain is fairly lean, consisting of low-temperature (<200°C) processes [7]. The deposition of the hydrogenated amorphous silicon (a-Si:H) is usually implemented by plasma-enhanced chemical vapour deposition (PECVD). The transparent conductive oxide (TCO) layers, typically indium tin oxide, are deposited by sputtering, whereas the metal contacts on the front side are currently fabricated by screen printing of silver-containing pastes or electroplating of copper [2,8].

Screen-printed metallization for HJT solar cells

Owing to the temperature sensitivity of the a-Si:H layers [9], low-temperature screen-printing pastes are used as the metal grid electrode on top of the TCO layer. Being a conductive metal, silver is widely used; a promising alternative, however, is copper, which takes advantage of the low process temperatures. Similarly to conductive adhesives, low-temperature metallization pastes mainly consist of a polymer (or more than one polymer) and a conductive metal in the form of particles or flakes. The thermal treatment after printing, typically performed at a temperature ≤200°C, forces the solvents to evaporate from the paste.

"Since the polymer remains in the low-temperature metallization paste after curing, guaranteeing low resistivity is a challenge."

Most commonly, thermo-setting pastes are used, where the polymers cross-link and form a matrix in which the conductive metal is stabilized during the curing process. Thus, in contrast to high-temperature metallization pastes with sintering temperatures above 700°C, the polymer is not thermally removed from the resulting metallization; furthermore, the polymer determines the adhesion and conductivity properties of the paste after curing. Since the polymer remains in the low-temperature metallization paste after curing, guaranteeing low resistivity is a challenge. Typically, the line resistivity is a factor of two to three times higher (typically 5–8μΩcm) than that for sintered high-temperature silver pastes. In contrast, the contact resistivity of the metallization on the TCO can be as low as that for high-temperature process schemes (<4mΩcm^2) [10].

The paste composition is highly affected by the cell interconnection concept (discussed later) and the curing process used; this means that there will need to be a trade-off between the required conductivity, fine-line printability and adhesion properties of the wafer surface and the ribbon for interconnection. For a metallization approach with busbars, printing processes for busbars and fingers can be split into two single process steps, allowing separate paste optimizations. A cured busbar of an HJT solar cell is shown in the scanning electron microscopy (SEM) image in Fig. 2.

In the last couple of years, the processability and fine-line printability of low-temperature pastes have improved remarkably, already allowing screen openings for the contact fingers down to 40μm in an industrial production environment. On a laboratory scale, a printed line width of <35μm with a screen opening of 30μm and below has been demonstrated with a reliable single screen-printing process [10].

Another aspect of paste development focuses on the reduction of the curing time. To date, a curing duration of up to 30 min is typically employed in order to achieve sufficient conductivity and adhesion. To allow high throughput in an industrial environment, cassette furnaces are widely used; here, the wafers are sorted into heat-stable carriers, which are then transported through the oven. As an alternative, inline furnaces with multiple wafer tracks on ceramic rollers or on a mesh belt can be used; however, these furnaces are often space-consuming because of the length of the process chamber required to provide high throughput.

Interconnection technologies for HJT solar cells

Besides the choice of materials for module integration, the interconnection of HJT cells is still challenging and research is ongoing. The most widely known approaches are briefly presented below, with the focus being on the busbar-based low-temperature interconnection by soldering and gluing.

Low-temperature soldering

Busbar interconnection

For the interconnection of HJT solar cells, the cheapest and most straightforward implementation into existing fabrication lines is soldering at lower temperatures; this allows the use of standard stringing equipment for ribbon soldering on automated stringers. Solder-coated Cu ribbons are aligned on both sides of the cell to contact the Ag busbar and to electrically connect several cells in series. To satisfy the requirement of lower process temperatures for HJT solar cells, bismuth (Bi)-based solders serve as an alternative to lead-containing solder alloys. Details and current challenges for low-temperature soldering on the low-temperature metallization of HJT solar cells will be presented in a later section.

SmartWire Connection Technology

As an alternative to conventional busbar-based interconnection processes, Meyer Burger Technology AG commercializes SmartWire Connection Technology (SWCT) [11,12]: this approach combines lamination with interconnection using thin round Cu wires coated with a low-temperature solder. For accurate positioning, the wires are embedded into an additional polymer foil before lamination. A 335Wp module with 60 cells and an average cell efficiency of 23.5% has been reported [13].

ECAs

An option for realizing a ribbon-based interconnection with low thermomechanical stress that is suitable for HJT solar cells is the use of ECAs [14]; this approach is commercialized by the company teamtechnik [15]. ECAs basically consist of a polymeric adhesive, such as an epoxy, acrylate or a silicone, filled with electrically conductive particles. The filler content is usually above the percolation threshold, which is 25–30%$_{vol.}$ for typical adhesives [16]. ECAs are applied by screen printing or other methods. After the material application, the ribbons are positioned and the ECA is thermally cured; the curing leads to cross-linking of the polymer chains

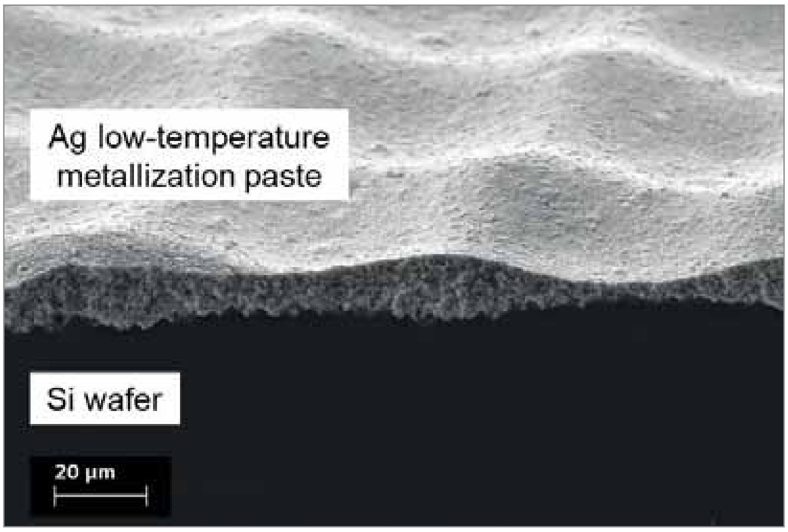


Figure 2. SEM cross-section image of low-temperature screen-printing paste after curing for the metallization of HJT solar cells.

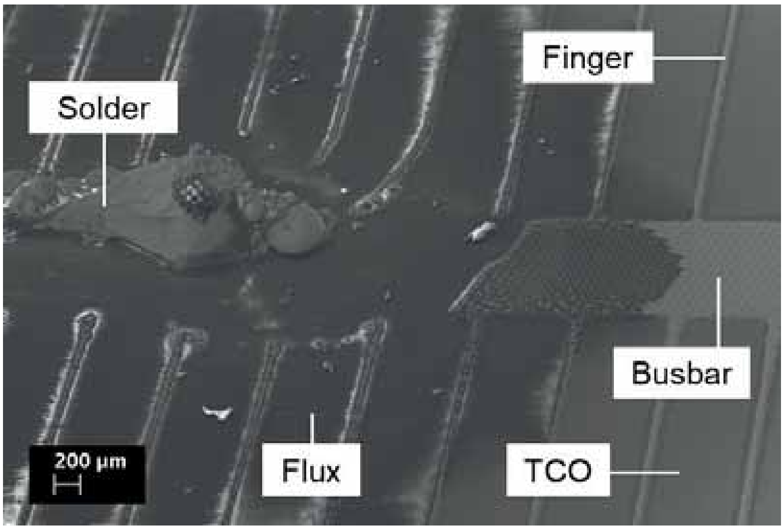


Figure 3. Top-view SEM image taken from a wetting test with liquid solder on a low-temperature metallization paste. The paste is breaking away from the cell surface directly after contact with the solder.

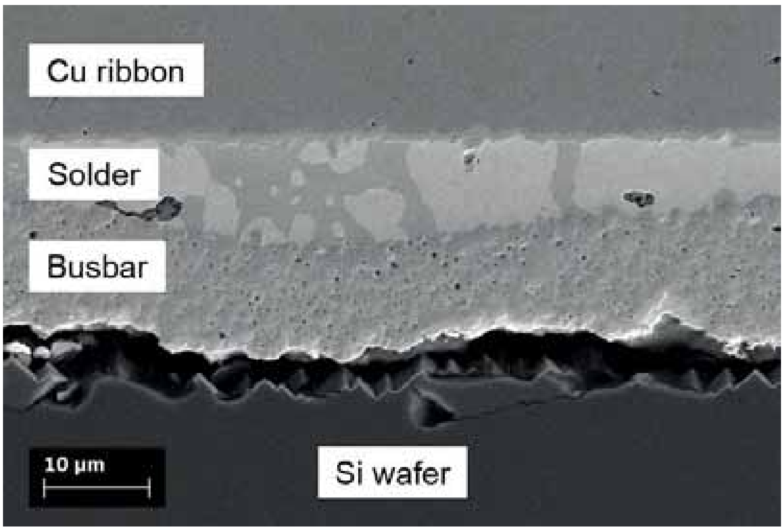


Figure 4. SEM image of the cross section of an HJT solar cell after soldering. Wetting of the busbar by liquid SnBi solder is conceivable, but the adhesion of the paste to the wafer is insufficient.

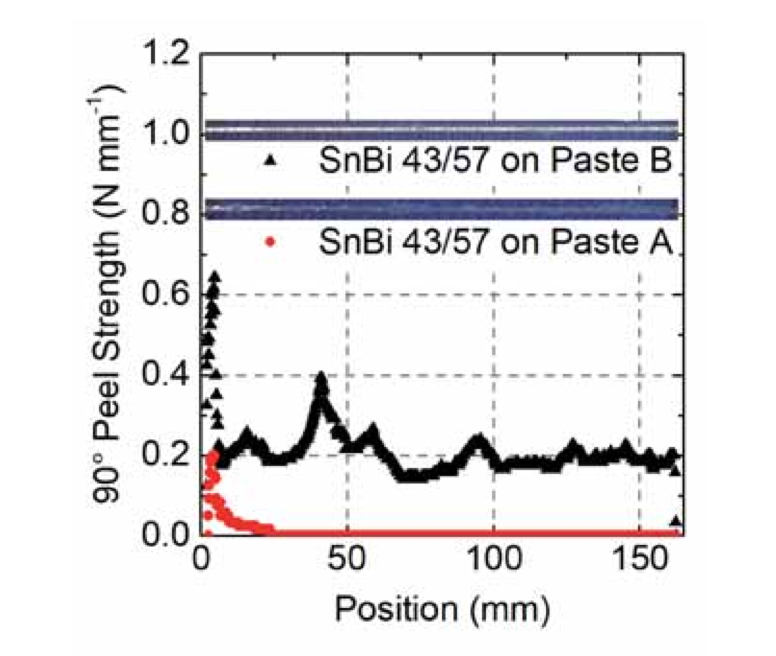


Figure 5. Results of a 90° peel test for SnBi-coated Cu ribbons soldered onto different low-temperature metallization pastes on an HJT solar cell. Corresponding fracture patterns (top-view images of the busbar after the peel test) are shown at the top. (Adapted from De Rose et al. [17].)

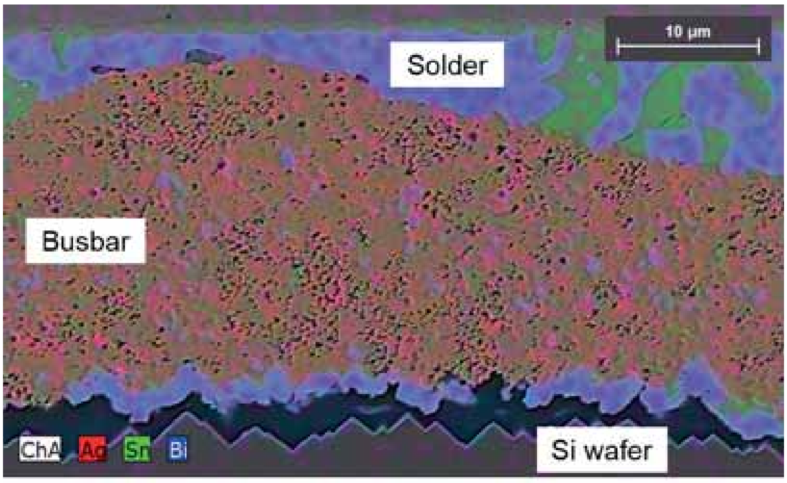


Figure 6. EDX mapping of a solder joint on an HJT low-temperature metallization paste. Diffusion of the solder (Sn, Bi) into the busbar (Ag) reduces the adhesion at the Si wafer. (Adapted from De Rose et al. [17].)

Figure 7. The TT1600 ECA solar cell stringer from the Germany-based company teamtechnik, capable of producing glued HJT strings at a throughput of 2.3 sec per cell and 1,600 cells per hour.

“The major challenge for the busbar interconnection of HJT solar cells is the metallization paste adhesion to the wafer surface.”

and to adhesion to the surfaces. The challenges for the interconnection of HJT solar cells with ECAs will be addressed in detail in a later section.

Challenges for busbar-based soldering technology

The temperature sensitivity of the a-Si layers on HJT solar cells, and the trend towards thinner Si wafers [5], limit the applicable processes and materials for interconnection. Since the a-Si passivation will not withstand temperatures above 250°C [7,9], solder alloys with a lower melting point than eutectic SnPb solder (T_{liq} ≈ 180°C, $T_{process}$ ≈ 250°C) have to be employed. Bi-based alloys have melting points between 120°C and 160°C and can be soldered at process temperatures below 200°C; moreover, they provide a lead-free alternative for compliance with the future restriction of hazardous substances (RoHS) requirements for solar modules.

Tape and shear tests on low-temperature pastes reveal that the adhesion before soldering is lower than that for standard Ag firing pastes [17,18]. The soldering process will usually reduce the initial adhesion on HJT metallization. When the molten solder comes into contact with the paste, it fully wets the busbar and, in most cases, quickly decomposes the metallization (see Fig. 3). After soldering a busbar with a SnBi-coated ribbon, the paste tends to detach from the wafer surface, which is illustrated in the SEM cross-section image in Fig. 4. The interaction with the solder is specific to each individual metallization, driven by different compositions of the low-temperature pastes.

In contrast to solder joints on high-temperature silver pastes, an evaluation with a 90° peel test in accordance with DIN EN 50461 reveals a peel strength below the required limit of 1Nmm^{-1} [19]. An example with two commercially available low-temperature pastes is given in Fig. 5. In this soldering example, the corresponding fracture patterns reveal an adhesive fracture with zero adhesion (paste A), and a mostly cohesive fracture within the paste with an average peel strength of around 0.2Nmm^{-1} (paste B).

It was found that the liquid solder penetrates the metallization during the soldering process, as detected by electron diffractive X-ray (EDX) spectroscopy (Fig. 6) [17]. Sn diffuses homogeneously, whereas Bi clusters and agglomerates at the interface with the wafer; this behaviour is highly dependent on the grain structure of the metallization paste. The formation of the Bi layer supports ablation of the paste, since Bi has a negative coefficient of thermal expansion and expands when it solidifies [20]. Other researchers assume that the temperature shock during soldering leads to a weaker interface between the paste and the cell [18]. Additionally, the coefficient of thermal expansion (CTE) mismatch between copper and the silicon wafer adds thermomechanical stress.

The major challenge for the busbar interconnection of HJT solar cells is the metallization paste adhesion to the wafer surface. On the way to creating a successful solar cell interconnection, the soldering parameters need to be carefully adjusted, and an adaptation of the low-temperature metallization pastes is essential. Besides an optimization of the conductivity and printability, the adhesion to the wafer has to be addressed and the diffusion of liquid solder prevented.

Challenges for ECA technology

A fully-automated stringer capable of the industrial interconnection of HJT solar cells either by low-temperature soldering or by gluing of ECAs is available at Fraunhofer ISE in Freiburg, Germany – the TT1600 ECA stringer is provided by the Germany-based company teamtechnik GmbH (see Fig. 7) [15]. With a throughput of 2.3 sec per cell with today's ECA cure durations, the stringer enables a production of 1,600 cells per hour. The stringer utilizes screen printing as an application method for ECAs, and is equipped with infrared lamps and heating plates to realize a fast and efficient curing process [21].

Conductive adhesives as a lead-free and compliant interconnection technology have been investigated by many groups over the last few years [22–27]. Recently, an increasing interest shown by the industry in this technology has been observed [28]. Within the joint research project KleVer (BMWi Contract No. 03258338), teamtechnik and Fraunhofer ISE assessed numerous commercially available ECAs in terms of printability, electrical properties, peel strength and cure speed, and module performance with the goal of improving ECA technology.

Printability

The printability of ECAs with the screen-printing unit in the stringer is evaluated in terms of pot life, print uniformity and lay-down (the amount of printed ECA). The *pot life* is the time period in which the mixed and thawed-out ECA (after having been stored in a frozen state) is processable without impairment of the printing or other important

"Thanks to recent developments in ECA chemistry, many materials today achieve a peel strength of more than 0.5Nmm⁻¹."

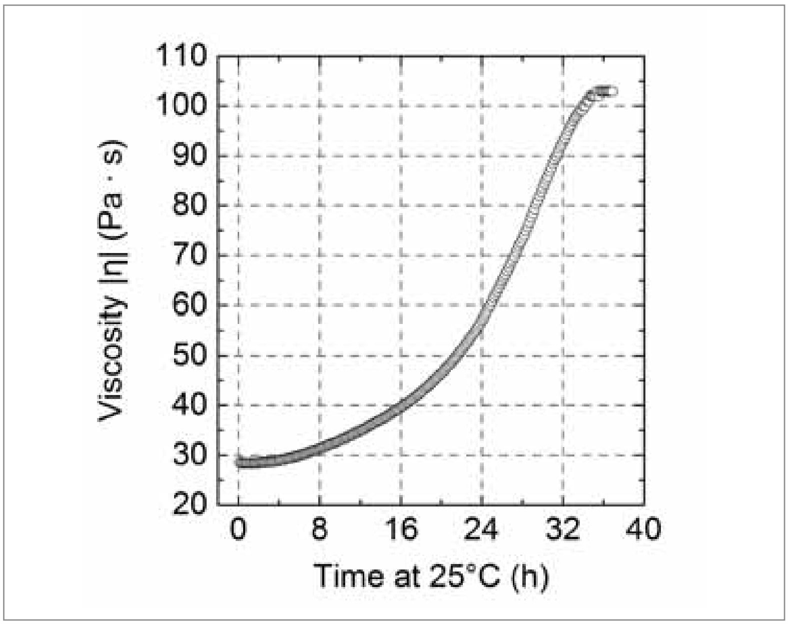


Figure 8. Dependency of the viscosity of a tested ECA on the exposure time at 25°C (measured with a plate–plate rheometer at a constant shear rate of 10s⁻¹).

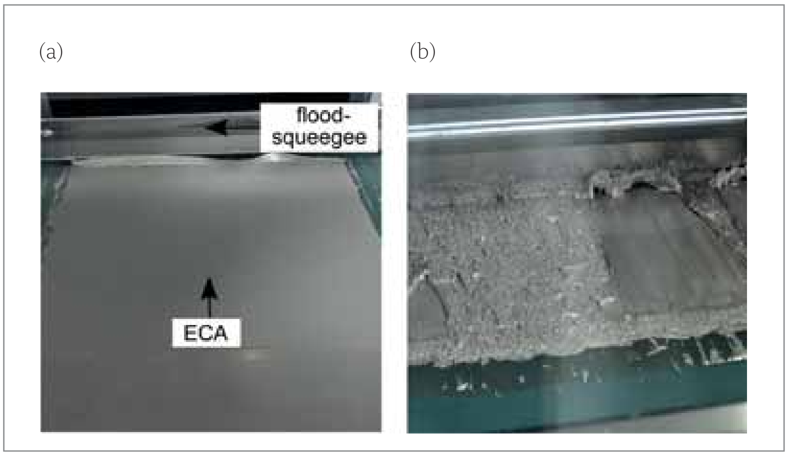


Figure 9. (a) Uniform flooding of the screen with ECA. (b) Non-uniform flooding of an ECA with a viscosity that is too high.

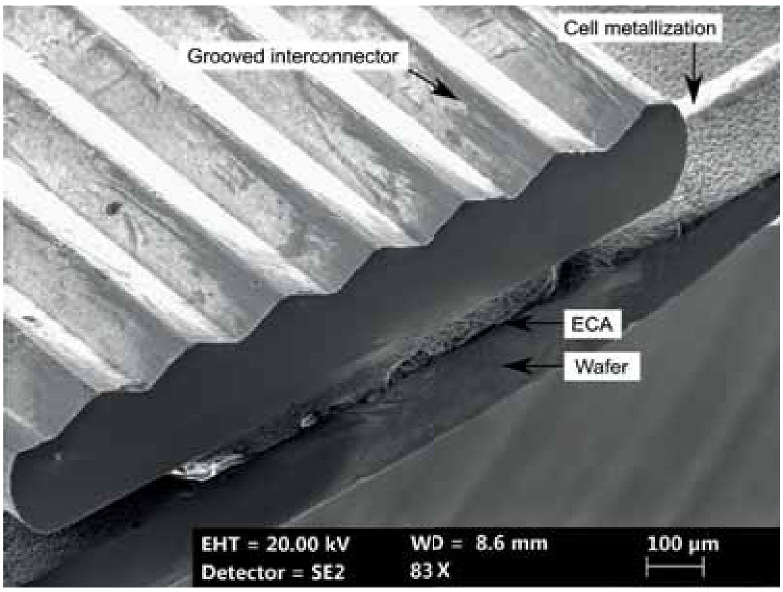


Figure 10. SEM image of a grooved interconnector glued directly to the finger metallization of a solar cell.

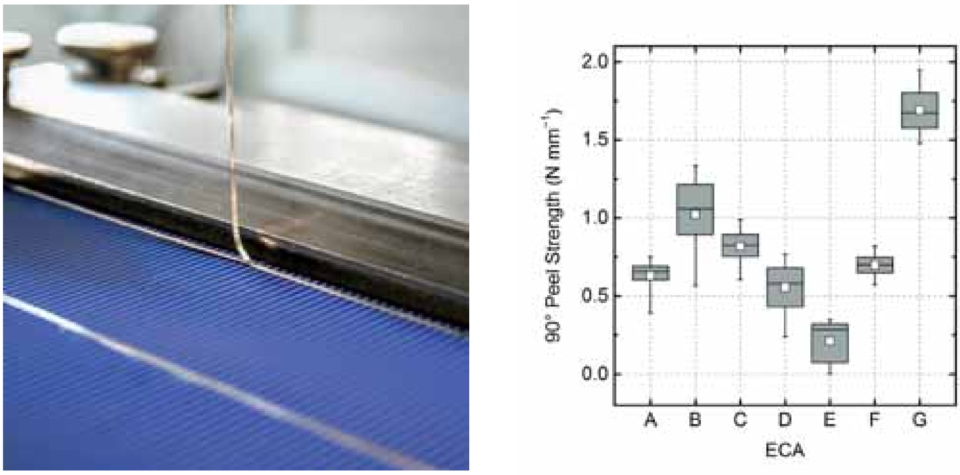


Figure 11. Peel test and peel strength data for ECAs. (Box = 25–75 percentiles; white square = mean; horizontal line = median; whisker = 5–95 percentiles.)

properties. It is limited by the reactivity of the glue components at ambient temperature and should exceed eight hours (i.e. one production shift).

The pot life can be determined by rheological measurements, as shown in Fig. 8. In this example, the tested adhesive has an initial viscosity of approximately 30Pa·s at a shear rate of 10s^{-1}; after eight hours at ambient temperature, the viscosity barely changes. In conclusion, the printability does not change very much in eight hours (see Fig. 9(a)). After 24 hours, however, the viscosity doubles, which could potentially give an undesirable printing result. In particular, very fast curing adhesives may suffer from reduced pot life. A fast cure is required for high throughput, but an overly high viscosity leads to non-uniform screen flooding as shown in Fig. 9(b), and to clogged screens and a lack of applied adhesive in a worst-case scenario.

The amount of printed ECA currently ranges from 6mg to 15mg per busbar and is highly dependent on the filler content of the adhesive, viscosity and screen configuration. With an optimized bond design there is room for further reduction in consumption.

An SEM image of a fully printed and cured ECA interconnection with the use of grooved interconnectors directly on the solar cell metallization is shown in Fig. 10. The grooved interconnectors consist of a Cu core and a thin (<1μm) Ag coating that protects the copper from oxidation. The grooved structure of the ribbon improves the short-circuit current of the module by 2–3% compared with conventional flat ribbons [29].

Electrical properties

The electrical properties of ECA interconnections are determined by the volume resistivity of the ECA and the contact resistivity at the bonded surfaces.

The volume resistivity is measured in accordance with the method specified in MIL-STD-883H (section 5011.5) [30], and often ranges between 10^{-4} and $10^{-3}\Omega$cm for many commercially available ECAs. This value is sufficiently low as to not reduce the fill factor of the PV module [31,32]. A correlation exists between volume resistivity and cure temperature: usually, increasing the cure temperature leads to stronger material shrinkage and a more efficient lubricant removal around the filler particles, and thus to a significant decrease in volume resistivity [33,34].

The contact resistivity of ECAs on silver surfaces is as low as that of a soldered bond, and lies within the range 10^{-3}–10^{-2}mΩcm^2 [26]. In the case of non-noble metal surfaces, however, the contact resistivity can be noticeably higher under initial conditions, and may further degrade if ageing takes place [35,36]. Nevertheless, stabilizing the contact resistivity on non-noble metals has the potential for further cost reductions, since the Ag coating around the ribbon could be replaced.

Threshold values for volume and contact resistivity are proposed in the authors' recent publication [31].

Peel strength and cure speed

Low peel strength is often regarded as a significant drawback of ECA technology, despite the demonstration of reliability in thermal cycling tests [37]. The reasons for the limitation in peel strength are partly synonymous with the above-mentioned difficulties of low-temperature metallization pastes. A liquid metal diffusion – relevant to low-temperature paste soldering – does not play a role in ECA interconnection strength; however, ECAs and low-temperature pastes are both based on filled polymers, which lack toughness compared with metals.

Thanks to recent developments in ECA chemistry, many materials today achieve a peel strength of more than 0.5Nmm^{-1}, sometimes even surpassing 1Nmm^{-1}; this is usually sufficient for handling the strings and for withstanding thermal cycling tests. Summarized peel strength data for ECAs glued onto HJT cells are shown in Fig. 11. The fracture mode for the tested ECAs is *cohesive*, indicating proper adhesion to the surfaces. Since higher peel strength is achieved by increasing the ECA lay-down, there is a trade-off with material consumption and costs, which has to be determined.

An improper cure is often the cause of inadequate peel strength. Fig. 12 shows the peel strength of adhesive A as a function of cure temperature and time. The default curing schedule of adhesive A is 30 sec at a constant temperature of 180 to

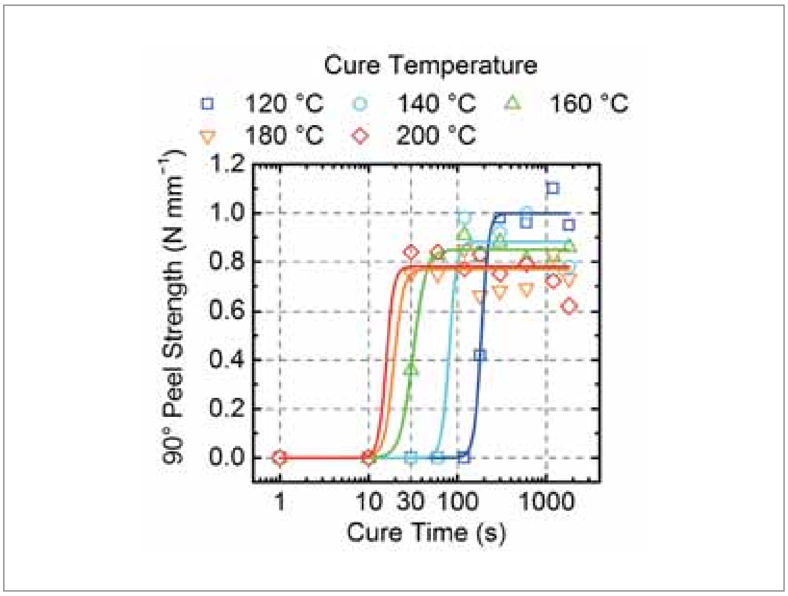


Figure 12. Dependence of the peel strength of adhesive A on the curing temperature and time. Each symbol is the average of several peel tests. (The interpolated solid lines are simply a guide.)

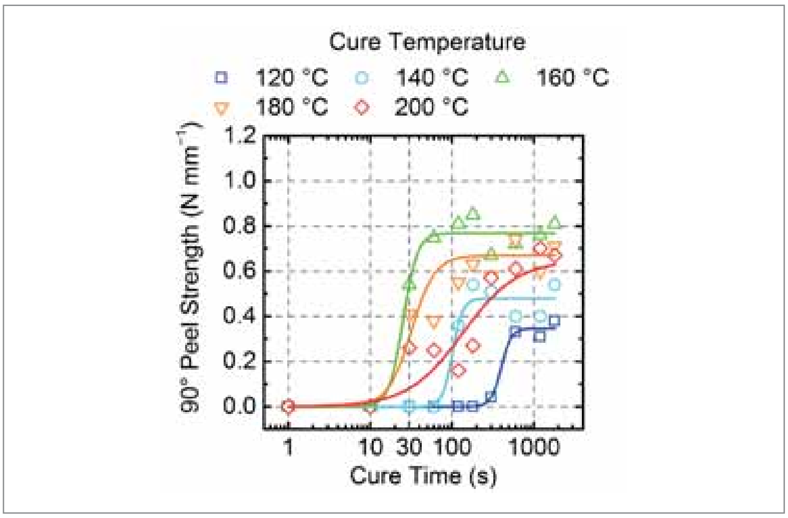


Figure 13. Dependence of the peel strength of adhesive B on the curing temperature and time. Each symbol is the average of several peel tests. (The interpolated solid lines are simply a guide.)

"A 320Wp module based on glued HJT solar cells was demonstrated to yield significantly more power than state-of-the-art PERC modules."

Figure 14. 320Wp HJT module, as produced in the Module-TEC laboratory at Fraunhofer ISE.

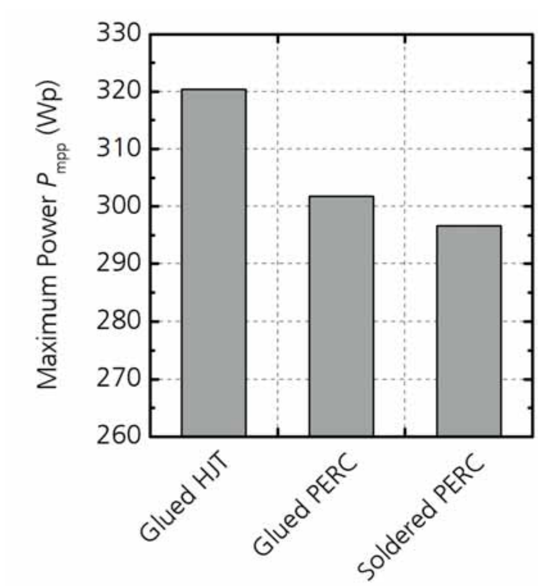


Figure 15. Power comparison of HJT modules and PERC modules.

200°C. With this schedule, adhesive A obtains its maximum peel strength of 0.8–1.0Nmm^{-1} and remains at this level, even after curing for a very long duration (e.g. in the case of a machine stoppage). The peel strength does not significantly decrease if the bond is exposed to prolonged heating – one of the differences from busbar soldering. A cure temperature of 160°C results in a cure duration of 60 sec before the adhesive achieves its full peel strength; for temperatures below 160°C, however, the adhesive requires several minutes to cure. Usually, a curing temperature that is too low results not only in unreasonably high cure durations but also in increased volume resistivity.

Fig. 13 depicts the peel strength of adhesive B as a function of time and temperature: a maximum peel strength is achieved after curing for 60 sec at 160°C. For temperatures above 160°C, the peel strength is reduced and is recovered only by prolonging the cure duration. In the case of adhesive B, a temperature below 140°C will not cure the adhesive at all, even after an extended cure time; this is because the activation of the curing agent in the adhesive chemistry is obstructed.

For chemistries such as adhesive A, it is sufficient to use a constant, relatively high temperature (180–200°C) to cure the material in the stringer. Other adhesives require an adjusted cure profile with soft ramp-up and cool-down phases, which needs to be tested case by case in production trials. Fraunhofer ISE has developed specific software to simulate the cure of ECAs and other polymers for complex temperature profiles [38].

Module performance

The module integration of HJT cell strings requires the appropriate choice of encapsulation materials in order to obtain a module yielding high performance and reliability. Recently, a module power of 320Wp with 60 cells was demonstrated by Fraunhofer ISE [21]; this module was produced in the Module-TEC laboratory and is depicted in Fig. 14. The current–voltage characteristic is marked by a high short-circuit current of 9.3A, thanks to the grooved interconnectors and AR-coated glass. Furthermore, the fill factor is high, with a value of 78.1%, as a result of an optimized finger design at the cell level, a good choice of ECA and the reliable processing of the teamtechnik stringer.

The use of heterojunction technology in combination with an ECA-based interconnection process leads to a boost in module performance by just over 20Wp compared with a state-of-the-art passivated emitter and rear cell (PERC) and conventional solder technology, as can be seen in Fig. 15.

Conclusion

Silicon heterojunction technology has the potential for further improvements in efficiency over PERC technology. However, the temperature sensitivity of the cell structure and, in particular, the low-temperature metallization pose new challenges for module integration. Besides a wire-based method with low-melting-point solders, there are options to use ribbon-based soldering with SnBi alloys or conductive gluing.

Low-temperature soldering with SnBi alloys is the most straightforward approach for the interconnection of HJT solar cells. According to Fraunhofer ISE's current research, the main challenge is the adhesion of the low-temperature metallization paste to the wafer surface. Because of the diffusion of liquid solder into the metallization, the peel strength of the interconnections is often critical for module integration. Further paste development with regard to grain structure, adhesion properties and microstructure may solve this problem, and thus enable a successful busbar interconnection with low-temperature solder alloys.

Low-temperature and lead-free RoHS-compliant ECA technology has significantly matured over the past few years thanks to the availability of high-throughput equipment for gluing, and because of the constant progress of adhesive manufacturers in improving printability, cure speed and peel strength and in driving down material costs. The TT1600ECA stringer at Fraunhofer ISE allows an analysis of ECAs in terms of their processability and readiness for mass production. Results regarding the challenge to preserve good printability at room temperature in combination with fast curing in the stringer have been presented. In addition, the complexity involved in finding the right cure profile for specific ECAs was highlighted. A peel strength of >1Nmm^{-1} was frequently measured during the testing. Finally, a 320Wp module based on glued HJT solar cells was demonstrated to yield significantly more power than state-of-the-art PERC modules.

References

[1] Green, M.A. 2017, "Solar cell efficiency tables (version 50)", *Prog. Photovolt: Res. Appl.,* Vol. 25, No. 7, pp. 668–676.

[2] Yoshikawa, K. et al. 2017, "Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%", *Nat. Energy*, Vol. 2, No. 5, 17032.

[3] Masuko, K. et al. 2014, "Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cell", *IEEE J. Photovolt.*, Vol. 4, No. 6, pp. 1433–1435.

[4] Adachi, D., Hernández, J.L. & Yamamoto, K. 2015, "Impact of carrier recombination on fill factor for large area heterojunction crystalline silicon solar cell with 25.1% efficiency", *Appl. Phys. Lett.*, Vol. 107, No. 23, 233506.

[5] Taguchi, M. et al. 2014, "24.7% record efficiency HIT solar cell on thin silicon wafer", *IEEE J. Photovolt.*, Vol. 4, No. 1, pp. 96–99.

[6] De Wolf, S. et al. 2012, "High-efficiency silicon heterojunction solar cells: A review", *GREEN*, Vol. 2, No. 1, pp. 7–24.

[7] Korevaar, B.A. et al. 2008, "Influence of annealing on performance for hetero-junction a-Si/c-Si devices", *Proc. 23rd EU PVSEC*, Valencia, Spain.

[8] Rodofili, A. et al. 2017, "Laser transfer and firing of NiV seed layer for the metallization of silicon heterojunction solar cells by Cu-plating", *Solar RRL*, Vol. 114, DOI: 10.1002/solr.201700085.

[9] De Wolf, S. & Kondo, M. 2009, "Nature of doped a-Si: H/c-Si interface recombination", *J. Appl. Phys.*, Vol. 105, No. 10, 103707.

[10] Erath, D. et al. 2017, "Comparison of innovative metallization approaches for silicon heterojunction solar cells", *Energy Procedia,* Vol. 124, pp. 869–874.

[11] Soederstroem, T., Papet, P. & Ufheil, J. 2013, "Smart Wire Connection Technology", *Proc. 28th EU PVSEC*, Paris, France, pp. 495–499.

[12] Faes, A. et al. 2014, "SmartWire solar cell interconnection technology", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 2555–2561.

[13] Meyer Burger 2017, "Meyer Burger Technology Day 2017 premiers heterojunction / SmartWire module with 335 watt efficiency as confirmed by TÜV Rheinland; Strong momentum in incoming orders confirmed", Press release (Nov. 30).

[14] Scherff, M.L.D. et al. 2006, "10 × 10 cm^2 HIT solar cells contacted with lead-free electrical conductive adhesives to solar cell interconnectors", *Proc. 4th WCPEC*, Waikoloa, Hawaii, USA, pp. 1384–1387.

[15] Teamtechnik GmbH 2018, "Innovative adhesive technology for industrial serial production: Stringer TT1400 ECA" [https://www.teamtechnik.com/en/solar/stringer-tt/stringer-tt1400-eca/].

[16] Lu, D.D. & Wong, C.P. 2009, "Electrically conductive adhesives (ECAs)", in *Materials for Advanced Packaging*, Lu, D.D. and Wong, C.P., Eds. New York: Springer US, pp. 365–405.

[17] De Rose, A. et al. 2017, "Low-temperature soldering for the interconnection of silicon heterojunction solar cells", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands, pp. 710–714.

[18] Gierth, P. et al. 2013, "Comparison of NiV and polymer paste metallization as low temperature interconnection of high efficiency heterojunction solar cells", *Proc. 28th EU PVSEC*, Paris, France, pp. 464–467.

[19] DIN EN 50461 (2007-03), "Solar cells – Datasheet information and product data for crystalline silicon solar cells".

[20] Mei, Z. & Morris, J.W. 1992, "Characterization of eutectic Sn-Bi solder joints", *JEM*, Vol. 21, No. 6, pp. 599–607.

[21] Fraunhofer ISE 2018, "Fraunhofer ISE and teamtechnik demonstrate industrial maturity of electrically conductive adhesives for silicon solar cells", Press release (Apr. 25).

[22] Beier, B. et al. 2001, "Electrical conductive adhesives: A novel reliable method for interconnecting crystalline silicon solar cells", *Proc. 17th EU PVSEC*, Munich, Germany, pp. 812–815.

[23] Bennett, I. et al. 2007, "Low-stress interconnection of solar cells", *Proc. 22nd EU PVSEC*, Milan, Italy.

[24] Zemen, Y. et al. 2011, "Innovative and gentle interconnection technique for high efficiency c-Si solar cells and cost-of-ownership-analysis (COO)", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3125–3132.

[25] Schwertheim, S. et al. 2008, "Lead-free electrical conductive adhesives for solar cell interconnectors", *Proc. 33rd IEEE PVSC*, San Diego, California, USA, pp. 1–6.

[26] Geipel, T. & Eitner, U. 2013, "Electrically conductive adhesives: An emerging interconnection technology for high-efficiency solar modules", *Photovoltaics International*, 11th edn, No. 21, pp. 27–33.

[27] Schneider, A. et al. 2014, "Comprehensive study of material dependency for silver based conductive

glues", *Energy Procedia*, Vol. 55, pp. 509–518.
[28] Teamtechnik GmbH 2018, "Major contract for teamtechnik: Italian PV manufacturer orders stringers for production of high-efficiency modules with HJT cells", Press release (Feb. 12).
[29] Schneider, J. et al. 2014, "Combined effect of light harvesting strings, anti-reflective coating, thin glass, and high ultraviolet transmission encapsulant to reduce optical losses in solar modules", *Prog. Photovolt: Res. Appl.*, Vol. 22, No. 7, pp. 1–8.
[30] MIL-STD-883H: 2010-02, "Test method standard – Microcircuits.
[31] Geipel, T. et al. 2018 [forthcoming], "Optimization of electrically conductive adhesive bonds in photovoltaic modules", *IEEE J. Photovolt.*
[32] Hinz, I. et al. 2012, "Characterization of electrical conductive adhesives (ECA) for the photovoltaic-industry", *Proc. 27th EU PVSEC*, Frankfurt, Germany.
[33] Lu, D.D., Tong, Q.K. & Wong, C.P. 1999, "A study of lubricants on silver flakes for microelectronics conductive adhesives", *IEEE Trans. Compon. Packag. Technol.*, Vol. 22, No. 3, pp. 365–371.
[34] Lu, D.D. & Wong, C.P. 2000, "Effects of shrinkage on conductivity of isotropic conductive adhesives", *Int. J. Adhes. Adhes.*, Vol. 20, No. 3, pp. 189–193.
[35] Zwolinski, M. et al. 1996, "Electrically conductive adhesives for surface mount solder replacement", *IEEE Trans. Compon., Packag., Manuf. Technol. C*, Vol. 19, No. 4, pp. 241–250.
[36] Lu, D.D., Tong, Q.K. & Wong, C.P. 1999, "Mechanisms underlying the unstable contact resistance of conductive adhesives", *IEEE Trans. Electron. Packag. Manuf.*, Vol. 22, No. 3, pp. 228–232.
[37] Hoffmann, S. et al. 2017, "Analysis of peel and shear forces after temperature cycle tests for electrical conductive adhesives", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands, pp. 183–186.
[38] Geipel, T. & Eitner, U. 2013, "Cure kinetics of electrically conductive adhesives for solar cell interconnection", *IEEE J. Photovolt.,* Vol. 3, No. 4, pp. 1208–1214.

About the authors

Angela De Rose studied physics at RWTH Aachen and at the University of Valencia, and received her master's in 2015 from RWTH Aachen. In 2016 she joined Fraunhofer ISE as a Ph.D. student in the field of interconnection technology for silicon PV modules. Her studies focus on the interconnection of HJT solar cells, soldering on aluminium surfaces and solder joint evaluation regarding long-term stability.

Torsten Geipel studied information system technology at the University of Dresden, Germany. He worked on 2D simulation of heterojunction solar cells at Helmholtz-Centre Berlin and received his Diploma degree in 2007. After spending four years in R&D with the former PV module manufacturer Solon, he began his Ph.D. thesis on electrically conductive adhesives at Fraunhofer ISE in the PV modules department. He recently completed his thesis and is currently working on cell interconnection and module integration.

Denis Erath studied printing technology at the University of Printing and Media in Stuttgart, Germany, and received his Diploma degree in 2005. Since then he has been with Fraunhofer ISE, working on various topics related to printing technologies for silicon solar cells and proton exchange membrane (PEM) fuel cells.

Dr. Achim Kraft studied electrical engineering at the University of Applied Science in Hanover and renewable energies at the University of Applied Science in Berlin. He received his master's degree in renewable energies before joining Fraunhofer ISE as a Ph.D. student in 2012. In 2015 he received his Ph.D. in the field of plated-copper front-side metallization for silicon solar cells. Since then he has focused on solar cell interconnection technologies and processes as head of the interconnection technologies team at Fraunhofer ISE.

Dr. Ulrich Eitner studied technical mathematics at the University of Karlsruhe (TH) and received his Diploma degree in 2006 for his development of a simulation method for multibody dynamics. From 2006 to 2011 he worked in the field of PV modules at the Institute for Solar Energy Research Hamelin (ISFH), and obtained his Ph.D. from the University of Halle-Wittenberg in 2011 for his investigations of the thermomechanics of PV modules. In 2011 he joined Fraunhofer ISE in Freiburg as head of the PV modules group, focusing on interconnection technology for crystalline silicon solar cells, analysis of cell-to-module efficiencies, and novel module concepts.

Enquiries

Angela De Rose
Team Interconnection Technology
Division Photovoltaics
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstraße 2
79110 Freiburg, Germany

Tel: +49 (0)761 4588 5856
Email: angela.de.rose@ise.fraunhofer.de

Power rating and qualification of bifacial PV modules

Xiaoyu Zhang, Christos Monokroussos, Markus Schweiger & Matthias Heinze, TÜV Rheinland Group

Abstract

The extra energy gain offered by bifacial PV modules has helped make them an increasingly popular choice in the global PV industry. But the question of how to define, measure and rate the electrical output from bifacial modules is a hotly debated topic, given the extent to which the rear-side contribution is dependent on a range of variable factors relating to local environmental conditions and system configurations. Drawing on in-house modelling and simulation software developed at TÜV Rheinland, this paper explores the power rating issue for bifacial devices, examining the definitions of rear irradiance, measurement test method, power stabilization and verification for type approval. Relevant reliability and safety tests are discussed, with additional modifications and suggestions for bifacial PV modules.

Introduction

The global PV industry is experiencing a boom in bifacial PV modules. Coming with extra energy gain from the rear side, bifacial PV modules are finding themselves with versatile and promising application possibilities in many fields, from building-integrated photovoltaics to utility-scale power plants. These application advantages are reflected in the forecasts of bifacial technology development in the market: according to the recently released international technology roadmap for photovoltaics (ITRPV) 2017 results [1], the world market share of bifacial PV modules will steadily increase to about 35% by 2028. Compared with monofacial PV modules, energy yields of around 10% higher (or even more) from bifacial modules in the field have been consistently reported by various parties [2,3]. Such increases in yield can considerably reduce the levelized cost of energy.

Bifacial PV technology is not a new concept in the PV community. As early as 1966, a US patent regarding an n-type bifacial solar cell with a p^+np^+ structure was granted to a Japanese researcher [4]. Nowadays, passivated emitter rear totally diffused (PERT), passivated emitter rear cell (PERC) and heterojunction (HJT) are the three mainstream technologies for bifacial PV devices [5]. It is feasible to increase the competitiveness of PV manufacturers through a transformation from the production of traditional monofacial PV modules to bifacial ones with little additional cost.

"Rear-side irradiance is highly dependent on environmental factors and installation configurations."

The most important reference in setting the price of PV modules is still the power rating under *standard test conditions* (STC), defined as follows: a device temperature of 25°C, and an incident irradiance of 1,000W/m^2 with the spectral distribution AM1.5G. This leads to the first technology-related problem of how to define, measure and rate the electrical output power of bifacial PV modules, taking into consideration the rear-side power contribution. These tasks also stir up heated arguments in the PV industry, because the rear-side irradiance is highly dependent on environmental factors and installation configurations. The fact is that the ground albedo, installation location, tilt angle, ground clearance, shading (including self-shading) and other elements can all affect the rear-side irradiance and energy yield of a bifacial PV module.

In response to the strong demand for an appropriate power rating method for bifacial PV modules, the international standard IEC 60904-1-2 has been proposed, which describes the test methods and additional requirements for the *I–V* characterization. Since there is still no standard definition of rear irradiance under AM1.5G conditions, it is proposed that the measurement results for the bifacial device under test with a front irradiance of 1,000W/m^2, along with different levels of rear irradiance (namely 100W/m^2, 200W/m^2 and a third undefined level), be reported in accordance with the IEC standard [6]. Much as the standard is trying to give a solution for *I–V* measurement, the power rating issue for bifacial PV modules remains unresolved. The manufacturers and PV product buyers are confused by so many power results, and cannot find common ground on which the bifacial devices can be priced and on how the quality of different bifacial products can be evaluated and compared. To look into the power rating problem associated with bifacial PV devices, it helps to break it down into the following issues: 1) definition of rear irradiance; 2) test method of measurement; 3) power stabilization; and 4) verification for type approval.

The reliability and safety issues with bifacial PV modules come next in line. Because of the rear contribution to energy generation, bifacial PV modules in the field often operate at higher currents, which may impact the reliability of PV systems. In addition, to maximize the bifacial gain, special mounting designs for bifacial PV modules are often used to reduce the shading caused by racks. The test conditions for IEC 61215-2 and IEC 61730-2 may need to be modified accordingly in order to encompass the potential reliability and safety issues.

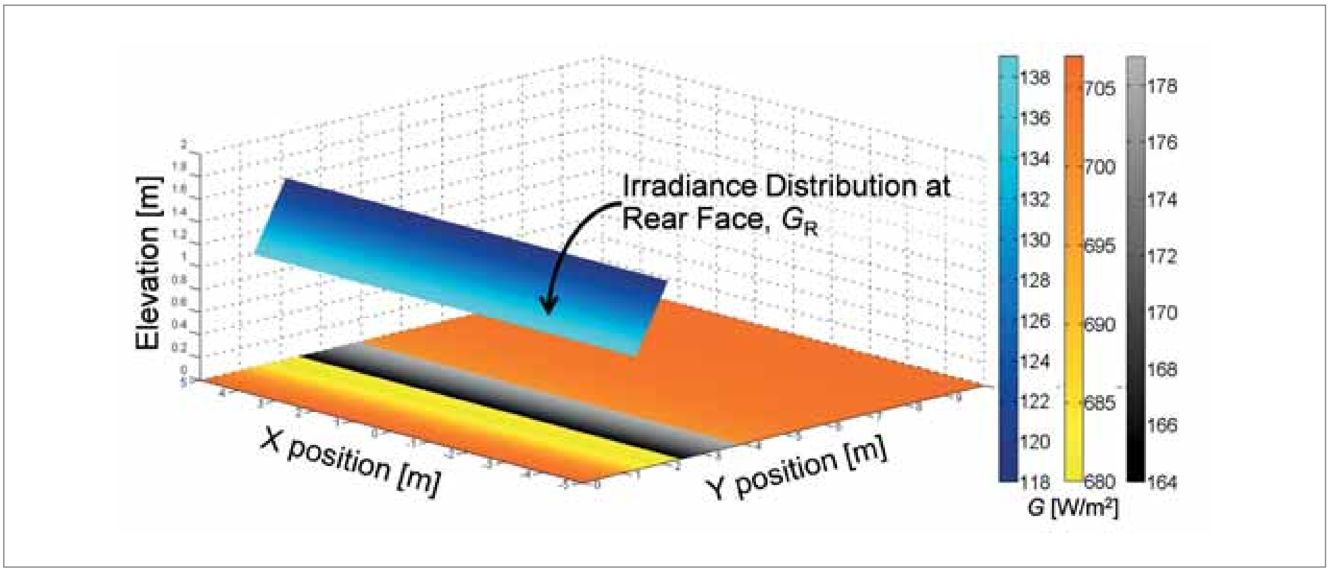


Figure 1. Irradiance distribution for a single-row bifacial PV array simulated in the conditions shown in Table 1, without taking into consideration the influence of the racks. The blue bar represents the distribution of irradiance G_R at the module's rear face (shown here facing the front). The orange and black bars represent horizontal ground irradiance: black signifies the area shaded by the modules, and orange the area which is not shaded.

Definition of rear irradiance

From an objective standpoint, in-house computer coding has been developed by TÜV Rheinland to model and simulate the expected rear irradiance under the environmental conditions defined in IEC 60904-3, with additional ground clearance of the PV module (details in Table 1) [7]; the simulation results are presented in Fig. 1. The higher end of the PV array receives slightly less irradiance than the lower end when the bifacial modules are installed at a tilted angle of 37 degrees and with a ground clearance of 1m. According to TÜV Rheinland's simulation, the rear irradiance on the PV array varies in the range 118–138W/m^2 with a spatial non-uniformity of 7.8%, which is in good agreement with other published research [8]. This theoretical work has laid a solid

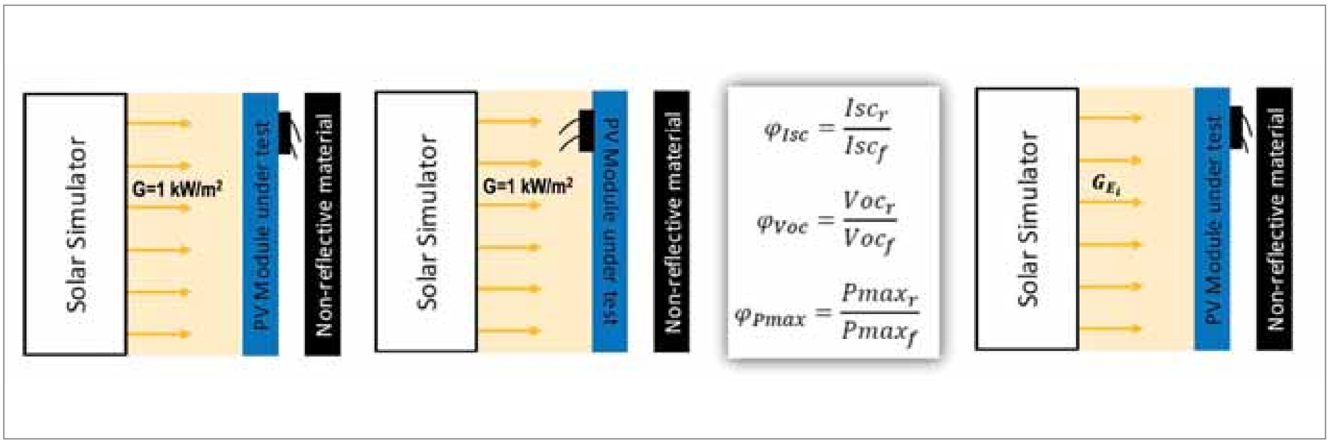


Figure 2. Schematic of the single-side illumination test method for bifacial PV modules.

foundation for bifacial standard test conditions and the TÜV Rheinland internal standard 2PfG 2645/11.17, which defines requirements for supplementary power rating and label verification of bifacial PV modules.

Bifacial standard test conditions (BSTC) are defined by a rear irradiance of 135W/m², corresponding to the 1m ground clearance of a bifacial module in the same environment as that specified in IEC 60904-3. The equivalent irradiance for bifacial PV devices can therefore be calculated using the formula (as shown in Table 2):

$$G_E = (1{,}000 + \varphi \cdot 135)\mathrm{W/m^2} \quad (1)$$

where φ is the smaller of the two values of the bifaciality coefficients φ_{Isc} and φ_{Pmax} for I_{sc} and P_{max}. The benefits of BSTC are not only the compatibility with STC and IEC 60904-3, but also the direct comparability of the PV performance between bifacial and monofacial PV modules under the same conditions. Furthermore, the photovoltaic performance data under BSTC could provide useful information for PV installation and power plant design.

Test method of measurement

The TÜV Rheinland internal standard 2PfG 2645/11.17 allows both single-side illumination and double-side illumination test methods as defined in IEC 60904-1-2, although the single-side version is currently used in the TÜV Rheinland laboratories. Regardless of the stipulation of BSTC, the I–V measurement results with a rear irradiance (G_{ri}) of 100W/m² and 200W/m² can also be provided as supplementary information in the test report. As shown in Fig. 2, the bifaciality is determined first by measuring the front and rear sides of a bifacial PV module separately under STC. Next, the bifacial module is measured again on just the front side with an equivalent irradiance (G_{Ei}), which is calculated using the equation:

$$G_{Ei} = 1{,}000\mathrm{W/m^2} + \varphi \cdot G_{ri} \quad (2)$$

where $\varphi = \mathrm{Min}(\varphi_{Isc}, \varphi_{Pmax})$ and G_{ri} = 135W/m², 100W/m², 200W/m², ...

Modelled parameter	Bifacial reference condition
Air mass	1.5G
Beam and circumsolar irradiance	As defined in IEC 60904-3
Diffuse irradiance	As defined in IEC 60904-3 Isotropic diffuse
Ground albedo	Lambertian diffuse reflector Light sandy soil with spectral albedo as given in SMART
Inclination angle	37 degrees
Shading	PV array self-shading on the ground No near-object shading
Module transmittance	Spectral transmittance data for glass/EVA/glass and glass/POE/glass structures of bifacial modules

Table 1. Summary of the parameters used in the simulation.

Front irradiance	1,000W/m²
Rear irradiance	135W/m²
Equivalent irradiance	1,000W/m² + φ·135W/m²
Module temperature	25°C
Angle of incidence	0 degrees
Irradiance spectrum	AM1.5G

Table 2. Parameter definitions for BSTC.

Power stabilization

In accordance with IEC 61215-1,-1-1,-2 standards, PV modules should be electrically stabilized before any further measurement. As bifacial PV devices are mostly PERT, PERC and HJT technology based, issues such as light-induced degradation (LID) exist and should not be neglected.

LID is a phenomenon whereby PV modules undergo a performance and power degradation as a result of illumination exposure; this deterioration is related to various factors such as the cell technology, wafer quality and manufacturing processes [9].

"The relevant test conditions in IEC 61215-2 and IEC 61730-2 should be modified in order to reflect the higher current flows observed for bifacial modules in the field."

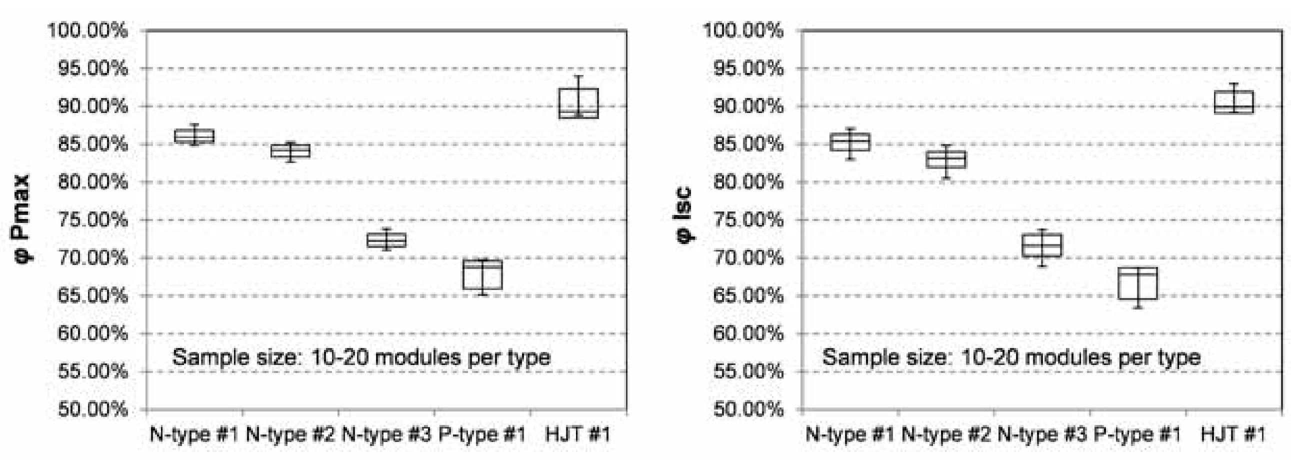


Figure 3. Variations in bifaciality coefficients (φ) of P_{max} and I_{sc}, evaluated by measuring modules in production from different manufacturers.

Test	Monofacial PV	Bifacial PV
I_{mpp} applied → $I_{mpp}@G_E$		
MST 21 – Temperature	Near I_{mpp} applied during the test	Near $I_{mpp}@G_E$ applied during the test
MQT 11 / MST 51 – Thermal cycling	I_{mpp} applied in sequences	$I_{mpp}@G_E$ applied in sequences
MQT 09 / MST 22 – Hot-spot endurance	I_{mpp} applied while finding the hot-spot-sensitive cells and the shading rate	$I_{mpp}@G_E$ applied while finding the hot-spot-sensitive cells and the shading rate
I_{sc} applied → $I_{sc}@G_E$		
MQT 18 / MST 25 – Bypass diode	Applied current: • I_{sc} for first hour • I_{sc} × 1.25 for second hour	Applied current: • $I_{sc}@G_E$ for first hour • $I_{sc}@G_E$ × 1.25 for second hour
Relevant test		
MST 26 – Reverse-current overload	Declared I_R by manufacturer × 1.35	To consider: $(n–1) \times I_{sc}@G_E \times 1.25 \times 1.35$ (if this value is higher), where n is the maximum allowable number of strings in parallel

Table 3. Supplementary test conditions on relevant test items in IEC 61215-2 and IEC 61730-2 for bifacial PV modules (G_E = 1,000W/m^2 + φ·300W/m^2). (As specified in IEC 61730-2, the applied reverse current shall be equal to 135% of the PV module's over-current rating, hence the factor 1.35.)

Several degradation mechanisms have been reported: boron–oxygen complex activation (B-LID), for example, is the most commonly known LID mechanism in boron-doped Czochralski-grown c-Si devices, and has been under investigation since the 1970s [10]. Recently, light- and elevated-temperature-induced degradation (LeTID) was reported initially in rear-passivated mc-Si solar cells; it is more severe in PERC devices and can lead to an efficiency loss of up to 10% [11].

Most industrial crystalline silicon solar cells and modules suffer from some type of LID. A drop in power of even 1% could result in considerable energy and capital losses; an initial stabilization is therefore essential in order to accurately specify the power rating for a bifacial PV device. However, whether both sides of a bifacial module need to fulfil the requirement of initial electrical stabilization is still under investigation.

Verification for type approval

Variations in the bifaciality coefficients have been observed on the production lines of different bifacial PV technologies (see Fig. 3); therefore, the verification of rated values is necessary for the labelling of modules under BSTC. The TÜV Rheinland 2PfG 2645/11.17 standard establishes a label verification system for photovoltaic data under BSTC, with the same requirements for measured P_{max}, mean P_{max}, V_{oc} and I_{sc} as defined in IEC 61215-1:2016 [12]. An additional requirement of P_{max} under BSTC for the minimum power class is particularly enforced in order to guarantee the quality of PV modules, even at the lower end power class:

$$P_{\max(\mathrm{BSTC})}(\mathrm{Lab}) \cdot \left(1-\frac{|m_{1(\mathrm{BSTC})}|[\%]}{100}\right) \le P_{\max(\mathrm{BSTC})}(\mathrm{NP}) \cdot \left(1+\frac{|t_{1(\mathrm{BSTC})}|[\%]}{100}\right) \quad (3)$$

where $m_{1(BSTC)}$ and $t_{1(BSTC)}$ are respectively the measurement uncertainty of the laboratory and the manufacturer's rated upper production tolerance for $P_{max(BSTC)}$ in per cent (NP = name plate).

Module reliability and qualification

Bifacial PV modules in the field are observed to continuously operate at higher currents than their monofacial counterparts because of the power contribution from the rear side. Higher currents can cause higher localized temperatures in PV modules, especially in areas where current crowding might occur; this may impact the reliability of PV systems, in particular with regard to solder bond fatigue and bypass diode endurance. Thus, the relevant test conditions in IEC 61215-2 and IEC 61730-2 should be modified in order to reflect the higher current flows observed for bifacial modules in the field.

Bifacial modules experience significantly higher total irradiances at higher albedos compared with monofacial samples, as highlighted in the modelling results (Fig. 4), under the conditions given in IEC 60904-3. The current stringency definition used in this work derives from irradiances corresponding to reflective ground conditions (1,300W/m^2 at 0.51 albedo). A rear irradiance of 300W/m^2 is considered to be a typical irradiance which represents the worst scenario in field operation. Thus, the affected test items in IEC 61215-2 and IEC 61730-2 are updated with additional requirements to account for the higher equivalent irradiance G_E = 1,000W/m^2 + φ·300W/m^2.

Table 3 lists the revised test conditions for bifacial PV modules, based on the original procedures for monofacial PV modules in the IEC standards. The applied currents, I_{mpp} or I_{sc}, are enhanced to their corresponding I_{mpp} or I_{sc} values under an irradiance of (1,000 + φ·300)W/m^2 in the temperature test (MST 21), thermal-cycling test (MQT 11/MST 51), hot-spot endurance test (MQT 09/MST 22) and bypass diode test (MQT 18/MST 25). As regards the current for the reverse-current overload test, it is recommended to use in the calculation the higher of:

- the module's overcurrent protection rating provided by the manufacturer;
- the maximum reverse current that could be reached ((n–1) × I_{sc}@G_E ×1.25, where n is the maximum allowable string number in parallel, and 1.25 is the safety factor).

The adapted test sequences for bifacial PV modules are undergoing a verification process in the laboratory at TÜV Rheinland to prepare the 2PfG standard regarding the reliability test for bifacial PV modules. Several module types from different manufacturers are being tested under the new test sequences; so far, no bifacial module failures in the above-mentioned tests have been encountered. The preliminary test results, however, have shown that module components, especially bypass diodes, can

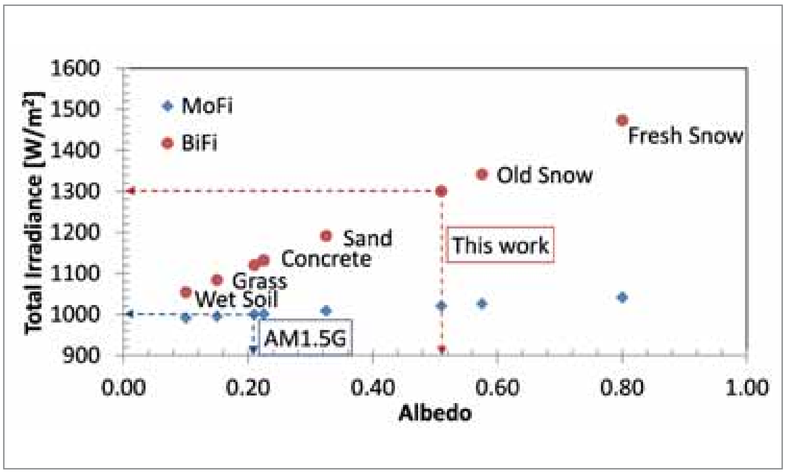


Figure 4. Analysis of the albedo sensitivity of total irradiance received by bifacial and monofacial PV modules. The simulation was carried out using the environmental conditions as defined in IEC 60904-3.

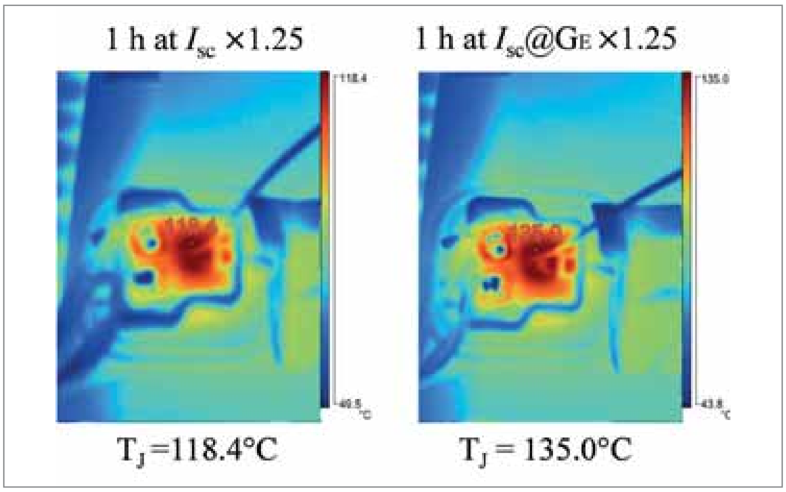


Figure 5. Example of elevated diode junction temperature observed by the TÜV Rheinland laboratory during the bypass diode thermal test with enhanced test current.

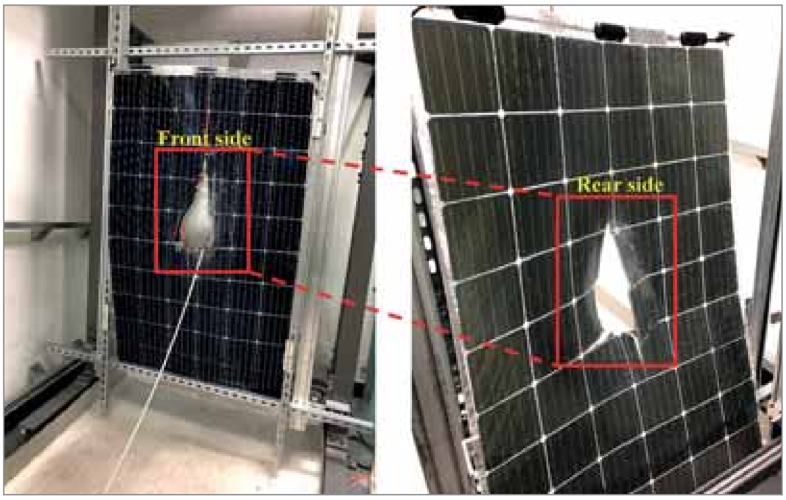


Figure 6. Examples of module breakage test failures of bifacial PV modules observed at the TÜV Rheinland laboratory.

"Module components, especially bypass diodes, can operate at 10–30°C higher temperatures with the enhanced test currents, which could critically test the endurance of the materials involved."

operate at 10–30°C higher temperatures with the enhanced test currents (Fig. 5), which could critically test the endurance of the materials involved. Other bifacial PV module failures in tests such as the module breakage test (MST 32) have been observed; these failures were mainly caused by the particular mounting design without supporting bars at the back (see Fig. 6). For safety reasons, this type of failure warrants more attention from constructors and end-users.

Another issue regarding the reliability of bifacial PV modules is potential-induced degradation (PID). In the field, PV modules are connected together in the form of a string to achieve a certain high voltage; at the same time, this string needs to be grounded for safety reasons. As a consequence, modules at either end of a string suffer from large electrical potential stresses between the frame and the solar cells, which can lead to severe performance degradation, referred to as *PID*. For crystalline silicon PV modules, there are two common PID mechanisms. The first of these is known as *Na^+ migration* in the high electric field between the glass and the solar cell, which results in significant shunts; these *PID* shunts are often observed in p-type c-Si technologies. As regards n-type c-Si PV technologies, *surface polarization*, the second PID mechanism, can be mainly responsible for the increased surface recombination and power drop [13].

IEC TS 62804-1:2015 provides indoor test methods for the detection of PID. The modules can be tested with a high voltage, either in damp heat using a climate chamber for 96h, or by contacting the surfaces with a conductive electrode for 168h. The test requires four representative and identical samples, two for the positive voltage bias test and two for the negative voltage bias test [14]. Thus, IEC TS 62804-1:2015 is currently capable of handling the PID test for bifacial PV modules.

Summary

Driven by the strong demand for reducing the levelized cost of energy, the market share of bifacial PV modules has increased rapidly in recent years because of the extra energy gain contributed by the rear side. The complexity of the technical problems with bifacial PV modules requires modifications and updates in respect of the current power rating and qualification standards. TÜV Rheinland has published its internal standard 2PfG 2645/11.17, which addresses the power rating issue for bifacial modules; it defines BSTC with a front-side irradiance of 1,000W/m^2 and a rear-side irradiance of 135W/m^2 in accordance with the 1m ground clearance for bifacial modules in the same environment as defined in IEC 60904-3. Supplementary reliability tests are proposed, with enhanced test conditions reflecting the worst scenario in field operation, for which a rear irradiance of 300W/m² is chosen. Laboratory verification is ongoing at TÜV Rheinland; the internal standard 2PfG concerning the reliability and safety tests in liaison with IEC 61215-2 and IEC 61730-2 will soon be published to assure the quality of bifacial PV modules for better and safer operation.

References

[1] ITRPV 2018, "International technology roadmap for photovoltaic (ITRPV): 2017 results", 9th edn (Mar.) [http://www.itrpv.net/Reports/Downloads/].

[2] Lossen, J. 2016, "Bifaziale PV-Module: Technologie und Anwendungsbereiche", 13. Workshop Photovoltaik-Modultechnik.

[3] Wei, Q. et al. 2016, "The glass-glass module using n-type bifacial solar cell with PERT structure and its performance", *Energy Procedia*, Vol. 92, pp. 750–754.

[4] Mori, H. 1966, "Radiation energy transducing device", U.S. Patent 3278811A.

[5] Chunduri, S.K. & Schmela, M. 2017, "Bifacial solar module technology 2017 edition", TaiyangNews report (Jun.) [http:// http://taiyangnews.info/taiyangnews-bifacial-solar-modules-technology-2017-download/].

[6] IEC DTS 60904-1-2, "Photovoltaic devices – Part 1–2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices".

[7] IEC 60904-3: 2016, "Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data".

[8] Deline, C. et al. 2016, "Evaluation and field assessment of bifacial photovoltaic module power rating methodologies", *Proc. 43rd IEEE PVSC*, Portland, Oregon, USA.

[9] Monokroussos, C. et al. 2017, "Energy rating of c-Si and mc-Si commercial PV-modules in accordance with IEC 61853-1,-2,-3 and impact on the annual yield", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.

[10] Sopori, B. et al. 2012, "Understanding light-induced degradation of c-Si solar cells", *Proc. 38th IEEE PVSC*, Austin, Texas, USA.

[11] Ramspeck, K. et al. 2012, "Light induced degradation of rear passivated mc-Si solar cells", *Proc. 27th EU PVSEC*, Frankfurt, Germany.

[12] IEC 61215-1: 2016, "Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements".

[13] Luo, W. et al. 2017, "Potential-induced degradation in photovoltaic modules: A critical review", *Energy Environ. Sci.*, Vol. 10, pp. 43–68.

[14] IEC TS 62804-1:2015, "Photovoltaic (PV) modules – Test methods for detection of potential-induced degradation – Part 1: Crystalline silicon".

About the Authors

Dr. Xiaoyu Zhang studied highly efficient dye-sensitized solar cells with liquid-state electrolyte and solid-state hole-transporting material at East China University of Science and Technology (ECUST), with a major in applied chemistry. In 2016 she obtained her Ph.D. in engineering from ECUST and then joined TÜV Rheinland (Shanghai) Co., Ltd, where she now works as a senior project engineer in R&D in the solar/fuel-cell technology department. Her interests lie in the accurate measurement and energy rating of PV modules, as well as in the power rating and qualification of bifacial PV modules.

Dr. Christos Monokroussos has 10 years' experience in the field of PV research, with activities centring on characterization of solar cells, PV modules, PV measurement systems and PV module reliability. He earned his doctorate in photovoltaics at Loughborough University, UK, and is an active member in the IECRE. Currently, he is the director of R&D in the TÜV Rheinland solar and fuel cells business field.

Dr. Markus Schweiger received his diploma in electrical engineering from the Technical University of Munich, and his doctorate from RWTH Aachen University. Since 2009 he has been working as a scientist and is currently a team leader with the solar innovation department at TÜV Rheinland. His expertise includes high-precision PV module characterization, performance behaviour of thin-film PV modules and energy yield of PV module technologies in different climates.

Matthias Heinze is the director of business development at TÜV Rheinland. He has several decades' experience in the field of PV plant qualification and monitoring, laboratory module and component testing, performance measurement and failure analysis. He holds a university degree in engineering, and is an active member of the IECRE.

Enquiries

Xiaoyu Zhang
TÜV Rheinland (Shanghai) Co., Ltd.
TÜV Building III, No. 177, Lane 777
West Guangzhong Road
Jingan District
Shanghai, China
Email: sherryxy.zhang@tuv.com

bifi PV workshop 2018

ISC International Solar Energy Research Center Konstanz | ines | ECN | zhaw School of Engineering | Sandia National Laboratories | NREL

Bifacial Workshop 2018

5th edition of bifiPV
Come and create the PV future with us!

REGISTER NOW!
www.bifiPV-workshop.com

September 10-11, 2018 | Denver | USA

- Sessions on: systems and bankability, cell and module technology, standardization, simulation
- Experts from academy and industry discuss the latest developments
- Podium discussions and networking activities in great atmosphere

Bankability and bifacial HSAT will be in the focus of bifiPV2018

sponsors

SUNPREME

中来股份 JOLYWOOD

media partners

naturblau

Photovoltaics

PVTECH

Advertisers and web index

To advertise within Photovoltaics International, please contact the sales department: Tel +44 (0) 20 7871 0122