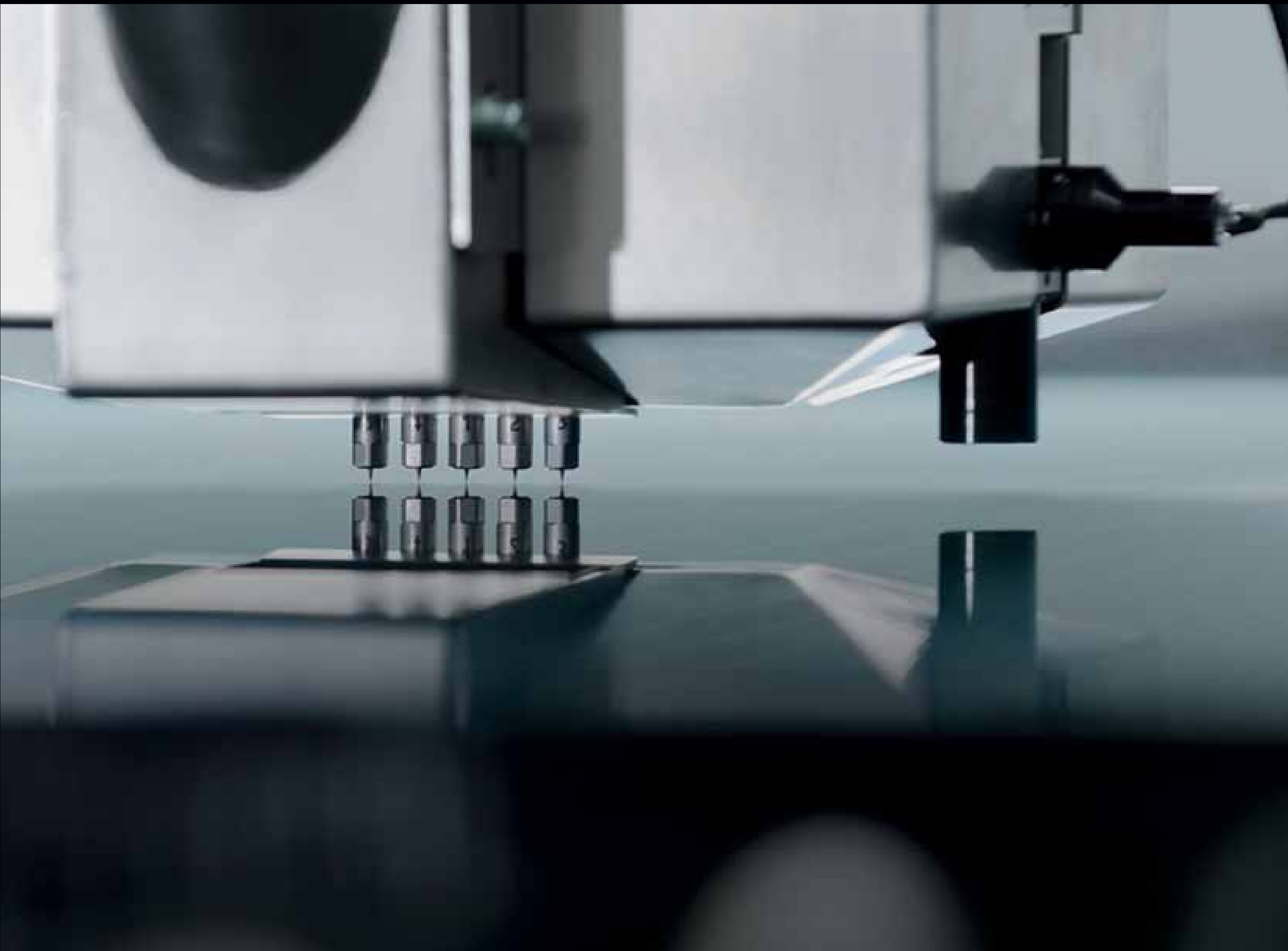
Thirty Fifth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS



Fraunhofer ISE In-line quality control in high efficiency silicon solar cell production

Canadian Solar 19.31%-efficient multicrystalline silicon solar cells using MCCE black silicon technology

Imec Progress in co-plating contacts for bifacial cells designed for multi-wire interconnection

ISC Konstanz Quo vadis bifacial PV?

TNO Innovation for optical, electrical and economic improvement of thin-film PV technology

Fraunhofer IISB HPM silicon: The next generation of multicrystalline silicon for PV

Solar Intelligence Solar PV manufacturing in 2017: factors driving technology change

First Quarter, February 2017

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Image courtesy of Manz AG

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Foreword

This issue of *Photovoltaics International* coincides with the second outing of the PV CellTech event organized by Solar Media, the publisher of this journal, in Malaysia in mid-March.

Since the event's debut 12 months ago, a new wind has been blowing through the world of upstream PV manufacturing. This time last year, the announcement of new or expanded production facilities was close to reaching its peak with plans for gigawatts of new capacity on the drawing board. But then the spectre of another overcapacity scenario raised its head, bringing with it a noticeable mood of caution within the industry.

The extent to which that is the case is graphically illustrated in our regular capacity expansion report on p.26. It reveals that after a particularly buoyant first half, the second half of 2016 saw new expansion plan announcements drop off substantially as overcapacity fears took hold.

Nevertheless, the mood within the industry remains broadly optimistic. Overall new capacity plans last year significantly outmuscled those of 2015, despite the fall-off in the second half of the year, suggesting expectations of robust end-market demand going forward. Significant new tool orders continue to grab headlines, notably a huge order for German equipment supplier Manz's CIGS thin-film production line.

Meanwhile, investment in high-efficiency cell technology production appears to be showing no signs of slowing down – quite the reverse. This ongoing investment by manufacturers in improving cell efficiencies is leading to something of a tussle between rival technologies vying to become the solar industry's next workhorse. On p.17 our Head of Intelligence, Finlay Colville, lifts the lid on some of the key themes to emerge from his ongoing analysis of the cell technology landscape, including his take on which, if any, of the high-efficiency cell technologies has what it takes to challenge p-type multi's current dominance.

Researchers from Germany's Fraunhofer ISE take up the theme with a paper exploring the question of quality control in the production of high-efficiency silicon solar cells (p.46). They look at some of the numerous tools and methods for optical and electrical quality control in mass production and assess their possibilities and limitations.

Meanwhile, scientists from the R&D team at Canadian Solar look at so-called 'black' silicon, one of the new cell technology concepts beginning to gain currency. They describe how nanostructured textured black silicon is particularly effective in trapping light and can be used to boost the efficiency of silicon-based solar cells.

And not forgetting the growing importance of thin-film technologies in the overall PV mix, we feature a paper from TNO examining possible innovations to boost the economic performance of thin-film cells (p.77).

Many of the topics in this issue will be under discussion at PV CellTech later this month by the stellar panel of leading industry figures we have lined up for the event. We hope to meet many of you there and to engage in what looks set to be a lively discussion.

John Parnell
Head of Content
Solar Media Ltd

Photovoltaics International

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

Editorial Advisory Board

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

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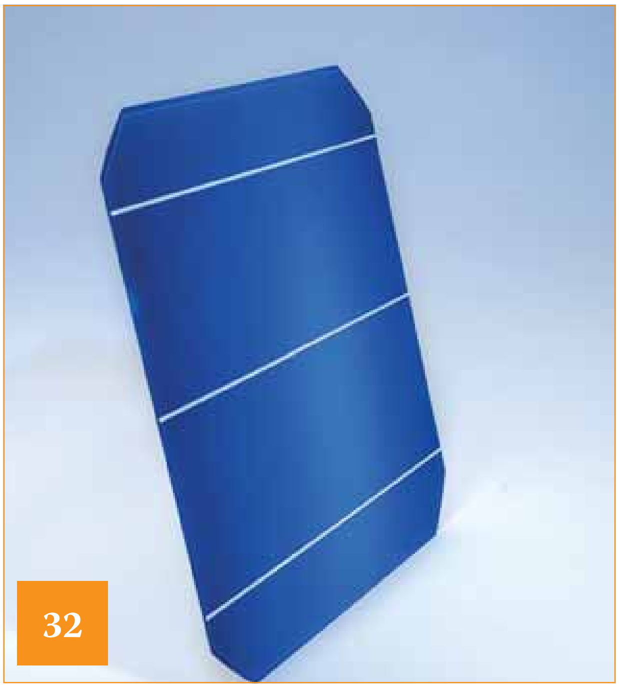

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Product Reviews

Fraunhofer ISE

Fraunhofer ISE develops software to analyse c-Si solar cell-to-module power losses

Product Outline: Fraunhofer ISE has developed a new software tool that determines the cell-to-module effects that occur when solar cells are integrated into a module. The SmartCalc.CTM software enables manufacturers of PV modules and materials to optimize the assembly and material combination in a PV module before fabricating a prototype.

Problem: C-Si cell-to-module (CTM) power losses vary according to a complex number of interactions that can limit the overall performance potential of PV modules. In order that PV modules benefit from advances in cell efficiency, the CTM integration process must be performed reliably with low losses.

Solution: The SmartCalc.CTM software starts with the cell power, calculating the optical losses and gains (e.g. from reflection), electrical losses (e.g. due to resistances) and the geometrical losses (inactive areas) in solar modules. The tool assists in analyzing potential yields, enabling PV manufacturers to determine how new materials or concepts would affect module efficiency. The software can quickly analyze the interplay between the influencing factors for a module design. The underlying models in the software provide detailed yet flexible control, while the properties of solar cells, encapsulation material or module glass can be adapted easily. The software can also be used to optimize costs; different less-expensive materials can be compared and evaluated.

Applications: Simulation of c-Si cell-to-module (CTM) power losses.

Platform: SmartCalc.CTM is based on a simulation model which has been published and is under development at Fraunhofer ISE since 2008.

Availability: Currently available.

SCHMID

SCHMID offers low-cost pre-treatment for texturing diamond-wire-cut multi c-Si wafers

Product Outline: SCHMID has launched a cost-effective process for the texturing of diamond-wire cut multi-c-Si wafers that can be easily integrated into existing production lines.

Problem: So far multicrystalline wafers have mostly been separated from the ingot with slurry saws. Diamond wire sawing is significantly cheaper since it is faster and wastes less silicon. However, the diamond wire leaves a smooth surface that cannot be textured with the standard acid texture process. Processes that have been presented so far were either too expensive, environmentally harmful or failed to meet quality requirements.

Solution: DW PreTex requires only one process step that roughens the relatively smooth surface of the wafers to allow the processing of diamond-wire cut multi-c-Si wafers with the proven standard texture HF/HNO3. The diamond wire-cut wafers have more uniform surfaces than slurry-cut wafers, enabling further increases in cell efficiency. DW PreTex can be integrated into the existing production as a modular wet process system without additional facility requirements. The process achieves uniform surfaces with a reflection value of $R < 23$ %. This is supported by operating costs of less than €0.01 per, according to the company

Applications: In-line wet process, suitable for both wafer and cell manufacturers for the texturing of diamond-wire cut multi-c-Si wafers.

Platform: DW PreTex is available in two versions: as a separate single unit that roughens the surface of the wafers and then uses the available texture capacity, or as a combined line for complete texturing.

Availability: Currently available.

Mondragon Assembly

Mondragon Assembly has developed a high-throughput 150MW 'Front Line' tabbing and stringing system

Product Outline: Mondragon Assembly has introduced a new 150MW annual capacity automated 'Front Line' tabber and stringer that includes an interconnect system. The high-throughput, small-footprint system provides improved space accommodation and flexibility for a wide-range of busbar configurations.

Problem: Module manufacturers increasingly require higher throughput production lines with higher degrees of automation and flexibility. As the number of busbars in PV cells increases, the bussing, or interconnected welding process, becomes a bottleneck in many production lines.

Solution: The Mondragon Front Line system consists of two of its MTS 2500 tabbers and stringers and an IC150 interconnect system, and is designed to manufacture panels with cells of up to six busbars. The MTS 2500 tabber and stringer also enables a net production capacity of 2,400 cells per hour in a single welding track, which is claimed to be the fastest in the market to date and significantly reduces production bottlenecks with increased busbar configurations. Mondragon Assembly's IC150 interconnect system is also designed to allow module manufacturers to increase the production rate while ensuring the product quality. The system is also suitable for half-cut cells.

Applications: High-throughput tabbing and stringing in a small footprint and is suitable for half-cut cells and different technologies and wafer sizes.

Platform: The compact design of the Front Line system only requires 7.5m2 of floor space.

Availability: Currently available.

Product Reviews

Monocrystal

Monocrystal introduces improved back-side silver paste for PERC cells

Product Outline: Monocrystal has launched its new MY-555 cost-saving back-side silver metallization paste for passivated emitter rear contact (PERC) solar cells. MY-555 was specially developed to meet the demand for product with efficient balance of silver content and paste consumption.

Problem: PV solar cell manufacturers constantly need to reduce processing costs, which are dominated by material consumption such as metallization pastes, notably with PERC solar cells. However, high adhesion for tabbing applications is required for greatest long-term reliability.

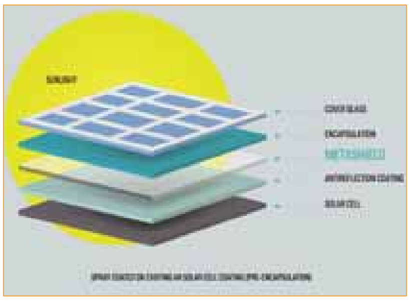
Solution: MY-555 was specially developed to be a low-cost alternative metallization paste for PERC solar cells with an efficient balance of silver content and paste consumption. MY-555 has 55% silver content along with 6% lower consumption per wafer to allow for a 10-15% cost of ownership reduction. MY-555 is claimed to provide up to 50% higher adhesion resulting in enhanced production yields which also contributes to cell and module reliability.

Applications: Back-side silver metallization paste for PERC solar cells.

Platform: MY-555 PERC silver metallization paste is formulated to be compatible with Monocrystal's EFX-series back-side aluminum PERC pastes. Monocrystal's PERC package allows customers to boost efficiency gain up to 0.18%. MY-555 does not penetrate the passivation layer and better protects the emitter during the metallization process. Monocrystal PV has the latest edition of ISO 9001 certificate by TÜV SÜD Shanghai.

Availability: Currently available.

MetaShield



MetaShield's embedded glass-based nano-coating improves light trapping

Product Outline: MetaShield's proprietary 'MetaSOL' nano-coating technology increases solar cell efficiency using advanced light trapping.

Problem: On average, 10% of the sunlight that enters a solar cell bounces around inside of the cell and eventually escapes, limiting possible improvements in conversion efficiencies.

Solution: MetaSOL is a patent-pending formula that is spray coated directly on to the existing anti-reflective coating on the solar cells and hardens at room temperature, forming a transparent ~200nm glass film. The embedded nanoparticles employ strong forward scattering to effect optical enhancement in solar cells. An independent study by the Utah Science Technology and Research Initiative (USTAR) TAP programme and verified by OAI-Optical Associates boosted triple junction (GaInP/GaInAs/Ge) solar cell efficiency by 1.2% (absolute) from 29.39% to 30.59%. MetaSOL's ability to provide a similarly dramatic enhancement to crystalline silicon photovoltaic cells is under development.

Applications: Initially triple junction GaInP/GaInAs/Ge solar cells and c-Si cell applications are under development.

Platform: MetaSOL requires no expensive vapour deposition, heating, or sputter coating. It adheres to most glass, metal, carbon-based and polymer materials. MetaSOL's light-trapping coating employs plasmonic and dielectric nanoparticles to enhance the forward scattering of light incident on solar cells, and hence increases the overall photo-conversion efficiency of these devices.

Availability: MetaSOL is said to be in beta production and available to solar cell manufacturers.

Aurora Solar Technologies

Aurora Solar Technologies offers first inline bi-facial solar cells measurement system

Product Outline: Aurora Solar Technologies has introduced an enhanced version of its 'Decima' inline measurement system for quality control of bi-facial solar cells during production.

Problem: Bi-facial solar cells have an open and active backside which enables collection of reflected light, generating up to 25% more power than traditional cells. However, bi-facial PV manufacturers have until now been forced to rely on manual sheet resistance sampling techniques that are wasteful and inadequate for control of the more complex and sensitive bi-facial cell fabrication process.

Solution: Aurora's system, called "Decima Gemini", consists of a specialized pair of Decima CD measurement heads. With this system, the sheet resistance of the wafers' back-surface field and emitter are measured accurately and simultaneously. Each Decima Gemini system is managed and controlled as a unit by Aurora's Veritas process visualization software. This measures doped semiconductor layers without contacting the cell or the need for an electrical junction between doped layers. Decima can accurately measure the bifacial cell's back-surface field without interference from wafer resistivity variations.

Applications: Inline measurement of bi-facial solar cells.

Platform: The Decima Gemini product is designed as a unit to fit above and below a wafer conveyor, and measures 100% of wafers at full production line speeds. Aurora's 'Veritas' process visualization software provides process engineers and operators with a simple, single point to monitor and control the critical back-surface field and emitter formation processes.

Availability: Currently available.

Product Reviews

Wickon Hightech

Wickon Hightech's 'SPEEDFilm Solar' system offers high-speed inspection of screen-printed paste structures

Product Outline: Wickon Hightech has developed a new model of the 'SPEEDFilm' inspection platform specifically for PV manufacturers. The 'SPEEDFilm Solar' system ensures 100% inspection of screen-printed paste structures with a very high throughput that is able to handle thinner printed structures on c-Si solar wafers.

Problem: Providing PV manufacturers with a high-volume, accurate inspection solution in a small footprint is required to meet quality control requirements of fine-line printing and higher quality control of printed pastes.

Solution: The SPEEDFilm Solar system takes two full resolution images to get a higher accuracy inspection result. Inspection is done with the printed layer upwards, while transporting from one segment to the next without losing process time. The lateral resolution is 5µm and the image acquisition time is only 1.25s for the complete wafer. The image is pre-calculated with the Wickon Hightech 'Dr.-M' (data reduction module) to speed up all calculations. The Wickon Hightech 'Wision' software has been widely used in automotive screen printing production lines with the ability of inspecting very complex layouts. The system detects paste spots out of the printed layout starting with a minimal size of 5x5µm as well as smeared paste along the printed conductor lines and logically interrupted conductor lines, providing 100% of inspection.

Applications: Volume production inspection of screen printed paste structures on c-Si solar cells.

Platform: The SPEEDFilm Solar system deploys a sensor and the PC in a compact conveyor and can be integrated in nearly all available conveyor systems.

Availability: Commercial product rollout is planned for October 2017.

Von Ardenne

Von Ardenne's 'SCALA' platform closes gap from R&D to production of heterojunction solar cells

Product Outline: Von Ardenne's 'SCALA' platform has been designed to close the gap between R&D and production of silicon heterojunction (HJ) solar cells.

Problem: Silicon HJ solar cells require only five major process steps, which in principle mean it is relatively easy to start manufacturing HJ solar cells. However, every process has its specific challenges and the interaction between all processes need to be kept in mind for optimization. The risks of up-scaling new developments have to be minimized but engineers and scientists need to be able to explore innovative ideas. Therefore, the tools and manufacturing logistics need to be designed to run only small batches for R&D purposes, but allow simulated full-scale production over several days or weeks, even in multi-shift operation.

Solution: A lab-scale HJ solar cell pilot line is often regarded as the best base for developing technology to be transferred to full-scale production and to support production lines that are already in operation. The SCALA LabX is a single-ended tool for horizontal batch processing and is ideally suited for process and application development at laboratory scale. The SCALA PilotX is designed for horizontal inline operation and therefore suitable for pilot production.

Applications: Front and back side deposition of contact layers such as TCO or metal stacks for silicon HJ solar cells and other crystalline PV applications.

Platform: SCALA uses process technology that is claimed to be 100% scalable and can be transferred from the laboratory to production scale. The process chamber is equipped with up to four different process stations in a sputter down arrangement. It enables simultaneous or sequential processing of different material compositions, which is particularly suited for R&D purposes.

Availability: Currently available.

Market Watch

News

Brussels passes 18-month extension of trade duties on Chinese products

EU member states have passed an 18-month extension of punitive trade duties on imports of Chinese solar products.

A 24-month extension was rejected in late January, but it is understood that member states have not stood in the way of an 18-month extension. The minimum import price (MIP) mechanism that allows participating members to avoid the duties will also be reviewed.

While the European Commission found evidence of Chinese firms 'dumping' modules into the EU below market price, it is keen to be seen to be weighing the value of supporting increased solar deployment.

"This case is the first to go to an Appeal Committee which shows how unpopular these measures are," said James Watson, CEO, SolarPower Europe, which has campaigned against the measures.

"The comission has been required to reduce the application period from 24 to 18 months on both anti-dumping and anti-subsidy measures. Yet, a much more sensible compromise for our industry would have been 12 months' application period with a clearer intent of ending the measures," added Watson.

Credit EU

The European Commission has extended trade duties on Chinese solar imports for a further 18 months.

Europe

European Commission approves French support schemes for 2.6GW of solar

The European Commission has approved French plans to develop 2.6GW of small- and large-scale solar and 60MW of hydropower.

The commission endorsed two separate solar schemes, which have a provisional budget of €8.8 billion (US$9.4 billion) over 20 years.

One scheme helps pay the feed-in tariff (FiT) subsidy to operators of small-scale solar installations (<100kW) on domestic and commercial rooftops. This will account for roughly 1.5GW installations.

The other support scheme is for operators of projects above 100kW with a 20-year FiT, following on from tenders for around 1.1GW of solar between July 2011 and March 2013.

France targets 23% renewables by 2020 under the Renewable Energy Directive.

France adopts law for self-consumption of renewable energy

The French parliament has adopted a draft law on self-consumption of electricity from renewable energy sources.

The law proposed back in July 2016 provides a legal framework for self-consumption of renewables and will introduce a definition of self-consumption, as well as collective self-consumption. Grid operators will also be obliged to help facilitate self-consumption.

The Energy Regulatory Commission will also establish a network usage tariff adapted for self-consumption systems. This tariff will take into account the savings related to reduced use of the network through generating one's own power. A release from the French Ministry for the Environment, Ecology, Sustainable Development and Sea said that minister Ségolène Royal is particularly keen on this network usage tariff to promote self-consumption.

There will also be a simplification of procedures for small-scale plants that are only under a partial self-consumption model. Tax exemptions will also be given for self-consumed electricity.

The bill also ratifies an ordinance from August 2016 relating to generation of electricity from renewables. This ordinance removes priority access and priority dispatch of coal-fired electricity facilities. Furthermore, it establishes a priority access and dispatch for renewables in non-interconnected areas, such as the French islands. There are also changes to the tendering process.

United States

2016 was US solar's biggest year to date with record-breaking 95% growth

In 2016, the US solar market nearly doubled its annual record, installing 14,626MW of new PV.

This represents a 95% growth increase over 2015's cumulative 7,493MW, according to latest figures from GTM Research and the Solar Energy Industries Association (SEIA).

Last year was a record-breaking year for US solar on many counts, as it ranked as the number one source of new electric generation capacity additions on an annual basis for the first time ever in 2016. Solar accounted for 39% of new capacity additions across all fuels sources.

The utility-scale segment was spurred dramatically this year by a pipeline of projects due to the extension of the ITC. This segment installed the most capacity and also had the highest growth rate up 145% from 2015.

Community solar also proved itself as a force to be reckoned with, adding a record total of more than 200MW, led by Minnesota and Massachusetts.

Furthermore, this segment surpassed the residential segment in solar growth for the first time since 2011. The residential sector

Credit SunPower

Utility PV was a key driving force behind a banner year for US solar in 2016.

did experience a slow-down, levelling out since its explosive growth in earlier years. In 2016 it still installed 2,583MW.

Republican and Democrat governors urge Trump to pursue wind and solar

The Governors' Wind and Solar Energy Coalition (GWSEC), a 20-member bipartisan group, has written a letter to president Trump, urging him to support renewable energy as it is critical to economic growth.

The letter comes in the wake of the fossil fuel-championing president pledging to cut federal spending on climate-related initiatives and the possibility of fewer incentives for renewables under the new administration.

Against that backdrop, governors from both ends of the political spectrum are seeking federal engagement with one of the nation's biggest industries, saying that "the growth of the renewable energy industry is an American success story built on federal research and development and policy leadership." Most recently, industry experts have feared that the National Renewable Energy Laboratory (NREL) – which is the only federal laboratory dedicated to research and development in renewables and energy efficiency – could be up for elimination, given Trump's stance on such funding.

The signatories of the letter are from states with successful clean energy industries including California, New York, Massachusetts, Colorado and Hawaii, who argue that renewables are key to transforming low-income margins of society, helping meet the growing demand for energy and to realising a low-cost alternative to conventional energy sources.

Emerging markets

MENA region's 2017 solar PV pipeline more than 4GW - MESIA

The MENA region has a solar PV pipeline of 4,050MW (AC) for this year, according to a new report by the Middle East Solar Industry Association (MESIA).

The highest capacities of this figure come from the 1.2GW Sweihan project in the UAE and 1.5GW under the second round of the feed-in tariff (FiT) regime in Egypt.

Combining both Solar PV and CSP projects, MESIA has calculated a grand total of 5.7GW (AC) of projects in the region at various stages of development.

- 885MW operational
- 3,618MW under execution
- 1,300MW under tender

The world-record low tariffs below US$0.03/kWh on Dubai Electricity and Water Authority's (DEWA) 800MW Phase III project from Masdar, attracted worldwide press attention. More attention then came in September 2016 when prices hit US$0.0242/kWh for Abu Dhabi Water and Electricity Authority's (ADWEA) Sweihan project.

Wim Alen, secretary general of MESIA, said: "These low prices have changed the perception of policymakers and industry leaders."

Eskom will sign outstanding renewable PPAs, says South Africa's president

South Africa president, Jacob Zuma, has said that the national utility Eskom will sign the outstanding PPAs won in the fourth round of the country's Renewable Energy Independent Power Producer Procurement Programme.

Eskom faced a backlash after refusing to sign any more renewable energy PPAs with IPPs under the programme back in late July. The utility initially said its reason for defaulting on the projects was because the integration of renewables was putting a strain on the grid. This did not sit well with the clean energy industry, with the South Africa Renewable Energy Council (Sarec) threatening legal action over the refusal, despite Eskom remaining bullish and citing overcapacity.

However, during his State of the Nation Address in early February, Zuma said renewable energy formed an important part of the country's energy mix. He also emphasised that the government would remain committed to signing PPAs with IPPs for all forms of energy, including coal and gas.

"Eskom will sign the outstanding power purchase agreements for renewable energy in line with the procured rounds," he confirmed.

Eskom conditionally committed to following Zuma's instruction, but said some projects may remain outside its ability to afford.

Asia & Oceania

China connected more than 34GW of solar in 2016

New data from China's National Energy Administration (NEA) has revealed that an additional 34.24GW of solar was connected to the country's grid in 2016.

There is now a total of 77.42GW of solar PV in the country. The 126% increase in annual installation outstrips the NEA's cumulative market growth figure of 81.6%. A surge in connections occurred in the first half of 2016 as developers looked to guarantee their feed-in tariff before a planned drop. Almost two thirds (22GW) of the 2016 total was installed in H1.

According to Frank Haugwitz, of the Beijing-based Asia Europe Clean Energy Advisory (AECEA) group, project completions have increased since November 2016. A slump in the wake of the H1 push had triggered fears of a drop in demand. This would appear to be easing. As a result AECEA is forecasting that China could again see 20GW of PV projects added to the grid in H1 2017.

The country has a target of 110GW of total installed solar capacity by 2020. Haugwitz believes, based on past experience, that this will be a minimum target to be exceeded, rather than a maximum level.

Australia set for 'huge year' in large-scale renewables

Investment confidence has rebounded in Australia's utility-scale renewables with more than 20 projects under or about to start construction this year, according to analysis from the Clean Energy Council (CEC).

With works to get underway on more than 2,250MW of projects, attracting AU$5 billion (US$3.8 billion) investments, CEC chief executive Kane Thornton said: "We are set for a huge 2017."

The 11 solar projects, two hybrid solar and wind projects, and eight standalone wind projects are also expected to create 3,000 direct jobs.

His claim that investors are flocking back to the renewable energy sector is particularly significant given that the industry came to a halt during uncertainty over the RET back in 2015 and even once the target was finally agreed upon, commentators still feared that it would take time for investor confidence to return. Thornton said that actions from state and territory governments had been critical to restoring this confidence.

The most large-scale activity will be in Queensland and New South Wales, with projects also coming up in South Australia and Victoria.

Credit Scatec Solar

Dreuburg South Africa's Eskom is facing pressure to sign off renewables PPAs agreed under round four of its IPP programme.

Solar PV manufacturing in 2017: factors driving technology change

Finlay Colville, Head of Market Research, Solar Media Ltd.

ABSTRACT

Having installed more than 75 gigawatts in 2016, the solar industry continues to create opportunities for cell and module manufacturers to expand capacities, while upgrading technologies and improving process flows. Supply remains dominated by p-type crystalline silicon modules, despite ongoing research into n-type variants and the addition of PERC on p-type mono cells. The efficiency increases from p-type mono are now driving p-type multi cell producers to accelerate changes to production lines from both black silicon and PERC. This is now setting new benchmarks for the supply of solar modules in 2017 to utility-scale solar installations.

There remains a high level of debate within the solar industry regarding the adoption of p-type mono as the preferred cell type. While not a new concept, the push in recent years has come from the expansions at the ingot and wafer stage by leading mono supplier LONGi Silicon Materials, coupled with the implementation of passivated emitter rear contact (PERC) on p-type mono production lines.

This article examines the factors that are impacting the balance of mono and multi cells produced by the industry, using the metrics from 2016 industry production. This is followed by a review of the issues that are likely to drive changes in cell and module technology during 2017.

End-market growth allowing companies to expand to multi-GW levels

The solar industry surprised all observers by the end of 2016, with overall demand for the year exceeding 75GW. At the start of 2016, almost everyone was forecasting demand levels to be in the 60-70GW band. The sharp uptick in demand appeared only to come to light in late December when figures were released from China, showing that the country's deployment in 2016 had over-performed by about 10GW.

In fact, China was the single reason the solar industry exceeded 75GW during 2016 and accounted for a staggering 35-40% of all solar installed globally in the year. During the past few years, China's dominance in terms of demand has had a strong impact on cell and module manufacturers and has directly affected the overall technology mix.

Indeed, Chinese companies continue to dominate cell and module supply to the industry, with many now having their own manufacturing facilities located in Southeast Asia or having access to cell and module supply through contract manufacturers in the region.

Leading cell suppliers in 2016

Cell manufacturing in 2016 was dominated by Chinese companies, as shown in Figure 1. Seven of the top-10 producers have headquarters in China, with all having manufacturing both inside China and other countries. First Solar is included here, using module production data as the reference point for analogous cell production rankings.

The two companies at the top of the table (Hanwha Q CELLS and JA Solar) are the two companies with the strongest background as cell producers with each moving into module production after having been established as industry leaders for cells.

Top-10 Solar Cell Producers in 2016

Ranking	Producer
1	Hanwha Q-CELLS
2	JA Solar
3	Trina Solar
4	First Solar
5	JinkoSolar
6	Motech
7	Tongwei Solar
8	Yingli Green
9	Canadian Solar
10	Shunfeng

Notes: Includes in-house cell production only. First Solar module production is scaled up for cell equivalent by blended c-Si CTM factor for ranking comparison. Shunfeng includes also cell production data from subsidiaries Wuxi Suntech & Suniva.

Figure 1. The top-10 cell producers in 2016 were dominated by Chinese-headquartered companies, with increased cell production now done across Southeast Asia.

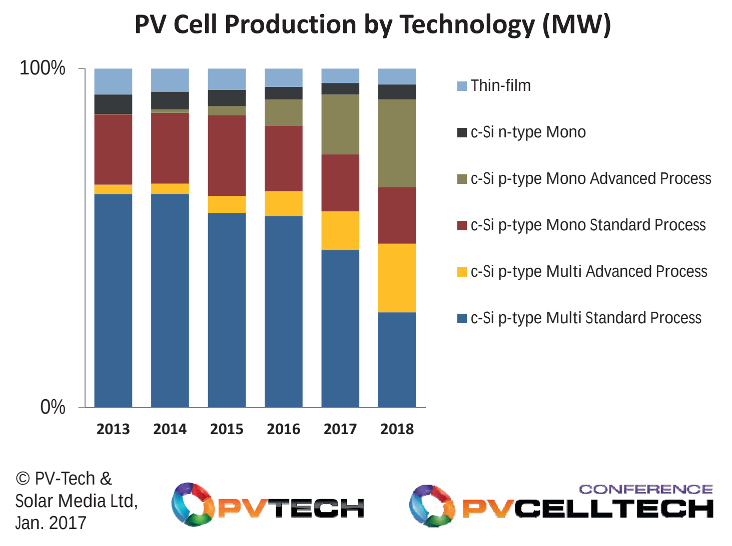


Figure 2. P-type multi c-Si technology remains dominant in the PV industry today, with many companies moving from standard cell process flows to advanced designs, especially PERC.

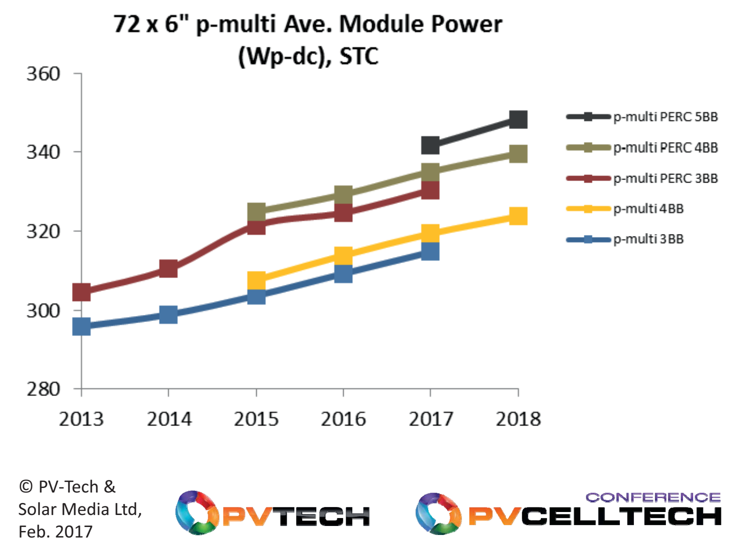


Figure 3. 72-cell p-type multi modules remain a preferred choice for many utility-scale markets, with the top performing modules expected to reach average powers of 350W by the end of 2018.

All the c-Si producers are heavily focussed on p-type production, with most of the production lines currently running on p-type multi. Most have p-type mono PERC, with Hanwha Q CELLS the clear leader using PERC on p-type multi.

The list is likely to be similar by the end of 2017. However, there are still over 100 companies outside the top 10 making solar cells today, with most in China. Many of these companies are only providing cells being used in modules that get shipped within China to its domestic market.

The dominance of p-type multi

Figure 2 shows the split of cell technologies produced in 2016, and reveals how resilient p-type multi has been in the past few years. The major changes have occurred by moving both p-type mono and p-type multi to advanced cell designs, reducing the percentage produced from the standard cell designs (full aluminium back surface field). This has been driving efficiencies higher, and is discussed below in the article in more detail.

In addition to the China end-market and domestic-production issues already mentioned, the other reason p-type multi has remained dominant is the utility segment of end markets globally. Utility-scale solar is the big driver for most of the leading end markets, and this segment has traditionally chosen p-type multi as the preferred module technology. In recent years, p-type multi has retained dominance with an increased move from 60 to 72-cell module configurations.

The main question from Figure 2 relates to the forecasting for 2017 and 2018 that shows p-type mono gaining market share. This is something that may change, however, if the leading multi wafer suppliers can continue to drive costs down, in particular through moving to diamond wire saw cutting. Coupled with creating black silicon texturing on the front surface of multi cells and adding PERC, this would certainly keep p-type multi as highly competitive in the market, potentially with a greater market share than shown in the forecast period.

Module power ratings from 60 and 72-cell designs

The easiest way to view the improvements from cell production is to look at the average power ratings from modules at standard test conditions (STC). This is shown in Figure 3 for p-type multi and Figure 4 for p-type mono.

The figures show the two key changes for cell technology in the past three to four years: the increase from three-busbar designs to four or five today; and the addition of PERC. Adding busbars to increase the efficiency has been the most common route for all cell manufacturers, with some often combining the busbar upgrades at the same time as moving lines for PERC.

Figure 3 shows the module power increases for 72-cell p-type multi. In 2013, the typical average module power was approximately 300W. By 2018, the five-busbar PERC versions are likely to be at the 350W level.

For mono, the graphic shown in Figure 4 is for the 60-cell design that remains popular in many rooftop installations, both residential and commercial. In addition to adding PERC and busbars, mono has also benefitted from the increased supply of larger wafer sizes from 156.0mm (M0) to 156.75mm (M2). In fact, M2-size wafers are also now coming through for multi. The efficiency gap between standard mono cells with three busbars on M0 wafers, and the top-performing mono PERC cells with five busbars on M2 wafers is significant and translates to premium module pricing in the market today.

Changes in manufacturing locations

During the past few years, cell and module manufacturing has increased across Southeast Asia, and in particular in Vietnam and Thailand. Alongside Malaysia, these are the three preferred countries today for many of the cells and modules that end up in the European and US markets. This has arisen largely due to the import tariffs introduced in these two regions in the past few years, and will likely remain a key factor in further expansions by leading cell producers in the next two to three years.

Figure 5 shows the geographic breakdown of capex by the PV industry. This covers the entire value chain from polysilicon to modules, but is most heavily influenced by the cell and module stages currently.

Capex remains one of the leading indicators in the industry today, both at the company level and for consolidated manufacturing trends. Tracking and forecasting capex allows visibility into changes 12-18 months out, including technology.

China still dominates overall PV capex, with maintenance spending and line upgrades alone more than most other country's total PV capex figures. In the past few years, there has also been a huge amount of new cell and module capacity added, often by companies only supplying to the China end market and using only Chinese-produced production equipment.

The graph shows the emergence of India, Thailand and Vietnam as new locations for PV manufacturing, with Thailand and Vietnam key regions for OEM supply. Spending on PV manufacturing in the US and Europe remains low, with the occasional module assembly plant being announced these days. The industry is awaiting the outcome of SolarCity's Silevo plans for a gigawatt-level cell and module facility, which would obviously be the most significant development for US PV manufacturing for many years.

Contract manufacturing returns

The PV industry has always seen strong outsourcing, where cells and modules are routinely made by third-party companies, either through spot-market buying or pre-arranged contracts. On the module side, there have been a few global contract manufacturers that had created solar factories to move into this area. These were located in Europe, North America and Southeast Asia.

In recent years, driven mainly by the restrictions on Chinese and Taiwanese cells to Europe and the US, there has been

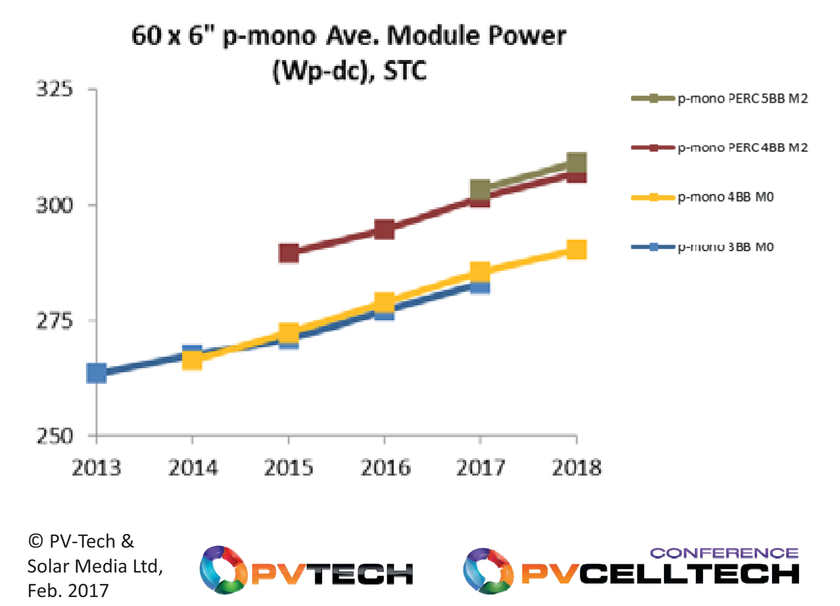


Figure 4. 60-cell arrangements remain common for p-type mono modules, especially for rooftop or space-constrained applications.

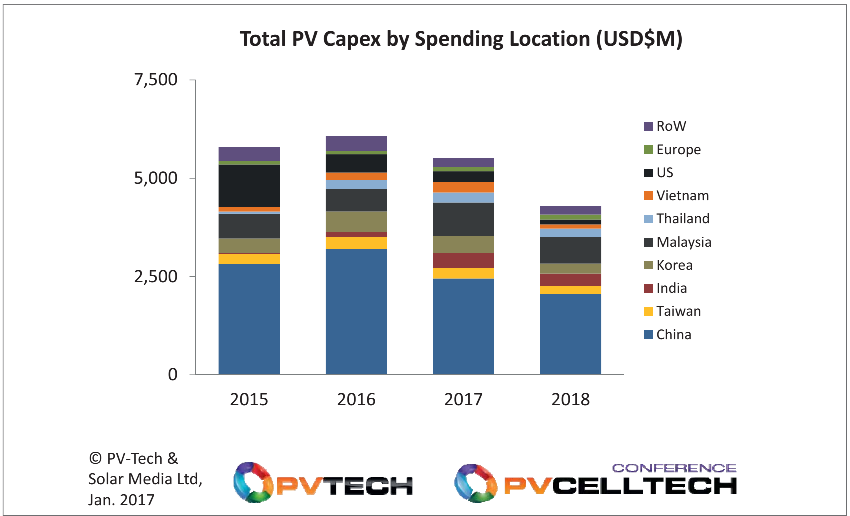


Figure 5. PV capex is now seeing stronger contributions from India, Thailand and Vietnam, with new capacity for both cells and modules still coming online in 2017.

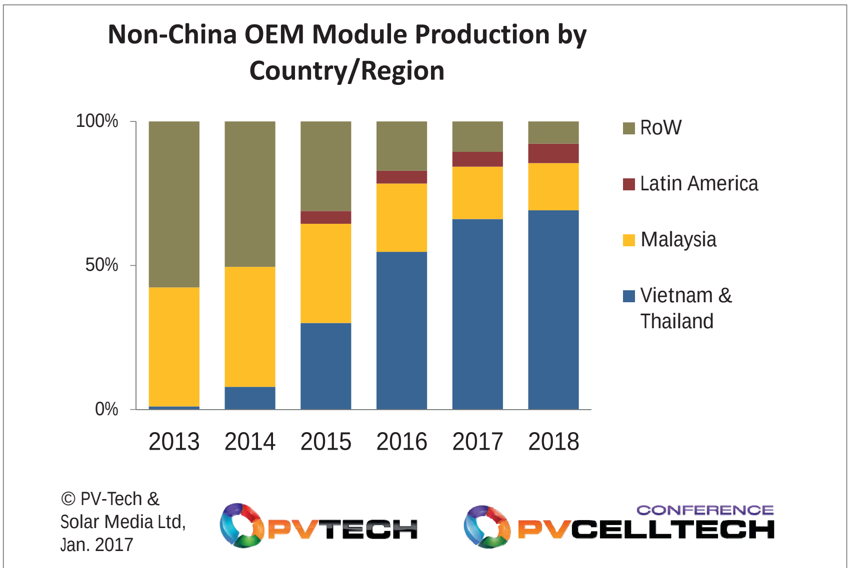


Figure 6. Vietnam and Thailand have now become the leading countries, outside China, for outsourced OEM or contract manufacturing of cells and modules.

a strong uptick in OEM manufacturing from PV-specific companies in Southeast Asia, especially Thailand and Vietnam. Some of these companies would appear to be financed and operated from mainland China, and end up doing cell and module production for branded modules being shipped to Europe and the US.

Figure 6 shows the changes in OEM contract manufacturing in the industry over the past few years, with mainland China companies excluded from the analysis. In the graphic, Vietnam and Thailand are grouped together, to emphasize the market changes expected to continue to the end of 2018 also.

Summary

Many of the issues that will impact PV technology in 2017 would appear to be the same ones as 2016, with the question of supply and demand to the Chinese end market being the most important. Cell efficiencies will continue to increase, with wafer size, busbars and PERC being the drivers to having the most competitive modules. The debate will likely focus on how much multi capacity is converted to black silicon variants, and what production equipment is finally chosen as the industry standard.

India is likely also to become a stronger contributor to cell manufacturing, with most of attention being on Adani when the full cell capacity is ramped up. Vietnam and Thailand may well slow down however, due to the volume of cell and module capacity located in Southeast Asia.

Finally, from a technology perspective, n-type is likely to be in a stronger position by the end of 2018, due to SunPower's upgrades to its higher efficiency platform, and new capacity from other companies in China such as Jolywood. There continues to be strong investments into n-type manufacturing, and this is probably the one factor that remains the largest threat to the p-type industry as a whole today.

About the Author

Finlay Colville is Head of Market Research at Solar Media Ltd, also the publisher of *PV Tech* and *Photovoltaics International*. Prior to this, Dr. Colville was Head of Solar at NPD Solarbuzz between 2010 and 2014. As the leading market analyst tracking PV manufacturing, technology and equipment spending trends, Dr. Colville has been active in the solar industry for more than a decade. Prior to NPD Solarbuzz, he held various senior sales and marketing positions at leading capital equipment supplier, Coherent Inc.

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China Sunergy to begin solar module production in Sacramento, California

CSUN is planning to begin module production in the US.

China-headquartered solar cell and module manufacturer China Sunergy (CSUN) said in a joint statement with the California Governor's Office of Business and Economic Development (GO-Biz) that it was establishing a solar module assembly facility at the McClellan Business Park near Sacramento, California.

An existing 140,000 square-foot building at the former McClellan Air Force base has been leased to CSUN, which was said to have the nameplate capacity to produce 400MW of modules per annum and would provide over 200 local jobs.

The module assembly plant would be highly automated and operations are expected to start as early as May 2017.

The move is a step towards CSUN expanding its US market share. CSUN had previously established production facilities and sub-contracting module assembly operations in South Korea and Vietnam, with relocated equipment from its China-based facilities to circumvent US anti-dumping duties on Chinese and Taiwanese made solar cells and modules. To complete the circumvention of US duties, CSUN is likely to import solar cells from its facilities in South Korea and Vietnam.

CSUN reportedly plans to complete renovation work on the existing facilities at a cost of around US$10 million in advance of tool install of two automated module assembly lines in the April-May timelines.

The company is only the third China-headquartered PV manufacturer to establish module production in the US after former global leader Suntech Power Holdings closed its small module assembly plant in Arizona in 2013. Major Chinese PV manufacturers such as JinkoSolar, Trina Solar, JA Solar and GCL have established manufacturing operations in Southeast Asia to circumvent US and EU anti-dumping duties.

Capacity expansions

Daqo starts production at 6,000MT polysilicon expansion

China-based polysilicon producer Daqo New Energy said it had started production at its Phase 3A facility, bringing an extra 6,000MT of polysilicon capacity online and an annual production run rate of 18,000MT.

Daqo noted that the construction and installation work related to Phase 3A at its Xinjiang polysilicon plant was completed by the end of 2016 and would be fully ramped by the end of the first quarter of 2017.

The company undertook technology upgrades and process improvements at the same time to meet demand for high-efficiency monocrystalline wafer production which requires higher purity polysilicon.

Suniva completes 250MW capacity expansion at Georgia headquarters

US-based PV module manufacturer Suniva has officially opened its 250MW capacity expansion at its US headquarters, located in Norcross, Atlanta, Georgia.

Suniva currently has 450MW of monocrystalline solar cell and module production, making it the largest c-Si cell producer in the US and the second largest c-Si module producer, after SolarWorld with 550MW.

"Our latest expansion demonstrates that American manufacturing continues to be a meaningful force in the global solar manufacturing industry," said Matt Card, executive vice president of commercial operations at Suniva. "The increase in solar cell efficiency we have achieved, along with our new capacity, brings even more of our high-power products to an even wider customer base. The marketplace continues to benefit from a strong American manufacturer."

Suniva is majority owned by China-based renewables firm, Shunfeng International Clean Energy, which also owns PV manufacturer, Wuxi Suntech.

Asia

Comtec Solar to sell Malaysian mono wafer plant to Longi Silicon Materials

Monocrystalline wafer producer Comtec Solar Systems Group has said it plans to sell its Malaysian facility and some of the installed production equipment to leading integrated monocrystalline ingot to module producer, Longi Silicon Materials.

Comtec Solar is selling the facility for around RMB 200 million (US$28.8 million), subject to shareholder approval. Longi is acquiring the land and facilities for around (US$20 million) and some equipment, primarily ingot pullers, for around (US$7.8 million).

The company noted that the sale of the key production plant assets was due to continued losses associated with the plant since 2013, which had totalled around (US$25.7 million). Comtec also cited a major monocrystalline silicon wafer user recently announcing the closing down of a production facility and the scaling back of capacity as another reason for the sale of the Malaysian plant.

Comtec has also previously said that it wanted to focus on the PV downstream market in the future.

Motech to invest US$29 million in China manufacturing operations

Taiwan-based PV manufacturer Motech Industries has said it will make further capital investments in its solar cell and module manufacturing operations in China, via its subsidiary, Motech (Suzhou) Renewable Energy in another subsidiary, Motech (Maanshan) Renewable Energy Co.

Motech said in a financial filing with the Taiwan Stock Exchange that the investment would be around RMB 200 million (US$29 million).

The company has invested a total of around US$54 million in its Chinese manufacturing operations since 2013 but had not made further investments in 2016,

Credit SunEdison

Flex has confirmed the size of the hit to its revenue from the bankruptcy of SunEdison

However, Flex was also saddled with an undisclosed quantity and value of finished solar module inventory produced at its assembly plant in Ciudad Juarez, Mexico for SunEdison since mid-2015 and its plant in Johor, Malaysia. The Flex partnership with SunEdison had started in May, 2011 and reached a module production milestone of one million modules produced in 2013.

According to Flex, a US$61.0 million bad debt reserve was recognised almost a month ahead of SunEdsion's officially bankruptcy date of 21 April 2016 for module inventory and assembly equipment assets related to SunEdison's module production.

according to the financial filing.

Shunfeng terminates sale of solar manufacturing operations to major shareholder

Diversified renewables firm Shunfeng International Clean Energy (SFCE) has terminated a memorandum of understanding with its major shareholder and Hong Kong property tycoon, Kin Ming Cheng, over the potential sale of its solar manufacturing operations which includes Wuxi Suntech.

Both parties were said to have agreed to end discussions on the potential US$760 million deal, which comes at the same time SFCE warned investors that it expected to generate losses of around US$133 million in 2016.

SFCE had signed a non-legally binding memorandum of understanding with Asia-Pacific (China) Investment Management Ltd, owned by Cheng back in June 2016. The company had not provided any updates on the discussions in the interim period.

Talesun supplying modules to 96MW US PV power plant from Thailand facility

Integrated PV module manufacturer Zhongli Talesun Solar is to supply 96MW modules from its production plant in Thailand to ColGreen North Shore for a single PV power plant in California.

Talesun said that its high-efficiency multicrystalline modules would be supplied to ColGreen North Shore through January 2017.

"We are proud to have reached another significant milestone through this supply agreement with ColGreen North Shore project. This 96 MW project will further strengthen our position in the US market," said Sheng Hao, company senior vice president.

Talesun started production at its integrated 500MW PERC cell production plant in Thailand in November 2015 and has plans to ramp the facility to 800MW.

North America

Flex confirms solar business with SunEdison went from US$500 million to zero

Major electronics manufacturer Flex has acknowledged the scale of the impact on its business with the bankruptcy last year of its largest solar energy client, SunEdision.

In reporting fiscal third quarter financial results, Flex management noted in the earnings call that its energy division (IEI), which includes its solar industry related customers, is expected to recover from the financial impact of SunEdison's bankruptcy last year and expects high single-digit year-over-year revenue growth in energy.

But in the earnings call, Christopher Collier, Flex CFO said, "We suffered our single largest customers in IEI departing this past year. You had almost a US$0.5 billion business with SunEdison inside of IEI go to zero.

PV Tech revealed last year that SunEdison owed its upstream suppliers more than US$321 million, according to papers filed with the Bankruptcy Court, which included debts to Flex subsidiary, NEXTracker, for over US$44 million.

Panasonic forms new company to produce solar cells and modules at SolarCity's Buffalo fab

Major Japanese electronics company Panasonic will establish a new entity as part of the agreement with Tesla to produce Heterojunction with Intrinsic Thin layer (HIT) solar cells and modules at the 1GW Buffalo fab in New York.

Panasonic said that a new entity, Panasonic Eco Solutions Solar New York America, would be established within its US-based Panasonic Corporation of North America division to produce cells and modules at the facility.

The necessary manufacturing support facilities and production equipment should be delivered, installed and commissioned with initial ramp of production started in the summer of 2017.

However, the original planned SolarCity/Silevo solar cell and module assembly production ramp of the 1GW plant would seem to have be delayed further. In the original SolarCity/Silevo plans, construction of the 1GW facility was set for the end of 2015, with construction starting at the end of 2014.

Mission Solar making second drastic workforce reduction at Texas plant

US-based high-efficiency integrated PV module manufacturer Mission Solar is to cut its existing workforce by a further 58% after closing its solar cell production lines at its facilities in San Antonio, Texas in October 2016.

According to a Workforce Adjustment and Retraining Notification (WARN) in the state of Texas, Mission Solar's second round of job cuts would result in the loss of 170 jobs, adding to the 87 jobs lost in October.

Mission Solar is expected to complete the workforce reduction at the end of March 2017.

The company had switched from

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being an integrated solar cell and module manufacturer using high-efficiency n-type monocrystalline technology to module assembly only, purchasing solar cells from Korea to avoid US anti-dumping duties in an effort to regain cost competitiveness with Asia-based PV manufacturers.

Celestica to exit solar module production at Toronto facility

Electronics Manufacturing Services provider Celestica will wind down solar module assembly operations at its Toronto, Canada production plant in Q1 2017.

Celestica management said in its earnings call that recent module overcapacity and plummeting prices had led to much lower demand from contract customers. A decision to exit solar module production for customers was said to have been made in the Q4 2016, to restructuring charges of US$21 million.

Celestica management noted that revenue from its module assembly operations amounted to around 1% of fourth quarter 2016 total revenue of US$1.62 billion or around US$16.2 million and around US$60 million in 2016.

Manufacturing operations were established in 2011 and had employed approximately 400 people. In 2013, Celestica's solar lab at the Toronto facility had received TÜV Rhineland PTL approval to provide testing services required for the certification of solar modules.

Credit Mission Solar

Mission Solar is cut up to 170 US jobs.

New ventures

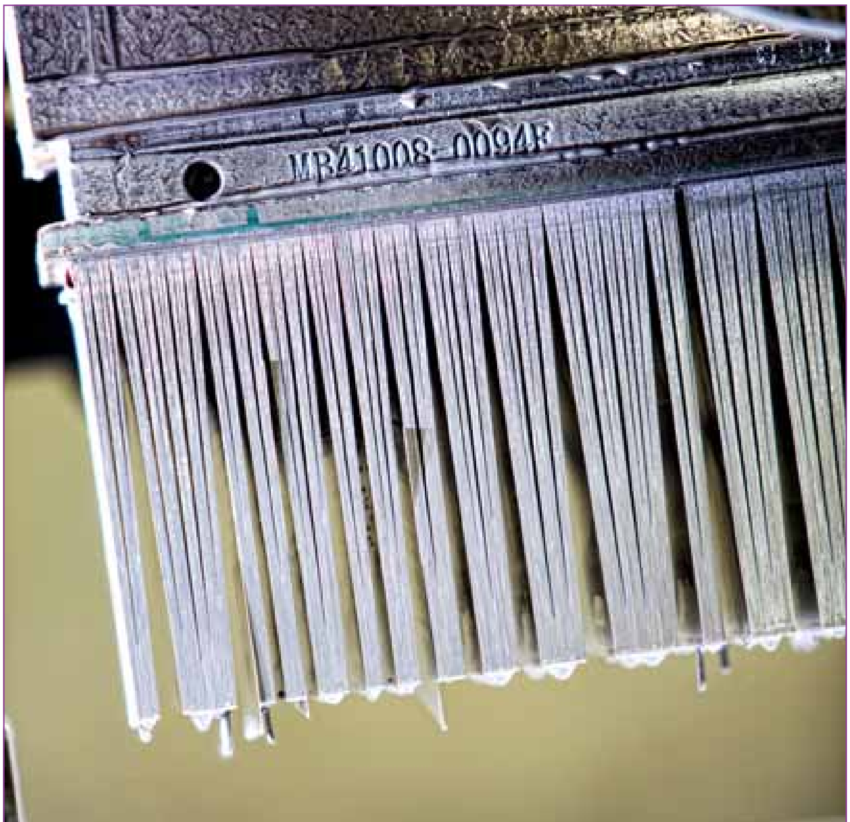
Longi, Trina Solar and Tongwei team on 5GW mono ingot plant

Three major Chinese PV manufacturers, Longi Silicon Materials, Trina Solar and Tongwei – via its polysilicon subsidiary – Sichuan Yongxiang, are to form a joint venture to own and operate a 5GW monocrystalline silicon ingot pulling production plant in Lijiang City, Yunnan Province, China, by Longi.

Longi said in financial filings that it would retain a 60% ownership in the planned production plant, while Trina Solar would hold 25% interest and Sichuan Yongxiang 15%.

Longi had previously announced plans for the plant in June 2016 and had initially planned to fund the facility in-house. However, Longi noted that a JV arrangement reduced financial and project risks. Trina Solar is expected to contribute an initial RMB200 million (US$28.8 million) to the project and Sichuan Yongxiang around RMB120 million (US$17.3 million). Longi still expects to contribute an initial RMB480 million (US$69 million), which is expected to incur capital costs of around RMB800 million (US$115 million).

The plant is expected to take more than a year to build and start ramping sometime in 2018.



Credit Trina Solar

Longi Silicon, Trina Solar and Tongwei are to join forces on a new silicon ingot plant.

Suntech establishes new European hub

PV manufacturer Wuxi Suntech has established a new sales and service hub in Europe since withdrawing from the EU Minimum Import Price (MIP) agreement in October 2016.

Suntech's main European operations will be based in Germany and will include local warehouses and logistics services to provide better customer support, according to the company.

Currently, Wuxi Suntech's manufacturing operations are located in Wuxi, China, while its parent company, diversified renewables firm Shunfeng International Clean Energy, has cell and module manufacturing operations in the US due to its acquisition of Suniva.

Suniva recently completed a manufacturing expansion to around 430MW.

Suntech also noted that it would be strengthening its cooperation with local PV module recycling organizations, and comply with the WEEE recycling rules for a full life-cycle customer service in Europe.

PV manufacturing capacity expansion plans in 2016 exceeded 55GW

Mark Osborne, Senior News Editor, Photovoltaics International

ABSTRACT
In this quarterly report on global PV manufacturing capacity expansion announcements we will provide a detailed analysis of 2016. Despite a significant slowdown in new announcements in the second half of the year, 2016 surpassed 2015 by around 16% to exceed a total of 55GW of thin-film, dedicated solar cell and module assembly and integrated PV expansion plans.

A game of two halves

As Figure 1 shows total global PV manufacturing capacity expansion announcements in 2016 were heavily weighted to the first half of the year with a total of nearly 48GW. The strongest quarter in 2016 was the first as May signalled a significant fall-off in announcements.

In stark contrast, the second half of 2016 accounted for only just over 8GW of planned expansions; July was he low point with just one 20MW planned solar cell capacity expansion announced. Only in November did total announcements push past 2GW in the second half of the year.

As shown in Figure 2, thin-film expansion announcements barely topped 1GW and were primarily (800MW) from CdTe leader, First Solar, which announced upgrades to mothballed lines and a new facility to house the expansion but did not provided a geographical location. Later in the year, First Solar announced a major restructuring of its manufacturing operations with a complete migration from Series 4 modules to Series 6 large-area modules. This restructuring effectively negated plans announced in April 2016.

Figure 2 also highlights the complete lack of integrated solar cell and module assembly plant announcements in the second half of the year, compared to 4.5GW announced in the first half of the year.

Dedicated module assembly announcements reached over 26.6GW in 2016, with around 23.5GW coming in the first half of the year. Overall, dedicated module assembly plans have typically tracked at higher figures than dedicated cell expansions, although the difference is relatively small.

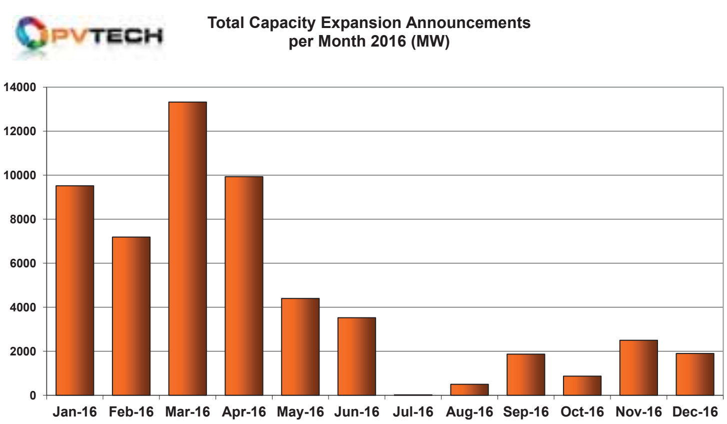


Figure 1. Total capacity expansion announcements per month 2016 (MW).

High-efficiency solar cells gain momentum

The migration to high-efficiency solar cells, whether monocrystalline or multicrystalline with passivated emitter rear contact (PERC) and n-type mono heterojunction (HJ), was also a key trend in 2016, having gained strong momentum since 2015.

As shown in Figure 3, overall high-efficiency monocrystalline solar cell capacity expansion announcements in 2016 accounted for around 40% of the global total of c-Si cell expansion plans, up from around 26% of the total in 2015.

In 2016, a total of around 38GW of c-Si solar cell expansion plans were announced globally, which included almost 11GW of dedicated mono c-Si cell capacity, compared with almost 27GW of multi c-Si solar cell plans.

However, many announcements in the multi-gigawatt scale were expected to be phased over several years. A more realistic analysis, with first-phase plans in the 500MW range, indicate around 23GW of total cell expansions, upgrades and new plant plans were announced.

In this analysis, we have only included solar cell expansion announcements that specifically stated that the plans relate to p-type or n-type mono as well as heterojunction and hybrid n-type mono cell architectures.

A key reason for this is that a number of PV cell and integrated manufacturers that can produce both p-type mono and p-type multi cells have typically not broken out whether the cell capacity expansions include both wafer types. Indeed, another challenge has been examples of later conversion of p-type multi cell lines to allocate some capacity to mono cell production.

With 2014 classified as the year that capacity expansions restarted after several years of chronic overcapacity, it is interesting to note that the ratio of mono to multi c-Si solar cell capacity plans was almost equal, albeit at low levels of 2.9GW and 3GW, respectively.

The significant amount of capacity expansion announcements in the later part of 2015 shifted the emphasis to multi c-Si cell lines and away from mono. In 2015, dedicated mono expansions totalled nearly 4.5GW, while multi cell expansions almost topped 17GW. Mono cell planned expansions fell to only around 26% of the total.

One of the key reasons for the dominance of p-type multi c-Si cell capacity expansions in 2015 was the significant expansions being made by the 'Silicon Module Super League' (SMSL) members (Trina Solar, Canadian Solar, Jinko Solar, JA Solar and Hanwha Q CELLS) with high reliance on multi and the establishment of meaningful new PERC cell technology capacity.

Another aspect that hindered mono capacity expansion plans was the lack of low-cost p-type mono wafers and limited 'effective' capacity expansions in 2015, which at around 3GW were actually less than the mono cell line expansions (4.5GW).

2015 can be seen as a transitional year for mono wafer cost competitiveness and availability, while 2016 can be seen as more transformative on both levels.

Not only did 2016 provide more than a doubling (10.96GW) of mono c-Si cell capacity expansion


Hanwha Q CELLS

Despite a slowdown in the second half of the year, PV manufacturing expansion plans in 2016 outstripped 2015.

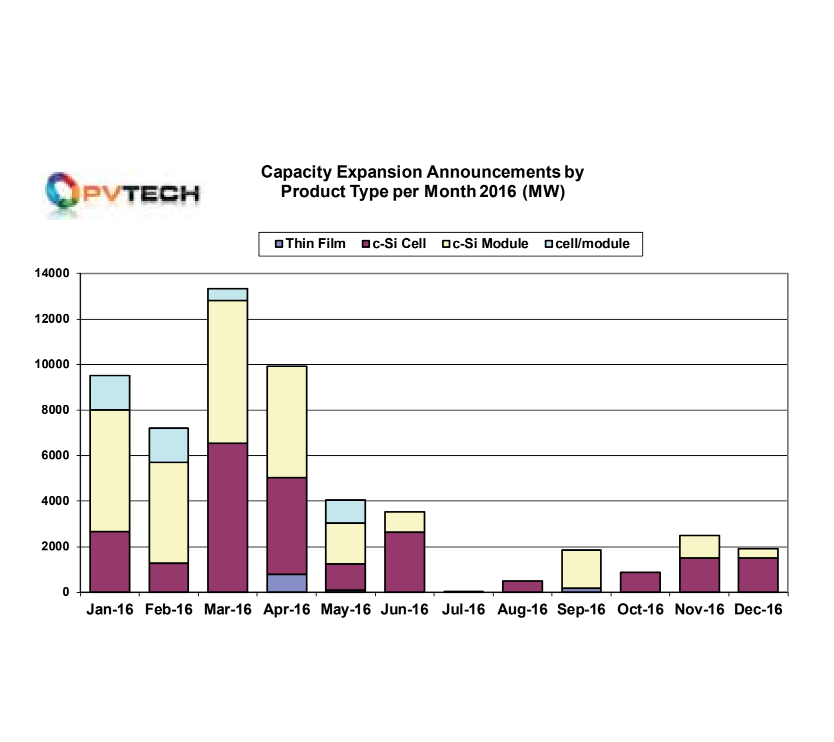


Figure 2. Capacity expansion announcements by product type per month 2016 (MW).

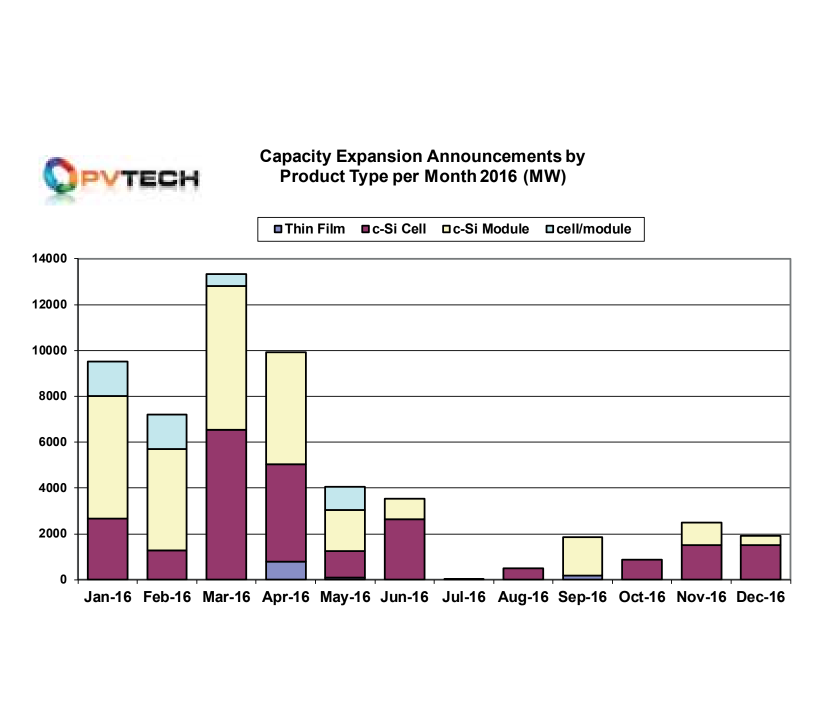


Figure 3. Monocrystalline silicon solar cell and ingot/wafer expansion announcements (MW).

announcements, a conservative 20GW of mono ingot/wafer capacity expansion plans were also announced that year.

The greater availability of mono wafers at cost-competitive pricing will remain a key adoption driver and could accelerate solar cell production migration away from multi to mono over the next few years. However, multi c-Si solar cell production is still expanding at higher capacity volume rates than mono and is expected to remain the workhorse of the industry through the next few years.

PERC on the rise

As with wafer type, not all multi and mono solar cell capacity expansion plans cite specific cell technologies being deployed. Indeed, even when a technology such as PERC is cited it is not always apparent as to the percentage of PERC capacity to standard BSF (Back Side Field) cell technology that is included in the total new nameplate capacity being added. There have been incidences in 2015 when PERC was announced but not actually deployed in the initial ramp of new facilities.

Therefore, even when only citing figures for PERC that were specifically stated in planned capacity expansions in 2015 and 2016, these figures could be compromised to some degree.

This also relates to BSF-to-PERC upgrades at existing manufacturing facilities. Not all PERC upgrades at exiting facilities are announced, although tracking cell equipment supplier orders does indicate higher amounts of upgrades via this route than the number of announced upgrades.

In 2015, PERC solar cell upgrades at existing facilities that were officially announced by manufacturers totalled only 460MW (see Figure 4), while tool orders were in the several gigawatt range. However, in 2016, PERC solar cell upgrade announcements reached 2,500MW.

Actual new capacity expansion announcements related to PERC in 2015 reached 7,200MW, while in 2016 the figure was lower at around 6,900MW. Again, it should be highlighted that any apparent decline is suspect, especially considering the significant increase in overall solar cell capacity expansion plans seen in 2016. The lower figure is more likely due to the lack of detail provided by manufacturers on the process technology or technologies being deployed.

Another interesting development is the momentum being built for HJ technology. In 2015, only 250MW of HJ cell expansion plans were officially announced, while this figure jumped significantly to 2,360MW in 2016.

Some of the announcements lacked timelines and other crucial information but around 1,000MW of HJ solar cell expansion plans in 2016 seem to have a good level of legitimacy, not least due to the end of year plans announced by Panasonic in partnership with Tesla at the SolarCity/Silevo 1GW Buffalo fab in the US.

Although both parties failed to highlight the planned nameplate capacity, we have estimated the plans to be around an initial 400MW.

With nearly 27GW of multi c-Si cell capacity expansion plans announced in 2016, the vast majority of which occurred in the first half of the year, it will not become clearer as to the amount of effective capacity that comes on stream or process technology deployed until the second half of 2017, notably due to facility construction and equipment lead times.

However, what is apparent from the capacity expansion announcements is growing momentum towards higher efficiency mono c-Si production and high-efficiency solar cells, primarily through PERC migration, a trend expected to continue over the next three to five years.

Key location trends in 2016

As Figure 5 shows, Asia has continued to dominate planned new PV manufacturing capacity expansions in 2016. The top seven countries (India, China, Vietnam, Malaysia, Thailand, South Korea and Taiwan) are all in Asia and accounted for around 46.2GW of new production plans from a total of around 49.2GW, globally or almost 94%.

Capacity expansions were announced in 21 countries in 2016, compared to 20 countries in 2015. However, the concentration of announcements in Asia has increased as Asia accounted for the top five selected destinations in 2015.

India surpassed China for the first time in 2016, accounting for just over 17GW of total announcements. New capacity plans in India increased by around 118%, compared with 2015.

However, the disparity between announcements and 'effective' capacity in India remain significantly high with much of the 7.8GW of announcements made in India in 2015, still unrealised into effective manufacturing capacity.

Capacity expansion announcements in China have slowed slightly in the last two years. Having peaked in 2014 at over 19GW, announcements fell to around 17.5GW in 2015 and topped 17GW in 2016.

Basically all of the 2016 announcements in China were made in the first half of 2016 with less than 50MW announced in the second half of the year. This is in contrast to 2015 when the majority of announcements were made in the second half of the year, providing over 34GW of announcements in a straight 12-month period.

However, China-based companies did not stop making announcements altogether in these periods of non-activity in China. Instead, plans were being announced by Chinese manufacturers for production plants outside China, predominantly in Vietnam, Malaysia and Thailand.

Perhaps the surprise location for capacity expansion announcements in 2016 was Vietnam which totalled almost 4GW, driven by some of the leading Chinese PV manufacturers such as JA Solar, Trina Solar, Canadian Solar and GCL System (GCLS).

Strong competition between Malaysia and Thailand as a major destination for PV manufacturing in Asia continued in 2016. Thailand (2.2GW) just topped Malaysia (2.1GW) in 2015, while the positions were reversed in 2016 with Malaysia attracting nearly 2.9GW of new capacity plans and Thailand 2.7GW.

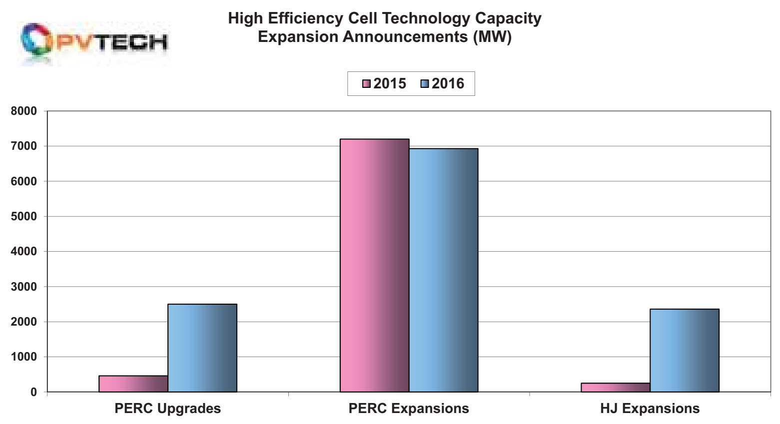


Figure 4. High-efficiency cell technology capacity expansion announcements (MW).

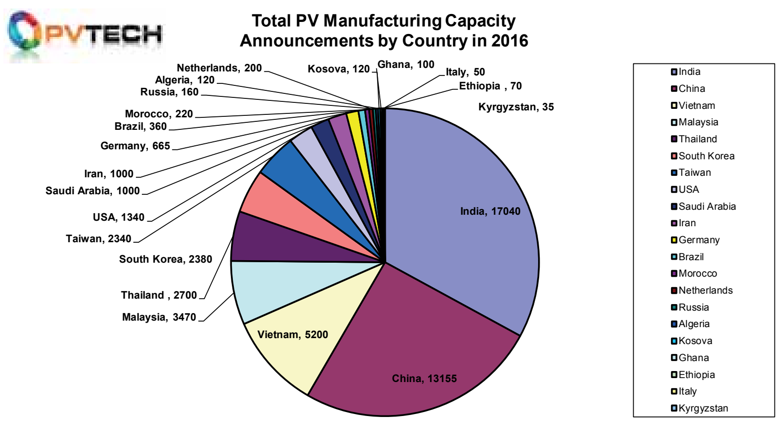


Figure 5. Total PV manufacturing capacity announcements by country in 2016.

The two other Asia countries accounting for the major share of announcements in 2016 were South Korea and Taiwan, both with over 2.3GW of expansion plans.

Despite the continued decline in the European downstream market, new PV manufacturing capacity plans are still being announced.

In 2016, European Union member countries announced just over 900MW of planned expansions, which included the acquisition and re-start of solar cell production by Trina Solar at the former Solland Solar facility in the Netherlands.

Within the EU, Germany remained the key destination with over 650MW of primarily reinstated module assembly capacity but significantly below the near 1,500MW announced in 2015. Overall, European capacity expansions announcements reached around 1,200MW in 2016, down from over 1,700MW in 2015.

Although Latin America is becoming a key emerging downstream market, manufacturing announcements remain limited in both number and scale, compared to emerging markets such as India.

In 2016, only Brazil announced new manufacturing capacity plans, but only 360MW compared to nearly 1,200MW in 2015. However, very few plans from 2015 materialised into effective capacity in 2016, yet indications are that some of the plans previously announced could materialise in 2017.

Other emerging markets such as those in the Middle East and North Africa (MENA) are also starting from scratch. In 2015, around 150MW of initial module assembly plans were announced in Egypt only. However, 2016 indicated over 2,300MW of manufacturing plans were being considered in the MENA region. The bulk of this comes from two 1,000MW planned facilities in Saudi Arabia and Iran. However, less ambitious plans exist in Morocco (220MW) and Algeria (120MW).

The vast majority of capacity expansion announcements in 2016 that have either been converted to effective capacity or are expected to become effective capacity in 2016 are located in China, Vietnam, Malaysia, Thailand, South Korea and Taiwan.

Although expansion announcements in India have been significant in both 2015 and 2016, many remain highly speculative at this time. However, with plans previously announced by the likes of Adani now becoming effective capacity, 2017 should see further conversions as the downstream market matures in India.

Outside of the seven key Asia countries, both Europe and the US expansion plans have a high probability of becoming effective capacity in 2017. A key measure will be the eventual manufacturing ramp at the Tesla/SolarCity/Panasonic facility this year.

On a geographical basis the emphasis in 2017 may turn to emerging markets and companies establishing local manufacturing albeit at small-scale capacity levels. However, as seen already in late 2016, manufacturing curtailment has already started and previously announced expansion plans being put on hold or cancelled outright may become the norm, regardless of location.

Conclusion

Despite the drastic slowdown in announcements in the second half of the year, 2016 activity proved to be a new record high for the solar industry. Chinese PV manufacturers continued to broaden their manufacturing footprints in response to anti-dumping policies in the US and EU, with much of the attention on Southeast Asia.

The drive to higher efficiencies, whether new build or upgrades at existing facilities also gained significant momentum. It would also seem that a period of digestion following the high activity levels seen in the fourth quarter of 2015 through to the end of the second quarter of 2016 is also underway.

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Matthias Trempa[1], Iven Kupka[2], Christian Kranert[2], Christian Reimann[1,2] & Jochen Friedrich[1,2]

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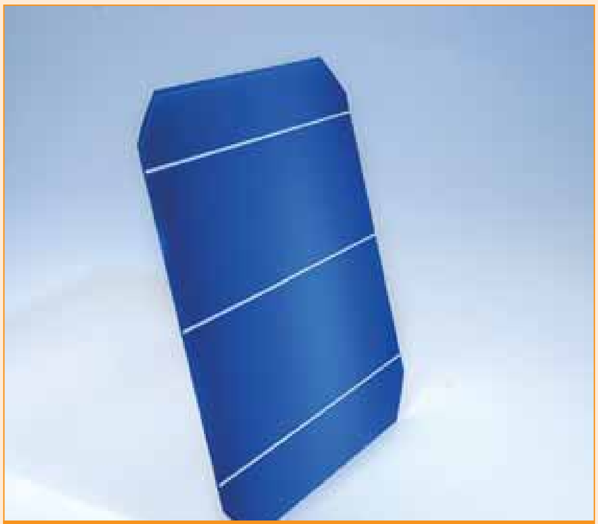
News

PERC solar cell migration to hit 25GW in 2017 – EnergyTrend



Credit Imec

PERC manufacturing capacity is expected to hit 25GW this year, according to EnergyTrend.

According to Taiwan-based solar market research firm EnergyTrend, the solar cell manufacturing capacity dedicated to passivated emitter rear contact (PERC) technology is expected to almost double in 2017, reaching around 25GW.

The firm said that global PERC cell capacity reached 15GW in 2016. Momentum for PERC migration is increasing, considering EnergyTrend previously guided PERC installed capacity reached around 2.5GW by the end of 2015 and 7GW plus in 2015.

EnergyTrend's 2017 forecast that 10GW of PERC capacity would be added in 2017 was said to come primarily from capacity expansion announcements in 2016 that would be completed in the first half of 2017.

Photovoltaics International sister website PV Tech recently reported the tracking of 6.9GW of capacity expansion announcements and 2.5GW of PERC upgraded production line announcements, totalling 9.4GW.

EnergyTrend's latest forecast expects PERC capacity to expand to 36GW in 2018, 47GW in 2019 and reach 61GW in 2020, accounting for almost 45% of total solar cell capacity of 138GW.

It said the strong migration to PERC was supported by the demand for high-efficiency modules and distributed generation systems in China, via the 'Top Runner' programme that currently requires only advanced, high-efficiency products to be installed and carry slightly higher feed-in tariffs payments.

However, market dynamics are also at play, according to EnergyTrend, which said the price difference between mono c-Si PERC cells and conventional mono c-Si cells had been kept at US$0.05/W or higher average price differential, providing higher and much needed margin advantage.

Trends

High-efficiency solar cell capacity expansions gain momentum in 2016

High-efficiency solar cell migrations, whether monocrystalline or multicrystalline with PERC and n-type mono heterojunction (HJ) have been gaining strong momentum since 2015, according to ongoing analysis by PV Tech.

Overall high-efficiency monocrystalline solar cell capacity expansion announcements in 2016 accounted for around 40% of the global total of c-Si cell expansion plans, up from around 26% of the total in 2015.

In 2016, a total of around 38GW of c-Si solar cell expansion plans were announced globally, which included almost 11GW of dedicated mono c-Si cell capacity, compared with almost 27GW of multi c-Si solar cell plans.

A key reason for this is that a number of PV cell and integrated manufacturers that can produce both p-type mono and p-type multi cells have typically not broken out whether the cell capacity expansions include both wafer types. Indeed, another challenge has been examples of later conversion of p-type multi cell lines to allocate some capacity to mono cell production.

China's rising polysilicon imports sets stage for repeat solar install boom in 2017

According to polysilicon market specialist, Bernreuter Research, polysilicon import levels into China surged between October and November 2016, while ASPs also recovered, a trend seen the year before and ahead of China installing a record 22GW of solar in the first half of 2016.

Bernreuter Research noted that polysilicon imports into China in October 2015 went from 7,504MT to 10,028MT in the following month, a 33.6% increase. Imports were said to have peaked at 13,866 MT in March 2016. The timing is in line with the upstream supply chain meeting PV module demand by the end of June, 2016 when FiT changes applied.

However, a new surge in polysilicon imports mirrored the previous cycle with 8,680MT imported in October 2016 and 13,584MT imported in November, a 56.5% increase. According to the Chinese

Credit SunPower

Migrations to high-efficiency cell concepts gained momentum in 2016.

customs statistics, polysilicon imports reached a new monthly record high of 14,449 MT in December 2016.

Although polysilicon imports indicate a repeat cycle from 2016, the end-market demand may be higher in 2017. Bernreuter noted that part of the spike in imports in Q4 was due to a large number of Chinese polysilicon producers curtailing production and carrying out annual maintenance of plants, though extended these operations due to market demand weakness through H2 2016. Recent official Chinese PV install figures for the second half of 2016 were 13GW, compared to 22GW in the first-half of the year.

However, domestic production quickly recovered from 12,600MT in October 2016 to a new high of 18,000MT in December.

Wafer

GET terminates wafer supply deal with sub-contractor Eversol

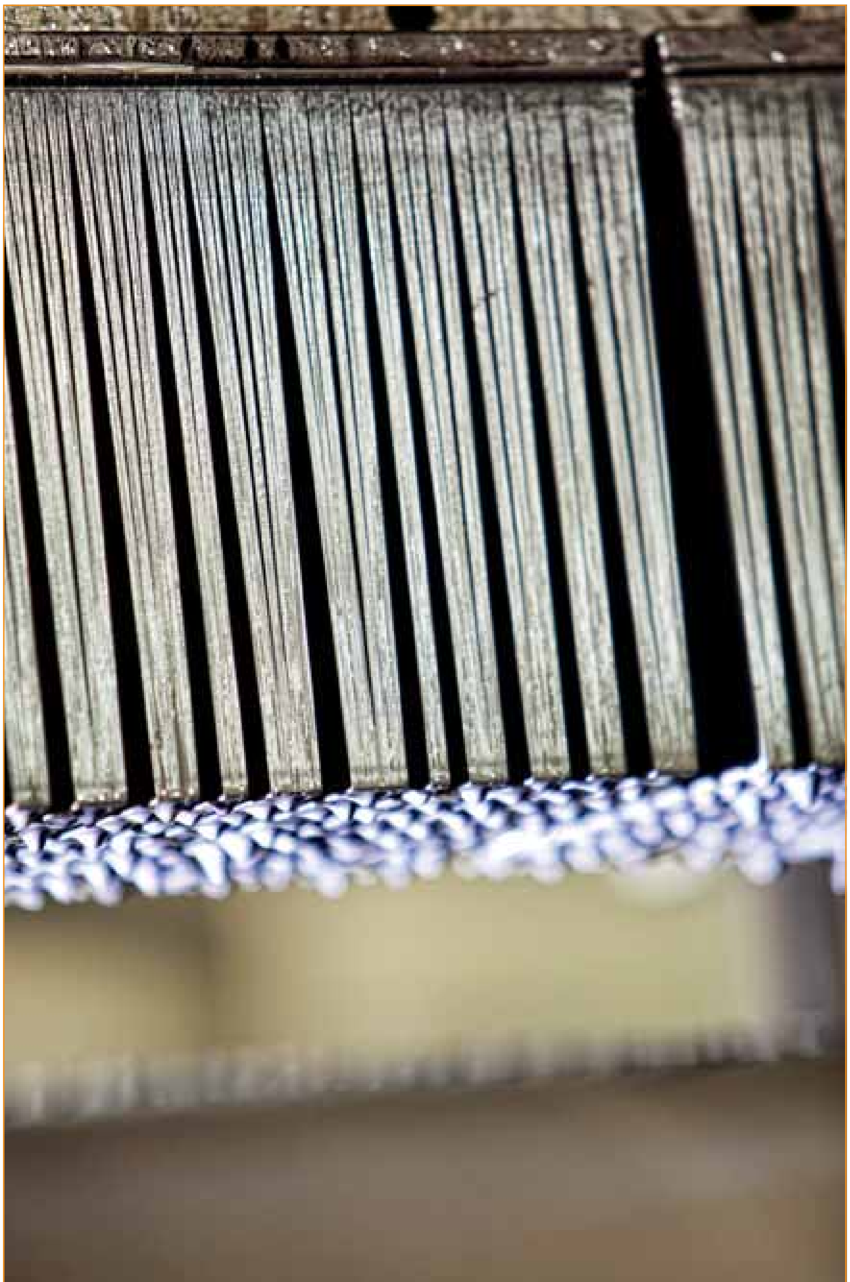
Taiwan-based multicrystalline wafer producer Green Energy Technology (GET) has s terminated a sub-contracting wafer supply deal with wafer producer Eversol Corporation.

GET had been using Eversol as third-party supplier since operating its existing wafer operations above 95% utilisation rates, due to strong demand from 2015 through to the end of June 2016. However, a slowdown in demand from Taiwan cell producers and customers in China in the second half of the year meant GET was forced to significantly reduce outsourced wafer capacity from third-parties to keep in-house utilisation rates high.

In the case of Eversol, GET noted that the wafer supplier had become embroiled in a lawsuit and the 'execution of provisional seizure by a third party' preventing Eversol from providing wafers to GET under an existing contract.

GET claimed that Eversol had provided only a small proportion of its outsourced wafer needs, however Eversol was touted to have around 1GW of ingot and wafer slicing capacity to GET's 2GW back in mid-2015 when the supply deal was started.

The legal and possibly financial problems surrounding Eversol may have been exacerbated by major Korean polysilicon producer terminating a polysilicon supply deal with Eversol late last year.



Credit Solargiga

Solargiga has seen product shipments increase as ASPs fall.

Solargiga's mono wafer shipments recover in fourth quarter but ASP decline hits revenue

China-based integrated monocrystalline PV producer Solargiga Energy Holdings has reported only a small year-on-year revenue gain in 2016, despite product shipments increasing 34% as ASP declines worsened in the fourth quarter of the year.

Solargiga reported unaudited full-year revenue of RMB3,021.3 million (US$438 million), 4.2% higher than the previous year, which included sales of mono c-Si ingots, wafers, cells and modules as well as downstream EPC services and sales of electricity from PV power plants.

Therefore revenue in the fourth quarter of 2016 was around RMB611.3 million (US$88.6 million), down around 11% from the previous quarter.

Solargiga reported product shipments in 2016 totalled around 1,543MW, up 34%, from 1,151MW in 2015. Shipments in the fourth quarter reached around 417.5MW, up from 376MW in the previous quarter.

The improved shipments in the fourth quarter were primarily offset by lower ASP's in the quarter.

InnoEnergy invests €2 million in NexWafe solar wafer production technology

InnoEnergy has invested €2 million in solar wafer epitaxial growth technology by NexWafe that increases the efficiency of solar cell manufacturing.

The technology, known as EpiWafer, is claimed by the companies to be revolutionary in enabling manufacturers to go straight from raw material to wafer form, by cutting out several development stages that are not only costly but time-consuming, saving up to 50% in the costs of PV wafer manufacturing.

In a joint pilot project known as

News

Credit SolarWorld

SolarWorld is its shifting production focus to mono PERC, at the cost of several hundred jobs.

Epicomm, NexWafe will develop solar cells and modules from its wafers, with designs to scale-up significantly. The project is backed by reputable research firms including Fraunhoefer ISE, ISC Konstanz and Ecosolifer and Fill Factory.

SCHMID expects over 5GW of orders for new diamond-wire-cut multi-c-Si texturing tool

PV manufacturing equipment specialist SCHMID Group has launched a new texturing tool for diamond-wire-cut multi-c-Si wafers that has already secured orders in the 500MW range and expects significant order intake through the first half of 2017.

The DW PreTex tool is claimed to be a low-cost alternative to plasma etch processes using standard texture HF/HNO3 chemistries in a high-volume wet bench configuration.

Claimed to provide a more uniform surface than slurry-cut wafers, the DW PreTex system is also said to provide potential cell efficiency gains.

SCHMID noted that apart from the 500MW of pre-orders, a further 5GW of new orders for the tool are expected in the first-half of 2017. The first systems are expected to be shipped in Q2 2017.

Company news

SolarWorld to focus on monocrystalline PERC production with 400 job losses

SolarWorld is to shift its production focus to monocrystalline PERC cells and modules and away from multicrystalline to build economies of scale with high-efficiency only products. With the realignment of production to mono PERC products, including bifacial modules, around 400 jobs would be lost by the end of 2019.

SolarWorld said that smaller production 'entities' in Arnstadt and solar cell production in Freiberg would be relocated with emphasis on production in Arnhem and Thuringia. Monocrystalline ingot/wafer production at its facility in Arnstadt would be expanded and diamond wire wafer saws used at the Frieburg facility. Module assembly would remain at its Freiberg facility.

The company also noted that it would invest a mid-double-digit million amount in the expansion and the improvement of its high efficiency technologies.

Overall module production would be raised to around 2GW over the next two years, up from around 1.3GW in 2016.

The company slashed around 500 jobs in September 2016. In a separate statement the company said that preliminary 2016 revenue increased by 5% compared to 2015, reaching €803 million.

INDEOtec enters heterojunction solar cell R&D programme with CSEM

PV manufacturing equipment specialist INDEOtec SA has been awarded a grant from the SWISS Commission for Technology and Innovation (CTI) to further develop its OCTOPUS deposition platform for heterojunction solar cells in partnership with Swiss research partner, CSEM.

INDEOtec said the funding was in the 'single-digit million Swiss Franc' range and would support further validation of its OCTOPUS II/PECVD-PVD cluster system for double-sided deposition, enabled by its 'Mirror Reactor' design that offers lower processing costs and higher conversion efficiencies for heterojunction solar cells.

INDEOtec noted that the R&D project with CSEM would target the ability to manufacture in typical volume processing environments cell precursors that would yield to >23% efficiency levels with low thickness non-uniformity for the deposited thin films of < 5%.

The company had previously sold its tools to other R&D facilities in Europe and the US.

Meyer Burger supplying diamond wire tools to European customer SolarWorld

Leading PV manufacturing equipment supplier Meyer Burger Technology is to supply its DW 288 Series 3 diamond wire cutting saws to an existing European customer.

The tool order was said to be worth around CHF8 million (US$7.9 million) with delivery and commissioning of the equipment scheduled to start in the second quarter of 2017. Meyer Burger also noted that the order included service support and on-site training for the DW 288 Series 3 diamond wire cutting platform.

The company recently announced new orders for its PERC cell technology, valued at around US$19.6 million.

HPM silicon: The next generation of multicrystalline silicon for PV

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Market Watch | Fab & Facilities | Materials | Cell Processing | Thin Film | PV Modules

ABSTRACT

High-performance multicrystalline (HPM) silicon, achieved by nucleation on special seed layers at the crucible bottom, is now increasingly replacing conventional multicrystalline (mc) silicon, which is solidified on the standard silicon nitride coating. The HPM material is characterized by a very fine initial grain structure consisting of small, regularly shaped grains surrounded by a large number of random-angle grain boundaries. These grain structure properties, which differ significantly from those of conventional multicrystalline silicon, lead to a much lower dislocation content in the material, and therefore result in higher efficiencies of the silicon solar cells produced. This paper gives a rough overview of the worldwide R&D activities on HPM silicon in recent years, supplemented by several research results obtained at Fraunhofer IISB/THM. The focus is on the different seeding methods, the grain structure properties and the development of the grain and defect structure over the ingot height, as well as on the main challenges for further improvements in material quality and production costs.

Introduction

Today, multicrystalline (mc) silicon is used for roughly 50% of all silicon solar cells produced worldwide. Even though the cell efficiency of mc silicon solar cells is a little lower than that of monocrystalline cells, mc silicon is expected to hold a significant market share over the next ten years, given its good material quality at reasonable production costs [1].

The most popular crystallization method for producing mc silicon is the *directional solidification technique*: silicon feedstock is melted in a square-shaped fused silica crucible that is coated with a silicon nitride powder on the inner surfaces. By extracting the heat in a downward direction, an mc silicon ingot (ingots with a weight of 600–800kg and an edge length of 840–1,000mm are typical nowadays [1]) is solidified from bottom to top. As a result, the initial nucleation of the silicon melt at the crucible bottom leads to the typical mc grain structure consisting of irregularly shaped grains, including many dendrites and twins. Until recently, the view of the majority of the mc silicon crystal growth community was that an mc grain structure with large grains and electrically inactive grain boundaries (especially twin boundaries) should lead to the best cell efficiencies [2]. Special growth methods – such as 'dendritic casting' in 2006 [3] or the 'mono-like approach' in 2008 [4] – were therefore developed in order to enhance the grain size and reduce the most harmful crystal defects in mc silicon, namely grain boundaries and dislocation clusters. However, both of the above-mentioned techniques presented some insurmountable problems concerning the propagation of dislocations in the ingot volume, especially on an industrial scale, and were therefore practically discontinued.

"It has been found that HPM silicon results in ~0.5%$_{abs.}$ higher solar cell efficiencies."

In 2011 a kind of revolution took place with regard to considerations about the best-quality mc grain structure. A new silicon material, the so-called 'high performance mc silicon', or HPM silicon, was first announced by the Taiwanese company Sino-American Silicon Productions Inc. (SAS) [5,6]. This type of material, obtained by special nucleation techniques (see below), exhibits a very fine grain structure in contrast to conventional mc silicon. It has been found that HPM silicon results in ~0.5%$_{abs.}$ higher solar cell efficiencies [6,7], which means that the grain structure properties significantly influence the eventual cell properties.

Since 2011 much R&D activity has been conducted in order to: 1) investigate the grain structure of this HPM material in detail; 2) understand the development of the grain structure as well as the crystal defects over the ingot height; and 3) further improve the material quality and the yield of high-quality wafers per ingot.

Grain structure and defect development in HPM silicon

In 2011 SAS found that the degree of undercooling of the silicon melt, adjusted at the initial state of solidification, was a strong factor in influencing the grain structure [5,6].

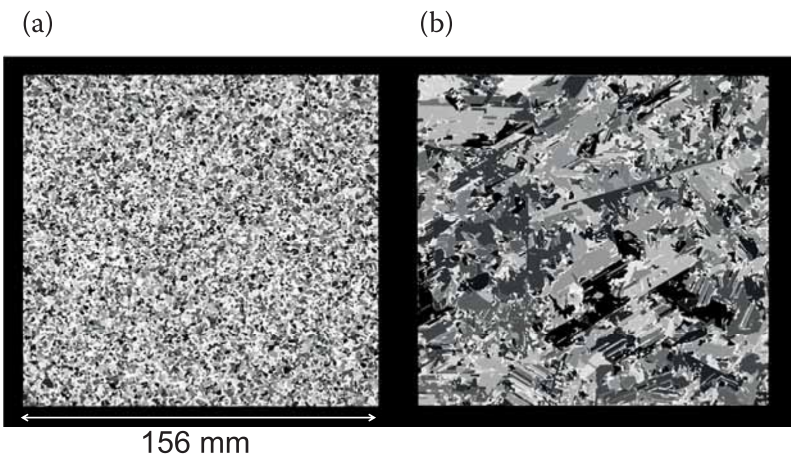

Figure 1. Images of typical grain structures, at a height of 20mm, of G1 silicon bricks grown at Fraunhofer IISB/THM: (a) HPM; (b) conventional mc.

Materials

However, the company also stated that the 'undercooling window' to generate a HPM structure with small uniform grains was quite narrow. Thus, if the undercooling is too low, a grain structure with large and non-uniformly shaped grains is generated, whereas if the undercooling is too high, very large dendritic grains are the result. In consequence, the implementation of a reproducible industrial-scale crystallization process to influence the grain structure by controlling just the undercooling is quite challenging.

Today, the most frequently used method for producing HPM silicon on an industrial scale is through solidification on a non-melted silicon feedstock layer [6,8], which is achieved by melting the feedstock charge downwards inside the crucible, from top to bottom. The melting-down has to be carried out very carefully in order to avoid a complete melting of the feedstock, especially in the border regions of the crucible. As a result, a layer of non-melted silicon feedstock particles, several millimetres thick, remains; these particles act as nucleation sites for the silicon melt. When the silicon melt solidifies on these silicon particles, the typical HPM grain structure containing very small grains (Fig. 1(a)) is uniformly generated; this is significantly different from the structure obtained using the conventional method without a seeding layer, just by nucleation on the standard silicon nitride coating (Fig. 1(b)).

At the beginning of HPM material development, there was a lack of suitable characterization tools that would allow an overall grain structure analysis on a full 156 × 156mm^2 wafer area in a reasonable timescale. A new tool was therefore developed at Fraunhofer IISB/THM in 2011 [9], which was a combination of optical grain detection and Laue measurements, enabling the determination of grain size, grain orientation and grain boundary type, including several statistic evaluations [10]. Typical images obtained from these measurements are shown in Fig. 2.

With the use of this tool, a comparison of several industrially grown silicon ingots created by the group at Fraunhofer [7] revealed typical grain structure parameters: for HPM silicon at 20mm growth length, the typical findings were: 1) a mean grain size of < 4mm^2; 2) a homogeneous distribution of grain orientations (coefficient of variation CV_{GO} < 1.5; the smaller this value, the more homogeneously distributed the grain orientations); and 3) a length fraction of random grain boundaries of greater than 60%. In contrast to those findings, conventional mc silicon ingots exhibit a much coarser grain structure with a mean grain size of 4–9mm^2, a CV_{GO} > 3, and a length fraction of random grain boundaries of less than 35% [7].

In the last few years, different researchers have found that this large difference in the initial grain structure is the main reason for the better performance of the HPM material in comparison to conventional mc silicon (e.g. [5,6,11–13]). Dislocations are inevitably formed during the growth of any mc silicon material; these can easily spread and multiply into the volume of conventional mc silicon ingots because of the large grains and the large number of Σ3 twin grain boundaries which the dislocations can go past [14]. In contrast, the dislocation movement within HPM silicon is prevented by a large number of random grain boundaries which the dislocations cannot pass [14]; further, the amount of spreading within the grains is limited because of their small size. In summary, there is a need for the smallest possible grain sizes, in combination with

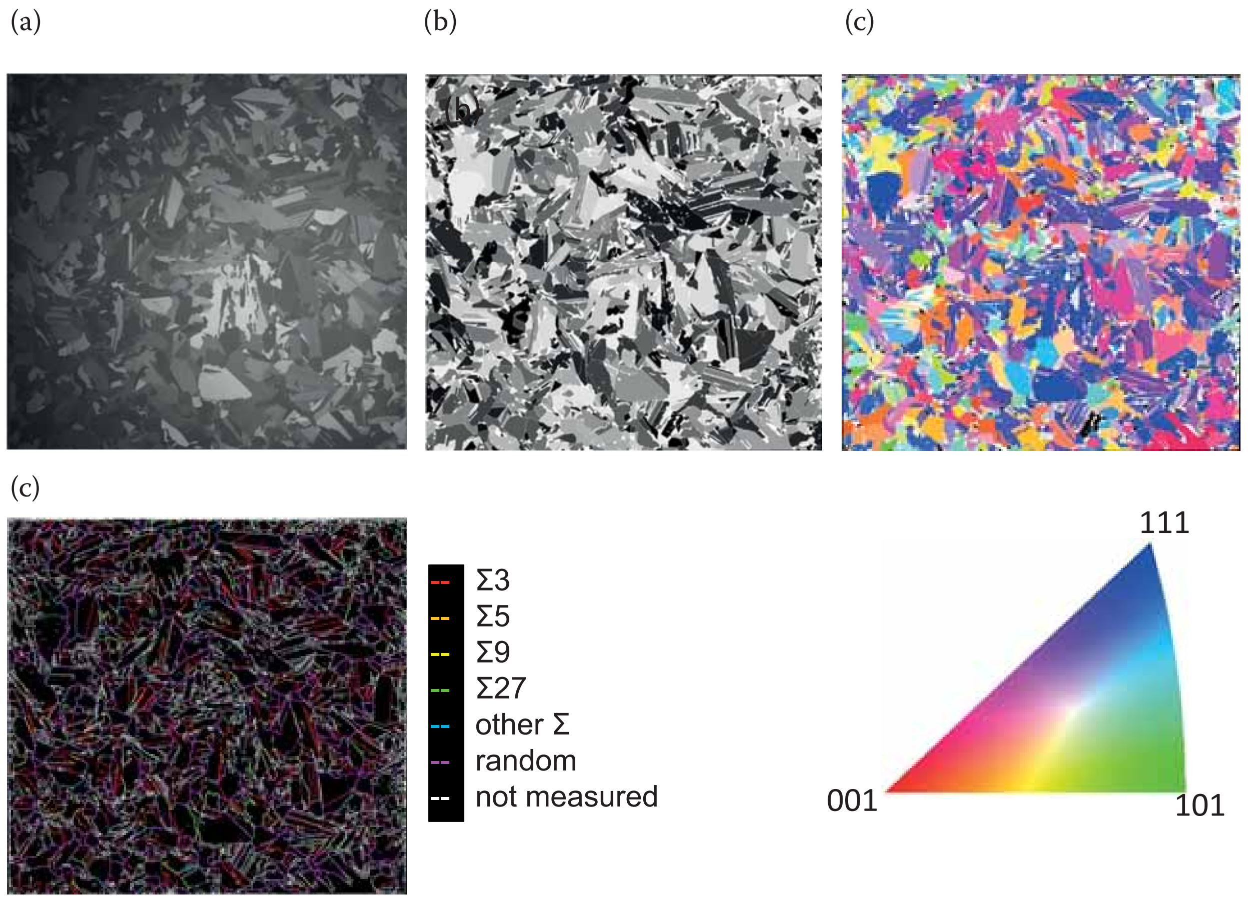

Figure 2. Resulting images from the characterization of a 156mm × 156 mm mc Si wafer: (a) photograph of the investigated wafer; (b) detected grain structure; (c) exact grain orientation; (d) calculated grain boundary types.

the largest possible number of random grain boundaries, in order to achieve a high-quality mc silicon material with a low dislocation content and thus a small recombination-active area.

During the research activities at Fraunhofer IISB/THM concerning HPM material, the initial seeding process was investigated in lab-scale HPM silicon experiments [15]. It was found that the initial grain size of the mc structure depends on the size of the microstructure of the feedstock used within the seeding layer (Fig. 3).

When single-crystalline silicon (SCS) feedstock particles from 12mm to less than 1mm in diameter are used, the resulting mean grain size decreases with decreasing feedstock particle size; this is because each particle represents one seed, and for small diameters more seeds can be located on the crucible bottom area (Fig. 3, left). On the other hand, when polycrystalline feedstock (e.g. from Siemens process (SIE) or fluidized bed reactor (FBR)) is used, one feedstock particle provides more than one seed because of its microstructure, which is characterized by an inner grain size of less than 1mm. As a result, the achievable mean grain size is slightly smaller than that for the smallest single-crystalline feedstock, whereas the differences between the tested polycrystalline feedstocks are not as large (Fig. 3, right). This conclusion has also been reached by other researchers [16], who measured a smaller inner grain size for the SIE chips (70–270µm) than for the FBR granules (700µm); however, the larger gaps between the irregularly shaped SIE chips also lead to bigger grains, and therefore offset this difference. The investigations have also shown that the initial length fraction of random grain boundaries slightly increases if the initial grain size becomes smaller [15].

A study of the dislocation content reveals a clear correlation between the random grain boundaries and the dislocation content (Fig. 4): specifically, the higher the length fraction of random grain boundaries, the lower the dislocation content or recombination-active wafer area. This means that a smaller initial grain size results in a higher random grain boundary fraction, and ultimately in a lower dislocation content in the HPM material.

Investigations of the grain structure development over the ingot, for both lab-scale [12,13,17] and industrial-scale ingots [6,7], reveal that the initially high random grain boundary fraction of 60–70% decreases during the growth of the ingot, while the number of Σ3 twin boundaries increases. This phenomenon has been studied in detail by different groups (e.g. [17,18]); they found that different grain boundary annihilation and formation mechanisms take place during growth, leading to a permanent diminishing of grain boundaries (especially high-fraction types), and simultaneously to the formation of new grain boundaries with low energy (especially Σ3 twin boundaries). In consequence, the dislocation content, and therefore the recombination active area, of HPM wafers increases with increasing ingot height.

> **"The advantage of HPM silicon is most evident in the lower parts of the ingot, where the difference in grain structure between HPM and conventional mc silicon is largest."**

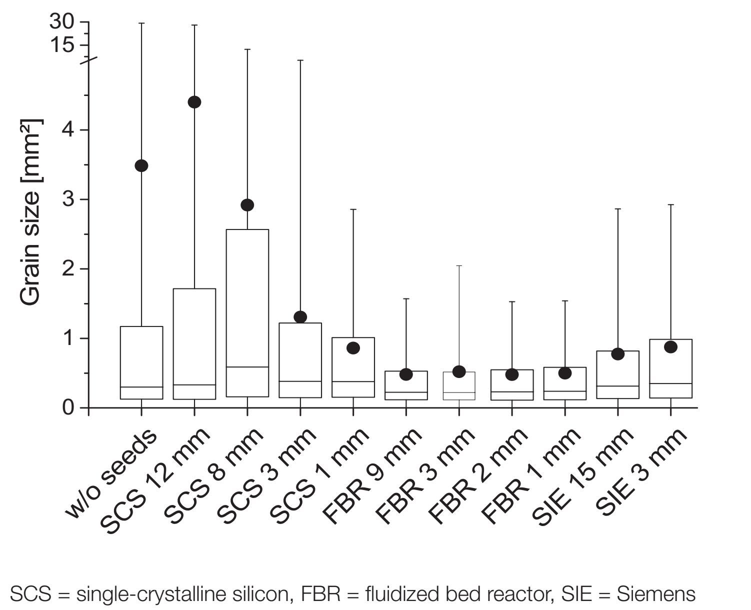

Figure 3. Grain size data at 5mm above the seeding position for HPM lab-scale ingots using several silicon feedstocks of different particle sizes, compared with a conventional mc silicon ingot without silicon seeds. (Data collected from Reimann et al. [15] with permission from Elsevier.)

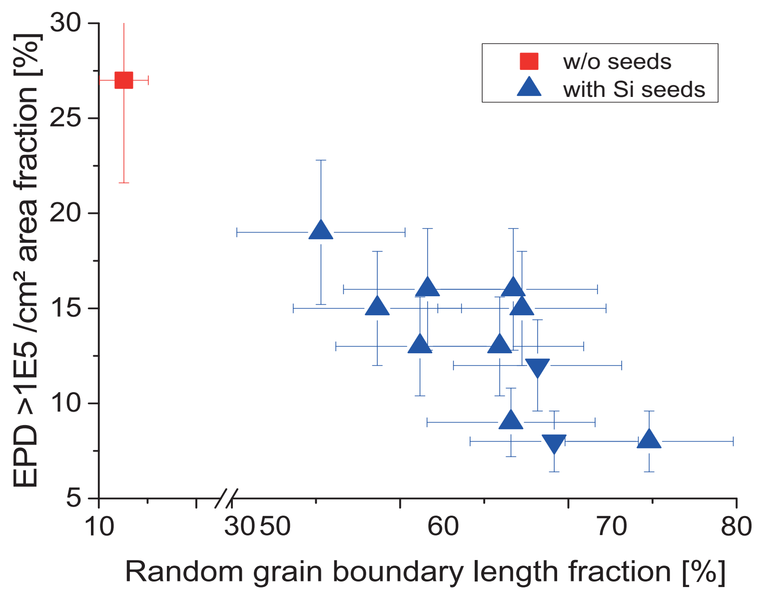

Figure 4. Fraction of areas with an etch pit density (EPD) >1E5/cm² vs. the random grain boundary length fraction at an ingot height of 25mm, for lab-scale HPM material experiments performed without and with silicon seeds. (Data adapted from Reimann et al. [15] with permission from Elsevier.)

If one compares the grain structure and recombination active area of industrial-grown HPM and conventional mc silicon ingots near the ingot top (~250–300mm ingot height), it is observed that the difference in grain structure properties, and also in the recombination active area between the two material types, is not as significant in the top region, since it initially occurs in the bottom region of the ingots [7]. From this observation, it seems that the advantage of HPM silicon is most evident in the lower parts of the ingot, where the difference in grain structure between HPM and conventional mc silicon is largest.

This theory has been confirmed by further investigations carried out by the group at Fraunhofer, for which exceptionally tall HPM and conventional ingots, up to 710mm in height, were grown [11]. The exceptional ingot height was obtained by the successive growth of eight G1 ingots (each with a height of 130mm), while a 20mm horizontal cut from the top region of the preceding ingot was used as the seed-plate for the subsequent ingot. The results show that the grain structure properties of both material types, although quite different at the ingot bottom, align with each other with increasing ingot height. This is already observable in the grain structure itself, but also in the grain-boundary-type distribution, which was identified as one key parameter in influencing the dislocation movement in the silicon ingots (see Fig. 5). While at the ingot bottom the grain-boundary-type distributions are significantly different between the conventional ingot (high Σ3 twin fraction, low random fraction) and the HPM ingot (high random fraction, low Σ3 twin fraction), the distributions align with each other with increasing ingot height, finally becoming very similar at a height of 250–300mm. Further, it was shown that, during the growth above 350mm, no significant changes occur through this region to the top of the ingots at 710mm.

For the recombination-active area it was found that, after an initial discrepancy up to an ingot height of 200mm due to the above-described mechanisms, an alignment takes place up to a height of 350–400mm. Finally, from this height to the top (710mm), constant values occur, which are equal for both material types (see Fig. 6). From this observation it is concluded that the growth of even higher HPM silicon ingots is of no benefit to industrial producers in terms of the advantage of HPM silicon over conventional mc silicon.

In general, it is clear that there is a strong correlation between the grain structure properties and the dislocation development over the ingot height. Thus, the control of the grain structure throughout the complete ingot is one of the main tasks for further improving the HPM material quality.

Alternative nucleation methods for achieving HPM silicon

The main advantage of the above-described method which incorporates the seeding on a non-melted silicon particle layer is its high reproducibility in industrial production. However, some drawbacks also exist, which reduce the economic profitability: first, the more complex melting process entails longer process times in comparison to the conventional growth of mc silicon; second, there are some yield losses in the bottom region of the ingot caused by the non-usability of the seeding layer for the wafer production and by an increased bottom red zone.

In the last few years some new approaches for the production of HPM silicon have been proposed with the aim of overcoming these problems. The key aspect of these methods is to provide foreign nucleating agents on the crucible bottom and to solidify the silicon melt directly on them in order to achieve the fine-grained HPM structure. These nucleation agents should be stable at high temperatures, should be wettable by the silicon melt in order to reduce the nucleation energy in comparison to the standard silicon nitride coating, and should not, of course, contain a large content of electrically harmful impurities (e.g. metals).

Initial investigations on small lab-scale ingots were performed in 2014 by Wong et al. [19] by applying silicon and silica particles in different mixing ratios (1:3 and 3:1) as a coating on the crucible bottom. It was observed that the higher the silica content in the coating, the larger the number of resulting small and uniform grains. However, those authors found no clear correlation with the random grain boundary fraction, which was less than 30% and still quite low. In all likelihood, the silica seed density on the bottom surface was too low to significantly influence the grain structure properties.

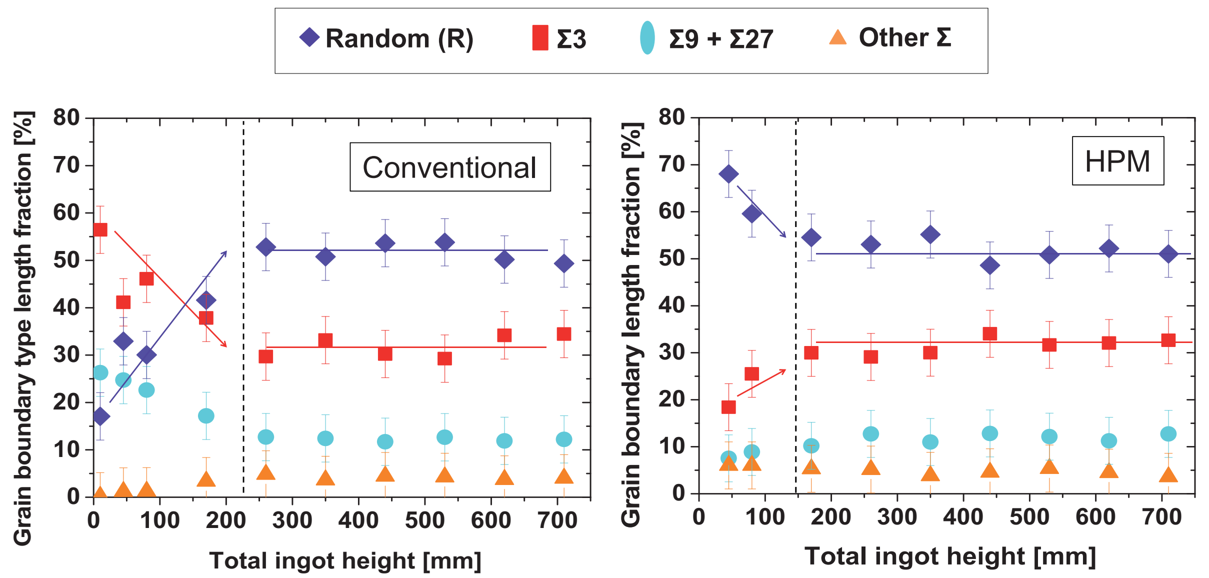

Figure 5. Grain boundary length fraction vs. total ingot height for the 710mm G1 conventional ingot (left) and the 710mm G1 HPM ingot (right). (Reprinted from Trempa et al. [11] with permission from Elsevier.)

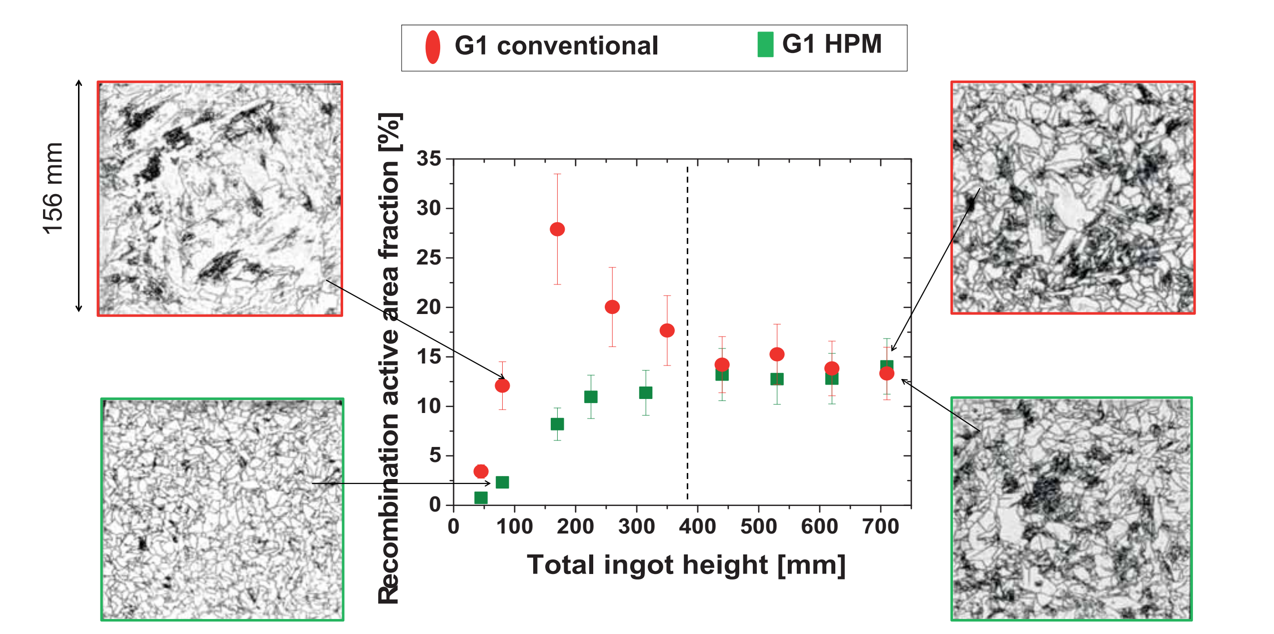

Figure 6. Recombination-active area fraction vs. total ingot height for the 710mm G1 conventional ingot (red circles) and the 710mm G1 HPM ingot (green squares). Photoluminescence (PL) images of both 710mm G1 ingots are shown for total ingot heights of 80mm (left side) and 710mm (right side). (Reprinted from Trempa et al. [11] with permission from Elsevier.)

The potential of a functional coating based on silicon dioxide (SiO_2) and silicon carbide (SiC) particles was investigated by Fraunhofer IISB/THM (the results will be reported in a forthcoming publication). This coating was applied to the bottom of G1 crucibles (220mm × 220mm) on top of the standard silicon nitride coating, either by spraying a particle–water suspension or by embedding particles in an additional wet silicon nitride layer. It was shown that, by the use of small SiO_2 particles (3µm in diameter), independently from the coating procedure, an initial grain structure with mean grain sizes of 1–4mm^2 and a random grain boundary fraction of about 60% could be obtained (see Fig. 7(a)); this is almost the same as for HPM silicon seeded on a silicon feedstock layer, shown in Fig. 1(a). The SiC-based coatings also reduce the mean grain size, but many dendrites and twins were also generated, leading to relatively low random fractions of less than 40% (Fig. 7(b)).

Another approach tested on lab-scale ingots was recently published by Babu et al. [20]; here, a mono-layer of small FBR granules (1mm in diameter) coated with a thin silicon nitride layer was used. Because of the thinness of the coating, the wavy surface morphology of the FBR layer, on which the nucleation process took place, was guaranteed. The results show that an initial random grain boundary fraction of 55% could be achieved by this method, leading to a reduced quantity of dislocation clusters in comparison to conventionally grown mc silicon.

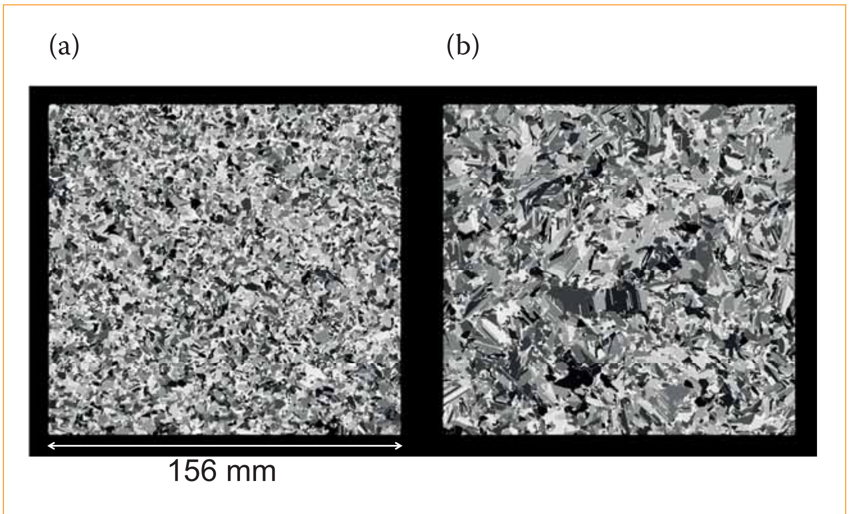

Figure 7. Grain structure images at 20mm height for two G1 mc silicon ingots grown at Fraunhofer THM by using (a) a SiO_2 coating, and (b) a SiC coating.

Zhang et al. [21] have presented the first test results of the application of their method in an industrial G5 crucible with inner dimensions of 840mm × 840mm. They proposed a technique providing a SiO_2 incubation layer, thinly coated with silicon nitride, which was achieved by a mask process. The material analysis showed that the new seeding method yields a comparable grain structure, as well as very similar cell efficiencies in most parts of the ingot, to classical HPM material. The slightly higher oxygen content in the bottom region of the ingots could be the only problem with regard to solar cell properties.

Further investigations on an industrial scale were recently carried out by Buchovska et al. [22], who used silica knobs of 0.5–5mm in length as nucleation sites at the bottom of the crucible. The results show that both the dislocation content of the wafers and the cell efficiencies compare very well to those of HPM silicon seeded on silicon chips. In the side and edge regions in particular, the new HPM material has demonstrated even better properties than the classical HPM ingot because the seeding process in these regions is better optimized.

In summary, the alternative nucleation methods are on the right path to replace classical seeding on a silicon feedstock particle layer in order to reduce the production costs of high-quality HPM silicon wafers, as well as increasing the yield. However, much research still needs to be done to increase the initial random fraction to values above 60%, while ensuring the reproducibility of the results on an industrial scale, as well as their robustness, because of the use of different crystallization processes and furnaces. Additionally, the oxygen contamination problem when SiO_2-based layers are used has not yet been completely solved.

> "HPM silicon material exhibits excellent structural and electrical properties and will thus increasingly replace conventional mc silicon over the next few years."

Summary and outlook

It is concluded that HPM silicon material exhibits excellent structural and electrical properties and will thus increasingly replace conventional mc silicon over the next few years.

The main challenge for making further improvements to the material quality of HPM silicon will be to maintain a high value of the random grain boundary length fraction along the entire ingot height in order to minimize the dislocation content. It is possible that this can be achieved by optimizing the growth parameters, such as the growth rate, the temperature gradient or the phase boundary deflection. The first suggestions were offered by Wong et al. [12] and Lin et al. [17], who observed that the higher the growth rate, the faster the decrease in random grain boundary fraction with ingot height because of the increase in newly formed Σ3 twin boundaries. Lowering the growth rate could therefore be promising, even if this counteracts the economical aspect, where slow growth rates are unfavourable.

Another challenge for further increasing the material properties of HPM material relates to the absolute contamination level resulting from the feedstock, the crucible, the coating and the furnace components.

Acknowledgements

The HPM material R&D activities at Fraunhofer IISB/THM were carried out partly within the HENSi project (0325449B) and the ENOWA-II project (0325805E), funded by the German Federal Ministry for Economic Affairs and Energy, in collaboration with SolarWorld Innovations GmbH, and partly within the frame of bilateral collaborations with Wacker Chemie AG. We would also like thank all our colleagues at Fraunhofer IISB/THM, SolarWorld and Wacker who have been working with us on these projects, for their contributions and fruitful discussions.

References

[1] SEMI PV Group Europe 2016, "International technology roadmap for photovoltaic (ITRPV): 2015 results", 7th edn (Mar.), Version 2 [http://www.itrpv.net/Reports/Downloads/].
[2] Nakajima, K. et al. 2010, *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA, pp. 817–819.
[3] Fujiwara, K. et al. 2006, *J. Crys. Growth*, Vol. 292, No. 2, pp. 282–285.
[4] Stoddard, N. et al. 2008, *Solid State Phenom.*, Vol. 131–133, pp. 1–8.
[5] Lan, C.W. et al. 2012, *J. Crys. Growth*, Vol. 360, No. 0, pp. 68–75.
[6] Yang, Y.M. et al. 2015, *Prog. Photovolt: Res. Appl.*, Vol. 23, No. 3, pp. 340–351.
[7] Lehmann, T. et al. 2016, *Acta Mater.*, Vol. 106, pp. 98–105.
[8] Zhu, D. et al. 2014, *J. Crys. Growth*, Vol. 386, pp. 52–56.
[9] Reimann, C. et al. 2011, *Proc. 5th Int. Worksh. Cryst. Si. Sol. Cells (CSSC-5)*, Boston, Massachusetts, USA.
[10] Lehmann, T. et al. 2014, *Acta Mater.*, Vol. 69, No. 0, pp. 1–8.
[11] Trempa, M. et al. 2017, *J. Crys. Growth*, Vol. 459, pp. 67–75.
[12] Wong, Y.T., Hsu, C. & Lan, C.W. 2014, *J. Crys. Growth*, Vol. 387, pp. 10–15.
[13] Prakash, R.R. et al. 2014, *J. Crys. Growth*, Vol. 401, pp. 717–719.
[14] Stokkan, G. et al. 2014, *Sol. Energy Mater. Sol. Cells*, No. 130, pp. 679–685.
[15] Reimann, C. et al. 2016, *J. Crys. Growth*, Vol. 434, pp. 88–95.
[16] Ekstrøm, K.E. et al. 2016, *J. Crys. Growth*, Vol. 441, pp. 95–100.
[17] Lin, H.K. et al. 2016, *J. Crys. Growth*, Vol. 439, pp. 40–46.
[18] Prakash, R.R. et al. 2015, *Appl. Phys. Express*, Vol. 8, No. 3, p. 35502.
[19] Wong, Y.T. et al. 2014, *J. Crys. Growth*, Vol. 404, pp. 59–64.
[20] Babu, G.A. et al. 2016, *J. Crys. Growth*, Vol. 441, p. 124–130.
[21] Zhang, H. et al. 2016, *J. Crys. Growth*, Vol. 435, pp. 91–97.
[22] Buchovska, I. et al. 2017, *Sol. Energy Mater. Sol. Cells*, Vol. 159, pp. 128–135.

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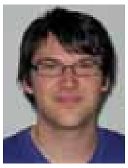

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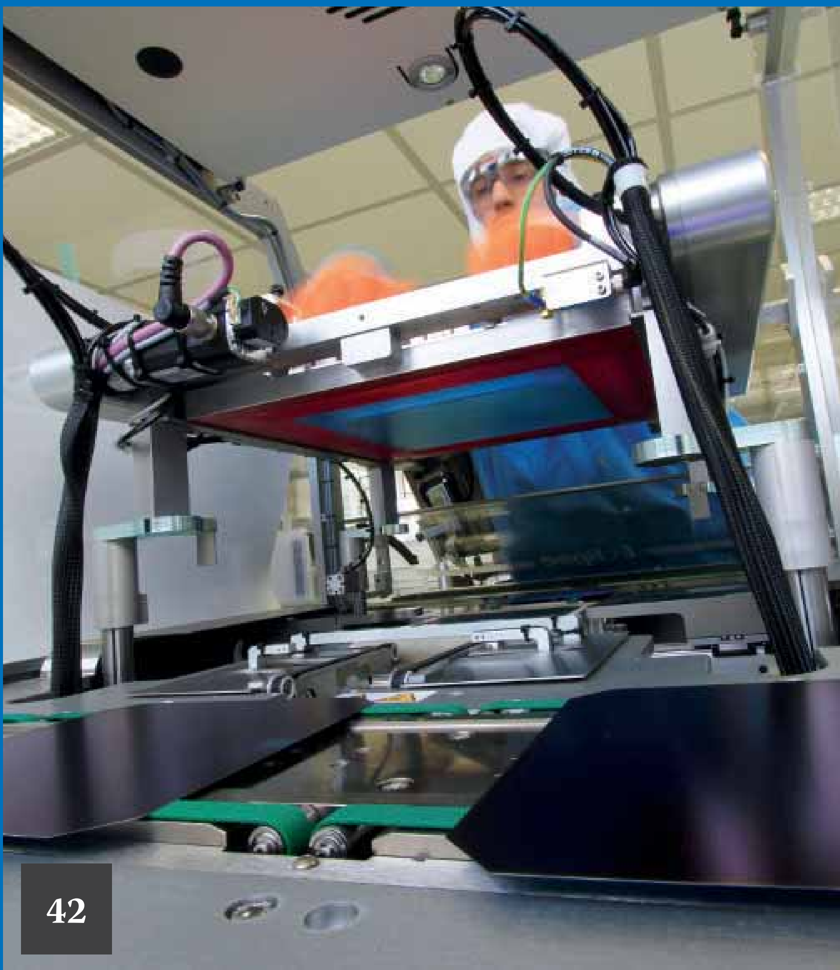
Cell Processing



SunPower hits average cell conversion efficiencies of 25% at Fab 4

Credit SunPower

SunPower claims to have reached a production average cell efficiency of 25%.

High-efficiency PV module producer and project developer SunPower has reached a production average cell conversion efficiency of 25% at its Fab 4 facility in the Philippines, the highest in the industry.

The company's Fab 4 facility is expected to complete ramping to its nameplate capacity of 350MW in 2017.

SunPower's management expected to spend around US$100 million in capital expenditures to upgrade its Fab 3 (800MW) solar cell facility in Malaysia to its next-generation n-type monocrystalline IBC (Interdigitated Back Contact) cell technology (X Series) that is being ramped at Fab 4. Total capex for 2017 was said to be around US$120 million.

R&D expenditures in 2017 will also be kept high to support its IBC cell development. R&D spend would also be allocated to further development of the firm's different integrated installation systems for residential and commercial rooftop sectors and its utility-scale ground mount tracking system technology. The company spent US$99 million on R&D in 2015, the second highest in the industry to CdTe thin-film producer, First Solar.

With the ramping of Fab 4 and the planned upgrades at Fab 3, SunPower could be expected to rely more heavily on its P-Series modules, which use sourced solar cells and are assembled at its consolidated module assembly plant in Mexico.

Cell performance

Copper plated solar cells meet industry module reliability standards – imec

Nanoelectronics research centre imec said that copper-based solar cells have reached the same reliability standards as traditional silver-based solar cells in recently completed rapid-cycle testing of a limited number of specially prepared modules.

Imec's Ni-Cu-Ag plated p-type Cz-Si cells, using Meco's 'Direct Plating Line' technology, followed by annealing in an inline belt furnace and interconnected with standard soldering and lamination processes, were able to pass a number of IEC61215 tests with results in line with conventional modules.

Ni/Cu/Ag plated cells are expected to become mainstream when SolarCity/Tesla start migrating process technology from its Silevo subsidiary to support the production ramp at its Buffalo fab in New York State, sometime in 2017.

Suntech reaches 20% multicrystalline PERC cell efficiencies in production

China-based PV module manufacturer Wuxi Suntech, a subsidiary of Shunfeng International Clean Energy (SFCE), has achieved multicrystalline passivated emitter rear contact (PERC) cell efficiencies of 20% in production.

Suntech noted that the 20% cell conversion efficiencies would convert to 330W modules in a 72-cell (large-format) module, 15W higher than its current product offering and specification sheets currently available.

The company did not say how much nameplate capacity was already allocated to PERC technology or how much capacity would be migrated to PERC in 2017.

Recently, parent company SFCE terminated a MOU with its major shareholder and Hong Kong property tycoon, Kin Ming Cheng, over the potential sale of its solar manufacturing operations, which includes Wuxi Suntech.

1366 Technologies and Hanwha Q CELLS hit 19.6% efficiency with 'Direct Wafer' technology

US-Based wafer producer 1366 Technologies and 'Silicon Module Super League' (SMSL) member Hanwha Q CELLS have jointly hit 19.6% efficiency for cells using 1366's 'Direct wafer' process.

The efficiency, independently confirmed by the Fraunhofer ISE CalLab, was achieved using 1366's kerfless, drop-in 156mm multicrystalline wafers using its 'Direct Wafer' method and Hanwha's Q.ANTUM passivated emitter rear

Credit Suntech

Suntech has achieved a 20% cell conversion efficiency with a multi-c-Si PERC cell.

contact (PERC) cell process.

The Direct Wafer process creates multicrystalline wafers directly from molten silicon instead of taking several steps that require more energy and expense. 1366 claimed that its technology can be adopted by 60% of the PV market, without manufacturers having to add any new equipment.

The wafers for the new record cell were produced at 1366's current production furnaces in Bedford, Massachusetts, while the cell fabrication was completed at Hanwha Q CELLS' Centre for Technology Innovation and Quality in Thalheim, Germany.

Trina sets new mono PERC cell efficiency record of 22.61%

'Silicon Module Super League' (SMSL) member Trina Solar has set a new world record of 22.61% efficiency for a p-type mono-crystalline cell with PERC technology at its State Key Laboratory of PV Science and Technology of China.

The large-area 243.23cm2 solar cell was fabricated on a large-sized boron-doped Cz-Si substrate.

The new cell efficiency has been independently confirmed by the Fraunhofer ISE CalLab in Germany and it surpasses Trina's previous record of 22.13% achieved in 2015. In July 2016, Trina Solar also claimed that its production lines were able to produce the same kind of PERC cells in large volume with an average efficiency of 21.12%.

Dr. Pierre Verlinden, vice-president and chief scientist of Trina Solar, said: "We want to demonstrate all the possibilities of PERC technology on an industrial scale, and to approach as close as possible to the 25% efficiency level."

Trina Solar sets 19.86% aperture efficiency record for p-type multicrystalline cell

'Silicon Module Super League' (SMSL) member Trina Solar has also set a new world record of 19.86% aperture efficiency for a p-type multicrystalline solar cell-based module, independently verified by the Fraunhofer ISE CalLab in Germany.

The record was set with half-cut cell interconnection, PERC technology and highly efficient light trapping on a module area of 1.514m2.

The new record represents an increase of more than 0.7 percentage points, or approximately 3.8% higher than the previously held efficiency record of 19.14% on a 1.515m2 module aperture area announced in April 2015. As with previous developments, the work was carried out at Trina Solar's State Key Laboratory of PV Science and Technology of China (SKL PVST).

REC touts best production line multicrystalline cell efficiencies of 20.47%

Integrated PV module manufacturer REC Group has claimed that a pre-production batch of multicrystalline solar cells at its manufacturing plant in Singapore achieved a best conversion efficiency of 20.47% measured by an in-house tester with an external calibration cell.

Upgraded wafer to cell processes were responsible for achieving an average cell efficiency of 20.21%, with the best cell at 20.47%. The process developments were to be applied to REC's production lines at the beginning of November last year.

"This great achievement is a strong testament to our R&D efforts at each step in the value chain," noted Steve O'Neil, chief executive at REC.

Despite having to trim its global workforce, the firm is committed to spending US$48 million to upgrade all production to its half-cut PERC cell technology, used in its 'TwinPeak' series modules.

Credit Hanwha Q CELLS

Hanwha Q CELLS was the top solar cell producer in 2016.

Company news

Hanwha restores Q-CELLS to number one solar cell ranking in 2016

Hanwha Q-CELLS was the number one solar PV cell manufacturer in 2016, based on megawatts of cells produced in-house across the year, according to PV Tech analysis.

In 2016, the firm became a reinvigorated and restructured cell manufacturing powerhouse across China, Malaysia and South Korea that is structured for maximum fab utilization and module sales profitability in markets that reduce the exposure to China, namely the US, Japan and Europe.

Crucially also, and a key part in the company becoming the top cell producer in 2016, has been a more diligent approach to the use of in-house components, compared to the likes of JinkoSolar and Trina Solar that have been putting more priority on end-market module shipment volumes, regardless of where the selling product was made or by whom.

Shunfeng heading for a US$133 million loss in 2016

Diversified renewable energy firm Shunfeng International Clean Energy (SFCE) expects to report a loss in 2016 of around US$133 million (RMB 923 million) due to a catalogue of issues.

Two of SFCE's previous acquisitions, Suniva and Lattice Power had generated losses for the year, while its existing PV power plant portfolio continued to suffer from grid curtailment issues in various regions in China. Furthermore, there were increased interest expenses related to the

Credit Meyer Burger

Meyer Burger orders topped almost US$150 million in the four months up to January 2017.

construction of PV power plants in the year that also contributed to overall losses in 2016.

Ongoing grid curtailment issues in Xinjiang, Gansu and Qinghai provinces meant the loss of approximately 600,000,000 kWh in potential electricity generation that equated to around US$69.3 million in lost revenue in 2016.

Tool orders

Meyer Burger wins new solar equipment orders over US$146 million in past four months

Leading PV manufacturing equipment supplier Meyer Burger Technology netted orders worth over US$146 million in the four months up to January 2017, including a new order worth CHF18 million (US$18.03 million) for its PERC cell technology and SiNA cell coating systems from two customers based in Asia.

More than half of the orders were booked in the fourth quarter of 2016, including a fully-integrated 200MW heterojunction production plant worth around US$67 million for a customer in Turkey.

At least US$70 million of the total has been equipment orders placed by customers in Asia, which includes PERC technology and diamond wire wafer cutting tools.

The latest order for its MAiA 2.1 technology platform and SiNA cell coating systems are expected to be shipped and commissioned in the second quarter of 2017, according to the company.

Aurora Solar breaks into China market with first cell emitter measurement tool order

Inline measurement equipment specialist Aurora Solar Technologies has won an initial order from an undisclosed customer in mainland China, its first order for its Decima measurement system and 'Veritas' software in the East Asian country.

Aurora said that process technology consultancy firm, NEXXERGY International, an affiliate of EXXERGY Group had placed the order, which includes a portable Decima 3T system for the emitter sheet resistance measurements within solar wafers and Aurora's Veritas software, which provides real-time 3D visualization of diffusion and annealing processes intended to optimise solar cell emitter processes for uniformity and yield.

Recently, Aurora secured a major order for its inline measurement systems from LG Electronics, which is expanding high-efficiency solar cell production from 1GW to 3GW by 2020.

3D-Micromac receives multiple PERC cell laser system order from REC Group

Laser micromachining equipment supplier 3D-Micromac has secured an order from REC Group to supply three 'microCELL' OTF laser systems for PERC solar cells from integrated PV module manufacturer REC Group.

3D-Micromac noted that the tools would be used for REC's volume PERC cell migration and the development of next-generation PERC solar cells at its main production facility in Singapore.

The microCELL OTF laser systems are used for laser contact opening (LCO) in the passivation film layer on the rear surface of the wafer and enables throughputs of up to 4,000 wafers per hour.

Amtech's new solar cell equipment orders reach US$60 million high

Orders from specialist PV manufacturing equipment supplier Amtech Systems topped US$60 million from the end of September 2016 up to late January, driven by PV manufacturers in China, Malaysia and Taiwan.

New order wins included its high throughput PECVD platform and n-type bi-facial solar cell turnkey order from a new customer in China. The majority of the orders were expected to ship within the next six to nine months.

The company's advanced n-type cell technology led to securing the turnkey order from the new customer in China, which would be the first part of a multi-phase 1GW cell and module expansion.

Amtech had previously reported new solar orders in its fiscal fourth quarter 2016 ended 30 September 2016 of only US$11.8 million and had achieved a new order high of US$28 million in its fiscal 2016 second quarter.

In-line quality control in high-efficiency silicon solar cell production

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ABSTRACT

There are numerous tools and methods available on the market for the optical and electrical quality control of high-efficiency silicon solar cells during their industrial production, and even more are discussed in the literature. This paper presents a critical review of the possibilities and limitations of these tools along the value chain, from wafer to cell, in the case of passivated emitter and rear cells, as well as a discussion of some showcases. Economic and technological challenges and future trends are addressed.

Introduction

Within the PV industry, every player on the market faces fierce competition. Solar cell and module manufacturers aim at reducing their costs and the use of consumables, while at the same time improving throughput and uptime, yield, process stability, cell reliability and cell output power. In order to achieve higher solar cell output power, more and more cell and module manufacturers seek salvation in switching from conventional silicon solar cells with full-area aluminium back-surface field to passivated emitter and rear cells (PERCs), as the latter concept allows higher output power with minimum change to the production line. However, the higher potential of this type of device comes with a higher sensitivity to material and process variations. In order to better control these variations, as well as to find further potential for process improvements, an intelligent use of in-line characterization techniques should ideally combine the required investigation of material and device properties with real-time process and production control.

In-line quality control along the PERC value chain, from wafer to cell

From the point of view of a solar cell manufacturer, in-line quality control can be prioritized as follows. Solar cell manufacturers buy wafers, fabricate solar cells and finally sell them. The output power of the cells under standard test conditions is very important for establishing the price at which they are sold. Thus, in the first place, cell manufacturers need to measure the output power or energy conversion efficiency; consequently, a current–voltage measurement tool with a sun simulator at the end of the cell production line is indispensable. Next, the manufacturers want to get hold of inexpensive and high-quality wafer material, which can be tested either at the end of the wafer production line or at the beginning of the cell production line. A specific

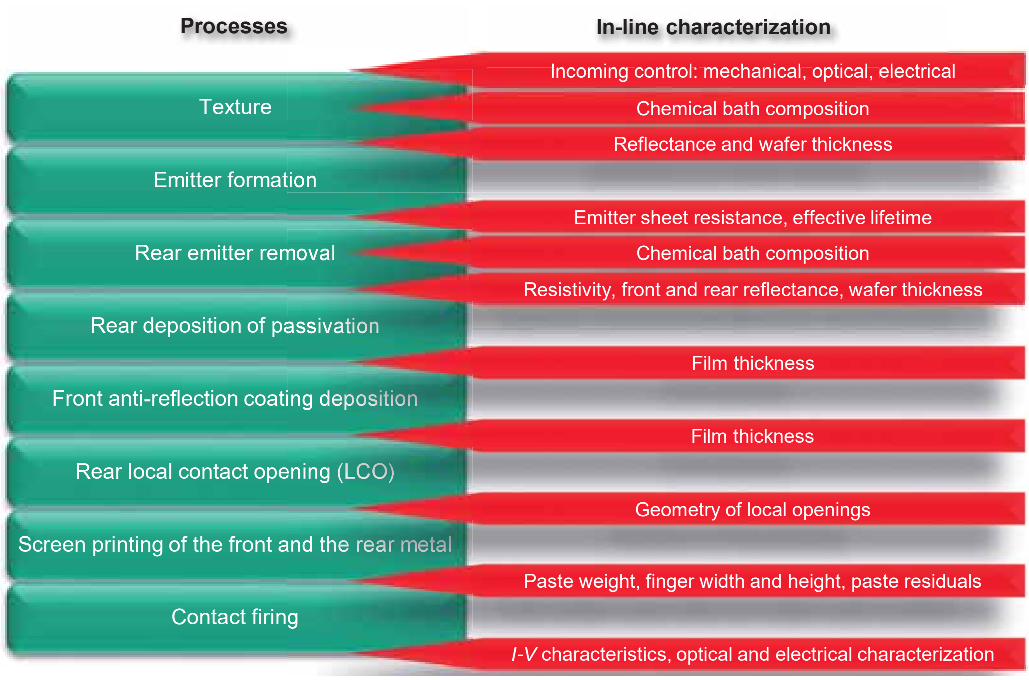

Figure 1. Simplified process flow typically used for the fabrication of PERC solar cells, along with important corresponding in-line characterization tasks.

type of incoming test is therefore also a high priority for cell manufacturers. During the production of solar cells, a high quality and stability of the individual process steps is required. For this purpose, many scientists and metrology suppliers have developed various methods and products that are available on the market, though little used in industry because of their obvious costs and arguable benefits.

> "A specific type of incoming test is a high priority for cell manufacturers."

A typical PERC manufacturing process will now be described and will cover the value chain from wafer to cell. Currently available tools for in-line quality control will be mentioned, and some examples of applications will be elucidated. Aspects of in-line quality control from crystallization and wafer manufacturing, however, are not discussed here but are covered elsewhere in the literature. The enumeration is not claimed to be comprehensive, but it certainly covers many important and interesting tools.

Process sequence

A simplified process flow for PERC cell production is shown in Fig. 1. First, the p-type mono- or multicrystalline wafers are wet-chemically textured. The n-type emitter is formed on the front and rear surfaces of the wafers in a diffusion oven. Prior to surface passivation, the rear emitter is typically wet-chemically removed, followed by a cleaning step. The passivation of the rear surface is realized, for example by an aluminium oxide (Al_2O_3) layer deposited by fast atomic layer deposition (ALD). A silicon nitride (SiN_y) layer serves as the capping layer on the rear. As regards the front surface passivation, typically a plasma-enhanced chemical vapour deposition (PECVD) SiN_x layer is used. The rear passivation layer stack is locally opened, for example by ablation using a laser process in order to obtain line-shaped local contact openings (LCOs). The front- and rear-side metallization is applied by screen printing. Finally, the contact firing is performed, for example in a conveyor belt furnace.

Incoming control

The high electrical and mechanical quality of wafers can be checked during the incoming inspection in solar cell production or during the final inspection in wafer production. Poor-quality wafers should be identified and discarded at an early stage in the process in order to avoid unnecessary costs. The wafer properties that are accessible in line are: the wafer thickness and its variation, the wafer size and geometry, and the extent of saw marks and roughness, chipping, holes and cracks. The electrical properties are: base resistivity, effective lifetime and crystal defects. In addition, surface contamination and reflectivity are optical properties that are worthy of investigation. Recent SEMI standards cover the measurement of most of these properties.

The measurement of wafer thickness is typically capacitance based. Tools measuring, for example, three traces with several hundreds of measurement points each allow the detection of not only the mean thickness (typically ~180µm), but also the total thickness variation (~20µm) and more details about the wafer shape. Slurry-cut wafers have a thinned edge, and whether this plays a role during production is worth investigating. Diamond-cut wafers, on the other hand, can have a specific large-scale saw-mark structure which might cause problems during screen printing (Fig. 2). Wafer size and geometry are identified using line or matrix cameras and are important parameters for machine alignment and handling tolerances. Special care needs to be taken as wafer sizes go up from 156.0 to 156.75mm or even further.

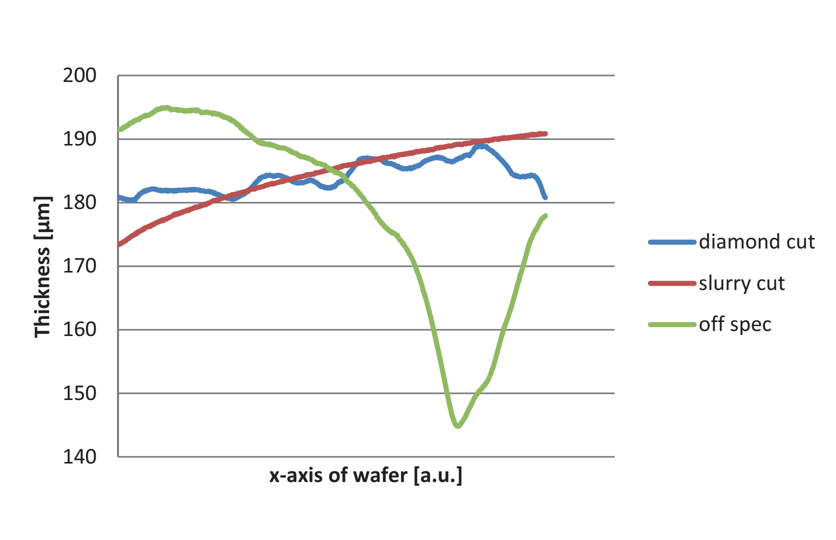

Figure 2. Three examples of thickness profiles. The diamond-cut wafer shows a typical large-scale saw-mark structure, the slurry-cut wafer shows a strong gradient, while the off-spec wafer shows a very distinct saw mark.

The presence of smaller saw marks and roughness with a spatial resolution of few micrometres can be determined using laser triangulation. We have seen no correlation of these parameters with the final solar cell results or with the manufacturing process, and therefore question the importance of such data. Chipping and edge-defects can be identified with high-resolution imaging, but automatic image processing can be problematic for wafers with strong grain contrasts or differences in reflectivity. Large and even small cracks, with lengths of a few millimetres and widths below a micrometre, can be detected using, for example, infrared transmission, infrared reflectance and photoluminescence images. In the case of monocrystalline material, the automated identification is relatively simple; in contrast, for multicrystalline material, advanced algorithms are required because of the muddled contrast between the grain boundaries and the dislocations [1]. The assessment of the criticality of a crack in the as-cut state and later process steps in terms of wafer breakage [1], solar cell efficiency losses and module hot-spot danger [2] is crucial for wafer, cell and module manufacturers.

Optical inspection using line or matrix cameras can reveal staining, residuals from cleaning, or other surface contaminations; although this method works well for slurry-cut wafers, the use of the same set-up for diamond-wire-cut wafers is not straightforward. The reflectivity of the wafers can be measured by means of a spectrometer. Since the reflectivity strongly depends on the cutting of the wafers, it can be used as a quality

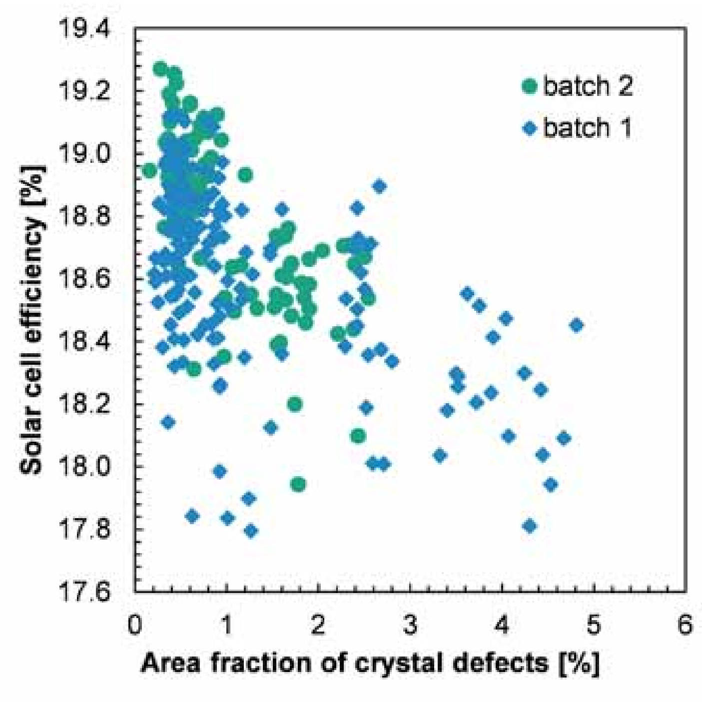

Figure 3. The solar cell efficiency of two mc-Si PERC batches is limited by the area fraction of crystal defects, here measured via photoluminescence on the as-cut wafers. Further variations in wafer properties and processes induce more efficiency variations.

parameter. In addition, reflectivity is an input parameter for the calibration of all optical detection methods that use cameras for detection or lasers for excitation.

The resistivity of the wafer is typically measured via inductive coupling: several traces with hundreds of measurement points each can be implemented. There are two obstacles when dealing with the resistivity measurements – one concerning monocrystalline silicon and the second concerning multicrystalline silicon. In Czochralski-grown monocrystalline silicon wafers, thermal donors can be formed during crystallization, depending on the oxygen concentration and thermal treatment. During heat treatments above 500°C, such as during emitter formation, these thermal donors are dissolved; hence, the resistivity measured in the as-cut state is higher for p-type and lower for n-type wafers than the actual value after thermal donor dissolution. Thermal donors therefore hinder the precise calculation of the emitter sheet resistance by combining the resistivity measurement in the as-cut state with a later measurement after

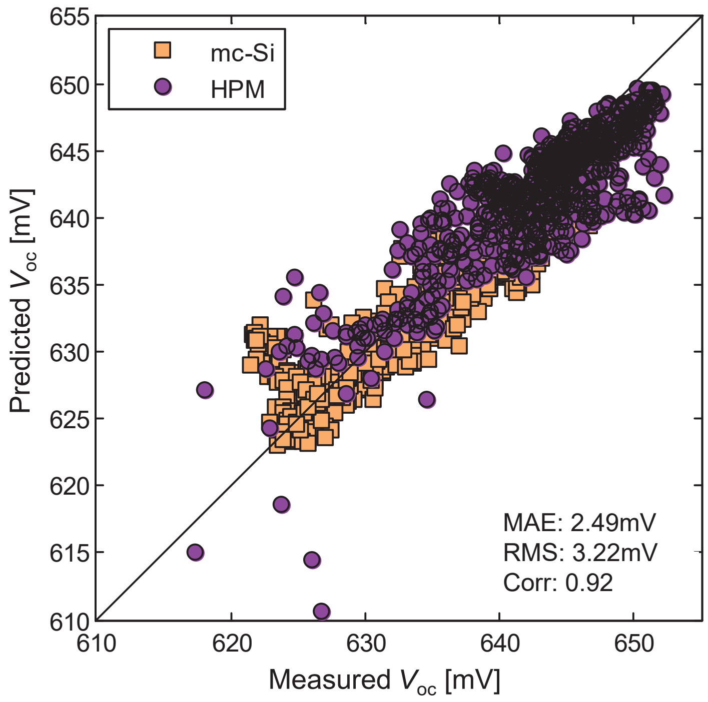

Figure 4. Predictions of the open-circuit voltage V_{oc} for more than 1,300 PERCs (adapted from [9]). The results are obtained using a regularized regression model based on empirical data, and are shown for conventional multicrystalline silicon (mc-Si) and high-performance mc-Si (HPM) wafers. The graph presents the evaluation, with the most challenging prediction of 'unknown' material shown for two unknown manufacturers whose material was not included in the training set. The approach performs well in predicting PERC data (mean absolute error MAE of 2.49mV, root-mean-square-error RMS of 3.22mV, Pearson correlation coefficient of 0.92).

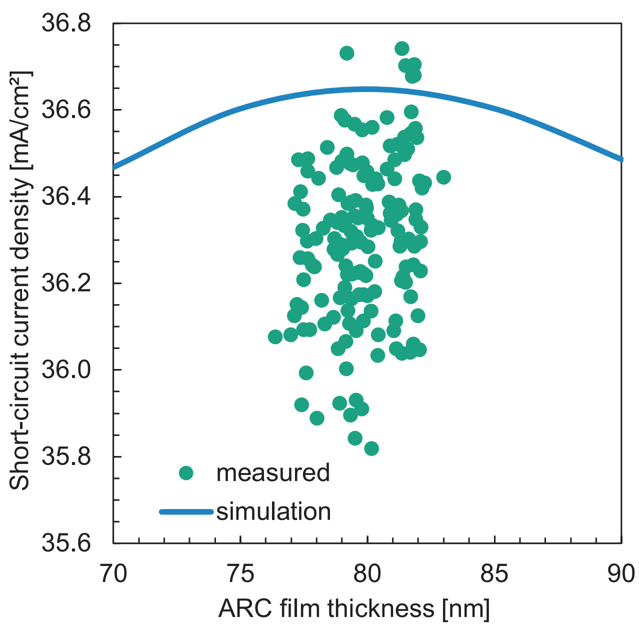

Figure 5. For these multicrystalline PERC cells, the ARC was deposited with a thickness ranging from 75 to 85nm. This variation does not degrade the short-circuit current density because of the surface texture and the very small thickness variation. From a simulation, a J_{sc} variation induced by the ARC thickness of less than 0.05mA/cm^2 is expected; the actual variation observed is mainly caused by other effects.

emitter formation; however, this can be overcome using photoluminescence imaging [3]. For multicrystalline silicon, potential barriers are formed at grain boundaries after wet-chemical treatments of the wafer and are annihilated by thermal processes, such as during emitter formation. These potential barriers increase the apparent resistivity [4]. The emitter sheet resistance should therefore be calculated by combining the resistivity measurements in the as-cut state and after emitter formation.

The bulk lifetime of minority-charge carriers is one of the most important parameters for characterizing the electrical quality of wafers. Unfortunately, in the as-cut state only an effective lifetime can be measured, which is severely limited by surface recombination and thus does not allow a correlation with the final solar cell parameters. Only wafers with very low lifetimes (e.g. as a result of crucible contaminations) can be identified and sorted out. Nevertheless, lifetime measuring systems based on microwave-detected photoconductivity (MPD) [5], microwave-detected photoconductance decay (MW-PCD) [6] and quasi-steady-state photoconductance (QSSPC) [7] measurements are available. To overcome the surface recombination limitation, the lifetime can be inspected at later process stages (e.g. after passivation).

For multicrystalline wafers in particular, crystal defects in the form of dislocation clusters can be detected with photoluminescence (PL) imaging [8], despite the high surface recombination; the technique shows the distribution of defects that severely degrade the lifetime. Such defects are detrimental to solar cell performance, as the example in Fig. 3 shows: maximum efficiencies decrease with increasing area fraction of crystal defects. (It will be seen later, in Fig. 6, that these crystal defects partly stay present during solar cell processing and reduce the efficiency of the finished cells.)

This correlation between defects and efficiency, along with the other data from the incoming inspection, can be utilized to set up a powerful prediction of solar cell efficiency, as shown in Fig. 4 [9]. Metrology suppliers are working on such prediction models for production lines, which is very difficult because prediction results are highly dependent on the solar cell process and are distorted by processing fluctuations. With Cz wafers, ring-like

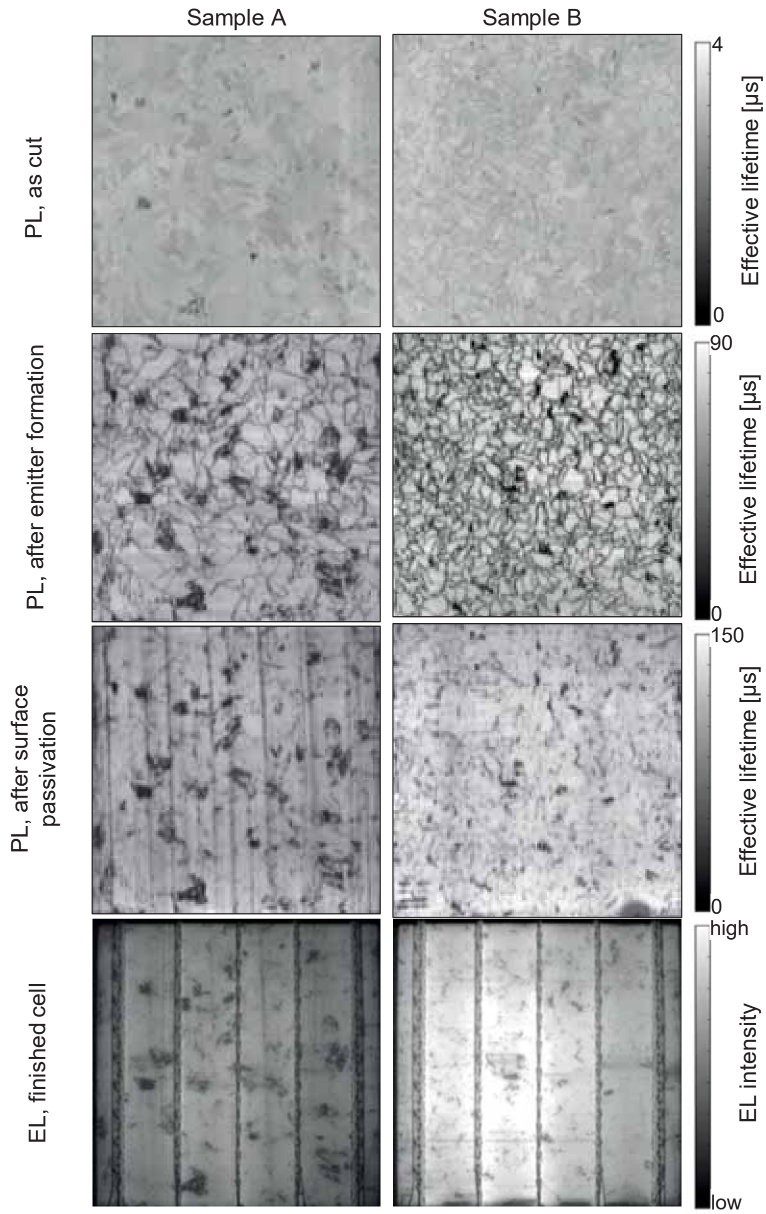

Figure 6. Photoluminescence (PL) and electroluminescence (EL) images of two multicrystalline samples at different stages of the PERC production sequence. In the as-cut state, dislocations and grain boundaries are visible and become even more pronounced after emitter formation. Following surface passivation, the grain boundaries are not clearly visible in both samples, but line-shaped defects (possibly induced by saw marks) become apparent in sample A only. In the finished cells, several material- and process-induced defects (possible saw marks, crystal dislocations, finger interruptions, edge shunts) are superimposed.

features may be detected: these are caused by thermal donors and might hint at efficiency-limiting oxygen-induced stacking faults [10].

Production processes

In-line quality control at an intermediate point between the incoming test of the as-cut wafers and the outgoing test of the finished solar cells is not believed to be very widespread. It is nevertheless a prerequisite undertaking in order to quickly detect problems that arise during production and to constantly achieve high solar cell conversion efficiencies, and one which increases in importance as the efficiency increases.

During the texturing, the concentration of chemicals in the bath can be continuously controlled using near-infrared spectroscopy. Acidic (HF, HNO_3) and alkaline (KOH, organic additives) baths that are typically used in silicon photovoltaics have been analysed [11–15]. After the texturization process, the reflectance of the wafer and its thickness can be measured and used to control the quality of the light-trapping properties and of the silicon removal respectively.

Many of the following methods require a combination of several measurements (e.g. resistivity and wafer thickness, or resistivity as-cut and after diffusion); thus, the data need to be attributable to specific individual wafers. For this purpose, methods for tracking a single wafer (e.g. using data-matrix codes) have been developed [16–18].

After the emitter formation, the resistivity can be measured and used to calculate the emitter sheet resistance. Care has to be taken in case of potential barriers at the grain boundaries in multicrystalline silicon [4], and because of thermal donors [3], as discussed above. Similarly to the as-cut state, inductive methods can be applied, but infrared techniques too are beneficial. The effective lifetime can be measured after the emitter formation, again using the same techniques as for the as-cut wafer; this is recommended in order to detect severe degradation of the bulk lifetime due to the high temperatures and large thermal budget required for emitter formation. Especially for Czochralski-grown silicon, the formation of oxygen-induced stacking faults can significantly reduce solar cell efficiency [10]. Relating the effective lifetime after emitter formation to the I–V parameters of the final cell (i.e. open-circuit voltage V_{oc} and efficiency η) is more meaningful than in the as-cut stage because of an active field-effect passivation from the emitter; however, the procedure is not straightforward.

After emitter removal on the rear side, the reflectance on the front of the wafers can be measured in order to track any wrap-around and the related degradation in texture quality. Likewise, the rear-surface reflectance can be used to track the rear-surface roughness, which is important in terms of the achievable rear-side passivation quality. Measuring the wafer thickness enables the silicon removal to be controlled. In the case of asymmetric emitter formation, for example caused by different surface structures or back-to-back boat loading, it is of interest to determine the emitter sheet resistance.

After the deposition of the thin

Cell Processing

dielectric films on the front and rear sides of the PERC cells, the film thicknesses can be determined from reflectance measurements [19] or by colour inspection. In the case of the front-side anti-reflection coating (ARC) shown in Fig. 5, the film thickness was deposited within a sufficiently small range to not degrade the final cell *I–V* parameters.

The samples can be weighed before and after screen printing of the front and rear metal, to determine the amount of silver and aluminium paste deposition. By optical inspection after screen printing, the finger width and paste residuals, as well as other grid defects, can be determined. The large contrast between the highly reflective front metal and the highly absorptive active cell area makes it challenging for in- and off-line 2D vision, and in particular for 3D vision, to determine the finger height [20].

Finished solar cells

After contact formation (i.e. when the cell is finished), extensive in-line characterization is available. Line or matrix cameras are used in visual inspection of the front side of the cells for detecting paste residuals and chipping defects, for measuring the finger width and cell dimensions, and for determining the colour of the ARC [21]. By inspecting the rear of the PERC cells with full-area Al print, the darkening of the aluminium at the LCOs caused by silicon alloying during the contact formation can be detected; this can in turn be used to detect inhomogeneous formation of the local back-surface field. In the case of bifacial solar cells, the visual inspection of the cell rear is in principle the same as that of the cell front: paste residuals, chipping, finger width and colour can be detected.

> "The most important in-line characterization for finished solar cells is without doubt the measurement of the *I–V* characteristics under standard test conditions."

The most important in-line characterization for finished solar cells is without doubt the measurement of the current–voltage (*I–V*) characteristics under standard test conditions (STC: 25°C, 1000W/m^2 illumination with AM1.5g spectrum); from this the energy conversion efficiency can be deduced and the cells can be sorted into the corresponding bins. The choice of calibration can have a significant impact on the measured values of short-circuit current and conversion efficiency [22]. Besides these measurements under constant illumination, the suns-V_{oc} characteristic can also be measured, as well as the forward and reverse *I–V* characteristics in the dark, which together allow a basic analysis of series resistance, ohmic and non-linear shunting, and hot-spot danger.

Besides the measurement of the *I–V* characteristics of the solar cells, there are upgrades available for the *I–V* testers. By measuring the resistance from one busbar to another, the resistance of the metallization can be determined in order to track the stability and quality of the front and rear printing steps. In-line measurements of the quantum efficiency or spectral response of the solar cells are offered, which allow losses occurring in the emitter to be distinguished from those occurring in the bulk and at the rear of the devices. Electroluminescence (see Fig. 6) and photoluminescence imaging allows the detection of cracks, finger interruptions and dark areas [23]. It will be interesting to see if advanced luminescence methods (e.g. [24–27]) with additional benefits can be implemented in-line in the future. Thermography is used to determine hot spots of the cells and to predict possible module hot spots locally [28–31]. Such a local analysis is preferable to an analysis of the global dark reverse current, because inhomogeneous reverse current and power dissipation within the cell is the norm, not an exception. This is highlighted in Fig. 7, where the thermography image of an mc-Si PERC cell shows a significant increase in temperature after only 40ms, which is likely to damage the module. Since the cell's reverse current at −12V is below 2A, this hot-spot danger cannot be predicted from the *I–V* characteristics.

The addition of more and more measurement tools to the cell tester means that the automat's footprint becomes larger, and that potentially more than one contacting unit with a corresponding power supply

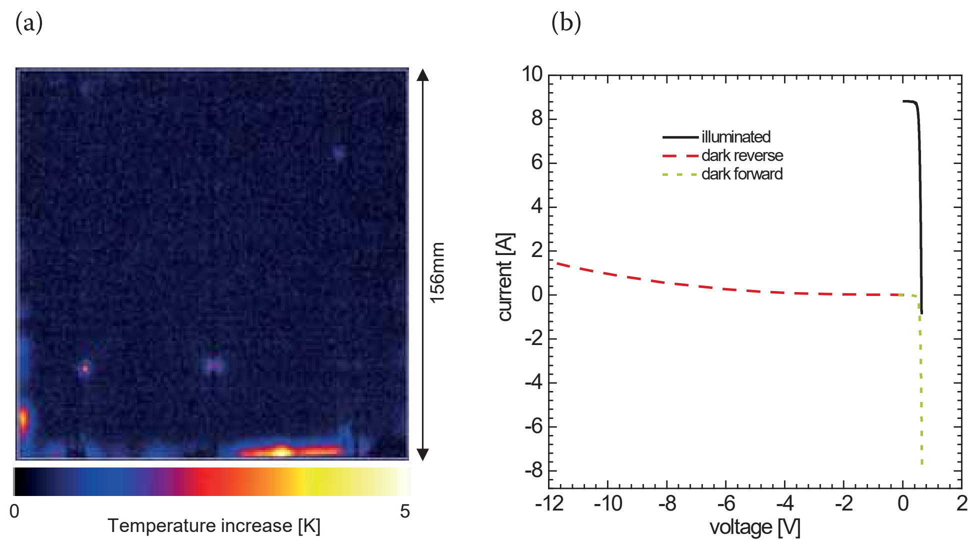

Figure 7. (a) Thermography image of an mc-Si PERC cell with a severe temperature increase of up to 5K after applying a reverse voltage of −12V for only 40ms, indicating hot-spot danger for the module. (b) *I–V* characteristics of the same cell, showing a moderate reverse current of less than 2A at a reverse voltage of −12V.

is required. Since this implies additional cost, the metrology suppliers are seeking to reuse the same hardware several times. However, when several measurements are combined within a single tool, the fraction of cycle time available for each measurement clearly decreases, implying that capacitive effects [32] and methods to deal with them [33] become increasingly important. For example, it is recommended to correct for capacitive effects when decreasing the measurement time for the *I–V* characteristics significantly below 40ms, and when increasing the open-circuit voltage of the cells above approximately 650mV.

Typical sorting criteria used to define the bins are: 1) the energy conversion efficiency or cell output power; and 2) the current at the maximum power point. The former is preferred by cell manufacturers (since a higher cell efficiency attracts a higher price), whereas the latter is favoured by vertically integrated cell and module manufacturers (since mismatch effects in the module can be minimized). Cells may also be sorted out on the basis of hot-spot danger or the presence of cracks.

Assessing the economic profitability of in-line characterization in production

When cell and module manufacturers are faced with decisions on whether to invest in advanced in-line characterization techniques, the first thing they want to know is the expected return on investment. In real production environments, parameters such as the uptime or the yield of a production tool are randomly influenced by failures, consumables and wafer quality, as well as other factors. It therefore often seems unclear how to distinguish between the positive effects of in-line quality control and the other factors affecting the performance of a production tool. This lack of clarity makes it difficult to appropriately prepare an investment decision for an in-line characterization technique.

To better understand the economic impacts of an integration of in-line characterization techniques into a production environment, a 500MWp/year monocrystalline PERC cell production process was simulated and examined using Fraunhofer ISE's cost of ownership (COO) calculation tool 'SCost' [34,35]. A calculation was made of the essential productivity improvement (in terms of cell efficiency gain) for the cell manufacturer with respect to the projected capital expenditures (capex) on in-line characterization in the production line – in other words, how much capex can be spent to break even with regard to the expected production performance enhancement.

For this analysis, the assumptions are a depreciation period of five years for the production equipment, and in-line characterization technique and wafer and module production costs of €ct78.8/wafer and €58.37/module, respectively. Moreover, it is assumed that uptime, production yield and line throughput are not influenced by the application of the in-line characterization technique.

Fig. 8 shows the resulting break-even analysis based on the Wp-cost equivalence before and after the application of the in-line characterization techniques. Since the advantage of a higher cell efficiency rises along the PV value chain, the analysis was done for the value chain stages by considering: 1) only the net costs of the cell production – excluding (for example) wafer costs – referred to as *net cell production costs*; 2) the costs of the cell production – including wafer costs, selling, general and administrative expenses (SG&A), and capital costs of the company – referred to as *all-in cell costs*; and 3) the all-in cell costs plus the corresponding costs for module manufacturing, referred to as *all-in module costs*.

The analysis shows that a capex spending of €250,000 for in-line characterization equipment is justified for a cell manufacturer if, immediately after its application for the time of usage (here five years), a mean cell efficiency increase from 20.614% to 20.657%, or 0.043%$_{abs}$, can be exceeded.

In the case of a vertically integrated cell manufacturer, or a cell manufacturer that has appropriate bargaining power with its customers (the module manufacturers), the module Wp costs instead of the cell Wp costs are preferably used for assessing investment decisions. For the break-even analysis in Fig. 8, it is seen that the capex spending of €250,000 is already justified for a cell efficiency increase of 0.026%$_{abs}$ from the reference efficiency of 20.614% to 20.640%.

If, by using the in-line characterization technique, the cell manufacturer realizes a higher cell efficiency increase than that stated above, the all-in cell (all-in module) costs decrease compared with the reference values. This influence of cell efficiency enhancement on the all-in cell costs is analysed in Fig. 9: the cell costs of a reference Cz PERC cell line (red line) are compared with four different Cz PERC cell lines (blue dashed lines) equipped with additional in-line characterization techniques at additional costs of €50k, €100k, €250k and €500k, respectively. It can be seen in this figure that the intersections of the reference cell cost line (black horizontal line) with the blue dashed lines mark the break-even points, which are also shown in Fig. 8. For each of the equipped cell lines, the cell efficiencies exceeding the values marked by the vertical lines lead to lower cell costs compared with those for the reference cell, as a result of the application of in-line characterization techniques.

This finding shows just how small the efficiency increase needs to be to justify in-line metrology; however, it also suggests, in general, the importance of the demonstration of such a cell efficiency increase induced by in-line control in order to prepare a clear and transparent investment decision regarding in-line control techniques. As noted previously, however, production parameters are strongly interlinked, and therefore economic investigations of the effects of in-line control on uptime, production yield, and so on should be carried out specifically for a dedicated application.

Challenges and future trends

In general, the most challenging question for cell manufacturers and metrology suppliers concerning in-line metrology relates to which tools and methods are required and economically advisable. A core question is how to control and improve the yield, the reliability, the

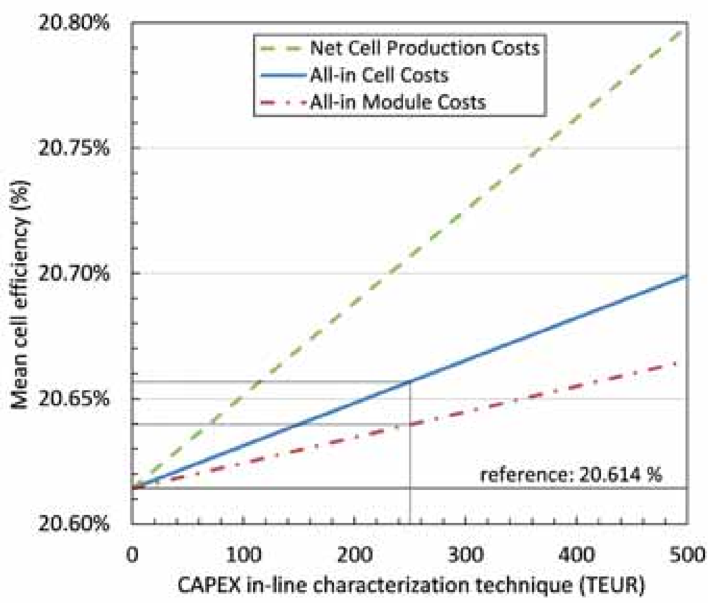

Figure 8. Break-even analysis of an in-line characterization technique, integrated into a 500MWp/year monocrystalline PERC cell production line. For the 'net cell production costs', the 'all-in cell costs' and the 'all-in module costs', the three lines indicate the respective gain in mean cell efficiency to be reached by the characterization technique in order to break even in respect of the additional expenditure for the characterization technique. These break-even points are calculated for a Wp-cost equivalence of a cell line without the characterization technique (the reference), and of a cell line enhanced by a characterization technique with a depreciation period of five years.

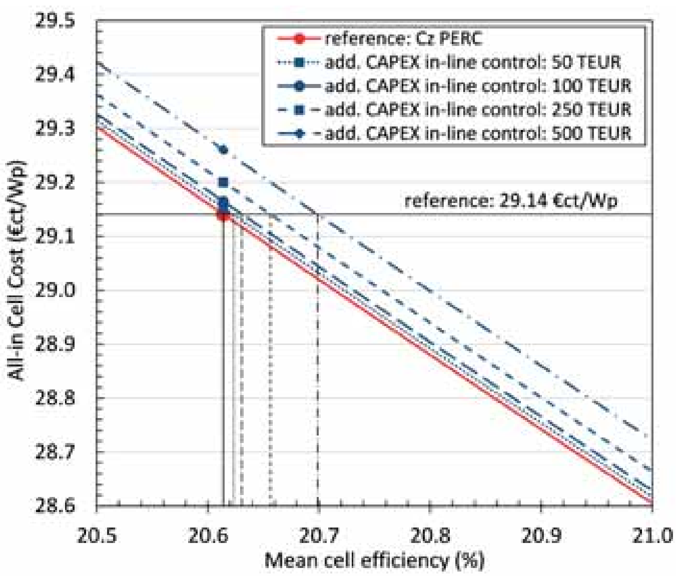

Figure 9. Sensitivity analysis of the mean cell efficiency influence on 'all-in cell costs' (including wafer, SG&A and capital costs). The red line shows the costs associated with the Cz PERC reference cell, and the red dot indicates the reference cell efficiency of 20.61%. The dashed blue lines represent the costs including the additional capex for in-line characterization. All figures are calculated for a 500MWp/year monocrystalline PERC cell production.

mean cell efficiency and the scattering of the efficiency distribution, and at what cost. Metrology suppliers have to demonstrate the benefits of their tools, either in the labs at research institutes (as in the Photovoltaic Technology Evaluation Centre PVTEC at Fraunhofer ISE) or directly in the industrial application. There are scientific approaches for identifying the stage of the production chain at which more quality assurance is advisable [36]. Giving feedback during or directly after a particular process step is clearly desirable, though not comprehensively possible, because the quality of a process may depend on, or may be assessed only after, subsequent processes. As regards the cost aspect, less expensive and more versatile metrology tools are required.

> "Less expensive and more versatile metrology tools are required."

From a technological point of view, there are several challenges at present. Thermal donors hinder the precise determination of the base resistance and hence of the emitter sheet resistance. The approaches discussed above to address this issue need to be improved and implemented. Another challenge is how to deal with the highly reflective surfaces of diamond-wire-cut wafers in the inspection tools.

Since imaging in-line metrology is still a young field, there are several challenges which have to be overcome. The image data need to be reduced, defects need to be detected reliably, and both robust and sensitive sorting criteria need to be derived; only then can the imaging metrology deliver its maximum potential benefit. Specifically, crack detection in photo- and electroluminescence images, for multicrystalline silicon wafers and cells in particular, needs to be improved. In addition, metal finger interruptions need to be reliably detected. With the growing interest in PERC cells, several challenges specific to this cell concept have arisen.

The first difficulty lies in separating the front and rear defects. In the electroluminescence image, for example, there are visible contrasts which might originate either from interruptions of the metallization fingers on the front side, or from incomplete formation of the back-surface field of the line-shaped rear contacts. Because of the preferred printing direction, the front fingers and rear LCOs are aligned with one another, provided the samples are not rotated after the rear-side printing step.

A second PERC-specific metrology task is the thickness determination of the passivation stacks. The thicknesses of the individual films can be determined separately from reflectance or ellipsometric measurements [37].

To the authors' knowledge, no tool currently exists for the in-line quality control of LCOs with typical dimensions below 50µm on the whole wafer, which presents a third PERC-specific challenge. The future will show whether the openings will need to be controlled as more and more PERC cell manufacturers enter the market.

After the introduction of monofacial PERC cells into industrial production, the likely next step will be to apply an aluminium grid instead of a full-area metallization at the cell rear, and hence convert the device into a bifacial solar cell with a potential increase in electricity yield. For this concept, the measurement of the *I–V* characteristics is again the biggest issue from the metrology point of view. It is not yet clear, either for calibration laboratories or for industrial production, whether it is sufficient to illuminate the samples from one side only, or whether this needs to be done from both sides separately or from both sides simultaneously. The construction and design of the measurement chucks, and especially the reflectivity in the infrared region, are of particular interest when measuring and reporting *I–V* data of bifacial cells. The rear inspection and the separation of front and rear defects (paste residuals, finger thickness and interruptions, etc.) are further issues to be addressed in the case of bifacial cells.

After the rear of a silicon solar cell has been improved by introducing the PERC concept, it is likely that the front of the cell will limit the conversion efficiency. Consequently, another probable step to be taken is to implement a selective emitter, which has already been discussed a couple of years ago [38]. As the highly doped structures and the metallized structures become ever narrower, the process stability and its precision must increase adequately. In order to align the highly doped structures and the metal grid, it is certain that new solutions and more quality control will be required.

Only time will tell if the currently hyped trend of 'Industry 4.0' will in fact become established, or if it will disappear into oblivion. It is certain, however, that intelligent machines and tools talking to and interacting with each other lead to improved quality and reduced cost. A prerequisite for this is the collection of data by in-line metrology tools, but the possible growth in in-line metrology will not happen on its own – it has to be elaborated step by step.

References

[1] Demant, M. et al. 2016, "Microcracks in silicon wafers I: Inline detection and implications of crack morphology on wafer strength", *IEEE J. Photovolt.*, Vol. 6, No. 1, pp. 126–135.

[2] Demant, M. et al. 2016, "Microcracks in silicon wafers II: Implications on solar cell characteristics, statistics and physical origin", *IEEE J. Photovolt.*, Vol. 6, No. 1, pp. 136–144.

[3] Broisch, J., Haunschild, J. & Rein, S. 2014, "Determination of the dopant-related base resistivity in presence of thermal donors", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 1171–1176.

[4] Spitz, M. & Rein, S. 2011, "Impact of potential barriers at grain boundaries of multi crystalline silicon wafers on inductively coupled resistivity measurements", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 338–343.

[5] Dornich, K. et al. 2009, "New spatially resolved inline lifetime metrology on multicrystalline silicon for PV", *Proc. 24th EU PVSEC*, Hamburg, Germany, pp. 1106–1108.

[6] Schmidt, J. & Aberle, A.G. 1997, "Accurate method for the determination of bulk minority-carrier lifetimes of mono- and multicrystalline silicon wafers", *J. Appl. Phys.*, Vol. 81, No. 9, pp. 6186–6199.

[7] Enjalbert, N. et al. 2005, "Automated in-line control of electrical parameters on large dimension mc-Si wafers on industrial scale", *Proc. 20th EU PVSEC*, Barcelona, Spain, pp. 1124–1127.

[8] McMillan, W. et al. 2010, " In-line monitoring of electrical wafer quality using photoluminescence imaging", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 1346–1351.

[9] Demant, M. et al. 2015, "Inline quality rating of multi-crystalline wafers based on photoluminescence images", *Prog. Photovolt: Res. Appl.*, Vol. 24, pp. 1533 – 1546.

[10] Haunschild, J. et al. 2012, "Cz-Si wafers in solar cell production: Efficiency-limiting defects and material quality control", *Photovoltaics International*, 15th edn, pp. 40–46.

[11] Dannenberg, T., Zimmer, M. & Rentsch, J. 2012, "Fully automated concentration control of the acidic texturisation process", *Energy Procedia*, Vol. 27, pp. 617–623.

[12] Mohr, L. et al. 2016, "Alternative inline analysis of acidic etching baths", *Proc. 32nd EU PVSEC*, Munich, Germany, pp. 929–934.

[13] Zimmer, M., Birmann, K. & Rentsch, J. 2010, "Online process control of alkaline texturing baths with near-infrared spectroscopy", *Vib. Spectrosc.*, Vol. 53, No. 2, pp. 269–273.

[14] Zimmer, M., Krieg, K. & Rentsch, J. 2014, "Online process control of alkaline texturing baths: Determination of the chemical concentrations", *Am. J. Anal. Chem.*, Vol. 5, No. 3, pp. 205–210.

[15] Zimmer, M. et al. 2008, "Spectroscopical inline analysis of wet chemical processes", *Proc. 23rd EU PVSEC*, Valencia, Spain, pp. 1057–1061.

[16] Krieg, A., Schmitt, C. & Rein, S. 2010, "Wafer identification using laser marked data matrix codes", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 1337–1341.

[17] Rein, S. et al. 2008, "Single-wafer tracking in PV production lines", *Proc. 23rd EU PVSEC*, Valencia, Spain, pp. 1125–1130.

[18] Waver, P. et al. 2010, "Every solar cell is an original: Laser marking of silicon solar cells yields new opportunities in quality control", *Photovoltaics International*, 10th edn, pp. 16–22.

[19] Krieg, A. et al. 2013, "Anti-reflection-coating thickness measurements on textured silicon surfaces: Evaluation and accuracy of different measurement techniques", *Proc. 28th EU PVSEC*, Paris, France, pp. 1820–1824.

[20] Strauch, T. et al. 2014, "Two image processing tools to analyse alkaline texture and contact finger geometry in microscope images", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 1132–1137.

[21] Krieg, A., Wallach, J. & Rein, S. 2009, "Impact of surface structures on the inline vision inspection of antireflection coatings", *Proc. 24th EU PVSEC*, Hamburg, Germany, pp. 2041–2044.

[22] Krieg, A. et al. 2007, "Accuracy of inline IV measurements under industrial conditions", *Proc. 22nd EU PVSEC*, Milan, Italy, pp. 368–371.

[23] Bothe, K. et al. 2006, "Electroluminescence imaging

as an in-line characterisation tool for solar cell production", *Proc. 21st EU PVSEC*, Dresden, Germany, pp. 597–600.
[24] Glatthaar, M. et al. 2010, "Evaluating luminescence based voltage images of silicon solar cells", *J. Appl. Phys.*, Vol. 108, No. 1, p. 14501.
[25] Haunschild, J. et al. 2009 "Fast series resistance imaging for silicon solar cells using electroluminescence", *physica status solidi (RRL)*, Vol. 3, No. 7–8, pp. 227–229.
[26] Hinken, D. et al. 2007, "Series resistance imaging of solar cells by voltage dependent electroluminescence", *Appl. Phys. Lett.*, Vol. 91, No. 18, p. 182104.
[27] Trupke, T. et al. 2007, "Spatially resolved series resistance of silicon solar cells obtained from luminescence imaging", *Appl. Phys. Lett.*, Vol. 90, No. 9, p. 93506.
[28] Ramspeck, K. et al. 2014 "In-line thermography for reliable hot spot detection and process control", *Energy Procedia*, Vol. 55, pp. 133–140.
[29] Seren, S. et al. 2008, "Shunt detection with illuminated lock-in thermography on inline relevant time scales", *Proc. 23rd EU PVSEC*, Valencia, Spain, pp. 1746–1748.
[30] Fertig, F. et al. 2011, "Impact of junction breakdown in multi-crystalline silicon solar cells on hot spot formation and module performance", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 1168–1178.
[31] Geisemeyer, I. et al. 2014, "Prediction of silicon PV module temperature for hot spots and worst case partial shading situations using spatially resolved lock-in thermography", *Sol. Energy Mater. Sol. Cells*, Vol. 120(Part A), pp. 259–269.
[32] Friesen, G. & Ossenbrink, H.A. 1997, "Capacitance effects in high-efficiency cells", *Sol. Energy Mater. Sol. Cells,* Vol. 48, No. 1–4, pp. 77–83.
[33] Ramspeck, K. et al. 2014, "Accurate efficiency measurements on very high efficiency silicon solar cells using pulsed light sources", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 1253–1256.
[34] Aßmus, M. et al. 2012, "Performance requirements of crack detection systems in silicon solar cell production", *Energy Procedia,* Vol. 27, pp. 147–153.
[35] 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.
[36] Wasmer, S. et al. 2017, "Impact of material and process variations on the distribution of multicrystalline silicon PERC cell efficiencies", *IEEE J. Photovolt.*, Vol. 7, No. 1, pp. 118–128.
[37] Greulich, J. et al. 2014, "Inline quality control of passivation stacks in high-efficiency silicon solar cell concepts: Thickness determination from spectro-photometry", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 1127–1131.
[38] Hahn, G. 2010, "Status of selective emitter technology", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 1091–1096.

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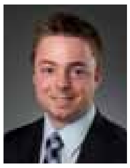

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Progress in co-plating contacts for bifacial cells designed for multi-wire interconnection

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ABSTRACT

For many applications, bifacial modules offer a cost-effective way of increasing energy yields, which explains why the interest in bifacial cells in the PV industry is steadily growing and is expected to continue. However, the metallization of bifacial cells creates new challenges, as the same materials and techniques developed for n surfaces are generally not directly, or simultaneously, applicable to p surfaces; this necessitates sequential metallization of each side, resulting in added cost and/or complexity. This paper introduces a simple co-plating approach with the objective of simplifying the metallization of bifacial cells in a cost-effective way, and which is designed for multi-wire module integration. The metallization route is described, and high cell efficiencies of up to 22.4% are demonstrated using this co-plating approach with bifacial nPERT+ cells (where '+' signifies the bifacial nature of these cells). Initial thermal-cycling reliability data of test structures and 1-cell laminates is presented. Finally, cost-of-ownership (COO) estimates are given, which predict the co-plating approach to be ~40% cheaper than bifacial screen-printed metallization. It is shown that the combination of the high efficiency potential of nPERT+ cells and the reduced costs of co-plating has the potential to deliver module-level costs of ~$0.25/Wpe (glass–glass configuration).

Introduction

Interest in bifacial solar cells is steadily growing in the PV industry, and this is reflected in the prediction by the 2016 ITRPV roadmap [1] of a 20% market share by 2026. The reason for this interest is that bifacial cells can offer an effective way of increasing module power without significantly increasing processing costs. When bifacial cells are integrated into glass–glass modules, energy yield gains above 10% (kWh/kWp) compared with monofacial cells have been reported with just 20% albedo [2]; significant gains have also been reported over a wide range of operating conditions [3–7]. An additional advantage is that bifacial cells can also harvest more light when integrated into traditional glass–backsheet modules, as less light falling between cells (compared with glass–glass integration), or otherwise absorbed at the monofacial cell rear, is lost [8]. Many companies are now offering bifacial glass–glass modules (Yingli, PVGS, Panasonic, SolarWorld, Motech, Sunpreme, etc.) and/or glass–backsheet configurations (LG, SolarCity [now Tesla], Mission Solar, etc.). Although the PV industry's interest in bifacial cells is on the increase, certain challenges remain with regard to measurement standards and to the increased complexity in predicting annual energy yields from bifacial systems, which increases uncertainty in bankability.

Currently, industrial bifacial cells are typically based on a passivated emitter and rear cell structure (PERC) using p-type wafers, or on passivated emitter and rear totally diffused (PERT) or silicon heterojunction (SHJ) structures using n-type wafers [9]. Compared with PERC, PERT cells are more tolerant of the use of thinner (and hence cheaper) wafers [10] but typically require more processing steps [11].

> "The metallization of bifacial cells is technologically more challenging than with monofacial cells."

The metallization of bifacial cells is technologically more challenging than with monofacial cells, as shading losses are required to be low on both the n and the p side, potentially increasing series resistance losses, and most techniques applicable to one side are not directly applicable to the other.

Screen printing is widely used but has certain disadvantages. On the n side, a poor contact resistance Rc is typical at low doping levels ($<5.10^{19}cm^{-3}$). On the p side, with the use of AgAl pastes it is difficult to avoid Al spiking, causing low V_{oc}/FF; in addition AgAl pastes also suffer from lower conductivity than Ag pastes. Forming p contacts using non-firing-through Al pastes is an alternative, but again these suffer from low conductivity and need to be aligned to (laser) openings, thus increasing the usable finger width and shading. Metallizing silicon heterojunction bifacial cells has additional restrictions, since they cannot withstand the temperatures used for firing standard pastes and require the use of expensive low-temperature Ag pastes, which also have lower specific conductivity than standard Ag pastes. Apart from these issues, there is the fundamental concern that silver is expensive and suffers from price volatility, which explains why much effort is made to reduce silver consumption in solar cells.

Metallization by plating is also challenging for bifacial cells, as light-induced plating (LIP) – a common technique used in plating monofacial cells – can only be used to plate onto the n-side contact area. One option is to plate the n and p sides separately, one after the other, using two different techniques: the n side using LIP, and the p side by field-induced plating (FIP) [12]. In the case of FIP, the n side is electrically contacted but not in contact with the plating solution, and the cell is forward biased, providing electrons at the p-contact area for the reduction of the metal ions in the plating solution and the deposition of metal [13]. This approach is sequential and therefore slow and high in capex, as well as requiring relatively complex cell contacting and manipulation. Another approach, used mainly with high-efficiency SHJ cells, features a blanket-sputtered seed layer, a mask and electro-plating, as described in Geissbuhler [14].

Very narrow and high-aspect-ratio fingers are achievable by masking, but this process introduces significant additional material costs (physical vapour deposition (PVD) seed layer, and mask deposition/removal) and higher capex costs (three tools are necessary).

Imec's bifacial cell metallization approach

At imec an attempt has been made to address some of the shortcomings outlined above in the current screen-printing or plating techniques used to metallize bifacial cells. Imec's metallization approach is based on fulfilling three main objectives: 1) low (or zero) Ag usage in order to reduce material costs; 2) a tool set that is simple and capable of high throughput in order to reduce capex costs; and 3) enable stable high cell/module efficiencies.

An approach believed to be capable of meeting these objectives is described below; it is based on electroless and immersion plating to enable simultaneous contact-free co-plating of n and p contacts. A multi-wire interconnection approach relaxes the finger line conductivity requirement in order to achieve good fill factors, so that sufficient line conductivity can be obtained by nickel plating capped with a thin immersion Ag layer. The metallization sequence developed at imec is shown in Table 1. As only two thin metal layers are required, the processing time is relatively short; moreover, being a batch plating process, the throughput can be easily scaled.

The key attractive features of this metallization route are:

- Self-aligned plating (no mask deposition/removal)
- Batch processing, with no contacting to cells
- Simultaneous co-plating of the n and p surfaces
- Low-capex equipment, with tank size determining the throughput

Process step (n and p surfaces)	Chemistry	Time	Function
Surface activation	Imec	< 2 min	Silicon selective surface activation
Electroless Ni	MacDermid	< 15 min	Ni plating on n and p surfaces
Immersion Ag	MacDermid	~2 min	For line conductivity and capping
Sinter < 450°C	Low [O_2] atmosphere	< 10 min	Reduces line and contact resistance

Table 1. The co-plating process sequence developed at imec.

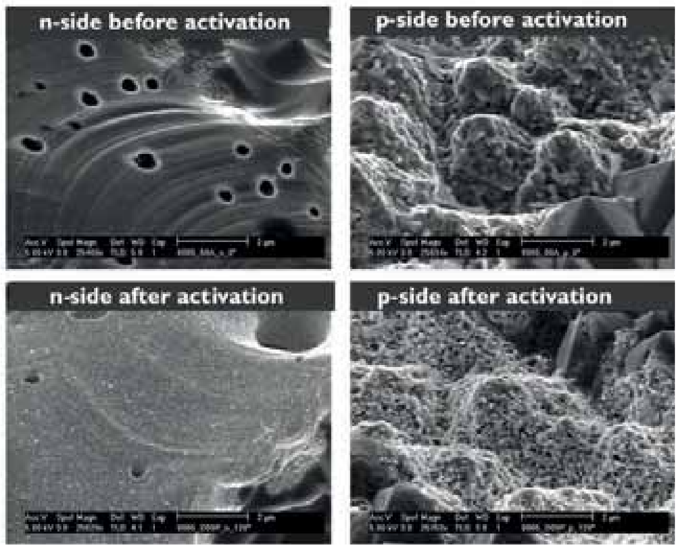

Figure 1. Laser-doped (locally-flattened) n surface and laser-ablated p surface, before and after the activation step prior to Ni plating. Note that the pits in the laser-doped n surface are artefacts of the doping process.

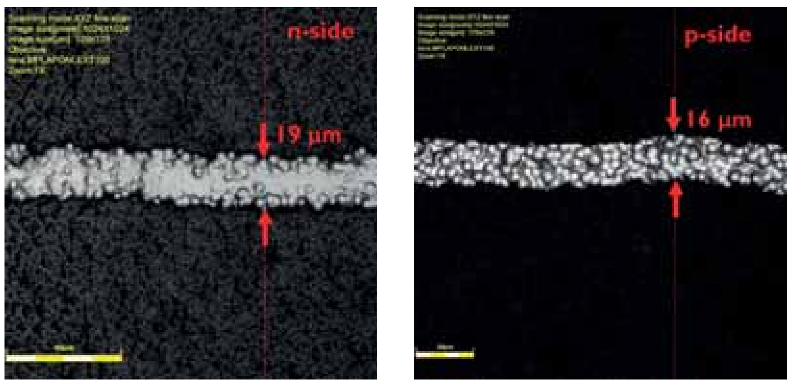

Figure 2. Optical microscope images of Ni/Ag co-plated lines on n and p Si opened by laser doping on the n side and by laser ablation on the p side (narrower laser opening).

"The surface activation step developed at imec is silicon selective, requires no post-anneal and is relatively inexpensive."

The main technical challenge in this plating sequence is to sufficiently activate the n and p surfaces to allow reliable electroless Ni plating without introducing unwanted effects. Although it is possible to simultaneously plate Ni using electroless nickel onto n and p silicon without an activation step, it is not possible using stable long-lasting electroless nickel-plating solutions and/or at similar rates on both surfaces [15]. A palladium activation step can be used, but this is relatively expensive and tends to also activate the areas where plating is not desirable, for example on silicon nitride, creating unwanted ghost plating [16]. The surface activation step developed at imec is silicon selective, and so only the silicon areas exposed for metallization will be activated. It requires no post-anneal and is relatively inexpensive (see later for a cost estimation). The technique is also effective, as it enables a thin conductive layer to be deposited on the n and p silicon surfaces, so that the subsequent electroless Ni plating effectively plates onto the same conductive surface on either side, rather than directly onto n and p silicon (Fig. 1).

The electroless Ni solution used

in this work is a standard commercial solution from MacDermid, designed for high stability and long bath life, but there are many suitable alternatives. Optical microscope pictures of plated fingers after electroless Ni plating and Ag immersion show the high selectivity of the activation and plating processes, with no ghost plating occurring (Fig. 2).

Cell results

The co-plating process described earlier was used to metallize bifacial passivated emitter rear totally diffused cells on n-type wafers (nPERT+). The cell structure is shown schematically in Fig. 3, and the processing sequence is outlined in Fig. 4.

After KOH saw-damage removal and texturing, the wafers are subjected to a BBr_3 diffusion to form the emitter. The diffused layer is subsequently removed from the rear by means of single-side wet etching. After a front-side masking step and $POCl_3$ diffusion to form a back-surface field (BSF), front and rear passivation is performed. A stack of thermal SiO_2 and SiN_x is applied to the rear n^+ surface, and a stack of atomic layer deposited (ALD) Al_2O_3 and plasma-enhanced chemical vapour deposited (PECVD) SiN_x is used for front-side p^+ passivation. Laser patterning then opens the finger contact areas, allowing narrow line widths without masking (no busbar is patterned). On the rear side, a laser-doping process using a phosphorus-containing spin-on dopant is employed [17]. On the front side, ps UV laser ablation defines the contact. Next, a defect annealing step is performed in a belt furnace to mitigate laser damage, before the metallization sequence as outlined in Table 1 is applied.

Cells with both n^+ and p^+ sides passivated with thermal SiO_2 and PECVD SiN_x have also been fabricated; the results are compared in Table 2. The cell *I–V* data in this table were obtained using a Pasan Grid^{TOUCH} measurement system [18] (with 30 wires for current extraction plus 5 wires for voltage measurement on the front and rear) on a low-reflection back chuck; J_{sc} is corrected to remove measurement wire shading [19]. Since finger line resistance R_{line} is relatively high in these cells, there is a small but significant voltage offset between the voltage and current wires in the Grid^{TOUCH} system, which causes cell fill factors to be overestimated. The data in Table 2 show the downward-corrected fill factor values (FF) obtained from re-plotting the *I–V* curve after taking this offset effect into account and with the knowledge of the cell finger line resistances.

The known superior passivation of p^+ surfaces using Al_2O_3 is clearly seen in these results: the overall cell efficiency is improved by ~0.5%$_{abs}$. High pFF (>84%) and V_{oc} (>690mV) values demonstrate the potential for high cell efficiencies, with 22.4% currently the

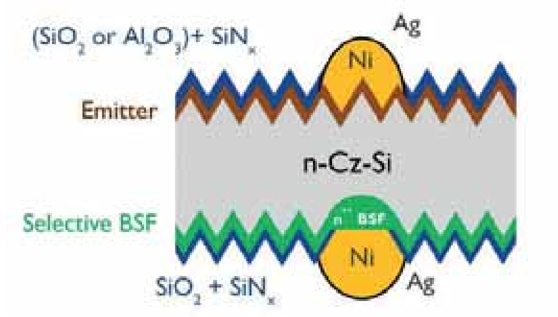

Figure 3. The nPERT+ cell structure.

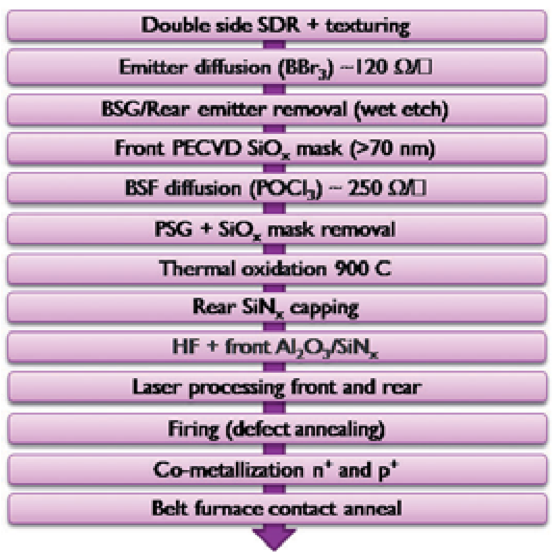

Figure 4. Outline of the nPERT+ cell process sequence.

P+ passivation		J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	η [%]	Bifaciality [%]	R_s [Ωcm^2]	pFF [%]
SiO_2/SiN_x	Average (4)	40.2±0.0	671±1	79.7±0.2	21.5±0.0	96.2±0.4	0.8	84.5
	Best	40.2	672	79.6	21.5	96.8	0.7	84.7
Al_2O_3/SiN_x	Average (4)	40.5±0.1	688±1	79.1±0.2	22.0±0.1	95.7±0.2	0.7	84.3
	Best	40.5	689	79.4	22.2	95.7	0.6	84.3
Al_2O_3/SiN_x (later run)	Best	40.6	692	79.9	22.4	95.7	0.6	84.3

Table 2. *I–V* data comparing two p^+ passivations, measured using a Pasan Grid^{TOUCH} contact system on a WACOM I-V solar simulator. (Cell area = 239cm^2, M0-sized wafers, wafer resistivity = 5Ωcm, wafer thickness = 180µm, *I–V* measurement based on a calibrated reference cell from Fhg-ISE Callab.)

best full-area cell result. The bifaciality (defined as the ratio of the J_{sc} measured when the back is illuminated to when the front is illuminated) is high, yielding values above 95%, which demonstrates excellent rear light-harvesting capability. Higher bifaciality values close to 100% have been obtained at imec if process modifications are made and if texture quality is not degraded during emitter removal on the rear side.

> "High pFF and V_{oc} values demonstrate the potential for high cell efficiencies, with 22.4% currently the best full-area cell result."

Laminate results

The proposed plating sequence providing relatively low finger line conductivity is designed for multi-wire interconnection; it is therefore essential that a low and stable contact resistance between the wires and plated fingers be achieved. To evaluate this aspect, 1-cell modules using nPERT+ cells and multi-wire foils based on the Meyer Burger smart-wire approach were fabricated. The modules were created using a glass–

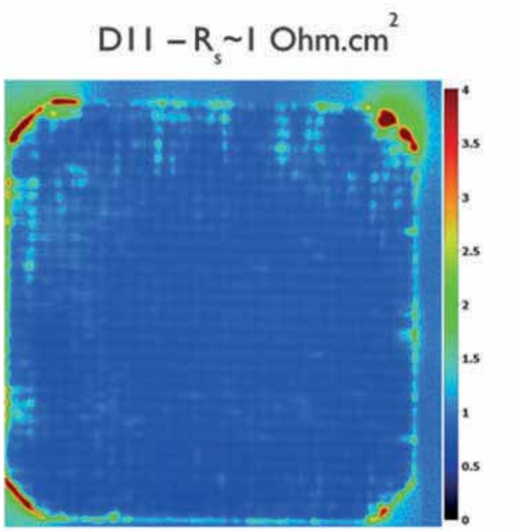

Figure 5. R_s map for laminate D11, showing increased R_s at the corners and at the cell edges.

backsheet configuration, and the multi-wire foils were created by embedding 30 equally spaced 320μm-diameter copper wires in a polyester/thermoplastic olefin (TPO) stack foil. During module lay-up, two such foils were placed either side of the cell, wires touching fingers, before finally front and rear encapsulants were added. The 30 Cu wires were coated by a thin layer of SnIn, which melts during the lamination process, creating the ohmic contact between the wires and the Ni/Ag plated fingers. Table 3 shows the *I–V* parameters of two nPERT+ cells before and after lamination.

The Grid^{TOUCH} measurements have J_{sc} and FF values adjusted as previously explained. The 1-cell laminates were measured using a 160mm × 160mm square mask to

Type	*I–V* details	Area [cm^2]	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	η [%]	R_s [Ωcm^2]	Wp [W]
Cell_D11	GRID^{TOUCH}	239	40.5	689	79.4	22.2	0.6	5.3
1-cell laminate	*I–V* probes	256	*37*	689	77.8	*19.8*	1	5.1
Cell_D13	GRID^{TOUCH}	239	40.4	688	79.1	22	0.7	5.3
1-cell laminate	*I–V* probes	256	*37*	690	77.1	*19.7*	1.1	5

Table 3. *I–V* data before and after lamination, for two 1-cell laminates.

	I_{sc} [A]	V_{oc} [V]	FF [%]	1-cell laminate power [W]	60-cell module power [W]	η – full module [%]**
nPERT+ Bifacial/multi-wire/Ni/Ag glass/backsheet-M2	9.68*	41.3	77.8	5.19	311	18.9
LG Neon 2 Bifacial/multi-wire/SP glass/backsheet-M2	10.05	40.9	77.9	5.33	320	19.5

*I_{sc} is adjusted from M0 to M2 wafer size by the area ratio of the wafers.

**A module area of 1.640m^2 is assumed.

Table 4. Predicted 60-cell nPERT+ module performance compared with the performance of an LG Neon 2 module.

simulate the optical enhancement from the white backsheet surrounding a cell, as in a normal module configuration (with 2mm distance between cells). The laminate J_{sc} was calculated using the larger masked area (256cm^2).

The cell and laminate V_{oc} values were quite similar. Fill factor values for the laminated cells will depend on the number of multi-wires used, their dimensions and the finger line conductivity. The increase of ~0.4Ωcm^2 in series resistance R_s after lamination and the lower fill factor are due to two factors: 1) an additional ~0.2Ωcm^2 is the result of the multi-wire resistance affecting the laminate measurement but not the Grid^{TOUCH} measurement; 2) the remaining additional ~0.2Ωcm^2 is attributed to non-ideal current collection near the cell edges in the laminates as a result of the fingers not extending sufficiently into the corners of the cell. R_s maps from the laminates clearly show the latter effect, as can be seen in Fig. 5; the central region of this map demonstrates good uniformity, with values of ~0.8Ωcm^2, which indicates excellent wire-to-finger contacting.

As a benchmarking exercise, Table 4 shows the predicted power of a 60-cell module using the D11 1-cell laminate data compared with the bifacial LG Neon 2 320N1C-G4 module. The nPERT+ data is adjusted to the M2 wafer configuration by increasing I_{sc} by the M2/M0 wafer area ratio.

Although the nPERT+ module prediction is lower with regard to I_{sc} and power than for an LG Neon 2 module, the result is encouraging, as several areas of the nPERT+ module are still to be optimized. For example, the cell ARC coating is not optimized for a module, and the number of multi-wires versus finger conductivity is not optimal.

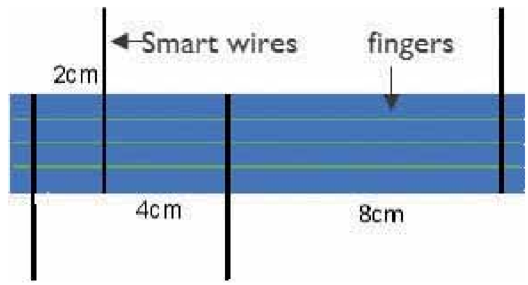

Figure 6. Design of laminate test structures for reliability testing.

Reliability results

To investigate the stability of wire-to-finger contacts when subjected to thermal cycling, a series of laminate test structures were constructed, as depicted in Fig. 6. Four single wires (cut from multi-wire foils), spaced 2, 4 and 8cm apart, contact the cell fingers on one side of a cell during lamination. By measuring the series resistance (4-wire method) for the six different distances between the wire contacts (2, 4, 6, 8, 12 and 14cm) and plotting series resistance versus contact spacing, the wire-to-finger contact resistance (Ωcm^2) and line resistance (Ω/cm) were able to be determined. Straight-line fits to the R_s versus wire spacing data yielded R^2 values of greater than 0.99, thus validating the approach.

Test structures were constructed with three different line widths using the same Ni/Ag plating by varying the laser ablation line width. Fig. 7 shows how the measured wire-to-finger contact resistance changed during 200 thermal cycles (–40°C to +80°C) for the three line widths. Wider fingers yielded a smaller change in wire-to-finger contact resistance on thermal cycling in this experiment, suggesting that the wire-to-finger contact area is important for stable contacts. Table 5 gives predictions of how the laminate fill factor would change as a result of the measured finger line conductivity and wire-to-finger contact resistance changes at 200 thermal cycles. These data provide encouraging evidence that integrating imec's bifacial co-plating process with multi-wire interconnection in accordance with IEC 61215 module reliability criteria is achievable.

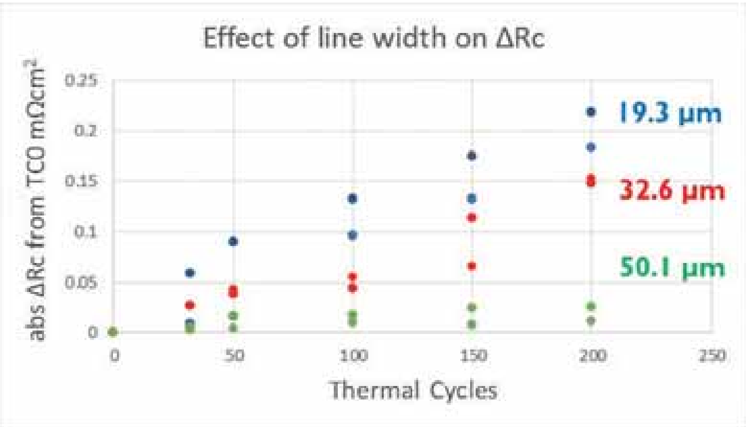

Figure 7. Change in wire-to-finger contact resistance during thermal cycling for three different plated-finger thicknesses.

Samples	Plated line width [µm]	Estimated ΔFF from ΔR_{line} @TC200 [$\%_{abs}$]	Estimated ΔFF from wire-to-finger ΔR_c @TC200 [$\%_{abs}$]
2	19.3	–0.01	–2.4
2	32.6	–0.00	–1.1
2	50.1	–0.01	–0.09

Table 5. Predicted laminate FF changes derived from line and contact resistance changes measured at 200 thermal cycles.

"One key advantage of imec's co-plating process is that it is cheaper than alternative bifacial metallization routes."

The initial data from two 1-cell laminates subjected to thermal cycling, shown in Fig. 8, are also encouraging. Two metallization routes for the nPERT+ cells were used, while the laminates were made using the glass–backsheet configuration previously described. One control cell was metallized using a salicide process, in which Ni was blanket sputtered on both sides and sintered to form $NiSi_x$; the remaining Ni was etched off, followed by electroless Ni/iAg, as in the co-plating process. The other cell was metallized using the co-plating process, with the surface activation step replacing the PVD Ni/sintering step. The plated line widths were ~19µm. At 250 thermal cycles, both 1-cell laminates showed a P_{max} loss of less than 3% (Fig. 8), which is in line with the test-structure data.

Future work will investigate the optimization of the finger width and the wire and wire-coating thicknesses for reliability. More extensive reliability

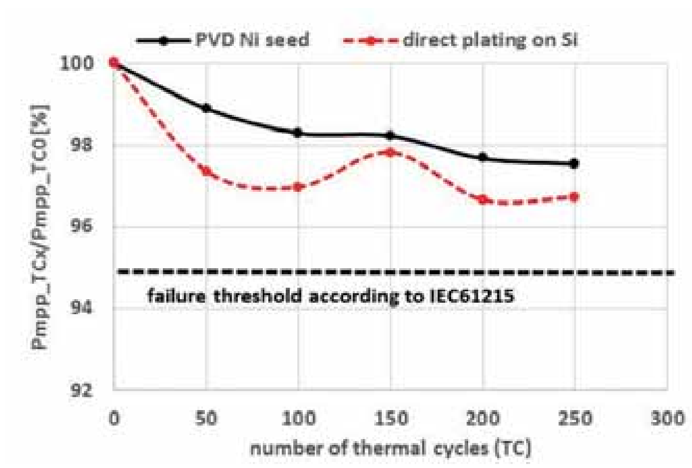

Figure 8. Change in P_{max} during thermal cycling for two 1-cell laminates, fabricated either using a PVD Ni seed layer or by co-plating directly on silicon.

Screen print (SP)	Ni/Ag
3,600 wfr/hr	3,600 wfr/hr
• AgAl front (fingers) • Dry • Ag rear (fingers) • Dry • Fast-firing • Test/sort	• Laser front (fingers) • Laser rear (fingers) • Fast-firing • Ni/Ag plating • N_2 anneal • Test/sort

Table 6. Process steps included in the metallization COO comparison between screen printing and co-plating of bifacial nPERT+ cells.

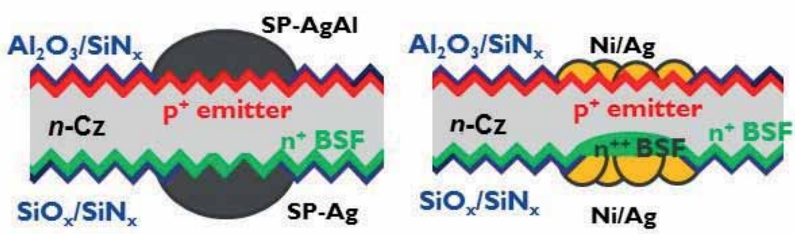

Figure 9. Screen-printing and co-plating cell structures used for COO comparisons.

testing is planned with 60-cell modules and additional tests conforming to IEC 61215 (e.g. damp heat and humidity–freeze/thermal-cycling sequences in accordance with IEC 61215).

Co-plating cost of ownership (COO)

One key advantage of imec's co-plating process is that it is cheaper than alternative bifacial metallization routes. With traditional Ag screen-printing technology, the use of multi-wires enables reductions in finger conductivity and in the consumption of Ag (and hence in cost). When Ni/Ag co-plating is used, an additional reduction in cost is achieved, driven by further savings in Ag consumption (to ~5mg/cell), but differences in other processing costs between the two technologies also need to be taken into account. On the basis of the processing sequences shown in Table 6 and of the cell structures depicted in Fig. 9, the costs of using screen printing and Ni/Ag co-plating to metallize nPERT+ bifacial cells were estimated. These projected costs include not only material costs but also costs related to depreciation, labour, waste, utilities, floor space and yield losses, as shown in Fig. 10.

Some key assumptions in the cost estimates are:

- Equipment depreciation is taken to be over seven years.
- Labour costs typical for Asia are used.
- 60mg/cell of AgAl is used for the emitter side.
- 40mg/cell of Ag is used for the BSF side.
- Waste disposal costs for contaminated rinse water and plating chemicals are included in the case of plated contacts.
- Multi-wire lamination costs are the same for both cases.

The breakdown comparison of metallization costs in Fig. 10 reveal the co-plating sequence to be ~40% cheaper than bifacial screen printing. Furthermore, it is calculated that at the module level the nPERT+ cell process can result in manufacturing costs as low as \$0.25/Wpe. The 'equivalent' Wpe here refers to the additional power obtained from the bifacial illumination. Key assumptions in this calculation are a 22% average cell efficiency on 140µm-thick M2-sized wafers, a glass–glass module with a CTM ratio of 97%, and a 10% bifacial energy yield gain, resulting in a 72-cell module power of 411Wpe. This represents a significant reduction in costs compared with the current mainstream p-type mono-PERC, which achieves ~21.5% average cell efficiency and costs around \$0.35–0.4/Wp.

Summary and outlook

An n and p surface Ni/Ag co-plating process has been developed at imec for the metallization of bifacial cells that is suitable for multi-wire module integration. Key features are very low Ag usage (typically <5mg/cell), line widths below 20µm, and batch cassette processing (no electrical contacts required to cells), enabled by a novel silicon selective activation step prior to Ni plating. Efficiencies of up to 22.4% have been achieved on nPERT+ bifacial cells using this metallization process, with a V_{oc} of greater than 690mV and a bifaciality of greater than 95%. Limited 1-cell laminate reliability data are so far encouraging, with IEC 61512 thermal-cycling test criteria being met.

Driven by much-reduced Ag usage and low-capex/high-throughput tools, the costs associated with this metallization process are estimated to be ~40% lower than with fine-line, busbar-free, bifacial screen printing for multi-wire interconnection. The cost of ownership at the module level is estimated to be potentially ~$0.25/Wpe using reasonable assumptions, which is around 40% lower than for current mainstream modules.

Future work will focus on boosting module efficiency and further reliability testing at the 60-cell module level. Improved module efficiency, in particular module J_{sc}, is expected through the optimization of wires (number/diameter) and finger line conductivity, better UV response, and the use of a cell anti-reflection coating (ARC) optimized for laminates. A 22% average cell efficiency on 140µm-thick wafers is targeted with a cell-to-module (CTM) ratio of 97%, to provide a 72-cell module power of 411Wpe (assuming a 10% bifacial energy yield gain).

> "Future work will focus on boosting module efficiency and further reliability testing at the 60-cell module level."

Co-plating may also be applied to other cell architectures; for example, it is expected that this technology will also be advantageous for current pPERC+ bifacial cell structures. Another possibility is to capitalize on the fact that once a conductive 'seed' layer is applied by co-plating to both the n and the p side, it is relatively simple to simultaneously electroplate copper to both polarities if busbars exist. This opens up the possibility of Ni/Cu/Ag co-plating bifacial cells with busbars that require greater finger line conductivity than is achievable using non-contacting Ni/Ag co-plating. Inexpensive plated bifacial cells suitable for the Schmid multi-wire approach [20,21], or with three to five busbars for traditional interconnection, are potentially feasible using this approach.

Finally, although much work is still required before industrialization, the authors believe that the key elements relating to the viability and usefulness of co-plating for bifacial cells have been demonstrated.

References

[1] SEMI PV Group Europe 2016, "International technology roadmap for photovoltaic (ITRPV): 2015 results", 7th edn (Mar.) [http://www.itrpv.net/Reports/Downloads/].

[2] Kopecek, R. 2015, "Cost/kWh thinking and bifaciality: Two allies for low-cost PV of the future", *Photovoltaics International*, 30th edn, pp. 88–97.

[3] Kopecek, R. 2014, "Bifaciality: One small step for technology, one giant leap for KWh cost reduction", *Photovoltaics International*, 26th edn, pp. 32–45.

[4] Yusufolu, U.A. 2014, "Simulation of energy production by bifacial modules with revision of ground reflection", *Energy Procedia*, Vol. 55, pp. 389–395.

[5] Wang, S. 2015, "Bifacial photovoltaic systems energy yield modelling", *Energy Procedia*, Vol. 77, pp. 428–433.

[6] Fertig, F. 2016, "Economic feasibility of bifacial silicon solar cells", *Prog. Photovolt: Res. Appl.*, Vol. 24, pp. 800–817.

[7] Romijn, B. 2012, "Industrial implementation of efficiency improvements in n-type solar cells and modules", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 533–537.

[8] Singh, J.P. 2015, "Comparison of glass/glass and glass/backsheet PV modules using bifacial silicon solar cells", *IEEE J. Photovolt.*, Vol. 5, pp. 783–791.

[9] Dullweber, T. 2016, "PERC+: Industrial PERC solar cells with rear Al grid enabling bifaciality and reduced Al paste consumption", *Prog. Photovolt: Res. Appl.*, Vol. 24, pp. 1487–1498.

[10] Tous, L. 2015, "Evaluation of

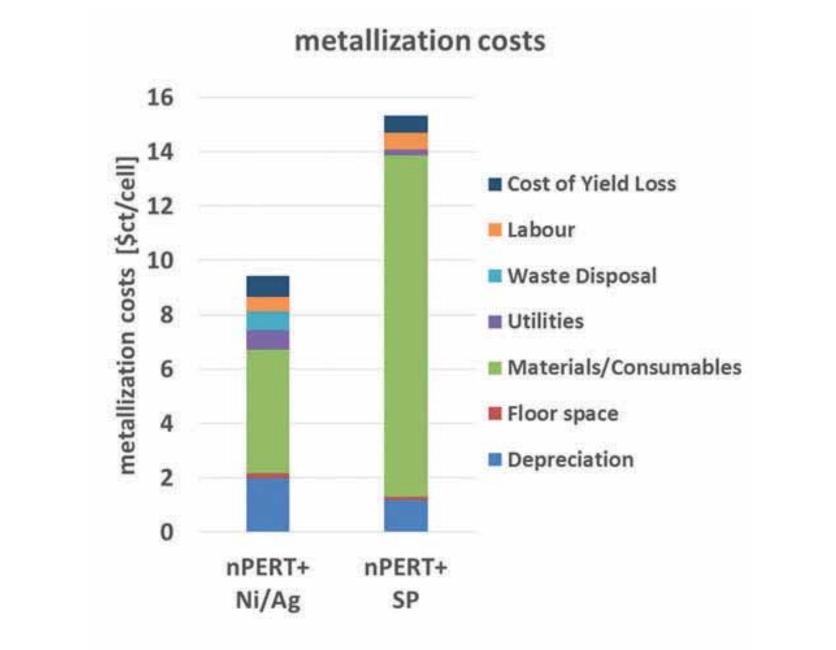

Figure 10. Screen-printing vs. co-plating metallization COO breakdown for nPERT+ bifacial cells.

advanced p-PERL and n-PERT large area silicon solar cells with 20.5% energy conversion efficiencies", *Prog. Photovolt: Res. Appl.*, Vol. 23, No. 5, pp. 660–670.

[11] Dullweber, T. 2016, "p-PERC or n-PERT: Who will be the winner?", *Proc. 6th SiliconPV*, Chambéry, France.

[12] Wang, X. 2014, "Laser-doped metal plated bifacial silicon solar cells", *Sol. Energy Mater. Sol. Cells*, Vol. 131, pp. 37–45.

[13] Kamp, M. 2016, *Electrochemical Processes for Metallization of Novel Silicon Solar Cells*. Stuttgart: Fraunhofer Verlag, pp. 61–64.

[14] Geissbuhler, J. 2014, "Silicon heterojunction solar cells with copper-plated grid electrodes: Status and comparison with silver thick-film techniques", *IEEE J. Photovolt.*, Vol. 4, No. 4, pp. 1055–1062.

[15] Guo, J.H. 2005, "Metallization improvement on fabrication of interdigitated backside and double sided buried contact solar cells", *Sol. Energy Mater. Sol. Cells*, Vol. 86, pp. 485–498.

[16] Karmalkar, S. 2004, "Effects of nickel and palladium activations on the adhesion and IV characteristics of as plated electroless nickel deposits on polished silicon wafers", *J. Electrochem. Soc.*, Vol. 151, pp. C554–C558.

[17] Uruena, A, 2015, "Beyond 22% large area n-type silicon solar cells with front laser doping and a rear emitter", *Proc. 31st EU PVSEC*, Hamburg, Germany, pp. 410–413.

[18] Bassi, N. 2014, "Grid$^{\text{TOUCH}}$: Innovative solution for accurate IV measurement of busbarless cells in production and laboratory environments", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 1180–1185.

[19] Fakhfouri, V. 2014, "Measurement accuracy and precision: The Grid$^{\text{TOUCH}}$ contacting system", Meyer Burger White Paper [http://www.meyerburger.com/fileadmin/user_upload/meyerburger.com/Downloads/Publikationen/Dokumente/2014_PV_Annual_GridTouch.pdf].

[20] Walter, J. 2014, "Multi-wire interconnection of busbar-free solar cells", *Energy Procedia*, Vol. 55, pp. 380–388.

[21] Schindler, S. 2013, "Soldering process and material characterization of miniaturized contact structures of a newly developed multi-busbar cell metallization concept", *Proc. 28th EU PVSEC*, Paris, France, pp. 480–483.

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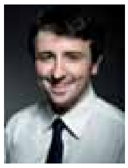

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19.31%-efficient multicrystalline silicon solar cells using MCCE black silicon technology

Xusheng Wang, **Shuai Zou** & **Guoqiang Xing**, Canadian Solar Inc. (CSI), Suzhou, China

ABSTRACT

A novel nanoscale pseudo-pit texture has been formed on the surface of a multicrystalline silicon (mc-Si) wafer by using a metal-catalysed chemical etching (MCCE) technique and an additional chemical treatment. A desirable nanoscale inverted-pyramid texture was created by optimizing the recipe of the MCCE solution and using a proprietary in-house chemical post-treatment; the depth and width of the inverted pyramid was adjustable within a 100–900nm range. MCCE black mc-Si solar cells with an average efficiency of 18.90% have been fabricated on CSI's industrial production line, equating to an efficiency gain of ~0.4%$_{abs.}$ at the cell level. A maximum cell efficiency of 19.31% was achieved.

Introduction

In most industrial production lines, the typical power conversion efficiencies η for single-crystalline silicon (sc-Si) and multicrystalline silicon (mc-Si) solar cells are over 19.5% and 18.5% respectively [1]. Cell performance has been improved by enhancing the electrical and optical properties, through higher-quality wafers, better passivation on the front and rear surfaces, more-effective light trapping via the interdigitated back contact and metal wrap-through, etc. [2–5].

In recent years mc-Si solar cells have been maintaining a firm hold on the leading position in the PV market. However, the higher light reflection at the front textured surface of mc-Si results in an η that is around 1–1.5% lower than that of sc-Si. In fact, the random pits or honeycomb texture formed on the surface of mc-Si via

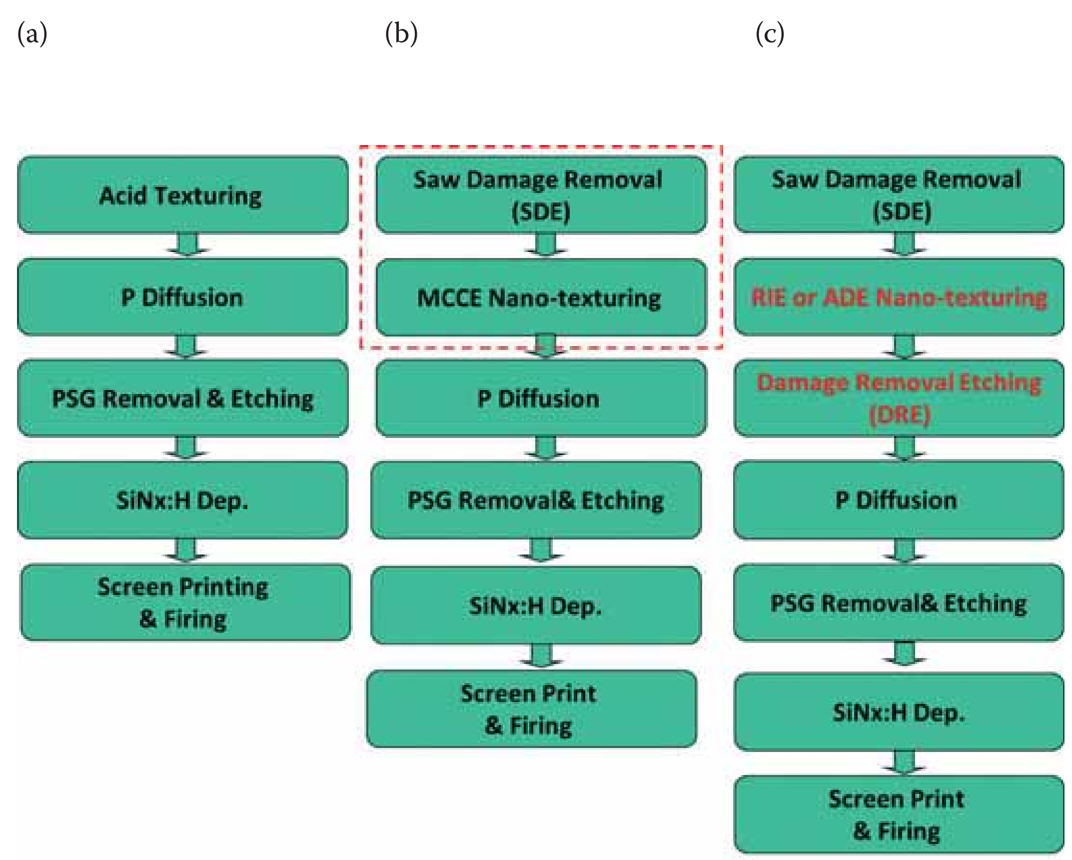

Figure 1. Process flow simplifications: (a) typical mc-Si solar cell; (b) MCCE black mc-Si solar cell; (c) RIE black mc-Si solar cell.

Cell (type, size)	Method	Passivation and ARC	R [%]	η [%]
mc-Si (p, 15.6×15.6cm^2)	RIE	PECVD-SiN_x	13.7	16.1 [10]
mc-Si (p, 15×15cm^2)	RIE	PECVD-SiN_x	N/A	17.1 [22]
sc-Si (n, 4cm^2)	RIE	ALD-Al_2O_3	1.9	18.7 [23]
sc-Si (p, 0.8081cm^2)	MCCE ($AgNO_3$)	Thermal oxide SiO_2	4.6	18.2 [20]
sc-Si (p, N/A)	MCCE ($AgNO_3$)	Al_2O_3	2.5	18.2 [24]
mc-Si (p, 4cm^2)	MCCE ($AgClO_4$)	PECVD-SiN_x	22	16.6 [25]

Table 1. State of the art of nanostructured Si solar cells.

isotropic acidic etching is not as effective at trapping light as the pyramid texture formed on an sc-Si wafer based on anisotropic alkali etching [6,7]. If more-effective light-trapping texture could be fabricated into mc-Si cells, there would be high potential for increasing η, and even surpassing 19%.

> "Nanostructure textured black silicon is more effective at trapping light."

It is well known, and has been proved, that nanostructure textured black silicon is more effective at trapping light, and therefore demonstrates significant potential in application to silicon-based solar cells [8–10]. Several advantages of black silicon solar cells can be inferred:

- Excellent light trapping over a wide spectrum range (300–2,000nm) [11].
- Possibility of eliminating the expensive vacuum process of plasma-enhanced chemical vapour deposition (PECVD).
- Wider acceptance angle for incoming light [12].

There are three main techniques for fabricating black silicon: 1) laser texturing [8,13]; 2) reactive ion etching (RIE) [10,14–16]; and 3) metal-catalysed chemical etching (MCCE) [9,17–19]. For industrial production, the RIE and MCCE methods show the greatest promise.

Process flow and experiment

Fig. 1 shows the process flow simplifications for MCCE and RIE black mc-Si solar cells, compared with the process flow for a typical solar cell. Clearly, MCCE is much more suitable for current production lines, in which the conventional texturing process is also based on wet chemical etching.

Oh et al. reported an efficiency of 18.2% for black single-crystalline silicon (Bsc-Si) solar cells [20]. Although this efficiency is still lower than that currently achieved at the industrial level, it demonstrates that significant progress is being made in the MCCE technique. The reported efficiencies for black multicrystalline silicon (Bmc-Si) solar cells based on either RIE or MCCE, however, are still very low, namely 12–16.6%.

Table 1 summarizes the state of the art of black Si solar cells; the techniques listed are still at the laboratory stage and have not yet been implemented on an industrial scale. While nanostructured silicon can certainly absorb sunlight over a broad range of wavelengths and incidence angles, it also introduces more recombination centres and non-uniform doping into the cell [20,21]. A trade-off between optical gain and recombination loss must therefore be considered in order to achieve high efficiency.

This paper reports on the work carried out on the formation of a novel nanoscale pseudo-pit texture on the surface of an mc-Si wafer by using an MCCE technique and an additional chemical treatment. Fig. 2 illustrates the main steps of the MCCE nanotexturing process. In the first step, a noble metal (such as Au, Ag or Pt) is deposited on the Si surface, usually as nanoparticles (NPs). In the second step, a porous layer on the surface is formed by dipping the silicon substrate into a mixed aqueous solution of an oxidizing reagent

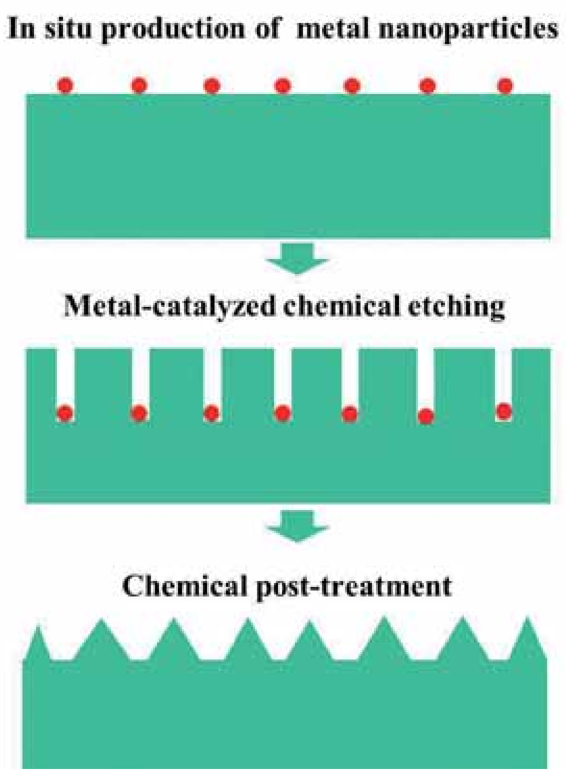

Figure 2. Main steps of the MCCE nanotexturing process.

(such as H_2O_2) and HF acid. Finally, to reduce the recombination due to a large surface area, the third step, i.e. chemical post-treatment, is crucial. In CSI's industrial production line, an average efficiency of 18.90% has been achieved, with the best-performing cell delivering 19.31% – the highest reported value so far for black silicon.

"In CSI's industrial production line, an average efficiency of 18.90% has been achieved, with the best-performing cell delivering 19.31%."

Results and discussion

The nanoscale structures of different sizes and shapes are shown in Fig. 3. It was found that the morphology of nanoscale structures is highly dependent on the concentration of metal ions, the volume ratios of H_2O_2:HF:DIW (de-ionized water), the post-treatment chemicals, and the etching times of the above process steps.

In CSI's experiments, by adjusting the recipe of the MCCE solution and using a suitable alkali post-treatment it is possible to obtain a nanoscale pyramid or inverted-pyramid texture: for instance, a high Ag ion concentration results in a nanoscale *pyramid* texture, whereas a low Ag ion concentration leads to a nanoscale *inverted-pyramid* texture. When the recipe of the MCCE solution is adjusted and a proper acid post-treatment is employed, a nanoscale *pseudo-pit* texture can be created. If a particular type of processing is added after the metal NPs deposition, an orderly nanoscale *wormhole* texture will be formed.

A desirable nanoscale inverted-pyramid texture was created by optimizing the recipe of the MCCE solution and employing a proprietary in-house chemical post-treatment, as shown in Fig. 4. It was possible to adjust the depth and width of the inverted pyramid within a 100–900nm range. An appropriate size of inverted-

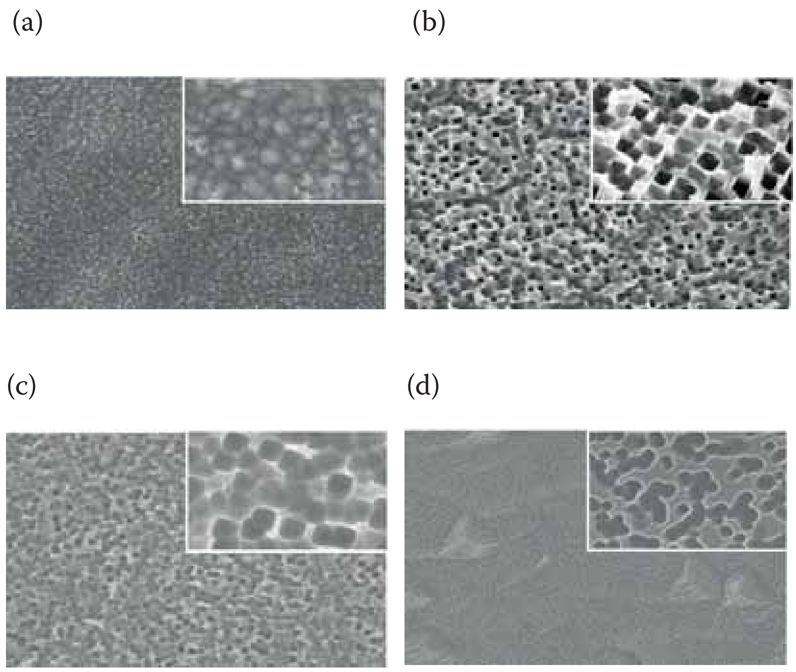

Figure 3. SEM surface images of nanoscale textures: (a) pyramid; (b) inverted-pyramid; (c) pseudo-pit; (d) wormhole.

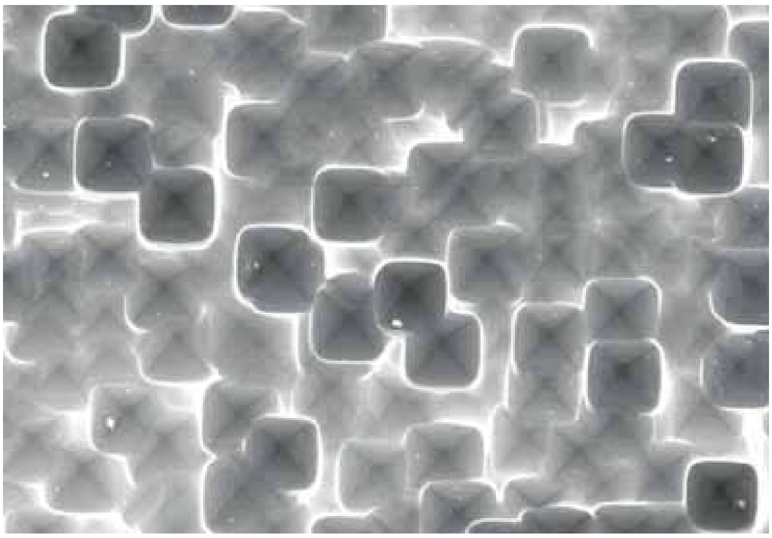

Figure 4. SEM image of a desirable nanoscale inverted-pyramid texture.

	V_{oc} [mV]	I_{sc} [A]	R_s [mΩ]	R_{sh} [mΩ]	FF [%]	EFF [%]
Baseline-Avg	637.6	8.842	1.80	506	79.90	18.51
MCCE-Avg	638.6	8.981	1.70	607	80.19	18.90
Best cell	642.4	9.109	1.68	599	80.31	19.31

Table 2. Main characteristics of mass-produced MCCE black mc-Si and typical mc-Si solar cells (baseline).

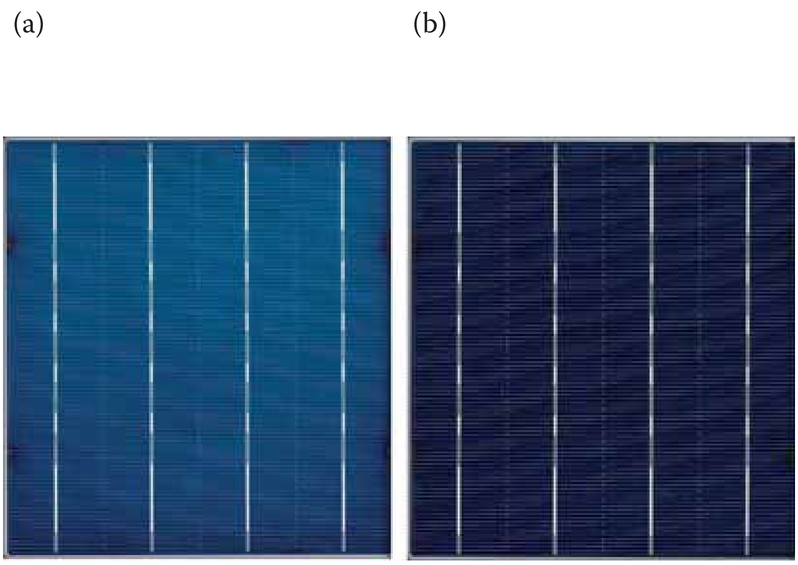

Figure 5. Cell photographs: (a) typical mc-Si solar cell; (b) MCCE black mc-Si solar cell.

pyramid texture can ensure a reduced surface recombination, while keeping the reflectance low.

With the above-mentioned optimization of the nanoscale structure texture, the average efficiency of mass-produced MCCE black mc-Si solar cells was 18.90%, while the typical mc-Si cells (the baseline) yielded 18.51%; this equates to an efficiency gain of ~0.4% at the cell level.

The mean parameters of the black cells are summarized in Table 2. As expected, the short-circuit current shows an increase of around 140mA, which can be mainly attributed to the enhanced light absorption of the cells. The average open-circuit voltage V_{oc} of MCCE black mc-Si solar cells is approximately 1.0mV higher than that of the baseline, thanks to the low J_{02} value of MCCE cells. On the basis of a two-diode model, the J_{02} accounts for the injection-dependent Shockley-Read-Hall recombination in the space charge region; moreover, such low injection recombination can be attributed to a flat p-n junction after MCCE texturing. Indeed, the average fill factor FF of MCCE black mc-Si solar cells is around 0.3% higher than the baseline.

Compared with the light-blue appearance of a typical mc-Si solar cell, the appearance of an MCCE mc-Si solar cell is dark blue, as shown in Fig. 5. The grains of an MCCE mc-Si solar cell, however, are more perceptible than in the case of a typical acid-textured solar cell, because of the different reaction rates of the grains in the random crystalline orientation in MCCE cells.

"There is still significant potential for improvement of the efficiency of MCCE black mc-Si cells through an effective passivation technique and further optimization of the MCCE process."

Conclusions

MCCE is a more economical and efficient approach for industrial black mc-Si manufacturing. A desirable nanoscale structure can be made by adjusting the recipe of the MCCE solution and using a proprietary in-house chemical post-treatment processing, which will ensure a trade-off between optical gain and recombination in order to achieve high efficiency. The conversion efficiency achieved at CSI of mass-produced MCCE black mc-Si solar cells was ~18.90%, which equated to an efficiency gain of ~0.4%$_{abs.}$ at the cell level; the efficiency of the best-performing cell was 19.31%. There is still significant potential for improvement of the efficiency of MCCE black mc-Si cells through an effective passivation technique and further optimization of the MCCE process. Moreover, the authors believe that MCCE is an ideal technique for solving texturing problems with diamond-wire-sawn mc-Si wafers and direct wafers.

References

[1] Lee, E. et al. 2011, *Sol. Energy Mater. Sol. Cells*, Vol. 95, pp. 3592–3595.
[2] Eisele, S.J. et al. 2009, *Appl. Phys. Lett.*, Vol. 95, p. 133501.
[3] Gatz, S. et al. 2011, *Energy Procedia*, Vol. 8, p. 318.
[4] Bateman, N. et al. 2011, *Energy Procedia*, Vol. 8, p. 509.
[5] Yin, W.W. 2013, *IEEE J. Photovolt.*, Vol. 3, p. 697.
[6] Panek, P. et al. 2005, *J. Mater. Sci.*, Vol. 40, p. 1459.
[7] Seidel, H. et al. 1990, *J. Electrochem. Soc.*, Vol. 137, p. 3626.
[8] Her, T.H. et al. 1998, *Appl. Phys. Lett.*, Vol. 73, p. 1673.
[9] Toor, F. et al. 2011, *Appl. Phys. Lett.*, Vol. 99, p. 103501.
[10] Yoo, J. et al. 2011, *Sol. Energy Mater. Sol. Cells*, Vol. 95, pp. 2–6.
[11] Halbwax, M. et al. 2008, *Thin Solid Films*, Vol. 516, p. 6791.
[12] Yuan, H.C. et al. 2009, *Appl. Phys. Lett.*, Vol. 95, p. 123501.
[13] Crouch, C.H. et al. 2004, *Appl. Phys. Lett.*, Vol. 84, p. 1850.
[14] Choulat, P. et al. 2007, *Proc. 22nd EU PVSEC*, Milan, Italy.
[15] Jansen, H. et al. 1995, *J. Micromech. Microeng.*, Vol. 5, p. 115
[16] Ruby, D.S. et al. 2002, *Sol. Energy Mater. Sol. Cells*, Vol. 74, p. 133.
[17] Koynov, S. et al. 2007, *physica status solidi (RRL)*, Vol. 1, p. R53.
[18] Koynov, S. et al. 2006, *Appl. Phys. Lett.*, Vol. 88, p. 203107.
[19] Bastide, S. et al. 2009, *physica status solidi (c)*, Vol. 6, p. 1536.
[20] Oh, J. et al. 2012, *Nature Nanotech.*, Vol. 7, p. 743.
[21] Kelzenberg, M.D. et al. 2010, *Nature Mater.*, Vol. 9, p. 239.
[22] Fukui, K. et al. 1997, *Sol. Energy Mater. Sol. Cells*, Vol. 48, p. 219.
[23] Repo, P. et al. 2013, *Energy Procedia*, Vol. 38, p. 866.
[24] Wang, W.C. et al. 2013, *ACS Appl. Mater. Interfaces*, Vol. 5, p. 9752.
[25] Tsujino, K. et al., *Sol. Energy Mater. Sol. Cells*, Vol. 90, p. 100.

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Thin Film


74

Manz finally awarded two turnkey CIGS thin-film lines valued at US$282 million

PV and electronics equipment manufacturing and automation specialist Manz has secured the largest equipment order in the history of the company after securing orders for two turnkey CIGS production lines totalling 350MW nameplate capacity with China-based Shanghai Electric Group and Shenhua Group.

Manz said that the orders amounted to €263 million (US$282.22 million), which included a CIGS production line with a capacity of 306MW and another one for a CIGS R&D line with a nameplate capacity of 44MW. The company said equipment installation would start in 2017 and be completed in 2018.

Credit Manz

Dieter Manz (front left) at the signing ceremony for the deal.

The production plant will be based in the city of Chongqing in south western China. Shenhua Group, the largest coal enterprise in China and the largest coal supplier in the world, teamed up with utility, Shanghai Electric to enter the solar market in China.

Dieter Manz, CEO and founder of Manz said: "This cooperation is absolutely outstanding in the solar industry worldwide. We were always convinced of the superiority and potential of our CIGS thin-film technology since CIGS modules from Manz already offer the lowest electricity generation costs in comparison to the crystalline silicon technology. Today's agreements mark the breakthrough in our solar business. Our confidence in our excellent engineering know-how will now pay off."

The company said that the 'CIGSfab' turnkey technology order would be the largest CIGS production line in China and the second largest world-wide. Solar Frontier in Japan has the largest CIS thin-film plant in the world at just under 1GW.

Orders

Midsummer secures CIGS system order from Asia

Sweden-based thin-film equipment specialist Midsummer AB has received an order from an undisclosed customer based in Asia for its CIGS, 'DUO' solar cell sputtering tool.

Midsummer said that the system would be used to fabricate lightweight flexible modules for both for portable market application and roof top installations.

Sven Lindström, CEO, Midsummer AB commented: "This order makes Midsummer's DUO the most widely distributed CIGS technology worldwide and confirms our leading position. Our new results showing solar modules with over 14% conversion efficiency have led to increased demand for our manufacturing systems."

Lindström was referencing a recent announcement from the company that its undisclosed customer based in Asia had passed conversion efficiencies of 14% (corresponding to 15.4% aperture area efficiency) for flexible CIGS modules, which had been tested at the testing firm, Chemitox in Yamanashi, Japan.

Midsummer claimed that the conversion efficiencies were achieved at the customer production line in normal production conditions, with standard process settings with a CIGS layer less than 1 micron in thickness. Unusually, the claims were not released by the manufacturer.

In March, 2016 Midsummer claimed Chemitox had verified CIGS solar cells (156×156 mm cell) in a flexible thin-film substrate had achieved a conversion efficiency of more than 13%.

The company said that the new tool order would be delivered in August 2017, having secured several follow-on orders from at a single customer at least in Asia, which in 2015 was cited as a "multinational corporation".

Singulus receives further CIGS thin-film equipment pre-payment from China

Specialist PV manufacturing equipment supplier Singulus Technologies said it had received the next contractually agreed pre-payment from the Chinese state-owned enterprise China National Building Materials (CNBM), owner of CIGS thin-film manufacturer, Avancis.

Earlier in 2016, Singulus signed a contract worth around €110 million (US$123 million) for CIGS thin-film production equipment for two 150MW production plants to be built in China using technology from Avancis for CNBM's entry into BIPV and BAPV markets.

Stefan Rinck, Singulus Technologies' CEO, said: "We are very pleased that the construction of the ordered machines for the first of the two CIGS factories is progressing timely. Following talks with our customer, we also expect the prompt setup of the second factory at the beginning of next 2017. We see ourselves very well positioned in China in the area of thin-film solar technology and here in particular for production equipment for CIGS thin-film modules."

Avancis was a previous customer of Singulus for its current manufacturing facility in Germany. Avancis has previously said that it had plans to expand capacity to 300MW per facility in China in the future.

Funding

WattGlass to commercialize anti-reflective/soiling solution after fund raise

US-based start-up WattGlass has secured a Series A round of funding led by material sciences firm, DSM that was said to support its efforts to commercialise its anti-reflective and anti-soiling coating for PV panels.

WattGlass was one of five winners of the 2016 SunRISE TechBridge Challenge, a competition organized by Royal DSM, Fraunhofer, and Greentown Labs, which concluded in July, 2016. Winners were said to receive Greentown Launch and DSM Partnership/Investment support.

Corey Thompson, CEO of WattGlass said: "DSM is a leader in our market and has extensive experience developing and commercializing material-based solutions for high-tech markets. We are excited to be a winner of the Sunrise challenge that enabled us to receive funding from DSM Venturing. This funding provides us the

Credit Midsummer

Midsummer has netted an order for its CIGS cell sputtering tool from a client in Asia.

resources needed to commercialize the research we are conducting under the NSF and DOE grants, and to bring our novel product to customers." WattGlass is looking to establish domestic production of their proprietary chemical blends for shipment to customers worldwide.

The technology development had also been supported by the National Science Foundation (NSF) Small Business Innovation Research (SBIR) programme, the Department of Energy (DOE) SunShot programme, and the Arkansas Economic Development Commission (AEDC).

DSM Venturing was said to have led the funding round, although the investment amount and investment partners was not disclosed.

Dyesol gets A$2.5m Australian government grant for perovskite commercialization

Thin film perovskite solar cell developer Dyesol has had an application granted by the Australian government for a AUD$2.5 million (US$1.9 million) in funding for an 18-month project to develop a large-area on glass product prototype that would coincide with the company establishing pilot line production in Australia.

The grant was awarded in collaboration with commercial partners, CSR Building Products, and its subsidiary, CSR Viridian, and CSIRO and comes under the Cooperative Research Centre Projects (CRC-P) programme, administered by the Australian Department of Industry.

Dyesol had previously noted in 2016 that it had applied for the grant and has relied heavily on grants awarded in other countries such as the UK to fund perovskite R&D to commercialise low-cost integrated PV roofing products.

Oxford PV garners more funding to avoid 'valley of death' commercialization

Perovskite solar cell developer Oxford Photovoltaics has secured another round of funding to support its IP licensing business model on the back of plans to produce working solar cells for customer evaluations after recently purchasing the former Bosch Solar CIS thin-film site in Brandenburg an der Havel, Germany.

The latest funding amounts to £8.1 million (US$10.3 million) and follows a recent series C funding of £8.7 million (US$11.0 million). The latest funding was led by Statoil ASA, Legal & General Capital and an unidentified technology-focused, family fund investor.

Although the company is not seeking to develop its own perovskite-based PV products, it has to demonstrate commercial-ready cells that can be either produced as a tandem layer on top of conventional crystalline solar cells, in line with amorphous layers used in heterojunction solar cells or standalone perovskite cells for thin-film formats.

The licensing business model avoids the need to invest significant amounts of money in volume production equipment and facilities, potentially avoiding the 'valley of death' scenario for PV start-ups that tend to fail by burning through raised capital before recouping investments through a successful commercial launch.

However, the IP model does not come without risk as this still requires investment in pilot production equipment

Credit Oxford PV

Oxford PV has secured further funding to take forward commercialization of its perovskite technology.

and facilities as well as capital to run extensive sampling for potential customers.

Oxford PV has also recently announced a joint development partnership with an unidentified mainstream c-Si PV manufacturer, critical at this stage ahead of pilot plant sampling operations.

Frank Averdung, CEO of Oxford PV, said: "In conjunction with our industry joint development partner, our perovskite technology now has a clear path and timetable to commercialisation and the formidable support of global market leaders to enable that to happen."

Company news

First Solar orders manufacturing equipment for Series 6 module transition

Leading thin-film PV manufacturer First Solar has ordered the major manufacturing equipment required to transition to its large-area Series 6 modules in the first quarter of 2017.

First Solar said in late February that Series 6 tool install would begin at its production plant in Ohio in the third quarter of 2017. The Ohio fab is home to First Solar's key pilot line. Production of its Series 4 modules at four lines in the Ohio fab stopped in the fourth quarter of 2016 to ready the technology transition.

In Malaysia, First Solar noted that eight production lines would stop production in the second quarter of 2017, while tool install for Series 6 modules would begin the fourth quarter of 2017 and run through the first quarter of 2018.

Series 6 module production is expected to start at its pilot line in Ohio in the second quarter of 2018, while production is expected to start in Malaysia in the third quarter of 2018 through the fourth quarter of 2018.

First Solar had previously said that it expects to invest around US$500 million in 2017 to transition to Series 6 modules, while allocating a further US$400 million in 2018 to have 3GW of Series 6 capacity in 2019.

Hanergy Holding hit with tough Hong Kong Stock Exchange demands barring founder

Li Hejun majority shareholder in PV thin-film equipment and module producer Hanergy Thin Film Power Group (Hanergy TF), via parent company Hanergy Holding Group, is set to be banned from being a director, directly or indirectly in the corporation for a certain period in Hong Kong.

The Securities and Futures Commission of Hong Kong (SFC) was said to have started civil proceedings to ban Li Hejun and four existing independent non-executive directors named as, Ms. Zhao Lan, Mr. Wang Tongbo, Professor Xu Zheng and Dr. Wang Wenjing from directorship positions, which Hanergy TF said in a financial filing would not be contested by either Li Hejun or the four independent non-executive directors. The SFC can impose up to a 15 year ban via the court proceedings.

The main complaint by the SFC was that Li Hejun and the four independent non-executive directors failed to back Hanergy TF over contracts signed

Li Hejun had stepped down from the chairmanship role in Hanergy TF since the stock trading had been halted.

Several other key demands by the SFC are expected to be met by Hanergy Holding Group to enable Hanergy TF shares to be traded again on the HKSE.

The SFC has also demanded from Hanergy TF 'detailed information on the Company, its activities, business, assets, liabilities, financial performance and prospects,' which were demanded by the SFC soon after Hanergy TF share trading was halted as long ago as May 2015 over stock trading and business models adopted by the company.

According to the Hanergy TF financial statement, it would also concede to providing the financial information demanded by the SFC. Hanergy TF had already engaged financial advisers to conduct due diligence and engaged auditors to conduct an audit on the consolidated financial statements to comply with the SFC demand.

Hanergy Holding will also be force to pay in full 'sales contracts' made by it and affiliate companies with Hanergy TF in 2010 and 2011 within 2 years of a court order being sought by the SFC.

These contracts primarily related to a-Si thin-film production lines, technology upgrades of production lines and module supply agreements, which were claimed to have been partially paid in the past but at least around US$205 million was left outstanding since the orders were claimed to have been fulfilled.

Innovation for optical, electrical and economic improvement of thin-film PV technology

Joop van Deelen & Marco Barink, TNO, Eindhoven, The Netherlands

Fab & Facilities
Materials
Cell Processing
Thin Film
PV Modules
Market Watch

ABSTRACT
Innovation in the field of thin-film cells, in addition to economy of scale and the manufacturing learning curve, is an important element in keeping the price of this technology competitive. Most papers on these cells focus on their technology; however, the economic potential of the technology is also important. Of even greater significance, a realistic estimation of the potential, along with the associated costs, of advanced technology, is part of the equation for profitability. Two examples of technology – metallic grids and texturing – are given in this paper; the designs are discussed, and a brief economic analysis is presented for various scenarios of the technologies. Although the profitability of these technologies can be considerable, it is shown that one should be wary of basing decisions purely on potential and on ideal scenarios, and how the cost of a technology can turn a great prospect into a trade-off.

Introduction

The cost of PV has fallen dramatically over the past decade. At one time far more expensive than wind energy, its cost now matches, or is below, that of many renewable alternatives; important drivers are low-cost production facilities, economies of scale and, not least, innovation. The PV market mainly consists of Si wafer panels, for which large factories with standardized equipment are available. For thin-film, however, it is a different story: company-specific technology and mainly in-house-developed technology are typical. At this point in time, there is some economy of scale with multi-gigawatt production, but even so, the industrial learning curve for thin-film began about 20 years later than that for wafer-based production.

An advantage of thin-film technology is that it does not require energy-intensive purification of Si; moreover, a panel consisting of a few deposited layers is inherently more easily scalable. The latest buzz in thin film is the development of perovskite cells, which suggests that, at the cell level, 20% efficiency could be achieved in just a few years. In short, there are a few compelling assets and developments in the thin-film community that make it worthwhile to investigate the kind of technology that is needed in order to further improve the performance/cost ratio.

The heart of thin-film technology is the absorber material and its interfaces, and most academic research focuses on that part of the cell. However, there are also other components of a thin-film panel that are interesting: for example, with the front contact a trade-off exists between transparency and conductivity, and the contact is therefore not ideal in respect of either of these two properties. A good solution to this could be a combination of various materials; their design and application is the first topic of this paper. The second topic relevant to thin-film PV (such as CIGS and perovskites) is that Si-based technology involves texturing; whether or not texturing is a route to pursue in CIGS and perovskites, from both a technological and an economical perspective, needs to be investigated.

> “Modelling has proved to be a valuable tool in determining the front-contact materials and in formulating a design of a pattern or texture.”

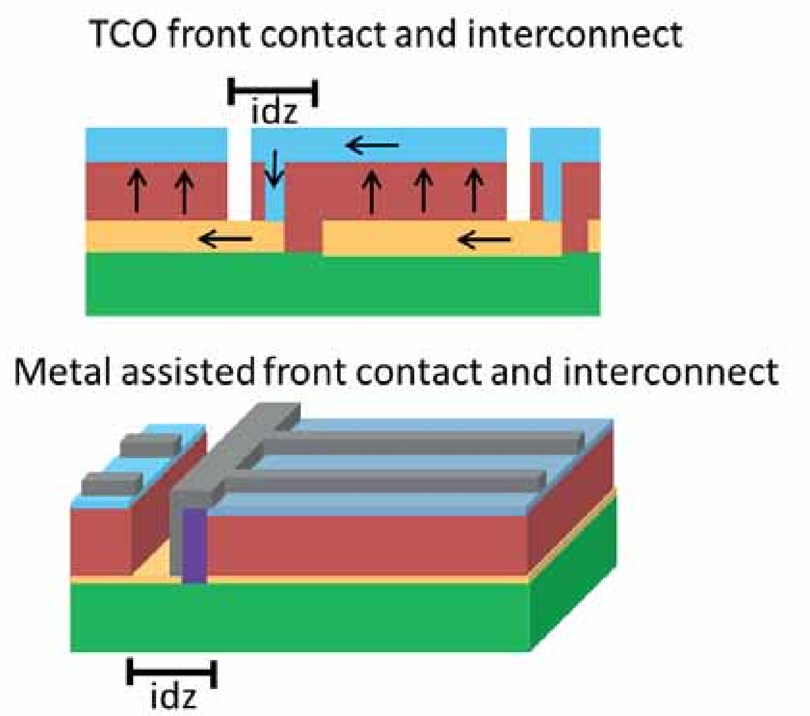

Figure 1. Front-contact and interconnection designs. The interconnection dead zone is represented by idz [1].

For both the above-mentioned topics, modelling has proved to be a valuable tool in determining the front-contact materials and in formulating the design of a pattern or texture. Moreover, in addition to design optimization, the ability to calculate the potential of a technology and the associated cost is essential in order to make smart decisions about innovation strategies. Design, technological and economic aspects will be addressed in this paper, along with a discussion of both the advantages and the limitations.

Thin Film

Multi material for the ultimate front contacts

Metallic grids and their sheet resistance

The front contact is an important part of the thin-film panel: its function is to be transparent to the light, so that the light can be absorbed by the absorber, while simultaneously serving as a current collector. Thin-film PV panels consist of parallel strips of cells; these are interconnected as shown in the schematic representation of a cross section of part of a thin-film PV panel in Fig. 1 (top). Each cell is connected to its neighbouring cells, and usually the front-contact material is also used as an interconnection material, indicated in blue in the figure. The entire width of the interconnection and cell separation area does not contribute to the efficiency, and for this reason is usually referred to as the *interconnection dead zone (idz).*

The arrows in Fig. 1 show the path of the electrons in the system: the electrons move through the front contact to the interconnection, and then through the back contact to the neighbouring cell. An alternative design of a metal-based interconnection is shown in Fig. 1 (bottom); this design also includes a metal-assisted front contact, the conductivity of which can be enhanced by adding the metal.

To what extent the conductivity can be enhanced by metallic grids has been investigated [2]. Fig. 2 shows a comparison between different front-contact options: 1) a transparent conductive oxide (TCO), which is the standard material currently in use; 2) a rectangular metallic mesh on top of a thin TCO layer; 3) a TCO/metal/TCO sandwich; 4) thin metal layers (thickness in the nm range); and 5) a rectangular metal grid. The plot shows the transmittance as a function of sheet resistance; clearly, a minimum sheet resistance at the highest possible transmittance is desirable. For single materials, a reduction in sheet resistance has only a minor effect on the transmittance down to a transmittance threshold of 90%, below which there is a marked decrease in transmittance. This is visualized by the blue and green lines, which represent the trends for single materials of TCO and metal respectively [3].

As can be seen in Fig. 2, for the purpose of a transparent conductor a TCO is a better-performing material than a metal. A TCO/metal/TCO sandwich performs even better; this is because the reflection of the metal is reduced if it is sandwiched between other materials. However, a patterned metal on top of a TCO (TCO + grid in the figure) works even better still. The different sheet resistances were obtained by using different rectangular grid designs of slightly different surface coverages. It can be seen that one can vary the sheet resistance of such a system by over an order of magnitude without incurring significant optical losses. More importantly, a patterned metal on top of a TCO outperforms the other materials.

The closed squares in Fig. 2 represent data for a square metallic grid on top of a TCO. However, in thin-film PV panels, a grid consisting of parallel metallic fingers (as depicted in Fig. 1) is more effective, since all the current needs to be transported in only one direction. The resistance of a metallic feature is

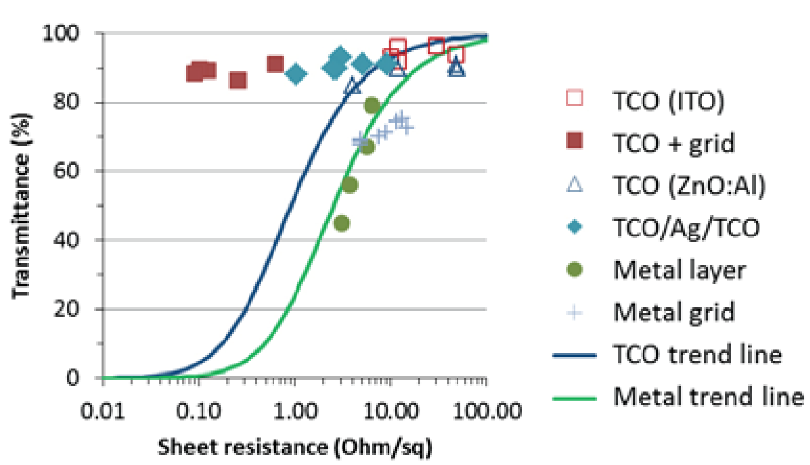

Figure 2. Comparison of various transparent conductors.

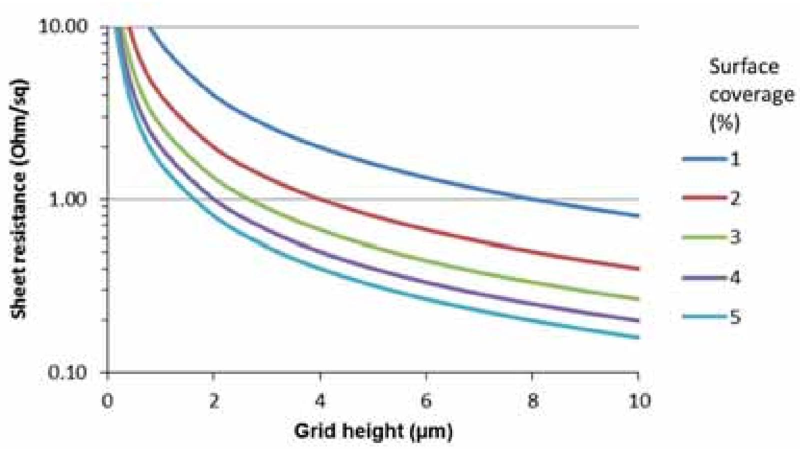

Figure 3. Overview of the sheet resistance of a linear wire grid as a function of grid height, for various surface coverages.

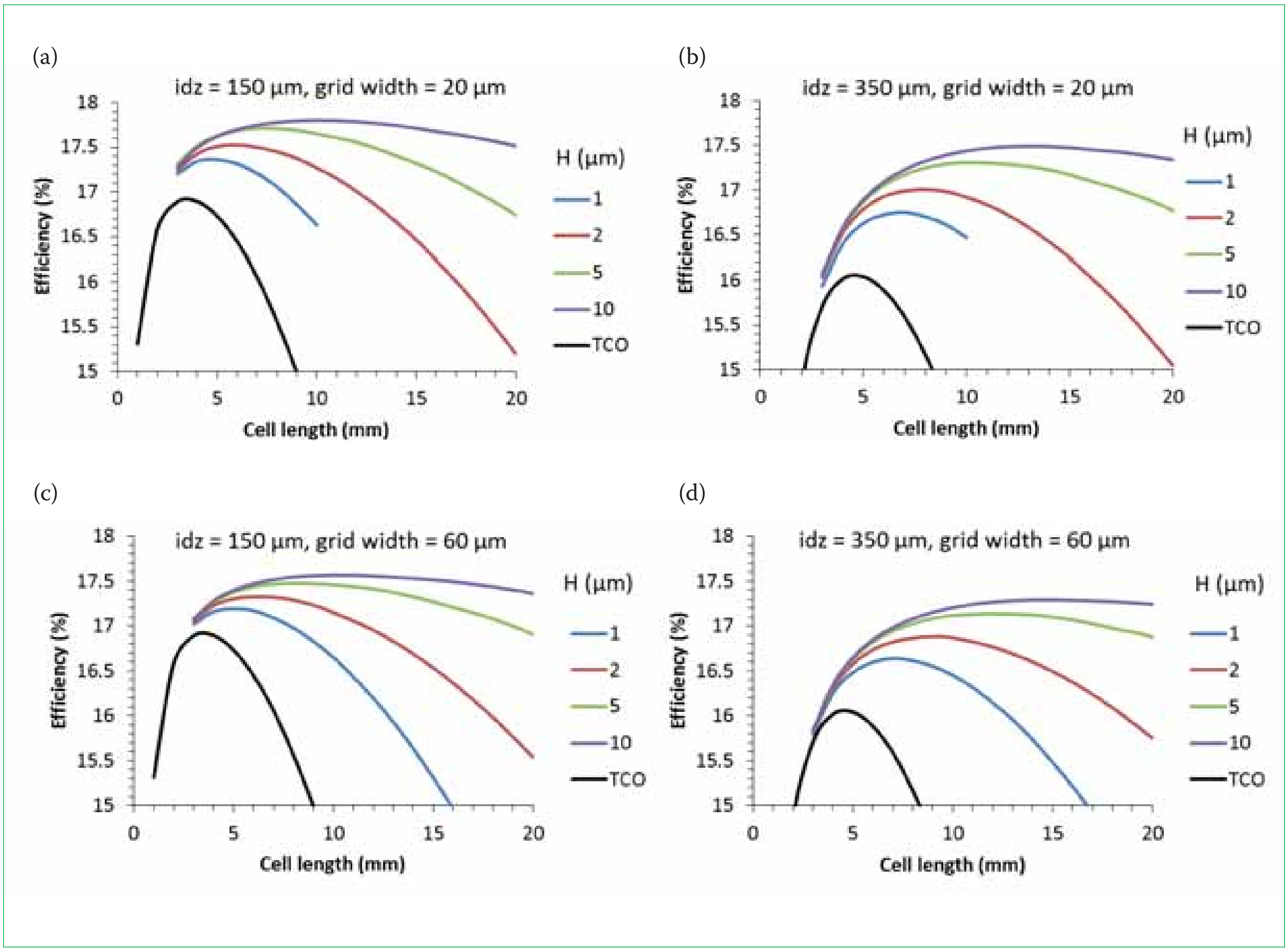

Figure 4. Panel efficiency as a function of cell length, showing the impacts of various grid finger heights (H), interconnection dead zones (idz) and grid finger widths [5].

given by the product of the resistivity and the surface area perpendicular to the direction of the current ($R = \rho \times A$). In the case of a finger grid, this surface area translates to the height and the surface coverage, the latter being a mathematically convenient expression for the number of fingers and the space between them. Fig. 3 shows an overview of the expected sheet resistance of such a metallic finger grid. A sheet resistance of around 1Ω/sq., which is only one-tenth of that of the front contact currently in use, seems feasible.

Application of grids to solar cells: design considerations

With the use of such material for the front contact as described above, the solar panel efficiency is expected to improve. Specific grid designs were developed in an optimization study [4], in which narrow lines of 20µm turned out to be a good choice, if a height/width ratio of 0.5 was assumed. However, in current state-of-the-art inkjet printing processes, such dimensions are not available. Calculations have therefore also been made with 60µm- and 100µm-wide grids [3] and an extensive range of finger heights [5], some details of which were presented in a previous issue of *Photovoltaics International* [6].

Besides grid design, the module design is also of importance: for instance, the optimal cell length depends on the idz. Fig. 4 shows the efficiency as a function of cell length for various heights of the grid. Clearly, a higher grid has more conductive material and therefore a lower resistance; this translates to a higher cell efficiency and also to a longer optimal cell.

In the very first study by TNO, the state-of-the-art width of the idz used in the industry was 500µm [3]. Not long ago, this width had decreased to 350µm, and 150µm is currently being reported by the industry as the next step. If the idz is reduced, the optimal cell length is also reduced. A lower fraction of surface area lost in the idz improves the optical performance; moreover, the optimal cell length shifts to a smaller value, because shorter cells will lead to reduced electrical losses in the front contact. It is important to check the benefit of grids for different idz cases, and to also consider all the effects associated with adding grids. For example, when the conductivity of the front contact is improved by adding a metallic grid (even with a small optical penalty), the optimal cell length is greater. All of these effects are summarized in Fig. 4.

As can be seen in all the graphs in Fig. 4, the application of a metallic grid improves the efficiency. The efficiency and the optimal cell length clearly increase with higher fingers, as the conductivity of the grid will increase. The current state of the art is effectively represented by Fig. 4(d). On the basis of a 19% small-cell efficiency covered with a commercial grade TCO of 10Ω/sq. and an idz of 350µm, the expected panel efficiency is about 16% with an optimized cell length of 4–5mm. A grid of 2µm in height would yield an improvement of just over $1\%_{abs.}$ for a 20µm-wide grid (Fig. 4(b)), and just under $1\%_{abs.}$ for a 60µm-wide grid (Fig. 4(d)).

A reduction in idz will yield a significant improvement in efficiency for the TCO-only sample, but a lesser one for the cells with a grid. The difference in magnitude between these two improvements mainly stems from the fact that cells with a grid are longer and the optical loss associated

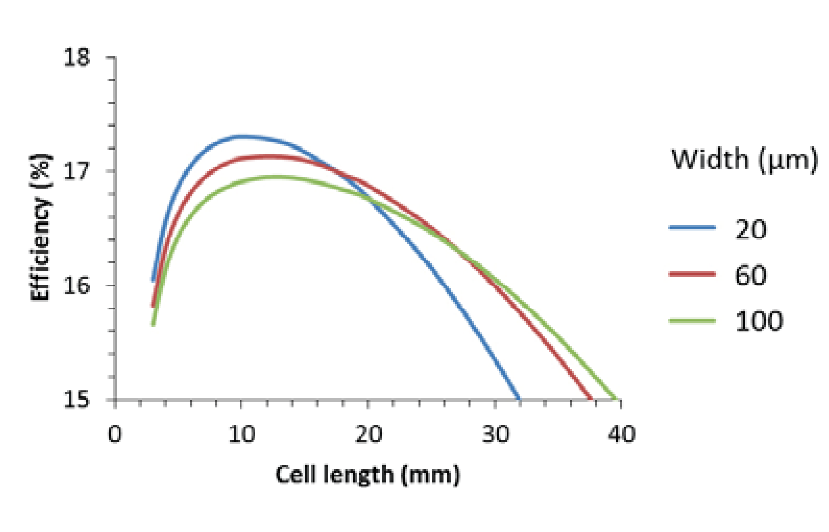

Figure 5. Efficiency as a function of cell length for various finger widths (grid height is 5µm).

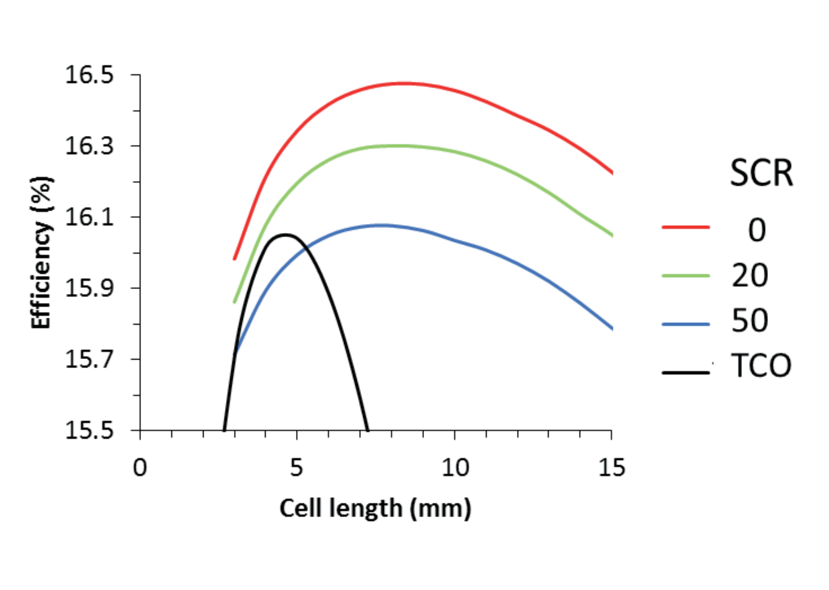

Figure 6. Efficiency as function of cell length, illustrating the impact of specific contact resistance (SCR, in mΩ·cm²). The grid is 1µm high and 60µm wide in order to represent the current inkjet state of the art. An SCR of 0 represents no contact resistance, and 'TCO' indicates the cell without a grid and with no contact resistance [5].

with the idz is lower than for the shorter TCO-only cells. Nevertheless, the efficiency increase when passing from TCO-only to grid-assisted front contacts is still about 0.5%. This shows that it is important to co-optimize the panel design and the front contact, because the optimal configuration is a function of interdependent parameters.

> "It is important to co-optimize the panel design and the front contact, because the optimal configuration is a function of interdependent parameters."

Fig. 5 shows another example, where the efficiencies calculated for various grid widths, while maintaining a height of 5µm, are compared. The values in this figure could serve as a reasonable benchmark and a technology decision aide, because a deposition technology that can achieve a grid width of 20µm will result in a higher efficiency than, for instance, printing technologies that can deliver 100µm. If a 0.1%$_{abs.}$ efficiency difference is estimated to have a value of around \$0.8/m^2 (see next section for details), then it is possible to determine how much added cost is allowed for a super-fine deposition technology, compared with a 'standard' 100µm line printer. Fig. 5 gives the answer: the difference in cost needs to be less than \$1.6/m^2, because otherwise there is no economic advantage in using the technology with the superior performance.

Not only do the configuration and technology play a role, but also the effect of suboptimal quality is an aspect that should be evaluated. For example, in the case of printing a metal on TCO, contact resistance might be present at the interface; this is represented by the specific contact resistance (SCR). A good specific contact resistance for metal printed on TCO is between 10 and 20mΩ·cm^2. Fig. 6 shows the calculated efficiencies of cells with a grid, plotted as a function of cell length for various contact resistances; the corresponding curve for a cell without a grid (and therefore no contact resistance) is also shown. The contact resistance reduces the benefit of the addition of the grid: however, it is estimated that the SCR will be less than 20mΩ·cm^2, and the impact could be minimized by dedicated ink development.

In short, although the potential for efficiency gain from grid-assisted front contacts is promising, there are a few boundary conditions, such as cell design and contact resistance, that have to be taken into account. A possible drawback of using a grid is the fact that an extra process is required. However, if a grid is used, the conductivity demands on the TCO are dramatically reduced; therefore, the TCO thickness can be much less, which results in not only increased transmittance of the TCO, but also reduced cost for TCO deposition in terms of materials and equipment. A careful cost–benefit calculation is necessary in order to determine the best options.

Technology options and cost–benefit balances

A new system was recently developed in which the cell separation and interconnection is made as a final step. In this case, the interconnection of choice would be a printed metal, as depicted in Fig. 1, which could seamlessly be combined with the metallic grid deposition [1]. In such an integrated separation/interconnection module, the positioning of the scribes would be much easier, and the expectation is that the idz could be reduced by switching to this type of system.

The economic values of several technological options were calculated and are compared in Fig. 7. The efficiency gain of adding a grid is around 0.5%$_{abs.}$, while the reduction in idz from 350µm to 150µm would yield a 0.8%$_{abs.}$ increase; the combination of the two adds 1%$_{abs.}$. These efficiencies are now translated into monetary values. It is assumed that the cost of making a solar panel is \$60/m^2 and that the total system is twice as expensive, at \$120/m^2. If this thin-film panel has an efficiency of a modest 15%, an additional 1%$_{abs.}$ in efficiency has a value of 1/15 × 120 = \$8/m^2, when just the costs mentioned above are taken into account. The ultimate value in terms of the value of electricity produced, however, is much higher: if a 1%$_{abs.}$ accounts for 10kWh/m^2 per year, which equates to around \$2/m^2 per year, then for a lifetime of 25 years that would add up to \$50!

The chart on the left in Fig. 7 shows the efficiency gain translated into \$/m^2. The middle chart shows the balance, which is the gain minus the associated cost of the grid deposition and change in manufacturing costs as a result of changes in cell length (number of scribes/m^2). In this middle chart, it is seen that reducing the idz contributes significantly to the balance, which is actually the profit. Adding a grid with an idz of 150µm yields a bonus in efficiency, but this effect is offset by the associated costs involved in the silver printing; such costs could be lower, however, once alternatives (such as copper-based inks) become available.

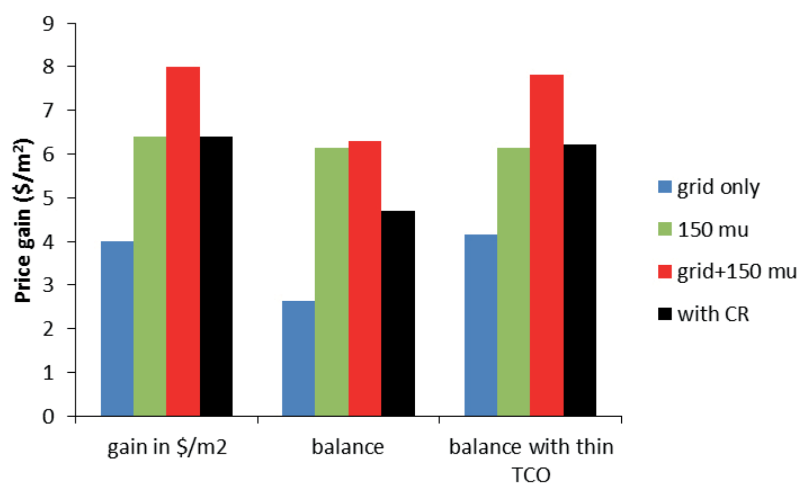

Figure 7. Gain, translated into \$/m^2, resulting from efficiency increases and cost–benefit balances of various technologies. The baseline is a cell with TCO-only and an idz of 350µm. In the legend, 'grid only' represents the addition of a grid, '150 mu' represents a TCO-only cell with an idz of 150µm, 'grid+ 150 mu' represents a combination of the two, and 'with CR' represents this same combination, but including the effect of contact resistance.

The set of data represented by the middle chart in Fig. 7 does not include the bonus of reduced manufacturing costs due to the thinner TCO; this is shown in the right chart. If reduced TCO costs are taken into account, the grid deposition in combination with 150µm, as shown by the red bar, seems an attractive option. Unfortunately, if the contact resistance is 20mΩ·cm^2, this cost benefit would be counteracted. Fig. 7 illustrates the advantage of putting benefit and gain–cost balance figures in \$/m^2 for various technological options next to each other; this can lead to the making of both technologically and economically viable decisions.

Texturing for black panels

Any light that is not captured by the absorber does not contribute to the solar panel operation. Maximizing the in-coupling of light has been a major topic for many decades. Thin-film PV offers the possibility of making layer

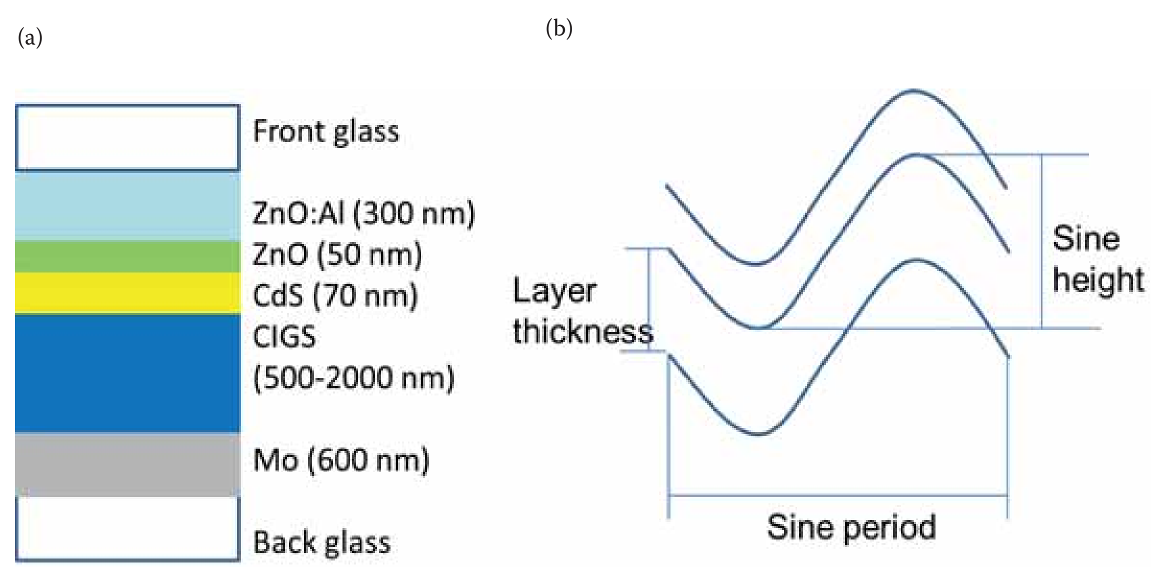

Figure 8. (a) Layer build-up of a CIGS cell. (b) An example of a texture as used in modelling.

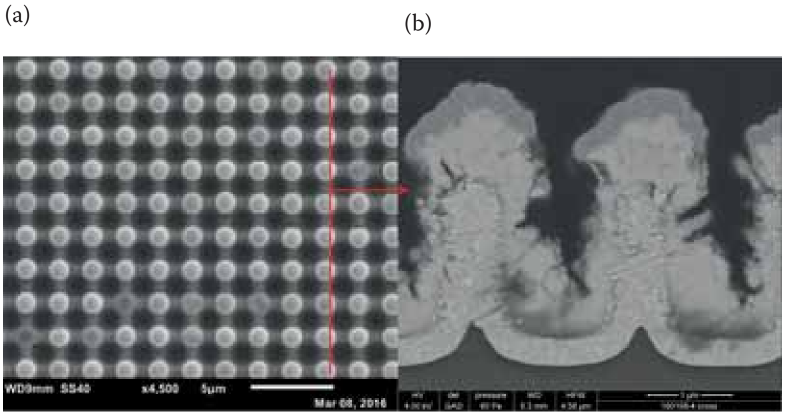

Figure 9. Scanning electron microscopy (SEM) images of textures: (a) top view of a texture with only a Mo layer; (b) cross section of a texture with a full cell stack.

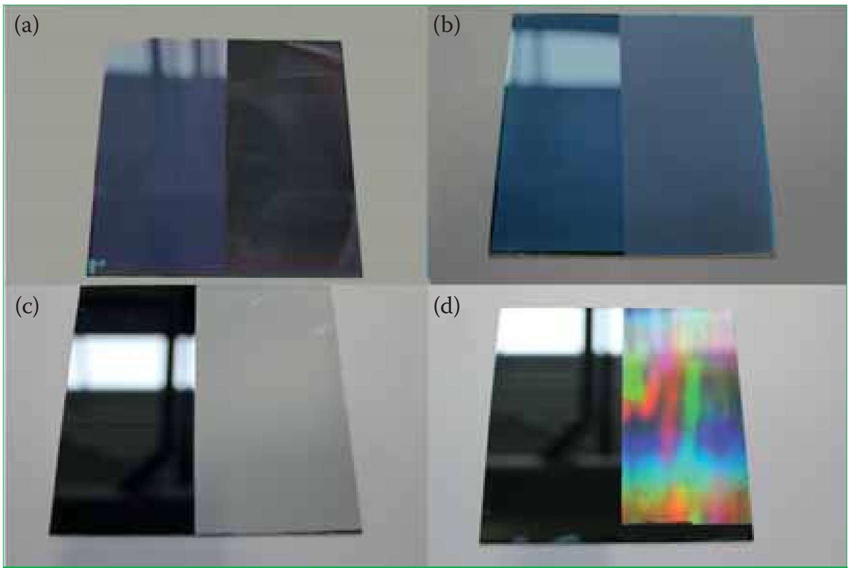

Figure 10. Examples of the optical effects caused by the choice of textures, with Mo+CIGS coatings on a texture (a,b), and a Mo coating (c,d): (a) high texture for 'black CIGS' appearance; (b) random texture for light-diffusing appearance; (c) random texture with strong light-scattering effect; (d) periodic texture with rainbow effect. The left-hand sides of the images are the smooth substrates, and the right-hand sides are textured. The whitish horizontal bar is a reflecting light source.

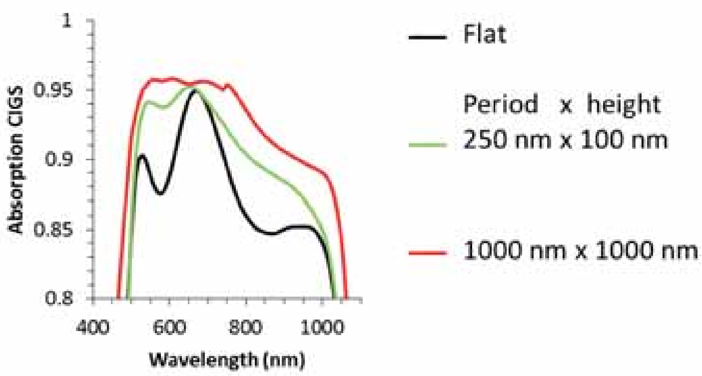

Figure 11. Examples of CIGS absorption spectra for different texture dimensions.

stacks on specifically designed textures; this has been developed especially for thin-film silicon, as it is an absolute necessity in this case because the Si layer needs to be thinner than optimal for light capturing.

For CIGS-based cells, however, much less has been done in terms of development in the texturing field. There has been some work on texturing the TCO, but it has only been very recently that the technology of texturing the substrate in order to enhance the performance of CIGS has surfaced as a point of interest. The main reason for this 'delay' is that CIGS layers can be made adequately thick so as to absorb most of the light. With the vision of thinner CIGS layers for cost reduction, work has been carried out on sub-500nm CIGS on textured substrates; however, the cell efficiencies achieved with such technology do not match the requirements of the industry at the moment. Nevertheless, it is worthwhile investigating the potential of back-contact texturing, because not only could it be useful for thinner layers, but it might also serve to eliminate internal reflections, i.e. create 'black' CIGS.

In air, the CIGS layer reflects more than 10%. Although this value is much less than that for Si (~30%), and the total stack in a CIGS solar cell is even less reflective, any gain in this domain directly translates to better performance. Back-contact texturing could therefore be a possible asset here, as well as for thick CIGS cells. In addition to random texturization, nano-imprint technology can be applied to create specific textures, and modelling can be used to determine the required functional texture dimensions. Fig. 8 shows a cross section of a CIGS cell layer stack and an example of a texture, in this case a sine texture. Periodic textures have a certain period and height, and even with just a simple sine shape, a large variety of textures can be obtained.

In addition to sine textures, another possibility is pillar-like textures, an example of which is shown in Fig. 9. When these pillars are coated by the solar cell materials, the vertical surfaces are coated too (almost). Fig. 9(b) shows a scanning electron microscopy (SEM) image of a cross section of a textured CIGS cell stack; the cross section is taken from the side of the pillars, indicated by the red line in Fig. 9(a). The imprint material (the dark layer on the bottom) therefore shows only a small texture at the location of the cross section, while the Mo (lowest bright material)

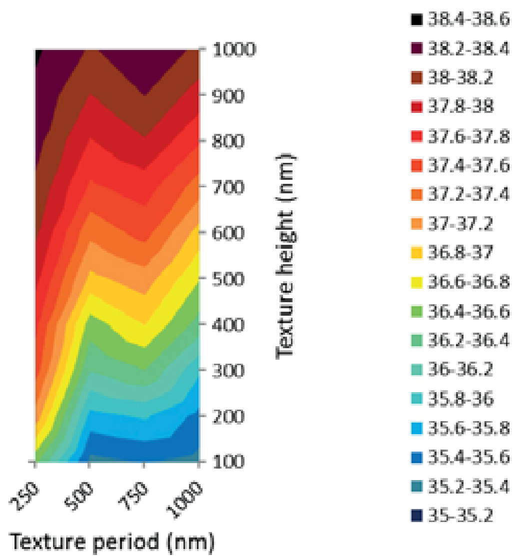

Figure 12. Area plot of modelled CIGS cell current density (mA/cm^2), represented by different colours, for various sine texture dimensions.

shows as a pillar in the image. Above and surrounding the Mo is the CIGS layer, and the slightly darker layer on top is the ZnO:Al. The CdS is located between the CIGS and the ZnO:Al layers, but is only visible on very close inspection of the image. The pillar texture results in a reduction in reflectance of more than 60%. Unfortunately, without substantial process development, the electrical performance of the cell with such an extreme texture does not match its optical performance. Nevertheless, this example shows that, from a deposition point of view, extreme textures are a possibility.

> "An interesting aspect of periodic textures is that tuneable colours can be produced."

Once the processing and coating steps have been developed, reducing the reflection of the CIGS (stack) is just one option, as shown in Fig. 10. Note that the left side of each of the images in Fig. 10 shows the untextured sample, and the right side shows the textured portion. In Fig. 10(a) there is a reduction in reflection of about 3%$_{abs.}$ for the textured sample; this sample has the same texture as the samples shown in Fig. 9. Fig. 10(b) shows a CIGS on top of a random texture, and the reflected light has become totally diffuse because of the texture. CIGS itself has already a certain amount of texture, but perfectly smooth Mo layers too can be made completely light-diffusing by the use of a random texture, as seen in Fig. 10(c). An interesting aspect of periodic textures is that, when choosing the appropriate dimensions, tuneable colours can be produced; a rainbow appearance, as shown in Fig. 10(d), is the result of a Mo coating on top of such a period texture.

Modelling as a design tool

There is a wide range of exciting optical properties that can be achieved by texturization, and the most compelling benefit is the associated increase in efficiency. In order to determine the potential of such technology, modelling can be a powerful aid. Even more usefully, modelling can also calculate the expected benefit of texture dimensions and their impact on the optical behaviour of the solar cell stack. Fig. 11 shows the modelled absorption of CIGS in a CIGS cell stack for a flat layer stack and for two different sine texture dimensions. Depending on the dimensions, the absorption can be increased either in certain wavelength ranges or overall. From the resulting generated optical data, the current density can then be calculated. Fig. 12 shows a full mapping of the CIGS cell current density over a full range of texture periods and texture heights.

The modelling includes all the optical phenomena on the assumption that all the layers follow the texture perfectly. It can easily be seen that a higher texture is beneficial, but also that some periods are more effective than others. In particular, a period of 750nm can be a good choice, as it creates an increase in current at moderate height/period aspect ratios. A period of 250nm has the greatest impact, but the height/period aspect ratios required in order to obtain these effects are not practical in a manufacturing environment.

In summary, the modelling not only indicates the benefits but also provides a tool to rationalize certain design options. A comparison of the modelling results and the reflection measurements has been made. According to the model, a texture can increase the absorption of the CIGS layer, which is mainly caused by a reduction in the reflection, as shown by the measurement in Fig. 13; the measured value is expressed as 100 – reflection (100 – R) for comparison purposes. The differences between the modelled and measured values represents the parasitic absorption of the layers on top of the CIGS.

Cost–benefit balance

Efficiency gain is only part of the whole story, because the cost associated with it has to be taken into consideration. Fig. 14 shows that the potential gain in terms of efficiency is substantial (this figure is solely intended as an illustration of how important it is to take account of all factors). In an ideal case, the modelling suggests that the translated value of the efficiency gain could be greater than \$10/m^2. However, on the basis of experience, and of theoretical and practical insights, it is estimated that the realistic gain should be somewhere around \$6/m^2. The cost of light-management technology can vary widely, and here a rather expensive \$4/m^2 estimation is chosen in order to demonstrate that something that looks highly promising on paper could yield much less of a benefit when taking into account all the factors, and that the balance (i.e. gain minus cost) is only a fraction of the potential benefit. If the gain achieved by light-management technology is higher and the costs are lower, the balance will, of course, be much more favourable.

> "A good dose of realism as to the actual potential of the technology and a clear idea of the cost involved are indispensable."

No claims are being made here that

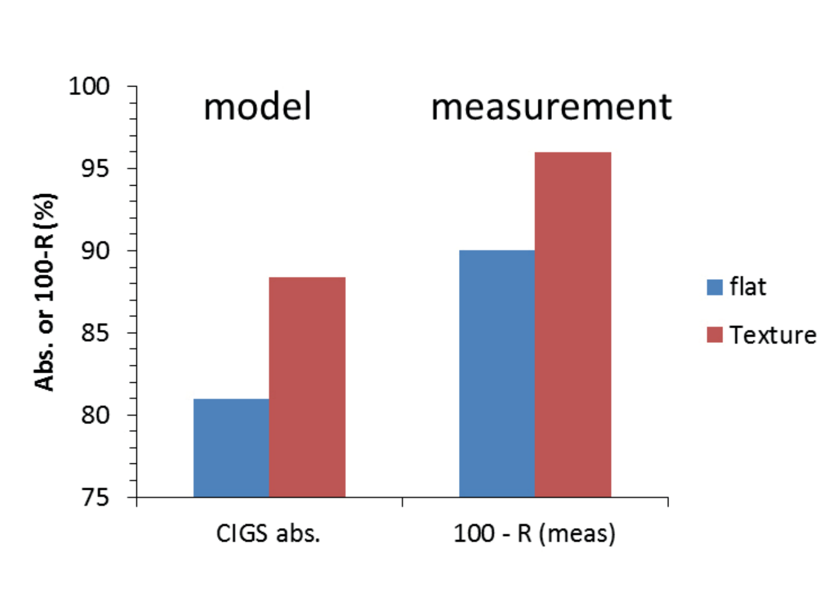

Figure 13. Modelled CIGS absorption for flat and texture surfaces of 1000nm × 1000nm, and optical measurements of flat and textured samples. The differences between modelled and measured values represent the optical losses of parasitic absorption in the ZnO:Al and CdS layers.

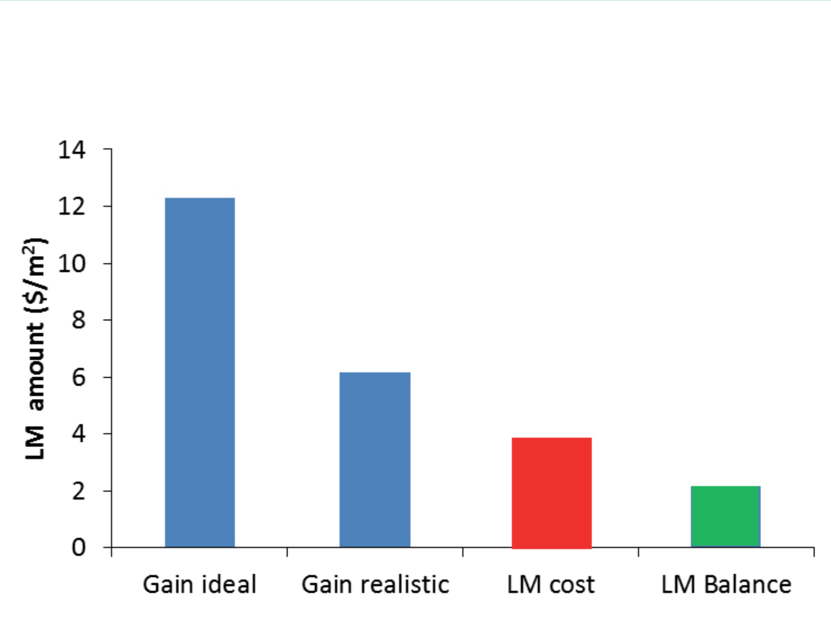

Figure 14. Calculated gain from using light-management (LM) technology for an ideal structure, along with the values for a more realistic scenario. Red signifies a very high estimation of the cost associated with LM technology, while green represents the balance, which equals gain minus cost.

nanotexturing and light management are not worthwhile: the intention is just to show that it is important to get the whole picture, and that both a good dose of realism as to the actual potential of the technology and a clear idea of the cost involved are indispensable. When the combination of all these important factors is considered, only then is it possible to make sensible decisions about innovation strategies.

Acknowledgements

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References

[1] van Deelen, J. et al. 2015, "Influence of the grid and cell design on the power output of thin film Cu(InGa)Se_2 cells", *Thin Solid Films*, Vol. 594, pp. 225–231.

[2] van Deelen, J. et al. 2014, "Improvement strategy of transparent conductive materials using metallic grids: modeling and experiments", *Thin Solid Films*, Vol. 555, pp. 159–162.

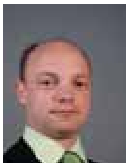
[3] van Deelen, J. et al. 2015, "Efficiency loss prevention in monolithically integrated thin film solar cells by improved front contact", *Prog. Photovolt: Res. Appl.*, Vol. 23, No. 4, pp. 498–506.

[4] van Deelen, J., Klerk, L. & Barink, M. 2014,"Optimized grid design for thin film solar panels", *Sol. Energy*, Vol. 107, pp. 135–144.

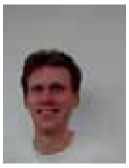
[5] van Deelen, J., Tezsevin, Y. & Barink, M. 2016, "Multi-material front contact for 19% thin film solar cells", *Materials*, Vol. 9, p. 96.

[6] van Deelen, J. et al. 2015, "Routes to increasing efficiency and reducing the cost of thin film solar panels", *Photovoltaics International*, 28th edn, pp. 46–52.

About the Authors



Joop van Deelen is a senior scientist at TNO with 20 years' R&D experience and over 60 publications, covering a broad range of thin-film PV-related topics, including deposition technologies, optics, front contacts, R&D strategy and business case development. In addition to his R&D activities, he consults for companies on technical and strategic levels in various parts of the world.



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

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PV Modules

Solar PV manufacturing activity high but new expansion announcements low in January

Credit JA Solar

PV manufacturing announcements in early 2017 were subdued.

PV Tech's preliminary analysis of global PV manufacturing capacity expansion announcements in January 2017 found they remained subdued and continued the trend set in the second half of 2016.

In contrast, PV manufacturing supply chain activity has been robust at the start of 2017. This was strongly supported by upstream manufacturing equipment order announcements for expansions targeting the second half of 2017 that were primarily announced in the first half of 2016.

Analysis of January 2017 capacity expansion plans indicates a total combined figure of 1,235MW was announced, down from 1,900MW in December 2016 and up from 500MW in December 2015.

The major announcement was news that PV and electronics equipment manufacturing and automation specialist Manz had finally secured orders for two lines, including a turnkey CIGS thin-film production line totalling 306MW of nameplate capacity and a 44MW pilot line from China-based Shanghai Electric Group and Shenhua Group.

Total thin-film announcements were around 370MW in January, the last being in September 2016. Both dedicated solar cell and module assembly announcements remained a very low levels with expansions plans including upgrades to PERC cell technology of 450MW and 415MW for module assembly.

Production

Fraunhofer ISE touts the future of frameless solar module production

A development programme initially sparked from a Fraunhofer ISE patent has been honed to industrial-scale production opportunities both in durability and cost advantage of conventional PV modules using top side glass, encapsulants and backsheets.

With the 'TPedge' assembly approach, solar cells are fixed in a gas-filled space between the two glass panes with special adhesive pins, eliminating encapsulants and backsheets as well as the aluminium frame and sealing.

Fraunhofer ISE has developed a special cost of ownership (COO) model on SEMI industry standards to accurately cost the TPedge assembly approach as well as a cell-to-module power analysis and measurements from the CalLab PV Modules.

"The results show that the specific module costs of the TPedge concept are approximately 2% less than the conventional glass-foil-laminate concept," noted long-standing project head at Fraunhofer ISE, Max Mittag. "The cost reduction is mostly due to lower material costs. Material costs are crucial since they are responsible for ca. 90% of the total module production costs, including cells."

'Ghost' solar manufacturing in Europe on the rise – SolarPower Europe

European solar trade body, SolarPower Europe, has reported in a new survey of PV manufacturing in the EU that module production and utilization rates have continued to decline in 2016.

Nameplate annual PV module assembly capacity in EU countries stood at 6.7GW in 2016, down 3% from 6.9GW at the end of 2015.

However, the stark figures relate to production output and utilisation rates. The survey revealed that production output was said to have declined by 16% in 2016 to around 2.7GW, down from 3.2GW in 2015.

Production utilization rates declined from only 46% in 2015 to 40% in 2016.

Michael Schmela, executive advisor and head of market intelligence at SolarPower Europe stated: "Our survey shows that unfortunately many of the EU module production facilities are simply ghost capacities."

Indian manufacturing

Obsolete module manufacturing lines taint Indian capacity figures

India's solar manufacturers have said that roughly 2.25GW of module manufacturing capacity that was previously deemed functional is either obsolete or too old to be counted as operational, according to consultancy firm Mercom Capital Group.

As of December 2016, Mercom had put the installed figures at 2,815MW of cells and 8,008MW of modules. Of this, 1,448MW of cell and 5,246MW of module capacity were deemed operational.

Since then manufacturers have told Mercom that the true operational module manufacturing capacity stands at roughly 3GW – around 2.25GW less than previously projected. This is due to some manufacturers reporting defunct manufacturing lines as operational.

India's manufacturers have been struggling for some time, especially since the plunge in prices for products coming out of China midway through last year. Mercom reports that Indian modules, that aren't part of local content rules, typically cost about 10% more than Chinese modules. Furthermore, projects with the latest record low tariffs at Rewa in Madhya Pradesh of INR2.97/kWh (with escalation) will only be viable with cheaper Chinese modules.

'No flow' of incentives to Indian solar manufacturers

Subsidies for Indian cell and module manufacturers are being hampered by delays, as shown by data from the Department for Electronics and Information Technology (MEIT).

A total of seven companies that have applied for an incentive for electronics manufacturers, known as the Modified Special Incentive Package Scheme

Credit Welspun

Indian module manufacturers could benefit from forthcoming legislation.

(M-SIPS), were still waiting for approval as of September last year, with some having applied a full year earlier.

Jasmeet Khurana, associate director, consulting at Bridge to India, said: "The key message is that a lot of people have been talking about setting up manufacturing in India, but only a very few of them have actually gone ahead and submitted applications to government for incentives under the existing policy and within that the sanctions are often fairly delayed – not just for solar but just M-SIPS programme overall."

The M-SIPS scheme offers a 20-25% capital subsidy for units engaged in electronics manufacturing. For high capital investment projects like fabs, it also provides for reimbursement of central taxes and duties.

While some of the M-SIPs incentives may have now come through – given the ministry data is from September 2016 – Khurana said: "There has been no flow of money."

India's GST Bill could aid domestic manufacturers

Plenty of uncertainty surrounds the potential effects of India's forthcoming Goods and Services Tax (GST) Bill, but the cost of solar could go up by as much as INR4.5 million/MW (US$67,000), according to a new study from the Council on Energy, Environment and Water (CEEW).

Originally due to come into effect on 1 April, but now touted by finance minister Arun Jaitley for a 1 July rollout, the GST sought to bring India under single tax rate. However, the GST Council recently decided to fix a four-tier GST tax structure.

On the flip side, if current tax exemptions were removed, the GST would improve the competitiveness of Indian manufacturers of solar cells and modules, with the potential creation of another 37,000 jobs in the sector by 2022.

Business

Neo Solar Power cites deferred orders for slump in November sales

Taiwan-based merchant cell and module producer Neo Solar Power (NSP) reported an unexpected slump in November sales after several months of recovery, due to deferred customer orders.

NSP reported November, 2016 sales of NT$ 898 million (US$28.2 million), a 20.03% decline from the previous month.

Sales for 2016 have reached NT$ 15,410 million (US$485.4 million) as of November 2016, a 21.28% decrease from the prior year period.

The company's relocation of production equipment to its new facility in Southeast Asia had been completed with the expectation that the facility would start ramping before year-end.

Hanwha Q CELLS garners US$317.1 million module supply deal with Florida utility

'Silicon Module Super League' (SMSL) member Hanwha Q CELLS has secured a major module supply deal with US utility, Florida Power & Light Company (FPL) valued at US$317.1 million.

The supply deal was for 2017 but the total megawatt amount of modules in the deal was undisclosed. FPL has plans to build another three PV power plants in 2017, totalling nearly 300MW.

However, the deal struck with FPL indicates the megawatts attributed to the deal are more than double FPL's announced plans for 2017, which is based on PV Tech's calculation of Hanwha Q CELLS' average module ASPs in the fourth quarter of 2016.

Credit Yingli Green Energy

Yingli is to supply its 1,500V modules for a 13MW project in Australia.

News

New PV production equipment orders impacted by China downstream demand weakness – VDMA

The German Engineering Federation (VDMA) has reported a slowdown in new solar PV manufacturing equipment orders from its members in the third quarter of 2016.

New orders from around 100 companies that operate in the solar industry that were members of the trade group were down 32% in the third quarter, compared to the previous quarter.

The slowdown was primarily due to the weakness in the downstream solar business in China after FIT changes at the end of June and new policies for 2017 still not released by government agencies.

However, VDMA noted that in the first three quarters of 2016, order intake was already higher than the total achieved in 2016.

In the third quarter, Asia remained the key market driver, accounting for 75% of the order volume, while the US accounted for 12%.

Yingli Green to supply 72-cell 1,500V series modules to Australian project

Yingli Green Energy, the eighth largest PV module manufacturer in 2016, according to the latest PV Tech shipment rankings, is to supply an unnamed customer in Australia with 13.3MW of its 72-cell 1,500V series modules.

The module format and voltage are becoming increasingly popular for utility-scale PV power plants, reducing BOS (Balance of System) costs and reduced installation times. Yingli Green introduced its 1500V series module in mid-2015, initially to the US market.

Yingli Green will deliver more than 42 thousand pieces of YGE 72 Cell 1,500V Series multicrystalline modules to the customer in the first quarter of 2017.

REC's solar module shipments in Q3 impacted by US market weakness

Integrated PV module manufacturer REC Group has reported around a 15% decline in third quarter, 2016 shipments, driven by around an 18% decline in shipments to its largest market, the US.

REC shipped a total of 276MW of modules in the third quarter, down from 326MW in the previous quarter. Although shipments to the US still accounted for 60% (167MW) of the total, US shipments fell from 202MW in the second quarter of 2016.

Market research firm GTM Research had recently highlighted a weakness in the US residential market in the third quarter, despite record total installs, driven by the utility-scale sector.

REC shipments to the APAC region were growing by 88% compared with the previous quarter, although REC did not disclose a MW figure. REC produces wafers, cells and modules at its facility in Singapore.

In the first nine months of 2016, REC has shipped a total of 916MW.

First Solar signs distribution deal with Turkey's Zorlu Solar

Leading thin-film specialist First Solar will transfer its existing business development resources in Turkey to Turkish industrial conglomerate Zorlu Solar and will close its Istanbul office.

This is a five-year agreement in which Zorlu will distribute First Solar's high-performance CdTe modules in 26 countries including Turkey, Afghanistan, Albania, Bosnia, Bulgaria, Cyprus, Georgia, Kosovo, Macedonia, Pakistan, Romania, Serbia, Turkmenistan, the Ukraine, and the Commonwealth of Independent States (CIS).

As part of the agreement, Zorlu will also power its own projects using First Solar technology.

This is the latest deal in line with First Solar's new global expansion strategy. In 2015, First Solar entered into a strategic alliance with Caterpillar to market and sell Caterpillar branded solar panels across the worldwide Cat dealer network.

Tata Power Solar hits 1GW PV module shipment milestone

Major Indian firm Tata Power Solar, a subsidiary of the mammoth Tata Group, has become the first Indian manufacturer to achieve the 1GW milestone in terms of PV module shipments worldwide.

The figure was achieved over a period of 27 years, although 60% of the shipments came in the last five years alone. Tata modules have now been shipped to more than 30 countries.

Ashish Khanna, executive director and CEO, Tata Power Solar, said: "Reaching the 1GW milestone is a testimony to our module's global competitiveness and superior quality, honed over the last 27 years. The global solar market is witnessing lucrative growth and this milestone is proof that we are a key Indian player in the domestic as well as international market. We have always believed that solar manufacturing is a key driver of jobs in the country, and will continue to build our base in manufacturing and provide the promise of brand Tata."

Credit First Solar

First Solar has opened up the market for its CdTe modules following a distribution deal with Zorlu Solar.

Quo vadis bifacial PV?

Radovan Kopecek & **Joris Libal**, ISC Konstanz, Germany

ABSTRACT

This paper presents a summary of the status of bifacial PV in respect of the technology in mass production, the installed PV systems, and the costs relating both to module production (cost of ownership – COO) and to electricity (levelized cost of energy – LCOE). Since the first bifacial workshop, organized by ISC Konstanz and the University of Konstanz, in 2012, many things have changed. Bifacial cells and modules have become cost effective, with installed systems now adding up to more than 120MWp and the technology becoming bankable. Large electricity providers have recognized the beauty of bifacial installations, as the lowest costs per kWh are attainable with these systems. The authors are sure that by the end of 2017, bifacial PV systems amounting to around 500MWp will have been installed, and that by 2025 this type of system will become the major technology in large ground-mounted installations.

Introduction

In a previous paper about bifacial PV by Kopecek, Shoukry & Libal [1], published in February 2016, the focus was on simulations of bifacial gain and on comparisons of real data from bifacial systems. A minimum bifacial gain of 10% was observed in every system, which reached almost 30% in systems in perfect conditions with regard to module properties, mounting system geometry, and reflection of the ground and surroundings (albedo). A bright future for the application of bifacial technology is forecast, as PV technology is becoming bifacial regardless: more and more module manufacturers are switching to glass–glass, cell manufacturers are switching to passivated rear-side devices (PERC, PERT, HJ), and more manufacturers are printing a grid on the rear in order to save material. In early 2016 the largest bifacial installation at the time (also reported in the above-mentioned paper) was nearing completion in Chile – the 2.5MWp 'BiSoN farm', named 'La Hormiga', which uses bifacial cells produced by MegaCell.

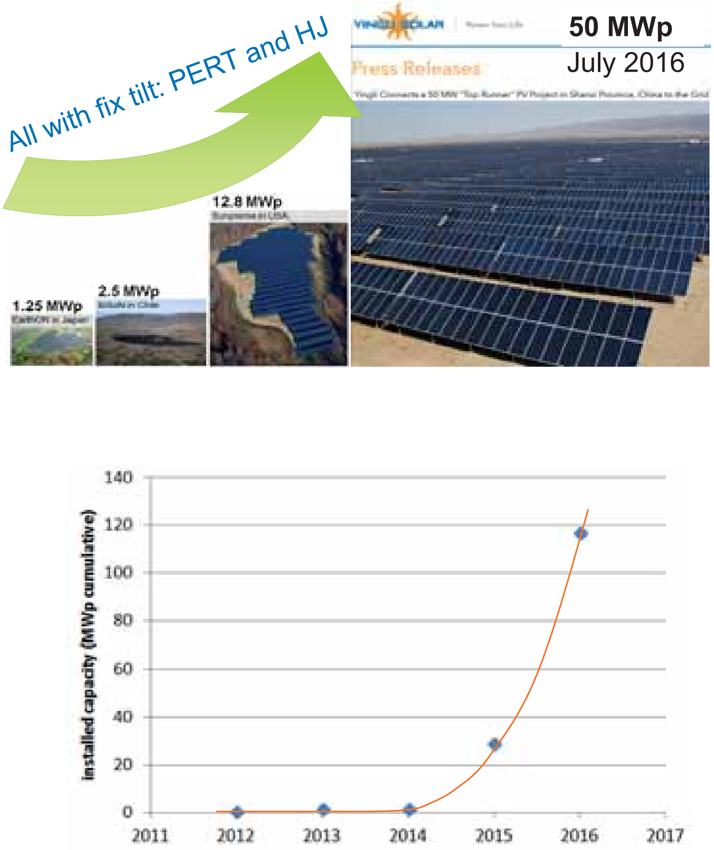

Figure 1. The largest bifacial installations at the moment (top), and the cumulated power for bifacial systems since 2012 (bottom).

Since that article in 2016, there has been a rapid 'explosion' in the number of installations of bifacial PV systems, so much so that the Chilean BiSoN farm is now quite a small bifacial installation, relatively speaking. The four largest bifacial systems at the moment (to the best of the authors' knowledge) are shown in Fig. 1.

The bifacial system from PVGS was for a long time the largest, with 1.25MWp very often quoted; it has now been surpassed in terms of size, but is still the one with the best reported data, with regard to the bifacial gains and duration of monitoring. The numbers can be found in the report by Nishiyama Sakata Electric Co., Ltd. [2]. The 2.5MWp system in Chile, which uses MegaCell-produced bifacial devices, is now up and running, and the owners are carrying out experiments regarding conditioning of the ground; for example, white pebbles are being placed below the modules in order to increase the albedo of the ground.

> "The largest installation at the moment is a 50MWp from Yingli in China."

The largest installation at the moment is a 50MWp from Yingli in China, followed by, in second place, the 13MWp system from Sunpreme in the USA. All these large installations are based on n-type technologies – nPERT (PVGS, MegaCell, Yingli) and heterojunction (Sunpreme). However, PERC+ (bifacial PERC) technology will also become important in bifacial systems, as will be seen in a later section.

The bottom graph in Fig. 1 depicts the cumulated installed bifacial MWp capacity in recent years; the current total bifacial power is estimated to be at least 120MWp. There are plans for large systems in 2017 from many electricity producers, such as the EDF project to install a 90MWp bifacial system in Mexico [3]. In addition, 8minutenergy is planning to install a 50MWp bifacial system in the USA. To the authors' knowledge both systems will be based on n-type technology in order to benefit from the better bifaciality of the modules. In 2017 it is expected that the number of bifacial installations will be at least triple that in 2016.

As illustrated in the cartoon in Fig. 2, serious discussions about bifaciality were first raised in 2000. At the moment, in 2017, there are still two split groups with two different views on bifaciality: one group says that bifaciality does not make sense, while the other claims that this technology will be the future. People from the second group are mostly from companies selling electricity and interested in costs per kWh, rather than from companies selling modules and more concerned with costs per Wp. The authors are convinced that, because in the end what matters is how high the system-generated electricity costs will be, bifacial technology will become the most important technology in the future; by 2025 this technology will be used in most of the newly installed ground-mounted systems, which will then produce electricity for less than US$ct1/kWh.

www. bifiPV-workshop.com

Since its foundation in 2005 ISC Konstanz has been working on bifacial technology. As the need to promote the information regarding this promising technology became evident, it was decided to begin organizing bifacial workshops (Fig. 3). The goal was to bring together the bifacial community and to start to work together on the most important topics in order to increase bifaciality's position in the market with regard to standardization, qualification, simulation and bankability. Three bifacial workshops have taken place so far, starting with the one in Konstanz in 2012 [4]. All the presentations of the bifiPV workshops are available for downloading, courtesy of SANDIA, from the PVPerformance Modeling Collaborative (PVPMC) website [5].

In 2015 an intermediate bifacial workshop in Chile was also organized in order to promote bifacial technology in that country, where the PV conditions are optimal. Bifaciality is now an important factor in Chile's roadmap for cost-effective solar technologies. Its government is planning large technology districts where bifacial systems will play an important role in the energy mix.

With many companies having introduced their bifacial products to the market and, as already mentioned, the number of installed bifacial PV systems having dramatically increased, the mood at the latest bifiPV in Miyazaki in 2016 was extremely positive. Fig. 4 summarizes the companies that currently produce bifacial solar cells.

There are basically three different bifacial solar cell concepts, namely pPERC, nPERT and nHJ; in addition to these, Luan is also involved in bifacial multicrystalline pPERCT production. Up until now, most bifacial cells have been based on n-type Cz-Si technology; however, as PERC technology has a total installed capacity of around 15GWp in Asia [6], 'PERC+' (bifacial PERC) technology is making a strong entrance into the market. The most prominent PERC+ manufacturers at the moment are SolarWorld, NSP and Sunrise. The bifacial factor, however, is much lower for PERC+ (60–75%) than for PERT (85–95%), although Al-paste development and improved

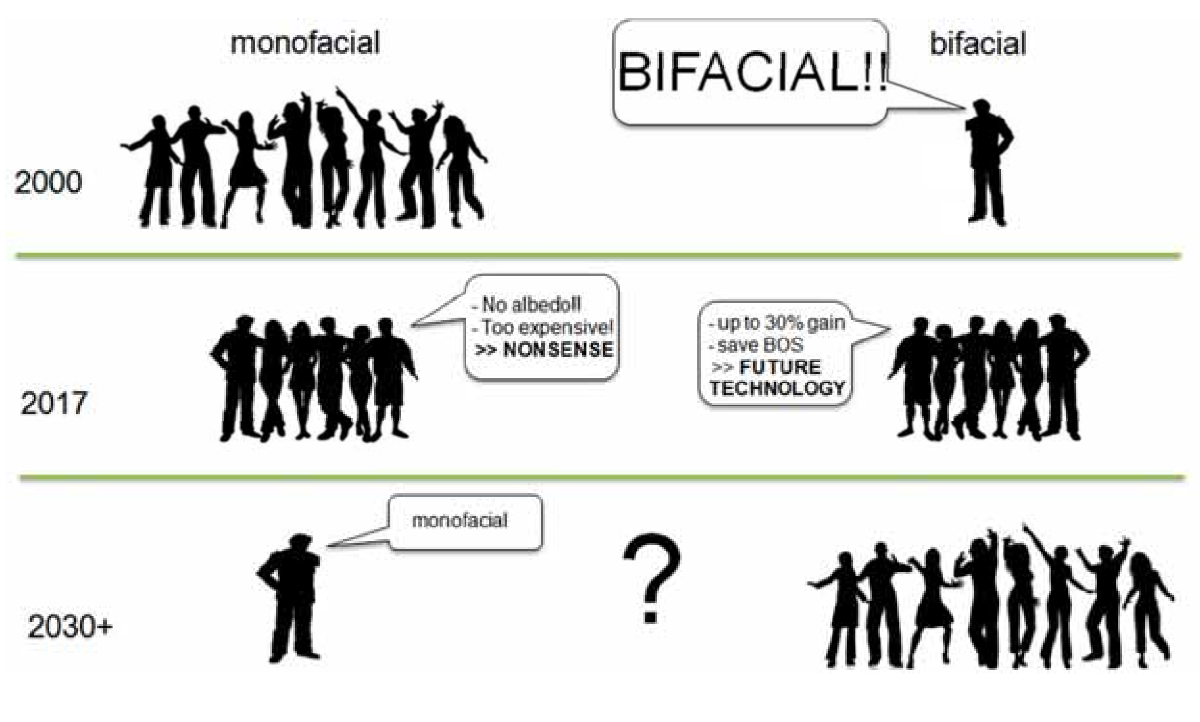

Figure 2. History of bifacial technology.

alignment of the Al-grid on the rear side are gradually improving this ratio. Nevertheless, the big advantage of PERT remains the totally diffused rear side, which means that high resistivity and high-lifetime wafers can be used; moreover, the surface passivation of the diffused rear side of the PERT cells is more stable over time.

"The total capacity for bifacial solar cell production is currently estimated to be circa 2GWp."

MegaCell, Mission Solar and First Solar have now discontinued the production of bifacial devices. However, there are more new companies (e.g. Adani) entering the market, there are companies (e.g. LG electronics) expanding their bifacial capacities, and there are companies (e.g. NSP) bringing new products, such as PERC+, on the market. The total capacity for bifacial solar cell production is currently estimated to be circa 2GWp.

COO and LCOE

When an investor has to decide which cell and module technology to implement in a PV system, there are two main criteria that will guide this decision:

1. **Bankability:** the track record of the technology and of the module manufacturers offering modules based on the considered technologies.

2. **LCOE:** the levelized cost of energy (US$/kWh).

The first criterion poses a challenge for any technology that is entering the market. In the case of bifacial PV technology – apart from the track record of the existing bifacial cell and module manufacturers, and from the specific technology to be evaluated – the most important issue is how much bifacial gain can be reasonably expected for a given installation. As pointed out above and in Kopecek, Shoukry & Libal [1], for ground-mounted and flat-rooftop PV systems, between 10 and 30% bifacial gain can be expected for nPERT and HJ technologies that feature a bifaciality higher than 90%. More than 30% bifacial gain is possible in the presence of very high (artificially increased) ground albedo, whereas less than 10% might be achievable in configurations that are not favourable for the application of bifacial PV (e.g. a dark ground surface with very low albedo, or installations where the modules are mounted very close to the ground or rooftop).

The quantitative analysis of the second criterion – the LCOE – requires, first, a reliable forecast of the total amount of electricity produced during the useful lifetime of the PV system when assuming the implementation of the various technologies under consideration. Second, complete information about

Figure 3. Pictures taken at bifacial workshops: the bifacial community in Chambery 2014 (top), and the conference and bifacial workshop organizers in Miyazaki 2016 (bottom).

In production

1) **PVGS: PERT** (EarthON)
2) **Panasonic: HJ**
3) **NSP: PERT** and now **"PERC+"** (bifiPERC)
4) **Yingli: PERT** (Panda)
5) Mission Solar: PERT – Ended
6) MegaCell: PERT (BiSoN) - Ended
7) **Solarworld: PERC+** (Bisun)
8) **LG: PERT** (NeON/CELLO)
9) **Sunpreme: HJ**
10) **HT-SAAE: PERT**
11) **Jolywood: PERT**
12) **QXPV: PERT**
13) **Shanxi Lu´an: mcPERCT+**
14) **Sunrise: "PERC+"**
15) + others

In pilot

a) **Motech: PERT**
b) **TRINA: PERT**
c) **Tesla/Panasonic: HJ**
d) **REC: PERT**
e) First Solar/Tetra Sun: "HJ" - Ended
f) + many others

Figure 4. Companies with bifacial solar cells in production or in pilot production.

the module and balance of system (BOS) cost is required, together with the data about the cost of financing and of operation and maintenance. While, for each specific case, taxes and potential feed-in tariffs would have to be included, in the present analysis these are omitted, as the situation varies significantly from one country to another and is also in continuous evolution.

Fig. 5 summarizes the results of the calculations for the cost of ownership (COO) for various module technologies currently in mass production, as well as the respective module efficiencies (expressed as the Pmpp of 60-cell modules) that have been used as input for the subsequent LCOE calculations. These COO calculations are based on an integrated 500MWp/year cell and module factory located in a low-cost country in Asia.

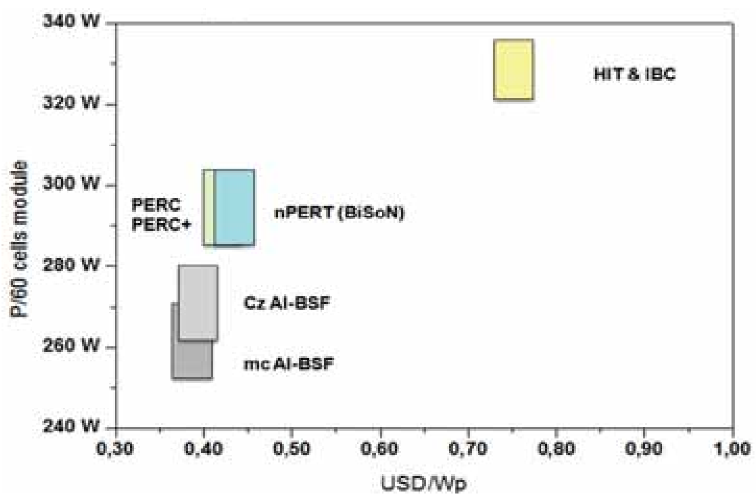

Figure 5. Summary of the results of COO calculations for monofacial and bifacial technologies currently in mass production (as of January 2017).

As regards electricity generation, a utility-scale ground-mounted solar farm located in an area with a yearly global horizontal irradiance (GHI) of 1,800kWh/m^2 was considered. Such a solar irradiation level is representative of, for example, the south of Spain, the USA and large regions of India.

The module lifetime is assumed to be mainly dependent on the module technology, and, as glass–backsheet is applicable to all module technologies, the useful system lifetime has been set to 25 years for all of them. In the case of bifacial technologies, glass–glass modules, with a useful lifetime that can be assumed to be around 35 years [7] and a lower yearly degradation rate (0.2% instead of 0.4%), have also been included in the comparison.

In order to evaluate the LCOE of various bifacial technologies under comparable conditions, the present considerations and calculations of the LCOE are based on a bifacial gain of 20% for PERT and HJ (90% bifaciality), while for PERC – because of its lower bifaciality of around 70% – a bifacial gain of 15% has been assumed.

The results of the LCOE calculations based on the above-mentioned assumptions are summarized in Fig 6. The outcome of this analysis indicates that high-efficiency but high-cost monofacial technologies, such as HIT and interdigitated back contact (IBC), currently in mass production at large manufacturers, are not competitive in terms of LCOE in the case of utility-scale system application. The results

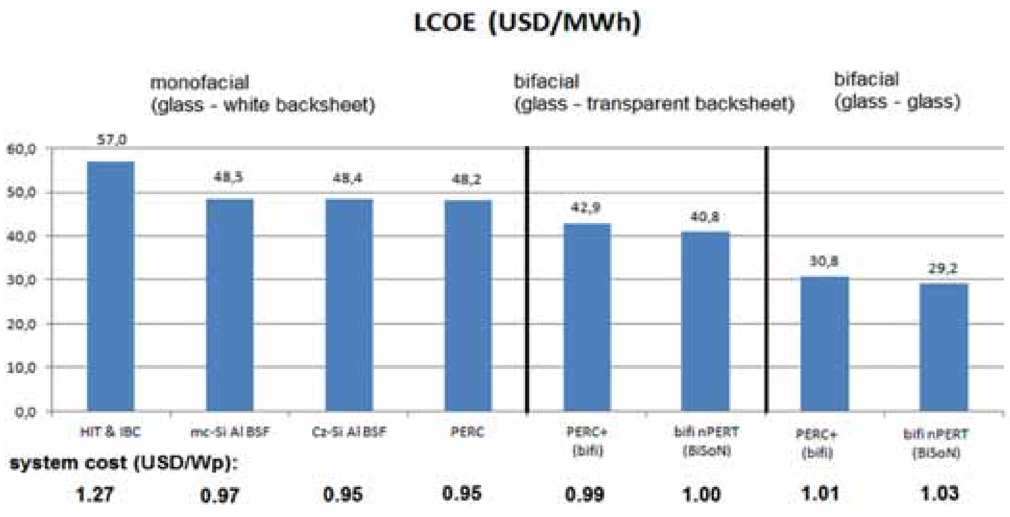

Figure 6. Summary of the results of LCOE calculations and system costs for the various technologies, based on the module COO shown in Fig 5.

Figure 7. The BiSoN farm 'La Hormiga' in Chile.

also show clearly that the mainstream monofacial technologies (mc-Si and Cz-Si Al-BSF, and Cz-Si PERC) can be considered equivalent with respect to LCOE. Bifaciality, with its reasonable module and system cost, achievable with PERC+ and nPERT, is the technological factor that results in a significant (around 14%) reduction in LCOE compared with monofacial standard technology. A further substantial reduction in LCOE of an extra 25% can be achieved by the use of glass–glass modules; this is due to the huge increase in cumulated electricity, produced during the 10 years of additional system lifetime.

Regarding heterojunction (HJ) and IBC solar cells, innovative cell concepts with lower-cost manufacturing processes are currently entering the market. With cell efficiencies of 22.5 to 23%, a module power of 320 to 330W can be achieved, while the module COO is expected to be significantly lower than that of today's HIT and IBC technologies. Both HJ and IBC are bifacially adaptable technologies; accordingly, the respective LCOEs of their modernized versions are expected to be significantly lower than for today's HIT and IBC, and slightly higher than for PERC+ and BiSoN (nPERT). In addition, there are other possibilities: for example, the company Solaround is developing a bifacial PERT solar cell technology [8] based on Cz-Si wafers, with an anticipated lower manufacturing cost than for PERC+ while featuring a bifaciality of 95% or higher.

An example of a large bifacial PV system is the previously mentioned 2.5MWp solar BiSoN farm 'La Hormiga' in Chile, which has been installed using bifacial glass–glass BiSoN (nPERT) modules produced by MegaCell (Fig. 7). The module design has also been optimized in order to guarantee a module lifetime of 35 years under the harsh desert climate conditions. The use of these modules, combined with a yearly GHI of around 2,500kWh/m^2, yields an LCOE of around US$23/MWh.

Summary and outlook

The time is ripe for new technologies to enter the conservative PV market. PERC technology has already pronouncedly penetrated the market, with a production capacity of around 15GWp in 2016 and an expected capacity of 25GWp in 2017 [6]. Fig. 8 shows the predicted PV market shares for cell technologies in future years (taken from the technology roadmap [9]).

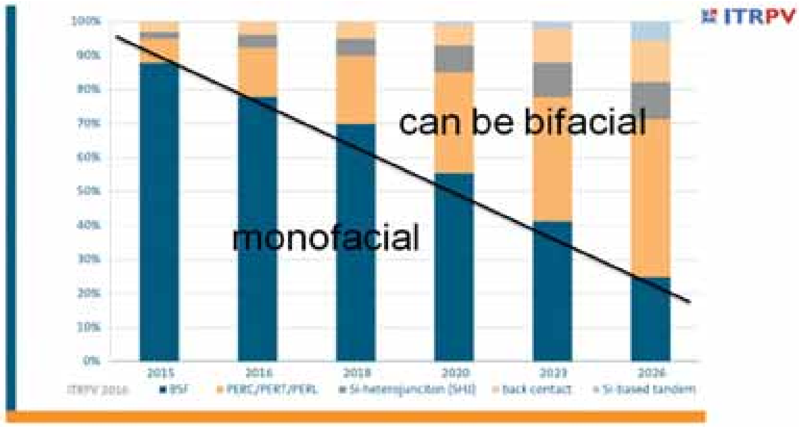

Figure 8. Projected shares in the PV market for different solar cell technologies [9].

"By 2026 the market will be dominated by solar cells that will be made bifacial and therefore result in the lowest LCOEs."

The standard Al-BSF solar cell, which has been dominant for decades, is being replaced to an increasing extent by technologies which feature rear-side passivation and can be made bifacial. PERC+ is now the latest trend for PERC producers to save material and to gain power by rear-side illumination. By 2026 the market will be dominated by solar cells – such as PERC, PERT, HJ and IBC cells – that will be made bifacial and will therefore result in the lowest LCOEs. In addition, a small contribution of tandem solar cells is predicted with a front-side efficiency exceeding 30%, for example by using perovskites in IBC cells.

A book on the topic of bifaciality is currently in preparation (due to be published at the end of 2017). The past, present and future of bifacial solar cell technology will be covered, and all the existing bifacial technologies on the market and in R&D will be discussed. In addition, the status of bifacial simulations will be reported, as well as standardizations with regard to bifacial cell and module measurements. Finally, bifacial PV systems, bankability and costs will be examined. Parameters collected from running bifacial systems will be available on the bifacial website, www.bifiPV-workshop.com.

Last, but not least, as it has been common practice to assign large-scale PV projects through a bidding process on the basis of who can achieve the lowest possible LCOE, the authors are convinced that, for utility-scale PV, bifacial technology will experience a marked increase in its market share in the next few years.

References

[1] Kopecek, R., Shoukry, I. & Libal, J. 2016, "Cost/kWh thinking and bifaciality: Two allies for low-cost PV of the future", *Photovoltaics International*, 30th edn, 88–97.

[2] Nishiyama Sakata Electric Co., Ltd. 2016, "Hokkaido Asahikawa-shi Kuranuma solar power station · Kitami solar power station: Dual solar photovoltaic power generation volume change data" (in Japanese) [http://www.nishiyama-s-denki.co.jp/pv/data/hokuto_kuranuma_all.pdf].

[3] pv magazine 2016 (Oct.), "EDF wins 90 MW solar project in Mexico's second auction" [https://www.pv-magazine.com/2016/10/04/edf-wins-90-mw-solar-project-in-mexicos-second-auction_100026345/].

[4] bifiPV workshop [www.bifiPV-workshop.com].

[5] PVPerformance Modeling Collaborative (PVPMC), "Bifacial PV project" [https://pvpmc.sandia.gov/pv-research/bifacial-pv-project/].

[6] EnergyTrend 2017, "PERC cell's global production capacity to reach 25GW in 2017, resulting in doubling of total annual output" [http://pv.energytrend.com/research/PERC_Cells_Global_Production_Capacity_to_Reach_25GW_in_2017.html].

[7] Meisel, A. et al. 2016, "SolarCity photovoltaic modules with 35 year useful life" [https://www.solarcity.com/sites/default/files/reports/SolarCity%20Photovoltaic%20Modules%20with%2035%20year%20Useful%20Life.pdf].

[8] Y. Eisenberg, L. et al. 2016, "Effective surface recombination of p^+ layers doped using ion implantation or surface deposited B sources", *Energy Procedia*, Vol. 92, pp. 16–23.

[9] SEMI PV Group Europe 2016, "International technology roadmap for photovoltaic (ITRPV): 2015 results", 7th edn [http://www.itrpv.net/Reports/Downloads/].

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Technical progress in high-efficiency solar cells and modules

Rulong Chen, **Xi Xi**, **Jie Zhou**, **TingTing Yan** & **Qi Qiao**, Wuxi Suntech Power Co., Ltd., Wuxi, China

ABSTRACT

This paper focuses on the technical progress of high-efficiency crystalline silicon solar cells and modules, specifically with regard to passivated emitter and rear cell (PERC) processes, module description and light-induced degradation (LID) data. Through appropriate optimizations of the solar cell and module processes, the cell efficiency achieved in mass production is 21.3%, with module power exceeding 300W. To solve the LID problem, hydrogenation technology developed by UNSW is used, bringing the cell LID rate down to below 1%.

Introduction

The passivated emitter and rear cell (PERC) concept was developed at the University of New South Wales (UNSW) over 25 years ago [1]. There are complications, however, when transferring the laboratory PERC solar cell process sequence to an industrial manufacturing setting. The focus will therefore be on simplifying the process sequence for industrial implementation, but aiming to obtain the same solar cell conversion efficiency as in the laboratory. In the manufacture of PERC solar cells, plasma-enhanced chemical vapour deposition (PECVD) is used to form the passivation layer, and laser opening contact is employed on the back surface. At the same time, integrated module technologies are used in order to achieve high module power.

The boron–oxygen (B–O) defect is a major concern to the PV community: it can reduce the efficiency of p-type Czochralski (Cz) silicon PERC solar cells by up to 2%$_{abs.}$ compared with the efficiency measured at the end of fabrication. In order to reduce the light-induced degradation (LID) of Cz PERC cells, hydrogenation technology developed by UNSW is used in Suntech's production line.

Solar cells

Commercial-grade boron-doped Cz p-type silicon wafers are used in the development of PERC solar cells at Suntech; the Cz-Si wafer specification is resistivity 1–3Ω·cm, thickness 200μm and size 156mm × 156mm. Solar cells are fabricated using the PERC processing sequence, as shown in Fig. 1. Prior to the deposition of the dielectric passivation layers, wafers are saw-damage etched and surface textured by KOH solution, followed by HCl/HF cleaning, phosphorus diffusion and edge etching. The sheet resistance of the emitter is ~90Ω/sq. An AlO_x layer is deposited using standard Roth&Rau remote microwave PECVD systems, and SiN_x layers are deposited using Centrotherm direct PECVD systems. The hydrogenation process takes place after printing and firing.

"To improve solar cell efficiency, the diffusion and screen-printing processes are optimized."

To improve solar cell efficiency, the diffusion and screen-printing processes are optimized once the PERC solar cell process sequence has been confirmed. An optimization of the diffusion process is first performed in order to obtain a low surface concentration and a deep junction depth. The best result achieved is a surface concentration of $2\times10^{20}/cm^3$, with a corresponding junction depth of 0.4μm. The efficiency can be increased by 0.15%$_{abs.}$; this increase can be attributed to the improvement in quantum efficiency

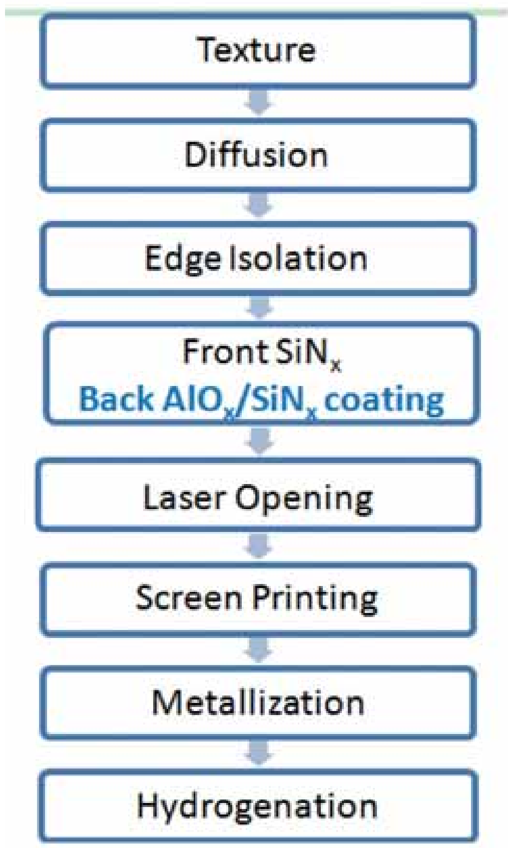


Figure 1. Process sequence for PERC solar cells.

(QE) at short wavelengths. The QE curve after the diffusion optimization is shown in Fig. 2.

The laser process, the selection of the Al paste, and the firing process are three of the most critical aspects of PERC production. The line width resulting from the laser opening, the number of lines, and the depth of the local back-surface field (LBSF) all influence the open-circuit voltage (V_{oc}), series resistance and fill factor (FF). The width and number of laser lines can be synthetically regarded as the surface proportion of the laser opening; on the basis of a series of experiments, the optimized opening proportion should be around 5.5%. In order to yield a satisfactory filling of the Al paste, the width of the lines is controlled to around 50μm. A deeper LBSF can exhibit a higher V_{oc} and FF; the depth of the LBSF is over 5μm as a result of improving the Al paste and firing process. Figs. 3 and 4 show the profile of the laser opening line and a scanning electron microscope (SEM) image of the LBSF respectively.

When all the above-mentioned optimized conditions are incorporated, the daily average efficiency achieved in mass production is over 21%. A cell selected from Suntech's PERC mass production line, not from the laboratory, yielded a maximum efficiency of 21.31% (Fig. 5), as documented in the measurement report from China PV Test Center (CPVT).

Solar cell LID

The properties and interactions of hydrogen in silicon have been extensively studied over many decades, with the beneficial effects shown as early as 1976 [2]. The use of hydrogen-containing anti-reflection coatings (such as PECVD SiN), particularly in the fabrication of multicrystalline silicon solar cells, is essential for bulk and surface passivation [3]. For monocrystalline silicon, recent studies have shown that hydrogen plays a critical role in the permanent deactivation of B–O complexes [4–5].

Hydrogen has been shown to be highly reactive, with the ability to interact with the silicon lattice and with virtually all impurities and defects within the silicon [6]. Subsequently, hydrogen passivation has been demonstrated to allow substantial improvements to the electrical performance of silicon solar cells through the deactivation of recombination activity associated with a wide array of structural- and impurity-related defects in these cells [3,4,7,8].

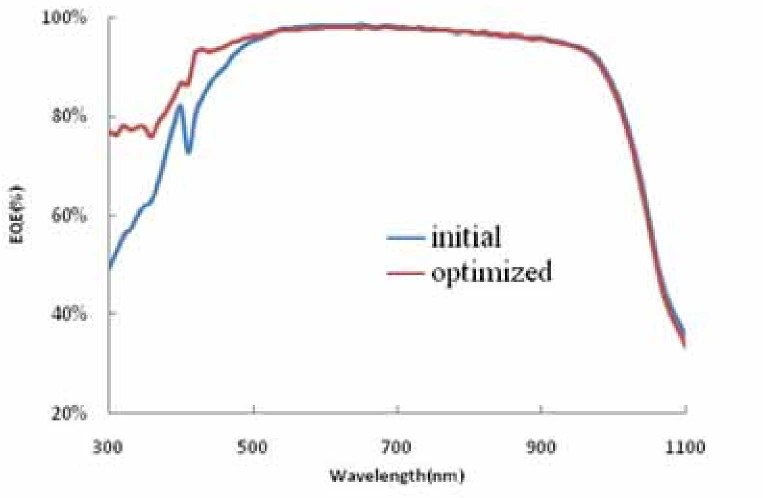


Figure 2. QE curve before and after optimization of the diffusion process.

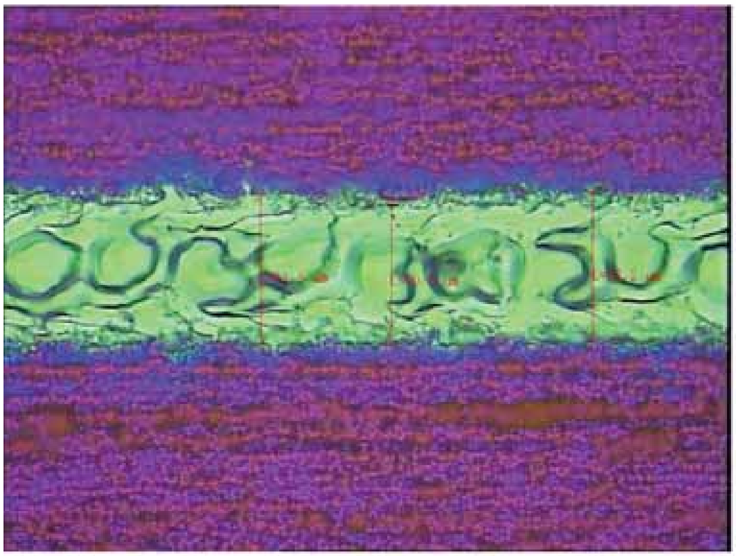


Figure 3. Profile of the laser opening line.

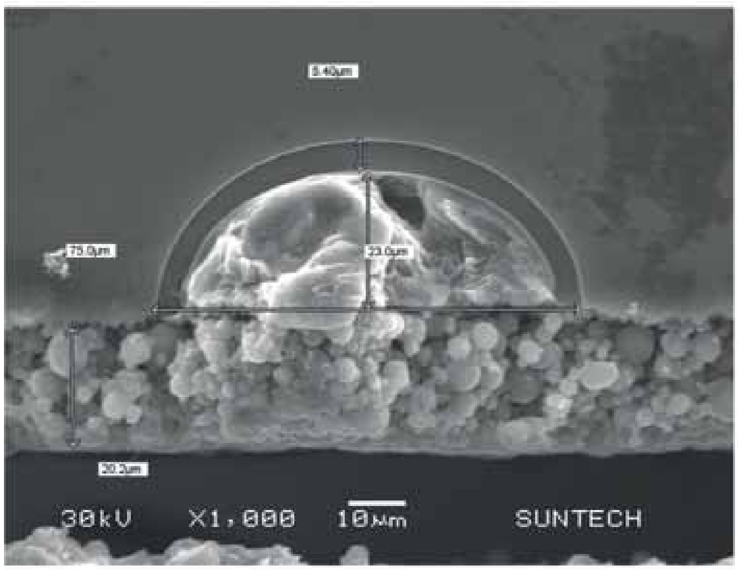


Figure 4. SEM image of the LBSF.

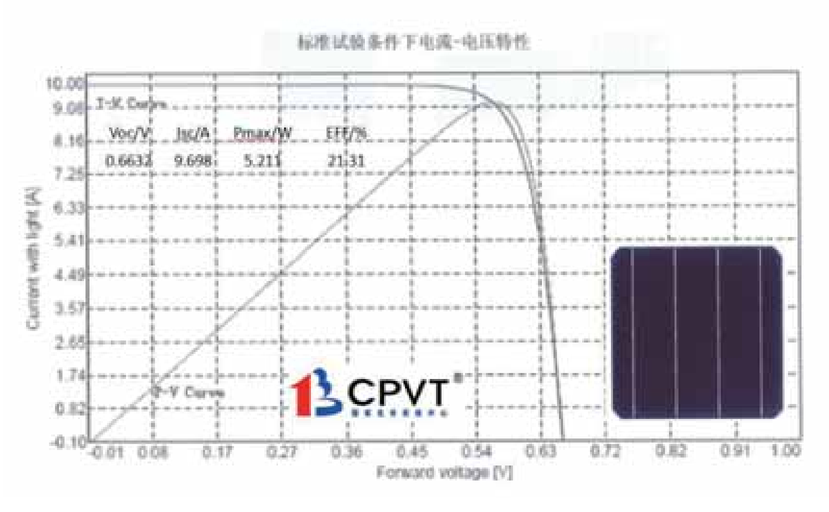


Figure 5. Cell test report from CPVT for Suntech's PERC mass production line.

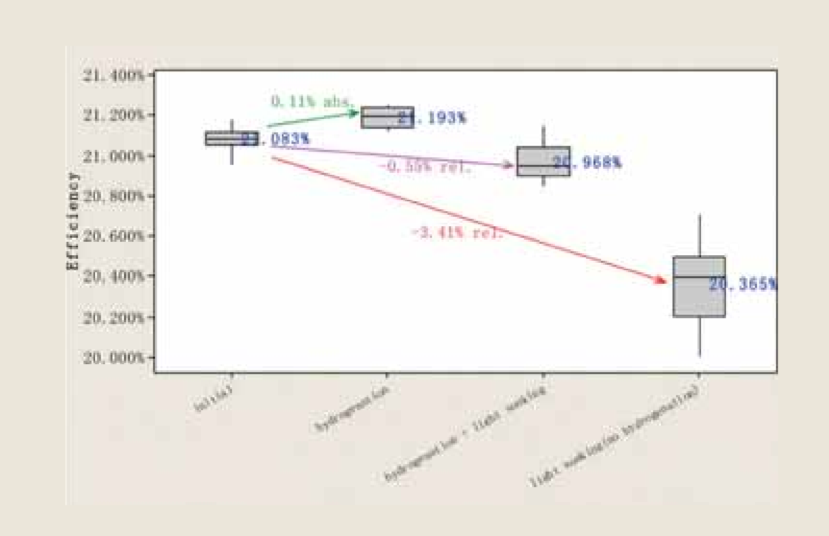


Figure 6. Effects of hydrogenation (light-soaking conditions: Xe lamp, 1kW, 5h @ 45°C).

Hydrogen is a 'negative-U' impurity in silicon with the ability to assume different charge states, taking on a positive (H^+), neutral (H^0) or negative (H^-) charge state [9]. The charge states of the interstitial hydrogen have important implications for both the diffusivity and the ability to interact with defects and impurities within the silicon [9]. For example, deep-level monovalent defects in crystalline silicon solar cells, including interstitial iron (Fe^+), interstitial chromium (Cr_i^+) and the B–O$^+$ complex, have been reported to need H^- for defect passivation [9].

The effects of hydrogenation are shown in Fig. 6: hydrogenation yields a stable increase in efficiency of 0.1%$_{abs.}$, with only a 0.55%$_{rel.}$ efficiency decrease after light soaking. Without hydrogenation, after light soaking there is a 3.41%$_{rel.}$ degradation in efficiency.

"Hydrogenation yields a stable increase in efficiency of 0.1%$_{abs.}$, with only a 0.55%$_{rel.}$ efficiency decrease after light soaking."

Undoubtedly, a number of B–O complexes are formed during cell fabrication; these are induced by hot carriers, since several high-temperature processes exist. The initial efficiency is limited by these B–O complexes, but hydrogen gives a perfect passivation in the bulk of the wafers, and increases the efficiency. The lifetime scanning maps of the cells before and after

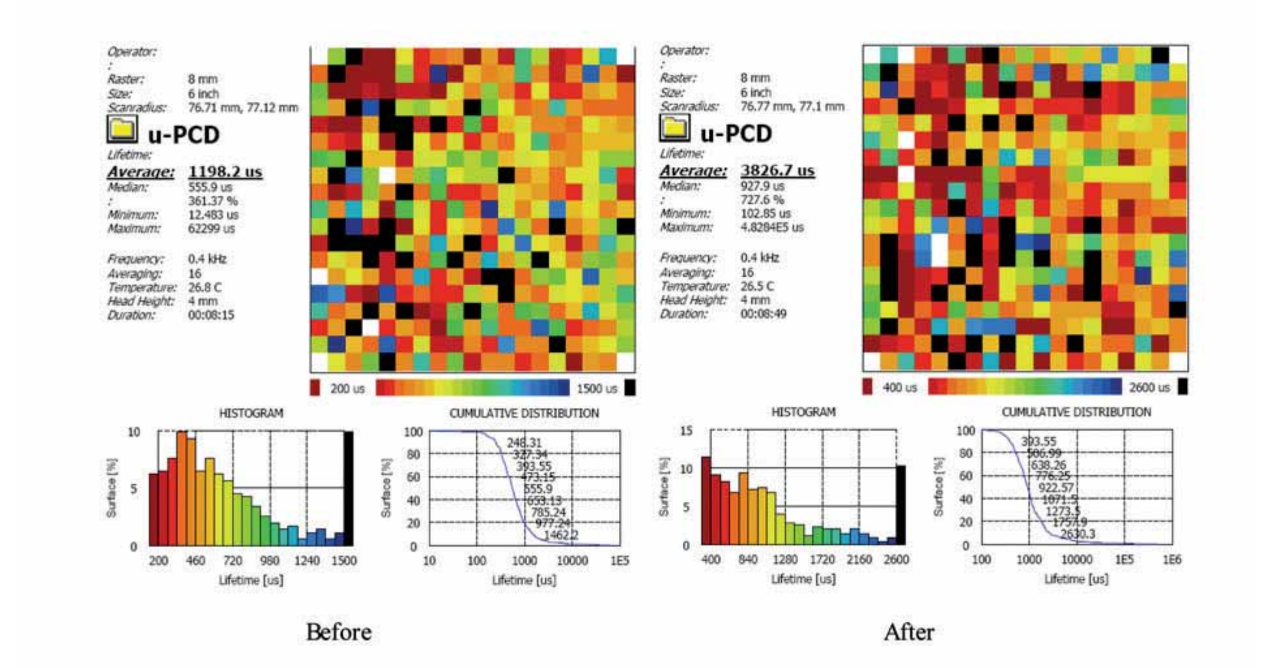


Figure 7. Lifetime scanning map before and after hydrogenation.

hydrogenation are shown in Fig. 7; hydrogenation results in a significant increase in lifetime, and generates an increase in cell efficiency.

Fig. 8 shows the daily average efficiency recorded for Suntech's PERC mass production line. It is clear that the efficiency increase after hydrogenation is stable in actual cell production.

Light soaking was carried out over a long duration in order to observe the stability of the hydrogenation process; Fig. 9 shows the process to be perfectly stable.

Modules

Module technology improvements are also implemented, to complement the Suntech high-efficiency PERC cells and to achieve a higher output power.

As noted earlier, the optimization of the diffusion improves the quantum efficiency at short wavelengths; a high-transmittivity of EVA and glass at short wavelengths is therefore required in order to benefit from cell improvements. In addition, at long wavelengths PERC cells demonstrate a higher response than standard-structure Al-BSF cells; thus, in order to carry through this advantage of PERC cells, EVA and glass with high transmittivity at long wavelengths are also necessary.

New types of EVA and glass have been chosen, with transmittivity curves as shown in Figs. 10 and 11.

When all optimizations are incorporated, the output power of the PERC modules increases by over 5W, with an average daily output power of 295.8W. The power distribution of Suntech's PERC modules in December 2016 is shown in Fig. 12; the measurement report from CPVT notes a maximum power of 303.4W (Fig. 13).

Outdoor module LID measurements have also been carried out. After two months' light soaking (summer 2016, July and August, in Wuxi, China), the degradation in module power is only $2\%_{rel.}$ (Table 1). The electroluminescence (EL) images show very little change after this long period of light soaking (Fig. 14). All the cells therefore demonstrate stable performance in an outdoor environment.

"The daily average output power of the mass production PERC module, incorporating high-transmittivity EVA and glass, was 295.8W, with the power exceeding 300W in a number of cases."

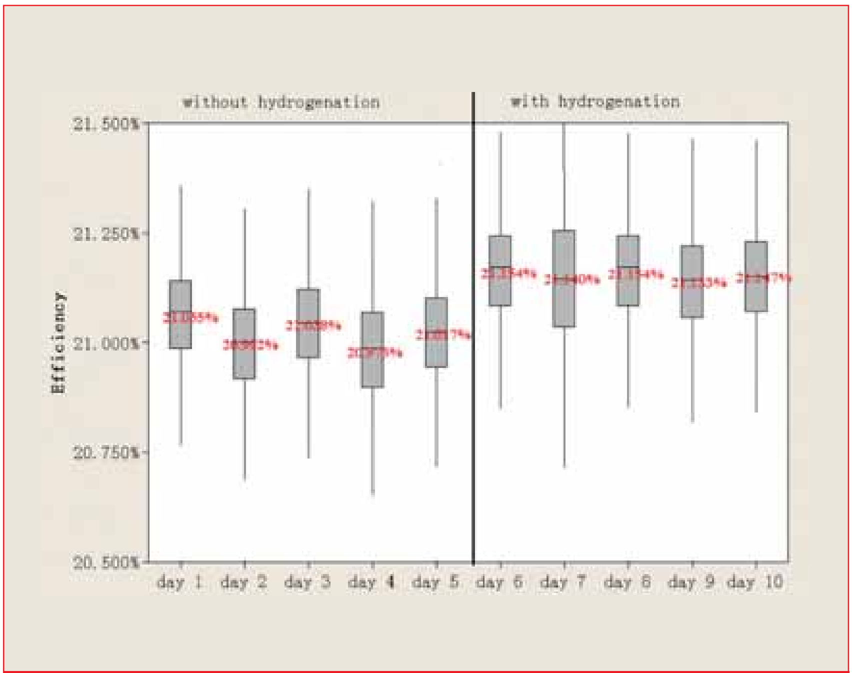


Figure 8. Comparison of data over 10 days for mass production without and with the use of hydrogenation.

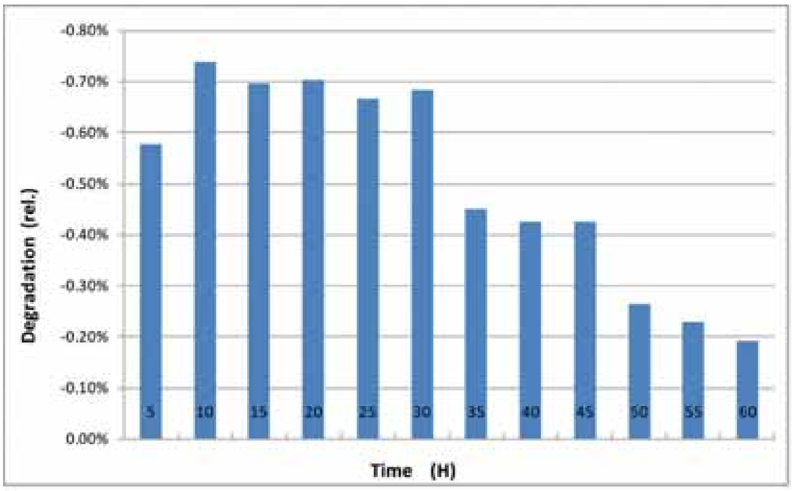


Figure 9. Long-duration light-soaking performance after hydrogenation.

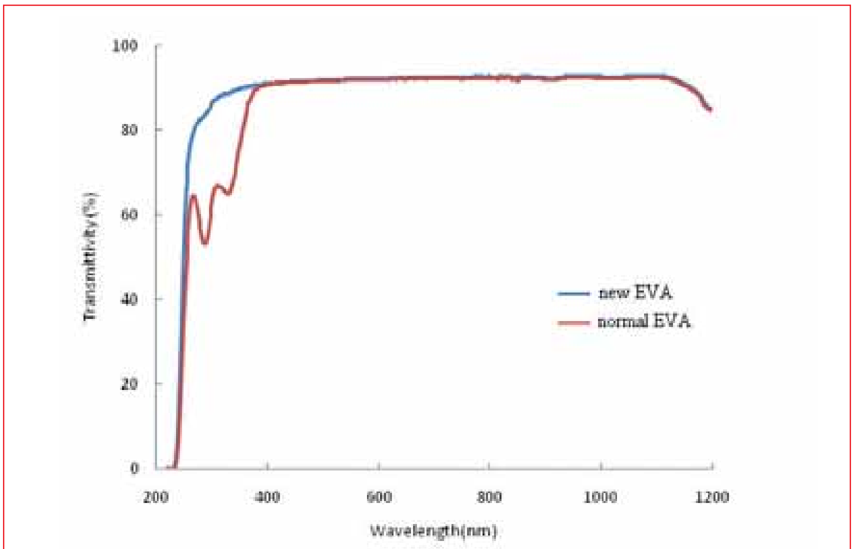


Figure 10. Transmittivity curve of the new type of EVA used for PERC module production.

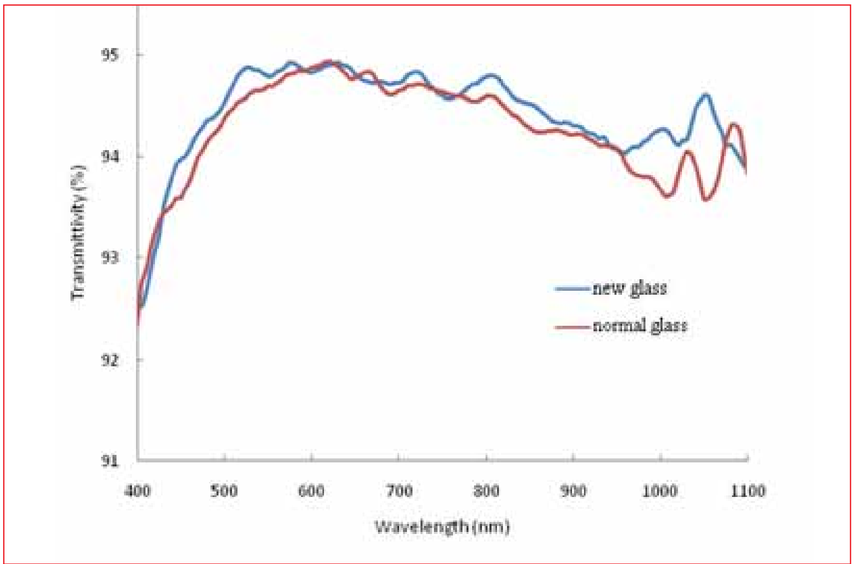


Figure 11. Transmittivity curve of the new type of glass used for PERC module production.

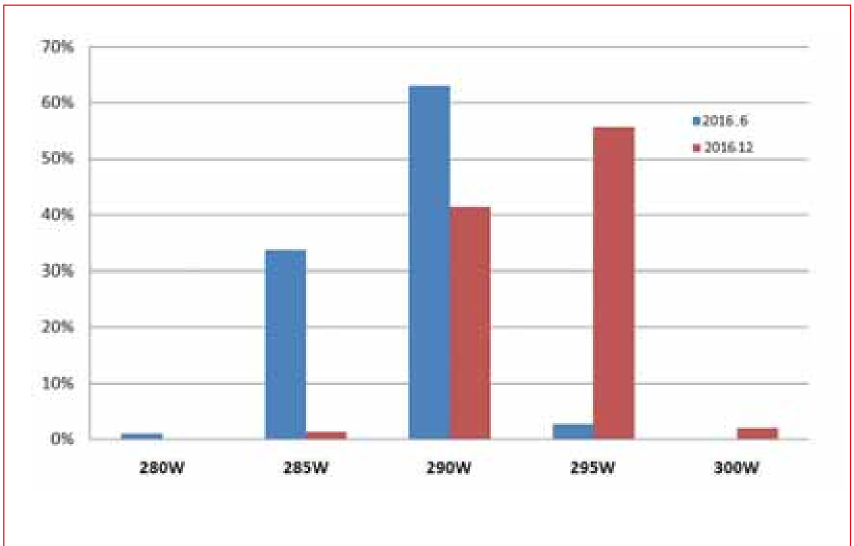
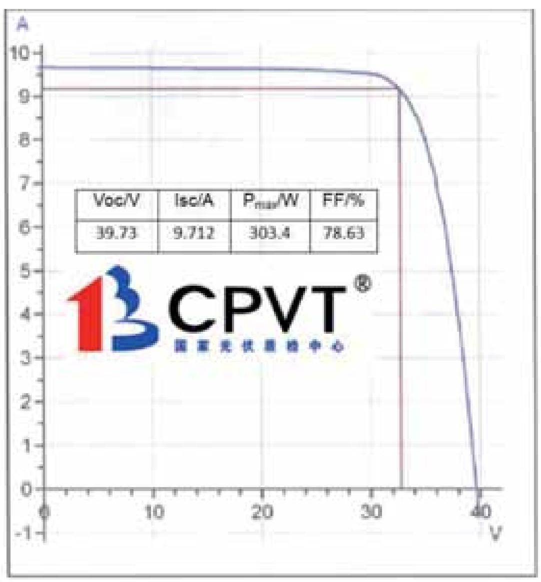


Figure 12. Power distribution of Suntech's PERC modules in December 2016.



Voc/V	Isc/A	P_{max}/W	FF/%
39.73	9.712	303.4	78.63

Figure 13. Module test report from CPVT for Suntech's PERC mass production line.

Conclusions

This paper has focused on the technical progress of high-efficiency crystalline silicon solar cells and modules, specifically the PERC solar cell process, module description and LID data. As a result of optimizing the diffusion, laser opening, Al paste selection and firing, as well as improving the passivation layers, the daily average efficiency of cells in mass production was improved to more than 21%. A major general concern in the PV domain, light-induced degradation is especially serious in the case of high-efficiency PERC cells; however, hydrogenation can completely overcome the issue of LID in cells. In Suntech's PERC production line, a gain of 0.1%$_{abs.}$ efficiency was observed after hydrogenation; moreover, an efficiency decrease of less than 1%$_{rel.}$ was recorded after light soaking (Xe lamp, 1kW, 5h @ 45°C).

In respect of modules, the daily average output power of the mass production PERC module, incorporating high-transmittivity EVA and glass, was 295.8W, with the power exceeding 300W in a number of cases.

Acknowledgements

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References

[1] Milne, A. 1991, "The passivated emitter and rear solar cell", Ph.D. dissertation, University of New South Wales.

[2] Paul, W. et al. 1976, "Doping, Schottky barrier and p-n junction formation in amorphous germanium and silicon by RF sputtering", *Solid State Commun.*, Vol. 20, No. 10, pp. 969–972.

[3] Aberle, A. et al. 2001, "Overview on SiN surface passivation of crystalline silicon solar cells", *Sol. Energy Mater. Sol. Cells,* Vol. 65, No. 1, pp. 239–248.

[4] Münzer, K. et al. 2009, "Hydrogenated silicon nitride for regeneration of light induced degradation", *Proc. 24th EU PVSEC*, Hamburg, Germany, pp. 1558–1561.

[5] Krugel, G. et al. 2011, "Impact of hydrogen concentration on the regeneration of light induced degradation", *Energy Procedia*, Vol. 8, pp. 47–51.

[6] Sopori, B. 2002, "Silicon solar-cell processing for minimizing the influence of impurities and

		V_{oc} [V]	I_{sc} [A]	P_{mpp} [W]	V_{mpp} [V]	I_{mpp} [A]	FF [%]	P. degr. [%]
1	Initial	39.17	9.38	287.48	32.42	8.87	78.2	–2.09
	After	39.07	9.24	281.48	31.99	8.8	77.99	
2	Initial	39.17	9.4	288.08	32.41	8.89	78.22	–1.81
	After	39.09	9.33	282.88	32.06	8.82	77.58	
3	Initial	39.18	9.4	287.29	32.42	8.86	78.03	–1.76
	After	39.13	9.28	282.22	32.03	8.81	77.77	

Table 1. Outdoor module LID measurement data – two months' light soaking (July and August 2016) in Wuxi, China.

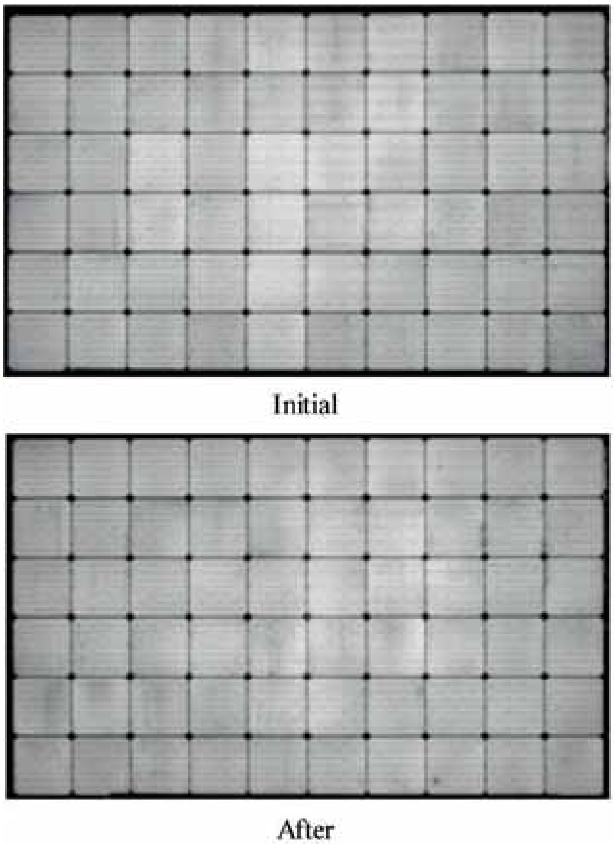

Figure 14. EL images taken before and after two months' light soaking.

defects", *J. Elec. Mat.*, Vol. 31, No. 10, pp. 972–980.

[7] Karzel, P. et al. 2009, "Mapping of hydrogen bond energies in EFG silicon samples by analysis of spatially resolved minority charge carrier lifetimes after annealing step", *Proc. 24th EU PVSEC*, Hamburg, pp. 2023–2027.

[8] Liu, A. et al. 2014, "Hydrogen passivation of interstitial iron in boron-doped multicrystalline silicon during annealing", *J. Appl. Phys.*, Vol. 116, No. 19, p. 194902,

[9] Hallam, B.J. et al. 2015, "Advanced hydrogenation of dislocation clusters and boron-oxygen defects in silicon solar cells", *Energy Procedia*, Vol. 77, pp. 799–809.

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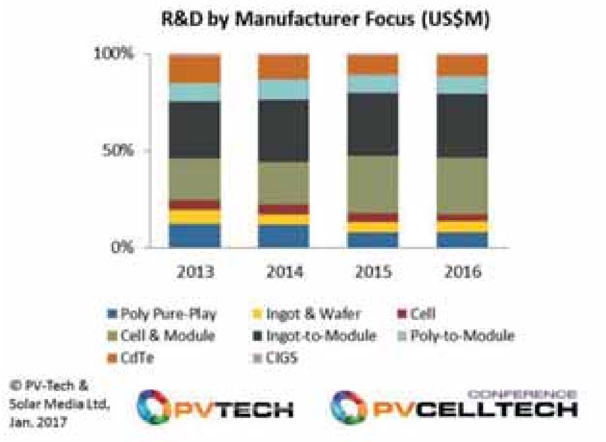
R&D spending by PV industry yet to drive new cell concepts

In our recent analysis of the key trends in solar manufacturing and technology we have constantly been reviewing the impact of technologies that fall outside the mainstream p-type mono and multi offerings that collectively have been gaining market share in the past few years, edging gradually into the low 90% territory of market supply.

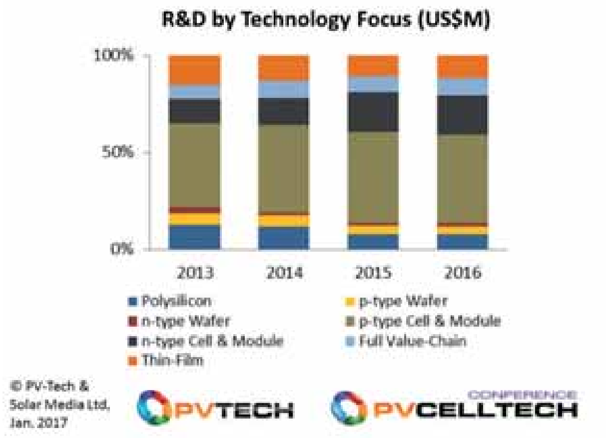
Here, we look at the latest updates to industry R&D spending. This became a key part of our in-house research during 2016 as we formed a bottom-up methodology that allowed us to view the industry's R&D spend by manufacturer type and technology focus.

Because we restrict our R&D analysis to commercial manufacturers only (not counting any R&D spend associated with academia or government funded research institutes), any key changes in R&D spending should be a leading indicator of technology changes set to come into the industry two to three years out.

The analysis shown below is adapted from the January 2017 release of our 'PV Manufacturing & Technology Quarterly' report. The themes are set to be discussed at the forthcoming PV CellTech 2017 event in Penang, Malaysia, 14-15 March 2017.



R&D spending is dominated by midstream ingot-to-module manufacturers, with the percentage from this grouping seeing gradual growth each year.



R&D spending has been seeing increasing contributions from n-type variants, perhaps reflecting changes in production from 2020 onwards.

Spending by manufacturer profile

Typically, R&D spending for PV has been trending in the US$1-1.3 billion range over the past few years, with a wide range of company-specific allocations, as a percentage of company revenues. R&D spending within the PV industry remains very different from the profiles seen in adjacent technology segments such as semiconductor or flat panel display.

Figure 1 shows the split by company 'type.' The analysis is not exact, because many companies fall outside of simple categorization, but we applied the dominant business for each company to one of the types shown in the graph legend below.

The graphs shows the dominance of the plans of the midstream segment for c-Si, with decreasing contributions from poly-to-wafer specialists. This would seem to make sense, given the push-back from FBR plans being side-lined, and the fact that integrated ingot-to-module producers have been focusing on cell upgrades or changes to module designs.

With there being just two thin-film options in the mix these days (CdTe and CIGS), it is interesting to see such low levels coming from CIGS. This would appear to contradict some of the recent CIGS tool orders in the past 12 months, but probably suggests these plans are being driven from outside research-based institutes or funding mechanisms.

What are the indicators for technology changes?

More relevant perhaps to the above is to segment out R&D spending by technology. This is shown in the graphic below. Again, this is not an exact science, but we have assigned R&D spending by each company based on what we believe is their real roadmap for production.

The main change here is actually coming from the increase in allocations for n-type research by the cell manufacturers. With overall n-type losing market share in the past few years, it still shows the fundamental assumption that, at some point, the only way to hitting average cell efficiencies in production at the 25% level will be n-type technologies.

The only question is whether, today, that is enough. Or does it even matter today? It may be that any real market-share gains from n-type do not come to fruition in the next five years, but are only seen to make meaningful contributions closer to 2025 than 2020.

When we were in an industry in the past few years of runaway dominance of p-type multi, thinking of widespread market-share gains from n-type seemed like a million miles away.

But, this all changes when p-type mono gains share, and the ingot stage moves from casting to pulling. At this point, there is an upgrade route to n-type, rather than having to perform unacceptable levels of fab retrofit.

Many of the commercial companies active in n-type mass production will be presenting at PV CellTech 2017. Further details are available at celltech.solarenergyevents.com.

This is an edited version of a blog post that first on pv-tech.org

Finlay Colville is Head of Market Intelligence at Solar Media.

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