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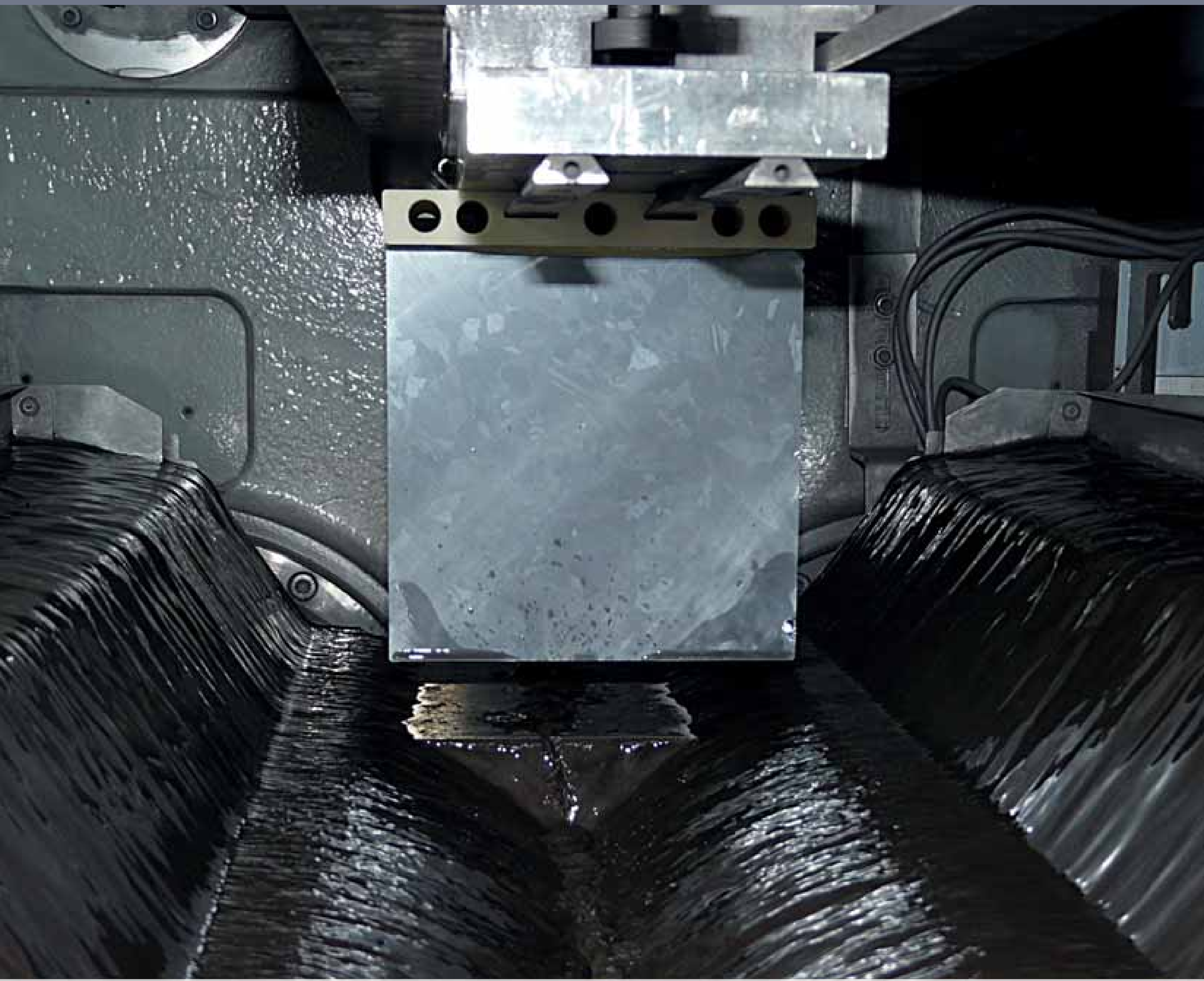

Edition 39

Ultra-thin heterojunction cells
CEA Tech-INES on the promise of cost reductions and innovatve module applications offered by SHJ cells

Diamond wire process monitoring
Reaping the benefits of diamond wire technology through accurate monitoring

Bifacial monocrystalline PERC
JinkoSolar on the path to developing high-efficiency mono-PERC cells

Cell-to-module losses
Accurate current voltage measurement of high-efficiency c-Si solar cells - CSEM

Organic PV
Volume production of customized organic photovoltaics

Top of the world
Who were the biggest module manufacturers of 2017? Find out in our exclusive listing

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Photovoltaics International

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Cover image: A Meyer Burger DW288 S3 diamond wire saw processing a multicrystalline silicon brick

Image courtesy of CEA Tech-INES

Printed by Buxton Press

Photovoltaics International
Thirty-Ninth Edition
First Quarter, March 2018
Photovoltaics International is a quarterly journal published in February, May, September and December.

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

ISSN: 1757-1197

USPS Information
USPS Periodical Code: 025 313

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

Foreword

Welcome to the thirty-ninth edition of Photovoltaics International. We go to press just a few days after the conclusion of our PV CellTech conference in Penang. The focus for all the PV CTOs, chief scientists, materials providers, equipment manufacturers and others gathered for the summit was how to keep pushing the industry towards a standard 20% efficiency while also expanding in scale. That expansion ought to be 100GW in three years if demand is to be met, according to one speaker.

The drive on both fronts, scale and efficiency, has been tracked in the pages of this journal and we continue to do so in issue 39.

CEA-INES researchers look at the benefits of exploiting the symmetrical a-Si/c-Si/a-Si structure of silicon heterojunction cells to use ultrathin wafers. They processed heterojunction cells on their pilot line using varying wafer thicknesses right down to 40μm. The results are discussed in their paper on p.49.

Another innovation that delivers materials savings is of course diamond wire sawing and, again, scale and efficiency are dual drivers. The industry is converting *en masse* to diamond wire wafering techniques. Here, CEA demonstrates the need for, and processes involved in, closely monitoring the cutting process (p.28) to ensure wafer quality is consistent and productivity can remain at the desired level.

We look at different sides of bifacial technology (pun intended) starting with JinkoSolar's appraisal of its mono PERC bifacial cells built using standard production technology and racking up average efficiencies of 21.8% (p.59). Later in the book, ISC Konstanz attempts to lock down some set definitions for the various bifacial applications available and, crucially, the expected power gains from these (p.87), a vital endeavour if these gains are to be accurately factored into project economics.

Away from the crystalline silicon world, German research firm OPVIUS explores how a combination of printing methods could open the door to freeform PV modules, unleashing an entirely new suite of product options and applications (p.67).

ECN Solar reveals the results of an industrial-scale trial process to develop an n-type bifacial IBC solar cell that is based on tube diffusion and a simultaneous single-step screen-print of contacts at both polarities. Details on the performance and cost savings, from eliminating the need for laser opening and simplified printing, are detailed on p.39.

Last but not least, CSEM looks at the impact the emerging diversity in cell technology and module architecture is having on metrology. Its researchers argue that in the absence of standards that can enable reliable, and comparable, measurements across these new technologies any and all quoted figures should be treated with a heightened degree of scrutiny (p. 78).

We look forward to your continued support in 2018 with the next issue of *Photovoltaics* International marking a decade of publishing the industry's outstanding efforts to reach the 100GW milestone.

John Parnell
Head of Content
Solar Media Ltd

Editorial Advisory Board

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

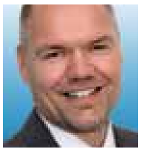
Our editorial advisory board is made up of senior engineers from PV manufacturers worldwide. Meet some of our board members below:

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

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

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

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



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

Dr. Dullweber's research focuses on high efficiency industrial-type PERC silicon solar cells and ultra-fineline screen-printed Ag front contacts. His group has contributed many journal and conference publications as well as industry-wide recognized research results. Before joining ISFH in 2009, Dr. Dullweber worked for nine years in the microelectronics industry at Siemens AG and later Infineon Technologies AG. He received his Ph. D. in 2002 for research on $Cu(In,Ga)Se_2$ thin-film solar cells.

Dr. Wei Shan, Chief Scientist, JA Solar

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

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

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

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

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

Sam Hong, Chief Executive, Neo Solar Power

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

Matt Campbell, Senior Director, Power Plant Products, SunPower

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

Ru Zhong Hou, Director of Product Center, ReneSola

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

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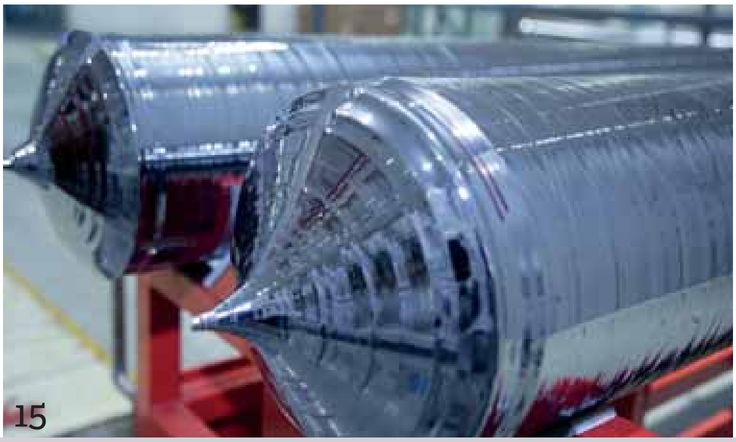

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News

Trump reveals 30% solar tariffs

President Trump has announced the tariff rates to be applied on global solar imports as a result of the Section 201 trade case.

Modules and cells will face a tariff rate of 30% in the first year declining 5% in each of the three subsequent years.

The first 2.5GW of cell imports will be exempt for the four-year duration of the tariffs.

The US International Trade Commission (US ITC) had recommended three potential courses of action to the President that in aggregate equated to tariffs of around 30%. The petitioners in the case, Suniva and SolarWorld Americas, had been pressing for tariffs closer to 50%.

In a statement, the administration said it would now look to open negotiations on existing anti-dumping and anti-subsidy duties on Chinese solar products and the reciprocal duties placed on US polysilicon by Beijing.

Credit: Gage Skidmore, Flickr

Donald Trump has ordered the imposition of tariffs on solar imports

SECTION 201 FALL-OUT

US solar tariffs to hike module costs 9-10 cents in year one - GTM and Deutsche Bank

The Trump administration's 30% tariff on imports of solar cells and panels will result in modules cost increases of 9-10¢/W in year one, reducing to 3-4¢/W in year four, according to separate analyses by GTM Research and Deutsche Bank.

GTM's number-crunching found that the tariffs would cause an 11% decrease in US solar deployment between 2018 and 2022, representing a 7.6GW reduction over the five-year period.

GTM also forecast an average module price increase in year one of 10¢/W, stepping down to a 4¢/W premium by year four.

Deutsche Bank's figures were not far off GTM's. Noting that module costs are currently in the high 20s to low 30s¢/W, the bank found that module price increases would be ~9¢/W in year one, ~7¢/W in year two (25% on 28¢/W cost), ~5¢/W in year three (20% on 25¢/W cost) and ~3¢/W in year four (15% on 20¢/W cost).

SunPower to reduce workforce by 3% in new restructuring round

US-headquartered high-efficiency PV module producer SunPower has announced plans to reduce its workforce by 3%, due to the Section 201 trade case decision by US President Trump to impose new import tariffs of solar cells and modules imported into the country.

SunPower said in a financial filing that it expected reduce its global workforce by 3%, accounting for between 150 to 250 non-manufacturing jobs. An unspecified portion of the job losses would be undertaken as part of a voluntary departure programme.

The company will incur restructuring charges of approximately US$20 million to US$30 million, primarily through severance benefits that were stated to be between US$11 million to US$16 million). Other charges relate to real estate lease termination and other associated costs put at between US$9 million to US$14 million.

The cash charges are expected to be between US$17 million and US$25 million and will be incurred in the first and second quarters of fiscal 2018.

SunPower has undergone several restructuring rounds since 2015 with the closure of older manufacturing facilities in the Philippines (cell & module) and South Africa (module) as well as job losses in its downstream PV power plant business and other non-manufacturing jobs.

EU requests consultation with US over solar tariffs - WTO

The EU is the latest body to wade into the Section 201 saga by demanding a consultation with the US over its imposition of tariffs on solar imports, according to a WTO filing from 7 February.

The US has identified the EU and its member state Germany in particular as major PV exporters that would be subject to the 30% US import tariffs.

In its WTO filing, the EU stated: "Having a substantial interest as an exporter in this case, the European Union requests consultations with the United States. [...] The aim of the consultations is, inter alia, to exchange views and seek clarification regarding the proposed measures and reaching an

Credit: European Commission

The European Union has waded into the ongoing trade row with the US following the imposition of tariffs on solar imports.

understanding on ways to achieve the objectives set out in Article 8.1 of the Agreement on Safeguards."

The EU wants to hold the consultations as soon as possible, preferably with the participation of representatives of the US' investigating authorities.

Taiwan, South Korea and China have already taken similar steps through the WTO on the US PV tariffs. However, both South Korea and China have also explicitly mentioned a demand for compensation in their WTO filings. Nor has the EU has accused the US of breaking WTO rules.

The last Section 201 case regarding steel tariffs imposed by the US, was overturned by the WTO in 2003.

INDIA

Indian PV manufacturers to refresh anti-dumping petition to avoid being 'short-changed'

The Indian Solar Manufacturers Association (ISMA) has withdrawn its anti-dumping petition regarding PV imports from China, Taiwan and Malaysia, but intends to soon file a fresh petition to strengthen its case.

The ISMA's original petition covered a period of investigation up to June 2017, but it now wants to "contemporize" the investigation to show what it claimed to be a period of even greater injury to domestic manufacturers. The association claimed that exports from the three subject countries between July and December 2017 – a period to be covered by the new petition – had increased by up to 45%, while module prices had decreased by around 25%, showing accelerated dumping in India.

H.R. Gupta, general secretary of ISMA and managing director of Indian cell manufacturer Indosolar, told PV Tech that putting in a new petition is likely to delay the whole process by another quarter. However, anti-dumping duty tenures tend to last for five years, so the ISMA was happy to interrupt current proceedings in order to make the strongest possible case for higher duties.

Gupta added: "It's a five-year remedy so we don't want to be short-changed."

WTO grants Indian request for compliance panel in solar spat with US

The WTO's Dispute Settlement Body (DSB) has granted India's request for the establishment of a panel to determine whether India complied with the previous ruling against its Domestic Content Requirement (DCR) for solar cells and modules.

The agreement came after India put in a second request for the establishment of a compliance panel since its first request was blocked by the US at a DSB meeting on 9 February, according to a Geneva trade official.

The compliance panel now has 90 days to issue its compliance ruling, but this ruling can take longer if specific reasons are given to the DSB and a new deadline date is set. The European Union, Singapore, Korea, China, Canada, Japan, Chinese Taipei, Indonesia, Norway and Russia reserve their third-party rights to participate in the panel proceedings.

India reiterated its belief that it had complied with the original ruling, however, Washington once again declared that India has continued to act in a way that is non-compliant with the WTO.

India investigates dumping of solar glass from Malaysia

India's Directorate General of Anti-Dumping and Allied Duties (DGAD) has initiated an anti-dumping investigation into imports of textured, tempered glass from Malaysia.

The sole petitioner was India's largest solar glass firm Gujarat Borosil, which was also the lone petitioner for a similar successful case against imports of tempered glass from China last year. Borosil is the only Indian supplier that produces its own annealed (raw) glass instead of relying on imports.

The Malaysian glass imports under investigation must have a minimum of 90.5% transmission and a thickness of less than or equal to 4.2mm (including tolerance of 0.2mm), with one dimension exceeding 1500mm. Such glass is often used in the assembly of solar modules.

Borosil vice chairman Pradeep Kheruka told PV Tech that the Malaysian petition came after the Chinese one because the Malaysian solar glass industry was only just starting out when Borosil lodged the complaint against Chinese imports. However, now that the Malaysian glass industry is operational, Borosil believes that its pricing strategy has been even more aggressive than that of China and merits an investigation. Kheruka said there is currently only one solar glass factory in Malaysia run by China's largest solar glass manufacturer Xinyi Glass Holdings (XYG).

Borosil has claimed that domestic industry suffered material injury from dumped imports, while demand for solar glass had increased over the injury period 1 October 2016 to 30 September 2017. DGAD decided there was enough merit to launch the investigation and will consider the period of injury extended up until 31 December 2017.


Broken Hill solar plant. Large-scale PV in Australia looks set to boom.

Credit: AGL

MARKETS

'Significant' utility-scale pipeline could send Australia shooting up PV ranks

Australia could shoot up the league table of countries by solar capacity if a "significant" pipeline of projects is realized, Wiki Solar has said.

Earlier this week the company produced its report for global utility-scale solar in 2017, ultimately concluding that global installed capacity had reached 143GW by the year's end.

While growth was largely dominated by China and India, Wiki Solar identified Australia as a particular area of promise for the forthcoming year as activity in the country looks all but set to ratchet up.

Wiki Solar said that while its list of the 15 top countries in the world in terms of operational utility-scale solar capacity remained largely unchanged – Brazil being the only new entrant to 2017's list – Australia could shoot up the rankings.

Speaking to PV Tech, Philip Wolfe, founder at Wiki Solar, said that Australia had around 300MWac/350MWp of operational utility-scale solar by the end of 2017, but this could swell quickly with more than 3GW of consented projects slated for completion this year.

Indian solar faces slowdown after record 9,255MW deployment in 2017 – Bridge to India

India deployed a record 9,255MW of solar in 2017, up 94% from the previous year, but uncertainty and a slowdown looms in 2018, according to the latest quarterly report from consultancy firm Bridge to India.

The 'India Solar Compass Q4', estimated just 6GW of total solar additions over the course of 2018, at just two-thirds of 2017's installation figures. To kick off 2018, Bridge to India expects utility-scale PV additions of 3,019MW in Q1 and 1,520MW in Q2.

The Compass, covering Q4 2017, reported a quarter that was well below expectations, with just 1,503MW of utility-scale PV commissioned, despite 5,100MW being scheduled for completion in this period. Indeed, part of the expected uptick in Q1 this year is likely to come from projects slipping through from Q4 2017. The slow Q4 was attributed to challenges in land acquisition and transmission connectivity in various SECI tenders, as well as Karnataka and Telangana state tenders. Meanwhile, module prices also grew 6% over the quarter. Indeed, Bridge to India noted that project execution costs have risen sharply by about 18% in only a six-month period.

The Q4 tally brought the country's total installed solar capacity to 19,516MW by the end of last year. Of this total capacity, 17,415MW was in large-scale, with 2,101MW in rooftop solar.

China's solar market to cool in 2018 as global demand edges over 106GW – EnergyTrend

Taiwan-based market research firm, EnergyTrend expects Chinese end-market demand to contract slightly in 2018, after posting record installations for several years in a row and accounting for around 50% of global solar installations in 2017.

EnergyTrend said that it expected Chinese market will slow down in 2018 through to 2020. Total annual grid connections, including ground-mounted projects, Distributed Generation, PV Poverty Alleviation and Top Runner projects combines would reach 46.7GW in 2018.

The recovery in the European market in 2018 is expected to support global demand of 105.88GW, according to the market research firm, up slightly from just over 100GW in 2017.

EnergyTrend reiterated that China installed 52.83GW in 2017, retaining its dominant position, while the US was the second largest market with installations of around 12GW.

India was said to have surpassed Japan as the third largest market, installing 9.26GW, compared to Japan's 6.09GW.

EnergyTrend noted that 2016 witnessed the highest growth in global solar market, increasing 42.5% over the previous year, while the growth in 2017 was 26%. Growth in 2018 would therefore be in the range 3 to 6%, only.

Top 10 module suppliers in 2017

Finlay Colville | Head of Market Research | Solar Media

Abstract

Following an extensive research process, we can now reveal the top 10 module suppliers (by shipment volumes) for the calendar year 2017. The final listing – and the underlying numbers – confirms the trends of recent years and the continued dominance of our self-penned 'Silicon Module Super League' (SMSL) group. This article shows the relative rankings of the top 10 module suppliers, and discusses the implications in terms of 100GW-plus annual deployment, further trade-related barriers in 2018/2019, and whether we have reached a tipping point where having anything less than multi-GW levels of supply will soon become a thing of the past.

Defining the terminology

Module supply is based on shipment volumes, to both in-house projects and third-party sales. It includes modules manufactured in-house by the respective companies and product that is produced under supply arrangement by OEM/contract manufacturers and subsequently rebranded by the final module supplier/seller.

Supply is based on factory-gate shipment, independent of downstream inventory levels that routinely fluctuate these days on a country-by-country level, influenced by specific interconnection tariff adjustment deadlines and trade case-based timelines for importing.

The full analysis therefore requires much more understanding of company operations, the share of internal modules to project businesses (or pure-play EPC work) and the levels to which, for example, companies in Southeast Asia have been utilized for non-China-based module assembly.

Compared to a few years ago also, fewer companies are reporting total module shipments, or failing to reveal how much third-party module supply is being used in downstream projects. This also requires a more traditional market research effort, than simply reading off sporadic and unsubstantiated module data coming out from the companies at random times.

Credit: JA Solar

Chinese module manufacturers dominated the world rankings more than ever in 2017.

Top-10 Module Suppliers in 2017

Ranking	Producer	
1	JinkoSolar	SMSL
2	Trina Solar	SMSL
3	Canadian Solar	SMSL
4	JA Solar	SMSL
5	Hanwha Q-CELLS	SMSL
6	GCL-SI	SMSL
7	LONGi Solar	SMSL
8	Risen Energy	
9	Shunfeng (incl. Suntech)	
10	Yingli Green	

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Source: PV Tech/Solar Media.

The top 10 module suppliers of 2017.

However, despite all this, the top 10 listing has become a relatively simple exercise this year, owing to the fairly significant gaps in shipments between the relative suppliers; any final adjustments at the ±200MW level that end up being reported in March filings are unlikely to make any difference to the rankings.

We have further crosschecked our data with a range of credible industry sources and believe that our listing represents the most accurate and correct picture of leading module supply volumes and rankings for 2017, despite the fact we were only just into 2018 at the time of writing. Any minor amendments will be discussed on PV Tech, should they alter any of the data behind this feature.

The 2017 rankings

The top 10 list is shown to the right. Nine of the companies were top 10 suppliers in 2016, with Risen Energy the only new entrant in 2017.

The top 10 module suppliers shipped 57GW in 2017, with the seven SMSL players occupying the leading positions. Nine of the companies are China-based operations.

Shown also are the seven companies we identified in the past 12-18 months as those we expected to be in the 4GW+ annual shipment level during 2017, forming the exclusive grouping we named as the Silicon Module Super League

Our forecast, methodology and selection of companies (making up the SMSL) have proven 100% accurate in this respect.

Indeed, only the top seven companies shown (all SMSL members) shipped in excess of 4GW each during 2017. It begs the question of whether we do indeed need to set the GW marker higher next year for the SMSL, or increase the number of companies included. We will review this in the coming months as we forecast in greater detail what is likely to unfold for module supply during 2018.

The main reason we segmented the SMSL companies was so we could analyse the tactics, technologies, cost, pricing, etc. for this specific grouping, as the benchmark for all the other module suppliers in the industry. The importance of this is likely to only increase during 2018 and beyond.

More China-centric than ever – so much for trade cases!

In 2017, the Chinese company contributions to the top 10 module suppliers ranking were greater than ever seen before in the PV industry. Nine of the 10 companies are Chinese-run operations, with only Hanwha Q-CELLS offering any non-Chinese elements.

Hanwha of course made its meaningful entry into the PV industry a number of years ago by acquiring Solarfun (Chinese), prior to the acquisition of Q -ELLS, rebranding to Hanwha Q CELLS, and subsequently setting up GW-based cell/module operations in China, Malaysia and South Korea.

The 90%-plus dominance then of Chinese-run companies in the top 10 for 2017 should beg the obvious question: why? Or how, given we have trade cases impacting major overseas markets, such as Europe, the US, and (start/stop) within India?

There are two reasons to explain this.

First, most of the top 10 module suppliers have company-run operations in Southeast Asia (Malaysia, Thailand and Vietnam) or have OEM arrangements with China-financed operations in Vietnam. Alone, this overcomes both European and US legacy import restrictions.

However, the other major reason is the China market, and the fact that only Chinese module manufacturers play in this segment. When this one country is accounting for more than 50% of global module shipments, it does not take a rocket scientist to conclude that multi-GW Chinese cell/module makers will be all over any global top 10 ranking for 2017 (and 2018).

JinkoSolar, Trina Solar and Canadian Solar: top three for three years running

Although there are many similarities in the companies within the top 10 ranking table – compounded by the fact that nine are Chinese-run operations – the top three form an exclusive top-tier ranking that is differentiated from every other module supplier globally.

In the past three years, JinkoSolar, Trina Solar and Canadian Solar have been the top three module suppliers to the solar industry and by some margin. These companies offer something that no other module suppliers have today: global brand recognition.

Indeed, with China more than half the global end-market for module supply, the leading global suppliers are by default Chinese, since the prospects of a non-Chinese produced module supplier having any meaningful sales in China are almost zero.

Therefore, JinkoSolar, Trina Solar and Canadian Solar can be regarded today as the three companies that are truly driving global sales into all the key end-markets, with established sales and marketing channels that remain the envy of most challenging competitors, in particular other Chinese suppliers. They set the benchmarks for all other Asian PV module suppliers, including the other companies in the top 10 listing above.

Is consolidation a factor yet?

Every year, the topic of consolidation comes up. And each time, the answer is a resounding 'no'. Indeed, this can be seen in 2017 again.

Yes, the top 10 module suppliers shipped more than 57GW in 2017, approaching a share of almost 60%, above the levels seen from the top 10 in recent years. But this should not be confused with consolidation in the number of companies offering modules to the industry.

The past two years have seen many more companies enter the industry (as prospective GW-level module suppliers) than companies that have exited the industry (through insolvency or acquisition). Going into 2018, we still see new entrants, in particular in China, stimulated by domestic drivers to create high-efficiency platforms based on n-type architectures, or sub-GW cell/module producers in China accessing funds to move to the multi-GW level.

If the industry's 2018 deployment is to be shaped by module shipment growth within China (uncapped), then the prospects of 60GW-plus being shipped in China is highly likely, as part of global supply this year that approaches the 120GW mark.

Companies no longer in the top 10

Being a top 10 module supplier these days excludes anyone not at the 3GW level. By default, this rules out many of the companies that have a GW-level share outside China and appear to the outside world as top 10-type entities.

Companies that have featured in the top 10 listings of recent years, but are now well below the 10GW marker from the top of the leaderboard include: First Solar, Renesola, Sharp, and SunPower. Of these companies, only First Solar has a roadmap to strongly increase module shipments in the next few years.

Last year, we featured a non-China (end-market) top 10 ranking table for module supply. The case for this in 2017/2018 is equally valid, with companies such as First Solar, SunPower and REC Solar (in particular) seeing an addressable market these days that is 50% of the global market, or less if you remove the ASP-depressed Indian market. This exercise will take more time to conclude, and we will cover this on PV Tech in detail once the final data is obtained by our research team.

What to expect in 2018

Looking at 2018 forecasts across the industry, the top 10 module supplier listing for this year is likely to consist of the same 10 companies making up the 2017 ranking list. Much of this is coming from the continued growth in China, with the industry as a whole in 2018 looking remarkably like 2017, from a China versus non-China shipment landscape.

The main difference this year however will be the technology mix making up the likely 120GW of production, in particular what 60GW may look like in China, and how much of this will come from n-type capacity being ramped up today.

We continue to monitor the rapid shift to multi-PERC, completing diamond-wire sawing on multi lines, a greater number of half-cut cell designs and more glass/glass and bifacial variants: this is all happening now, and many of these will simply drive mainstream module supply going into 2019.

The wildcard for 2018 is all about n-type, and China action. This is what will make 2018 different to 2017, regardless of the success of the new n-type GW factories being ramped up. While some of the noises may sound similar to those being voiced ahead of failed thin-film plans of the past, the difference here is that we are c-Si based (with potential n-type wafer supply available if needed) and the end-goal is efficiency (not cost) driven. Furthermore, the China operations would appear to be government, state and investor backed.

Several GW of heterojunction capacity in China at the start of 2019 certainly has the scope to be disruptive, from polysilicon consumption through to p-type PERC upgrade potential. The risk in ignoring today is simply too high

About the author

Finlay Colville joined Solar Media in 2015 as head of the new market intelligence activities. Until October 2014, he was vice president and head of solar at NPD Solarbuzz. Widely recognized as a leading authority on the PV industry, he has presented at almost every solar conference and event worldwide, and has authored hundreds of technical blogs and articles in the past few years. He holds a BSc in Physics and a PhD in nonlinear photonics.

Polysilicon consumption to decline below 4g/W in Q3 2018

Finlay Colville | Head of Market Research | Solar Media

Abstract

The in-house market research team at PV Tech, this journal's sister website, has developed a new model for forecasting trends in polysilicon consumption by the solar industry. This article analyzes how, based on this new model, the industry's use of polysilicon will dip below 4 grams per watt by the end of this year.

Consumption of polysilicon used by the solar industry will decline to below 4g/W during 2018, hitting 3.92g/W at the end of Q4'18, according to a new value-chain model developed by the in-house market research team at PV Tech, P*hotovoltaics International*'s sister website.

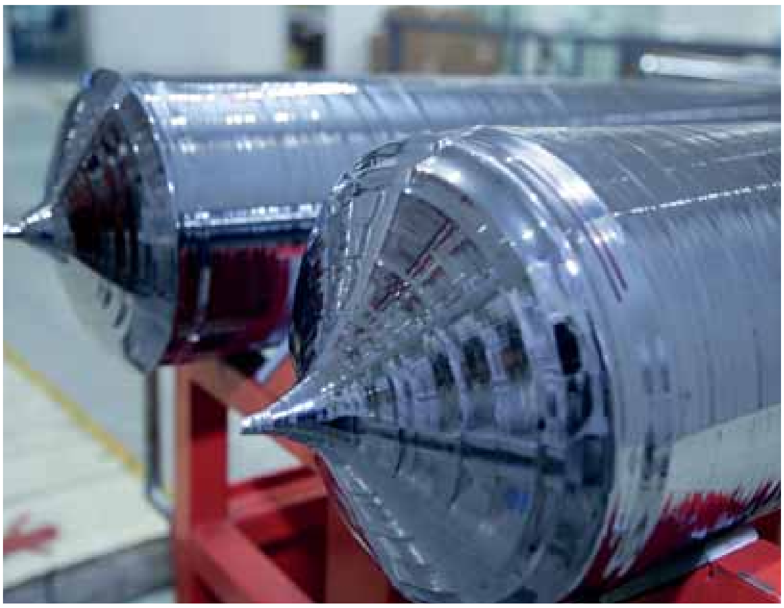
Just a few years ago, the industry was accustomed to levels of 5-6g/W, but all this has changed recently, driven by several factors running concurrently.

This article explains a new model developed by our research team which factors in every key aspect of material efficiency, and allows for highly accurate forecasting going forward.

Introducing PV Tech's new poly model

At the heart of the new analysis is our bottom-up tracking of manufacturers throughout the entire c-Si value-chain, and allocation of cell technologies across all variants that affect module efficiency and wafer thickness. This unprecedented detail is then backed up through wafering, ingot production and finally arriving at polysilicon grams-per-watt levels that can be compared to legacy top-down, back-of-envelope estimates undertaken in the industry.

Consumption of polysilicon by the solar industry will decline to below 4g/W during 2018, hitting 3.92g/W at the end of Q4'18, PV Tech analysis suggests.



Credit LONGi Green Energy

The analysis pulls out actual cell production, cell-to-module interconnection losses by technology, mono/multi usage (including n-type and p-type cell variants), diamond-wire saw adoption, kerf losses and many other factors that influence the ongoing reduction in polysilicon (g/W) used by the industry as a whole.

While the output from the analysis is fascinating in demonstrating how things have evolved – to end up with the current (blended) level today of 4.16g/W – the key advantage of the multi-variable input model is in forecasting, and assessing where the industry goes after 2018, when it is expected that polysilicon production (including the small allocation used by semiconductor applications) will reach 512kMT.

Diamond wires, mono and PERC drive down poly g/W

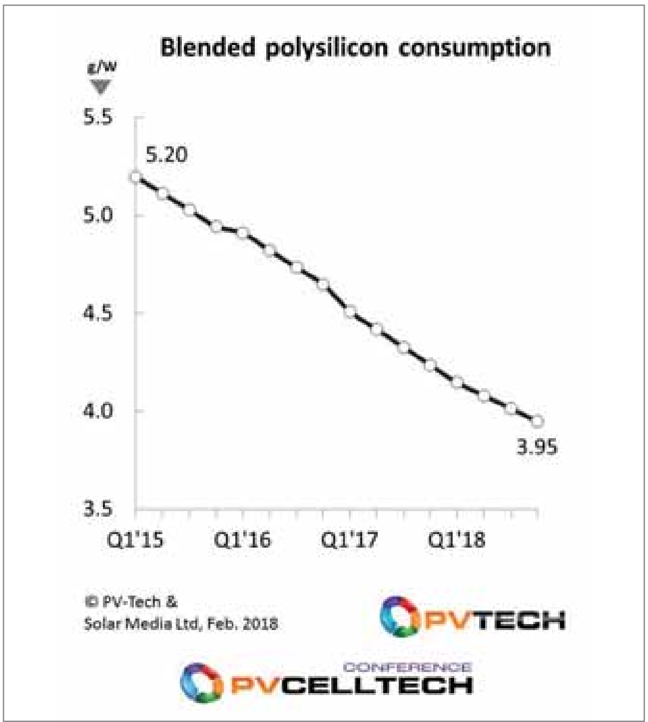
The major downward push on polysilicon g/W consumption is coming from two factors: diamond wire saws and cell efficiency improvements (more mono, and PERC in particular). By the end of 2018, almost all wafer manufacturing (mono and multi) will be using diamond wires, almost all mono will be PERC and multi will be well through its own PERC upgrade phase. The changes here dwarf incremental improvements seen at other stages (ingot casting/pulling, cell-to-module losses, and wafer thickness reductions).

The graphic in Figure 2, overleaf, looks at the percentage contributions coming from the various stages through the value chain, where the conclusions from the above come over clearly.

The rate of decline in g/W levels should slow down somewhat after 2018, with the industry largely having upgraded to diamond wires; the ongoing declines here coming now from annual kerf loss reductions that are much less pronounced.

Without any cell efficiency increases being factored in, increased share of p-mono alone will keep downward pressure on g/W levels. Cell efficiency increases will be less impactful also, with the move to glass/glass modules and bifaciality being factors more interesting to site owners when considering energy yields.

The upside will however come from higher penetration of n-type variants, although it is not



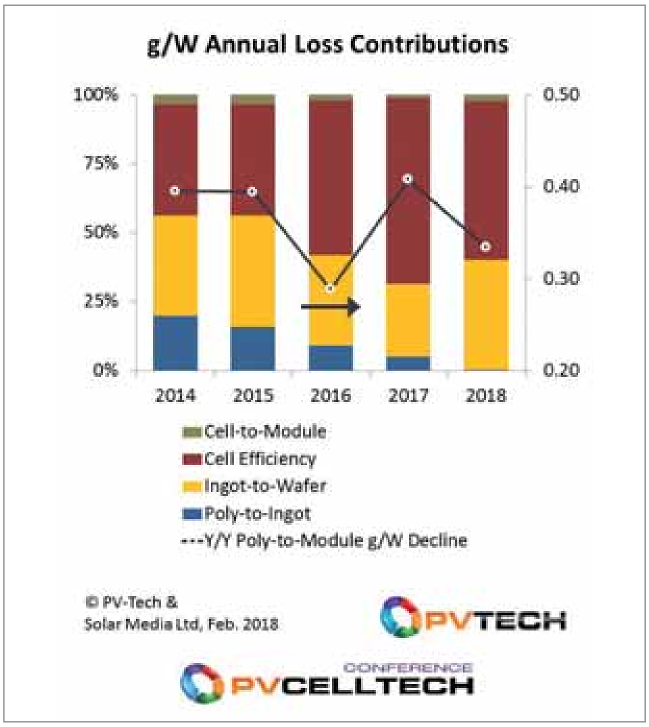


Figure 1 (top left). Polysilicon consumption is forecast to decline by 25% between Q1'15 and Q4'18, with blended levels down to 3.9g/W exiting 2018.

Figure 2 (top right). Increased mono wafer use, cell efficiency improvements, and the migration to diamond wire saws for mono and multi wafering, are key to polysilicon consumption declines today.

clear if the efficiency benefits (on circa. 180 micron wafers) will be significantly higher than leading p-mono offerings.

Wafer thickness reductions could re-emerge as key priority

This then takes us firmly back to wafer thickness reductions being the wildcard to any long-term polysilicon consumption analysis. Just how much longer can the industry go, without the inevitable shift to 140 microns as the likely first wafer reduction upgrade path?

Being in the diamond wire cut sector going into 2019, the prospects for thinner wafers are much more encouraging than at any other point in the past. For anyone looking at technology disruption over the next few years, this must be high up on the list. It is also worth noting that cell lines are more automated now, and this is one of the other key factors needed to move to thinner wafer use.

If the industry does embark on a wafer reduction path from 2019, it would basically halt all new polysilicon capacity expansion plans, over and above what is under construction and due to come online over the next 18 months.

Consider this as an example. If the solar industry goes through a 2x annual growth factor in the five-year period now (going from 100GW in 2017 to 200GW in 2022), then polysilicon required by the solar industry in 2022 would decline from approximately 670kMT (under a conservative g/W forecast using 180 micron wafers) to about 550kMT (if wafer reduction has largely moved to using 140 micron substrates).

This clearly highlights the frailty of polysilicon expansions beyond 2018-2019, with the industry comfortably on track to ship approximately 475kMT this year.

The caveat here of course is how much demand elasticity has set in, driven by the consequential material cost declines and solar as a whole being more competitive globally.

Polysilicon producers need to be cell experts to survive

However the next few years pan out for polysilicon consumption, it is bindingly clear that polysilicon producers need to be experts in what is happening with cell technology (from the basics of mono cell share, through to the plans for wafer thickness reduction), as cell line improvements will remain the dominant driver for g/W levels in the short to mid-term.

This was set to be a key theme at the PV CellTech 2018 conference in Malaysia, due to get underway as this edition of *Photovoltaics International* went to print. The conference was also due to include a panel session on kerfless wafering alternatives, which – while not discussed above – remain game-changers sitting in the wings.

About the author

Finlay Colville joined Solar Media in 2015 as head of the new market intelligence activities. Until October 2014, he was vice president and head of solar at NPD Solarbuzz. Widely recognized as a leading authority on the PV industry, he has presented at almost every solar conference and event worldwide, and has authored hundreds of technical blogs and articles in the past few years. He holds a BSc in Physics and a Ph.D. in nonlinear photonics.

News

PV manufacturing capacity expansion announcements collapse in Q3 2017

Credit: Hanwha Q CELLS

New cell capacity announcements were in short supply in the latter part of 2017.

After the significant upwards revisions made to global solar PV manufacturing capacity expansion announcements in the first half of 2017, the third quarter was characterised by much more tempered plans. The 'Silicon Module Super League' (SMSL) continued to execute on previously announced plans with some adjustments, while others in emerging markets such as Turkey and India retained grandiose nameplate targets but initial ramps remained small.

Total third quarter 2017 capacity expansion announcements reached only around 4,122MW, compared to 28,000MW in the previous quarter.

The subdued environment was driven by dedicated module assembly plans, which totalled 2,870MW, while integrated cell and module plans, absent so far in 2017, totalled 151MW. No new thin-film expansion plans were announced in the third quarter.

Although the third quarter of 2017 was subdued for capacity expansion plans, it has signalled an important milestone in PV manufacturing. Several facilities were opened in the quarter that relate to the concept of Manufacturing 4.0, which includes fully automated manufacturing lines and operated remotely.

In July, Silicon Module Super League' (SMSL) member GCL System Integrated Technology (GCL-SI) announced the establishment and operation of a module assembly workshop that was completely unmanned to test intelligent fully automated manufacturing tools and software systems. The workshop is expected to undertake tests for around two years.

LONGi restarts stalled solar cell and module manufacturing plans in India

Leading integrated high-efficiency monocrystalline module manufacturer and 'Silicon Module Super League' (SMSL) member LONGi Green Energy Technology has officially reignited previously suspended manufacturing plans in Andhra Pradesh, India.

LONGi will invest US$309 million, including around US$240 million in constructing a new facility with an initial nameplate capacity of 1,000MW of monocrystalline solar cells and expand its mothballed 500MW module assembly plant to 1GW.

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

LONGi had previously suspended the entire project in 2017, due to delays in gaining funding for the project in India and has decided to split funding between the parent company and its previously established Indian subsidiary, Lerri Solar Technology (India) Private Ltd, which is 40% owned by LONGi and 60% owned by LONGi Solar.

"The expansion of our Andhra Pradesh factory is part of LONGi's global growth strategy. While global demand for solar modules continues to grow, LONGi is making moderate capacity investments in select markets to hedge against the risks of trade protectionism, while remaining focused on the Chinese domestic market," said Mr. Wenxue Li, the president of LONGi Solar. "According to preliminary estimates, the new expansion will support $380 million in annual sales and roughly $19 million in net profit every year."

TOOLS

Amtech hits another quarterly solar revenue record but orders at new low

Specialist PV manufacturing equipment supplier Amtech Systems has continued to benefit from major solar orders placed with the company in 2017 that are continuing conversion to revenue in its fiscal first quarter of 2018.

Amtech reported fiscal first quarter 2018 revenue of US$49.2 million, up from US$30.1 million in the previous quarter, a new record high. The company reported total group revenue of US$73.6 million, compared to US$54.7 million in the preceding quarter.

Management noted that the sequential increase in revenue was due primarily to the shipment of all of the equipment for phase two of its major solar turnkey order placed with the company in March 2017.

Net income for the reporting quarter was US$6.5 million, compared to US$7.3 million in the previous quarter.

Amtech had a second sequential quarterly decline in new solar equipment orders. The company booked a total of US$7.3 million in solar orders in the reporting quarter, down from US$9.6 million in the previous quarter. New order intake peaked at US$54.2 million in its fiscal third quarter of 2017.

Amtech's solar order backlog was US$39.3 million at the end of the reporting period, down from US$81.4 million in the previous quarter.

A major drop in new orders, coupled to higher revenue recognition on shipments was behind the 50% decline, quarter-on-quarter. Backlog includes deferred revenue and customer orders that are expected to ship within the next 12 months.

Intevac's solar ion implant tool delivery dates slide again

Specialist semiconductor and PV equipment supplier Intevac is still having issues securing delivery dates for an order for 12 'ENERGi' solar ion implant tools to a customer in China, which is planning to ramp n-type mono IBC (Interdigitated Back Contact) solar cells and modules.

In reporting fourth quarter 2017 financial results, Intevac still had a total of 12 ENERGi solar ion implant tools in its order backlog, despite the purchase contract initially stipulating complete delivery of the order before the end of 2017.

Intevac had shipped the first three ion implant tools to the customer in the third quarter of 2017, with revenue recognition expected sometime in the first half of 2018. The company had cited delays with the customer in completing the construction of the manufacturing plants required for the initial 1GW nameplate capacity.

Intevac reported fourth quarter 2017 revenue of US$29.0 million, including US$19.3 million of thin-film equipment revenues which consisted of two 200 Lean HDD systems, one MATRIX PVD solar system as well as upgrades, spares and service.

Order backlog stood at US$64.0 million, compared to US$72.8 million at the end of the previous quarter, which includes 12 ENERGi solar ion implant systems.

Intevac reported full-year 2017 revenue of US$112.8 million and a net income of US$4.1 million, compared to a net loss of US$7.4 million in the previous year.

CHINESE FIRMS COURTED

JinkoSolar could be linking 1.75GW US module supply agreement to planned manufacturing plant

Leading 'Silicon Module Super League' (SMSL) member JinkoSolar could establish a manufacturing plant in the US to meet its US subsidiaries master solar module supply agreement for 1.75GW over the next three years.

JinkoSolar (U.S.) Inc., signed a major master solar module supply agreement with a US counterparty, which could be supplied via a US-based manufacturing plant that JinkoSolar would own and operate.

JinkoSolar's Board of Directors authorized planning for the construction of an advanced solar manufacturing facility in the US, without further clarification.

However, an un-named solar company secured funding to establish a manufacturing plant in Jacksonville, Florida. However, whether this plant is for both cells and modules remains unclear.

Credit: Intevac

Intevac returned to the black in 2017 though some order delivery dates slid.

The US President has recently imposed 30% import duties on all solar cells (after quota exceeded) and 30% import duties on all crystalline silicon modules made outside the US, although exemption is possible for countries who apply and for technology reasons.

Should JinkoSolar establish a manufacturing plant in the US it could easily be a highly automated assembly plant. Assembly plants come with minimal capital expenditure compared to wafer and cell production and can be established in a variety of existing buildings needing little specialist utility services and are faster to establish and close down, even with high-automation.

Pakistan invites Trina to set up solar manufacturing

Pakistan has invited Chinese Silicon Module Super League member Trina Solar to set up a module manufacturing facility in the south Asian country.

Prime minister Shahid Khaqan Abbasi said his government would provide support, including tax incentives to encourage domestic manufacturing, according to the Associated Press of Pakistan.

The invitation came at an auspicious time, following a proclamation from the US Federal Register that confirmed which countries would be exempt from US' 30% solar import tariffs, of which Pakistan is one. It should be noted that imports from exempted countries are restricted to 3% of US crystalline silicon solar imports per country and 9% for all exempt countries combined.

Pakistan's Abbasi offered the invitation to Trina during a meeting with chairman and chief executive Jifan Gao at the World Economic Forum in Davos, Switzerland. Gao thanked the prime minister and said his firm would seriously consider the option of setting up a facility in Pakistan.

Pakistan's downstream PV industry is showing promising signs with the announcement of its first tariff-based competitive solar auction to be held in the Province of Sindh.

Credit: Trina

Trina Solar is considering an invitation to establish manufacturing facilities in Pakistan.

Chinese firm plans 200MW solar cell manufacturing facility in Andhra Pradesh

China's CETC Renewable Energy Technology Company has signed a memorandum of understanding (MoU) with the Andhra Pradesh Economic Development Board (APEDB) to set up a PV cell manufacturing facility in the Indian state.

CETC Solar Energy Holdings project manager David Duan told PV Tech that the planned first phase would be of 200MW capacity.

The firm, whose parent company is Beijing-headquartered state-run company China Electronics Technology Group Corporation (CETC), already has an annual production of 1.5GW of solar cells and PV modules.

CETC will invest US$50 million in the facility, which is to be located in Sri City, Chittoor district, Andhra Pradesh. Around 300 jobs are expected to be generated in the first phase, followed by 1,500 for the entire project.

CHINA EXPANSIONS

Risen Energy plans new 5GW JV monocrystalline cell and module plant in China

Major China-based PV module manufacturer Risen Energy has recently signed a framework agreement to build and operate a 5GW monocrystalline cell and module plant in Changzhou City, Jiangsu Province, China.

According to financial filings, Risen will partner in a Joint Venture with Changzhou Xixi Modern Agricultural Development Co as designated by the local Jintan District government in a project expected to require approximately RMB 2.5 billion (US$383 million).

The JV framework agreement calls for Risen to provide RMB 1.5 billion (60% stake) and its partner RMB 1.0 billion (40% stake) towards establishing the new manufacturing facilities.

Risen also noted in a separate press release that total capital expenditures for the JV to reach the 5GW nameplate capacity of both cells and modules, as well as R&D activities would be approximately RMB 8.0 billion (US$1.23 billion).

The new manufacturing base was expected to be Risen's most advanced, producing leading-edge high-efficiency products by 2020 and providing the development of both upstream manufacturing clustering and downstream industries including project development in the region.

Jolywood raises over US$200 million for 2.1GW IBC solar cell fab

Major PV module materials and N-type mono IBC (Interdigitated Back Contact) bifacial module manufacturer Jolywood has recently secured over US$200 million for its first 2.1GW IBC solar production facility in a non-public share offering.

Jolywood said in financial filings that the non-public share offering resulted in raising around RMB 1.366 billion (US$210 million) for the production plant, which had been initially funded from in-house resources.

Limited production had started at the new facility in mid-2017.

Although many China-based PV manufacturers have been running R&D programs on IBC technology, Jolywood is one of the few to initiate volume production plans that exceed nameplate capacity of long-term IBC pioneer, SunPower Corp.

Aiko Solar meets cell capacity expansion milestones for PERC technology

China-based merchant solar cell producer Guangdong Aiko Solar Energy Technology Co., Ltd (Aiko Solar) said it had achieved a production capacity of 4GW for PERC solar cells, while initially ramping its new production plant on schedule near Yiwu City, central Zhejiang province, China at the end of 2017.

Aiko Solar had planned to become a major supplier of high-efficiency P-type mono PERC and bifacial cells to PV module manufacturers around the world after announcing major capacity expansion plans and new product introductions at SNEC 2017.

According to PV Tech's Finlay Colville, mono cell production is expected to account for 49% of all cell production in 2018, and is expected to be the dominant technology used in the industry by 2019.

Aiko Solar's high-efficiency PERC cells were able to achieve conversion efficiencies above 21.50%. The company had announced in 2017 plans to expand cell capacity to 8GW in the near-term.

PV manufacturing capacity expansion announcement plans and analysis for 2017

Mark Osborne, senior news editor, Photovoltaics International

Abstract

PV manufacturing capacity expansion announcements in 2017 far exceeded the three preceding years, despite the significant slowdown in new plans in the third quarter. The year was dominated by c-Si solar cell expansion plans and the return of CdTe and CIGS thin-film activity – the highest seen in many years. This quarterly report reviews the fourth quarter activity as well offering a full-year review and analysis of a record year across all segments of upstream manufacturing.

October review

The weakest month for capacity expansion announcements in the fourth quarter of 2017 was October, even though this represented an apparent major rebound from September, which had a combined total of only around 900MW of announcements.

A combined total of 3,250MW of new capacity was announced in October. The majority of this came from the c-Si module assembly segment, which reached 2,500MW. The remaining 750MW was accounted for by c-Si cell plans, the first significant activity in this segment for three months.

However, only one of the announcements in October had any meaningful substance. This related to leading Taiwanese solar cell and module manufacturer Motech Industries, which said it was entering into a joint venture (JV) called Taiwan Solar Module Manufacturing Corporation (TSMMC) with metallization paste supplier, Giga Solar Materials Corp, to establish a 1GW (estimated) solar module assembly plant in Taiwan to meet future domestic demand.

Motech is expected to reach around 3.6GW of annual solar cell capacity in 2017, which currently includes 1.6GW in China and 2GW in Taiwan. The expansions through 2017 are around 600MW.

In parallel with Motech's JV announcement, three of Taiwan's merchant solar cell and module producers, Gintech Energy Corp, Neo Solar Power (NSP) and Solartech Energy officially announced plans to merge and exit the 'foundry' business model and create a new entity, United Renewable Energy Co., Ltd. (UREC).

NSP is estimated to have around 2.2GW of total solar cell capacity of which around 700MW is primarily dedicated to monocrystalline cell production. The company had relocated around 100MW of mono cell production from its 500MW cell plant in Malaysia to Vietnam and planned to migrate around 500MW of capacity in Taiwan to mono-PERC and ultimately stop all multicrystalline cell production.

NSP had also announced in April 2016 that it would also establish a 50MW dedicated n-type monocrystalline heterojunction (HJ) line that offers higher potential cell and module conversion efficiencies than mono-PERC products.

Gintech is estimated to have around 2GW of cell capacity that includes at least 350MW in Thailand,

CIGS and CdTE thin-film manufacturing plans featured heavily in 2017's expansion announcements.

Credit Manz AG

while Solartech has around 1GW of cell capacity in Taiwan and access to around 350MW of cell and module capacity via a JV in Malaysia, TS Solartech.

Finlay Colville, head of market research at *Photovoltaics International* publisher Solar Media noted in a blog post at the time of the announcement that the new venture would become the fourth largest solar cell producer in the industry during 2018, placing it in an exclusive grouping with JA Solar, Hanwha Q CELLS and JinkoSolar.

All three companies have small levels of module assembly capacity but told Taiwanese media that the JV would establish manufacturing operations estimated to be 1GW (cell: 500MW & module assembly: 500MW) in the US as part of a broader global footprint drive as its turned into a selective integrated upstream manufacturer and downstream PV project developer.

The other significant announcement in October came from India-based engineering firm, Jakson Group, which plans to increase its solar manufacturing capacity to 1.5GW by 2020. The company plans a 500MW first-phase module assembly expansion, followed by a further 500MW expansion that will include an initial 250MW c-Si cell plant.

November review

The month of November set a new benchmark when China-based integrated and merchant PV manufacturer Tongwei Group said it would go ahead with capacity expansion plans at its subsidiary Tongwei Solar (Hefei) Co at two locations (10GW per location) in China at a cost of US$1.8 billion over the next three to five years, adding a total of 20GW. This is the largest ever single capacity expansion announcement.

Tongwei has a strategic goal of building a world-class clean energy enterprise and recently opened its high-efficiency monocrystalline solar cell plant in Chengdu, China with an initial nameplate capacity of 2GW as well as hosting the world's first technically unmanned monocrystalline solar cell production line under the intelligent manufacturing term, Industry 4.0, which we covered in the last report.

Tongwei plans to invest around CNY12 billion (US$1.8 billion) in total, constructing new cell manufacturing facilities at Hefei Solar's facilities in the Hefei High-tech Industrial Development Zone in Chengdu City to provide nameplate capacity of 10GW, while a further 10GW of capacity will be housed in the Southwest Airport Economic Development Zone of Shuangliu District, Chengdu City.

Construction on the new projects was expected to start in November 2017 and production to be ramped in phases over the next three to five years.

With the recent opening of its new 2GW plant, Tongwei has monocrystalline cell capacity of around 3.4GW. The company also has around 2GW of multicrystalline solar cell capacity and recently completed a 5,000MT polysilicon plant expansion, bringing nameplate production capacity to 20,000MT. The company is also undertaking the construction of a new 50,000MT polysilicon plant.

In November, a combined total of 20.8GW of new expansion plans were announced, the second largest month since we started monthly tracking for reports at the beginning of 2014. The record month remains November 2015 at over 26.5GW.

Aside from Tongwei's 20GW, a total of 800MW of module assembly expansion plans were announced in China and Taiwan.

December review

Momentum was maintained in December with combined new announcements reaching 16.1GW. Importantly, a level of 'normality' was restored with a variety of cell, module, thin-film and integrated cell/module announcements from a broader group of PV manufacturers across a broader geographical footprint.

Included in the 16.1GW total for December was 1.2GW of CdTe thin-film expansions, 7.35GW of c-Si solar cell expansions and 6.55GW of module assembly plans. There was also an announcement for a 1GW integrated cell and module plant.

Of note was the announcement by First Solar to build its second (1.2GW) CdTe module plant in Vietnam. First Solar said at its 2017 Analyst Day event that it was already building its second CdTe module plant in Vietnam to support the transition to its Series 6 large format panel.

The second fab is adjacent to its existing plant, which is undergoing readiness for the initial ramp of Series 6 panels. Both facilities have an initial nameplate capacity of 1.2GW each.

'Vietnam S6 Factory 2' is expected to be built and ready for tool installation in the third quarter of 2018. The company also highlighted that first module production was expected in the first quarter of 2019.

As a result of the capacity expansion, First Solar is expecting to reach a total global manufacturing capacity of 5.4GW in 2020 with capex of US$1.4 billion through 2020.

The company has also just produced the first Series 6 panel at its 600MW Ohio plant and is expected to ramp to volume production in the second quarter of 2018. Potential Series 6 nameplate capacity at the Ohio facilities is 1,100MW.

Major China-based PV module manufacturer Risen Energy has recently signed a framework agreement to build and operate a 5GW monocrystalline cell plant and a 5GW module plant in Changzhou City, Jiangsu Province, China. The company entered PV Tech's global 'Top 10 Module Manufacturers' rankings for the first time in 2017 (see p.12).

Risen is partnering with Changzhou Xixi Modern Agricultural Development Co as designated by the local Jintan District government in a project expected to require approximately CNY2.5 billion (US$383 million) in capital expenditures.

The JV framework agreement calls for Risen to provide CNY1.5 billion (60% stake) and its partner CNY1.0 billion (40% stake) towards establishing the new manufacturing facilities.

Risen also noted in a separate press release that total capital expenditures for the JV to reach the 5GW nameplate capacity of both cells and modules, as well as R&D activities would be approximately CNY8.0 billion (US$1.23 billion).

The new manufacturing base is expected to be Risen's most advanced, producing leading-edge high-efficiency products by 2020, and provide the development of both upstream manufacturing clustering and downstream industries including project development in the region.

December also included several speculative announcements via media outlets for c-Si cell and module assembly plant plans in Iran, Egypt and Morocco in the several gigawatt range but all lacked specific details.

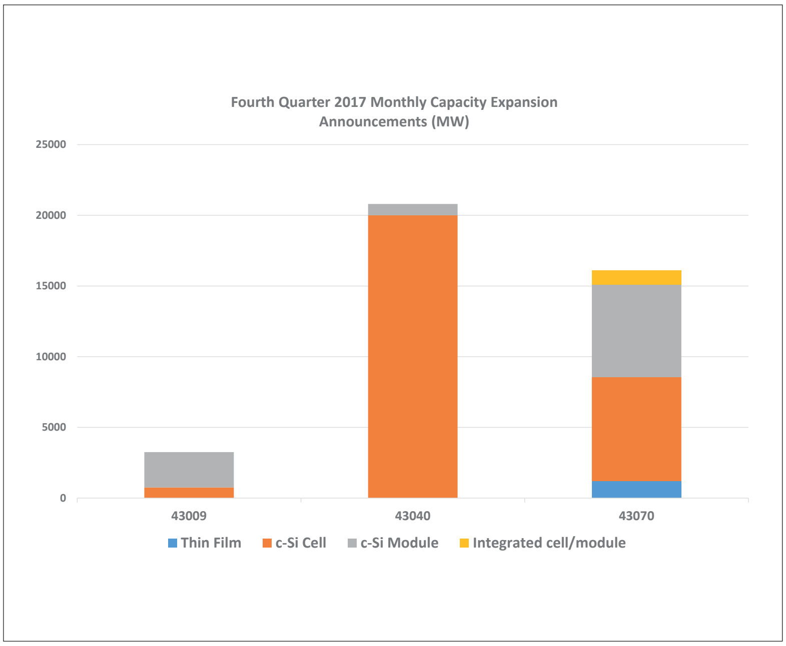


Figure 1. Fourth quarter 2017 monthly capacity expansion announcements (MW).

Fourth quarter review

The fourth quarter of 2017 smashed all multi-gigawatt quarterly records previously set since the beginning of 2014. Total combined capacity expansion plans exceeded 40GW.

This included a total of 1.2GW of thin-film expansion plans, over 28GW of c-Si solar cell and almost 10GW of module assembly plans. It should be noted that speculative plans topped 5GW in the quarter. Nevertheless, even discarding these plans until more definitive information is available, the fourth quarter still exceeded any previous quarter, regardless of the inclusion of speculative plans in the other three quarters of 2017.

It should be noted that just two companies accounted for 30GW of planned expansions in the quarter, which had Tongwei with 20GW of mono c-Si cell plans outlined and Risen with 5GW of mono c-Si cell and 5GW of module assembly plans also at new facilities in China.

However, both companies have experience of gigawatt-plus expansions in recent years and are major manufacturers based in China. The fact that these are phased expansions over specified and not-so-specified timelines stretching over several years does indicate a higher level of credibility and more chance the plans achieve 'effective' capacity status in the future.

It should also be noted that Tongwei is a major merchant cell provider to several leading module manufacturers, such as Canadian Solar, which has a strategy of limiting in-house cell capacity to around 50% of its in-house module assembly capacity and sources complete modules to supplement in-house module nameplate capacity.

SMSL update

There were only a few updates in the fourth quarter of 2017 from the 'Silicon Module Super League' (SMSL) members.

Canadian Solar reported stronger third quarter 2017 financial results than expected and increased full-year shipment and capacity expansion guidance. It has now made four revisions to capacity expansion plans for 2017 and provided expansion plans for 2018 for the first time.

The SMSL member noted that it had completed the ramp up of a new multicrystalline silicon ingot casting workshop at Baotou, China at the end of the third quarter of 2017, with a total annual capacity of 1,100MW, which included capacity relocated from its plant in Luoyang, China.

The company noted that it expected debottlenecking to push capacity to 1,200MW by the end of 2017, which is in line with the last two updated plans.

Canadian Solar said that it had plans further increase its ingot capacity to 1,720MW by June 30, 2018, and may expand to 2,500MW if market conditions justify.

Wafer manufacturing capacity had reached 3GW in the third quarter of 2017. The company had previously guided that it expected wafer capacity to reach 4GW at the end the year and was planning to add a further 1GW of wafer production to end 2018 at 5GW.

The company said that its solar cell manufacturing capacity reached 4.7GW at the end of the third quarter of 2017, which was the target in its third revision to its capacity expansion plans.

Canadian Solar also noted that it planned to add additional cell manufacturing capacity at its Funing and Southeast Asia plants by year end, bringing 2017 cell nameplate capacity to 5,450MW, a 750MW increase.

Subject to market conditions the compan said it planned to add another 1.5GW of cell capacity in 2018 to reach approximately 7GW by the end of 2018.

With respect to PV module manufacturing capacity, Canadian Solar is adding almost 1GW of nameplate capacity more than its third revision made in the second quarter of 2017, which would have led to a 2017 capacity of 7,190MW.

The company expects that its total worldwide module capacity would exceed 8,110MW by the end of 2017.

Subject to market conditions again, the SMSL member said it planned to add another 1,250MW of module capacity by the end of 2018, bringing nameplate capacity to 10.3GW.

Canadian Solar is the first manufacturer to guide nameplate module capacity to reach over 10GW.

The only other SMSL member, Hanwha Q CELLS, officially announced the start of construction of its wafer, cell and module facilities in Ankara, Turkey in December. Although the previously reported capacity of the new facilities was around 500MW each, local media that attended the launch event cited slightly higher capacity figures now that the construction had started, which is not unusual.

Per the local media reports, the SMSL is adding 150MW of initial solar cell capacity and a further 300MW of module assembly capacity to the initial plans announced in May 2017.

2017 review and analysis

Monthly review

On a monthly basis, 2017 produced some spectacular highs and lows, indicating once again that drawing any clear trends on a monthly basis should not be undertaken.

The year started relatively strong as total combined expansion plans topped 4GW, especially after muted activity through the second half of 2016, which managed a monthly high in November 2016 of 2.5GW, combined total.

Four out of the six first months of 2017 (February, March, May and June) exceeded total combined expansion plans above 5GW. May was notable for having the highest activity in the first half of the year (16.15GW), followed by February (13.9GW).

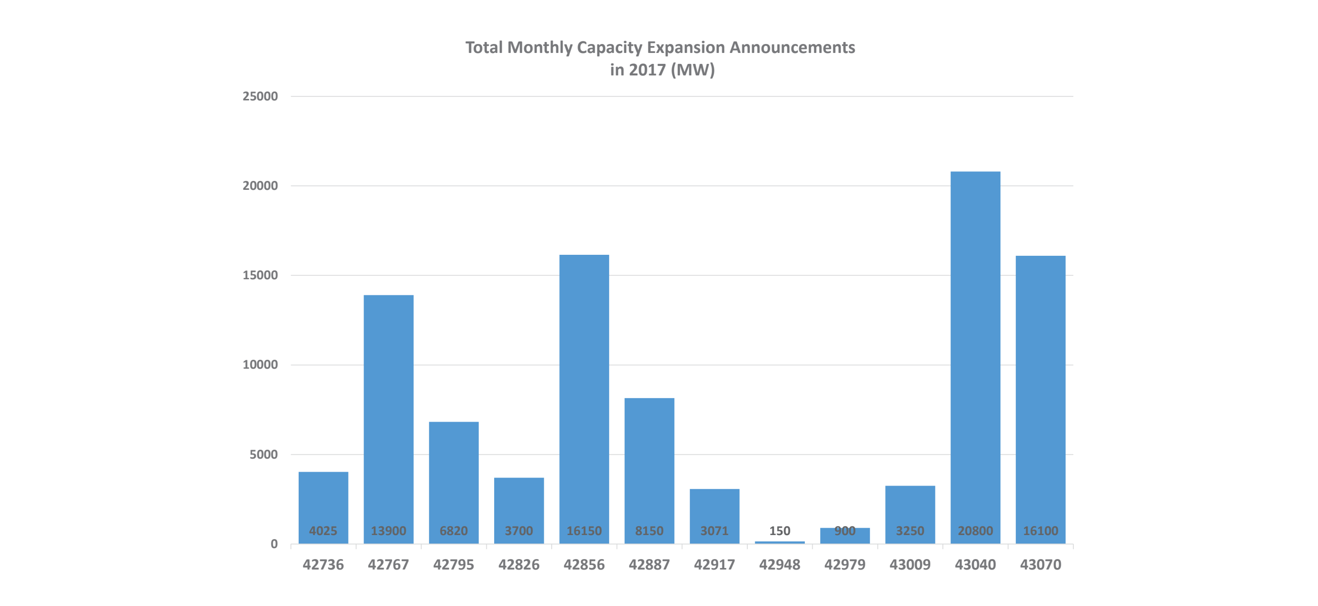
Activity levels declined again through August, which proved to be the low point in the year, although September struggled to reach 900MW of new capacity expansion announcements.

As already detailed in this report, November surprised with 20.8GW but with 20GW coming from one company, Tongwei. December was another strong month topping 16GW, led by 10GW of new plans from Risen Energy.

Quarterly review

Looking at the quarterly trends in 2017, clearly the first two quarters were strong and produced momentum from the first quarter (24.7GW) to the second quarter (28GW) but then collapsed considerably in the third quarter (4.1GW).

Such was the intensity of activity in the first half of the year with companies announcing multi-phase, multi-year and multi-gigawatt plans, a breather was



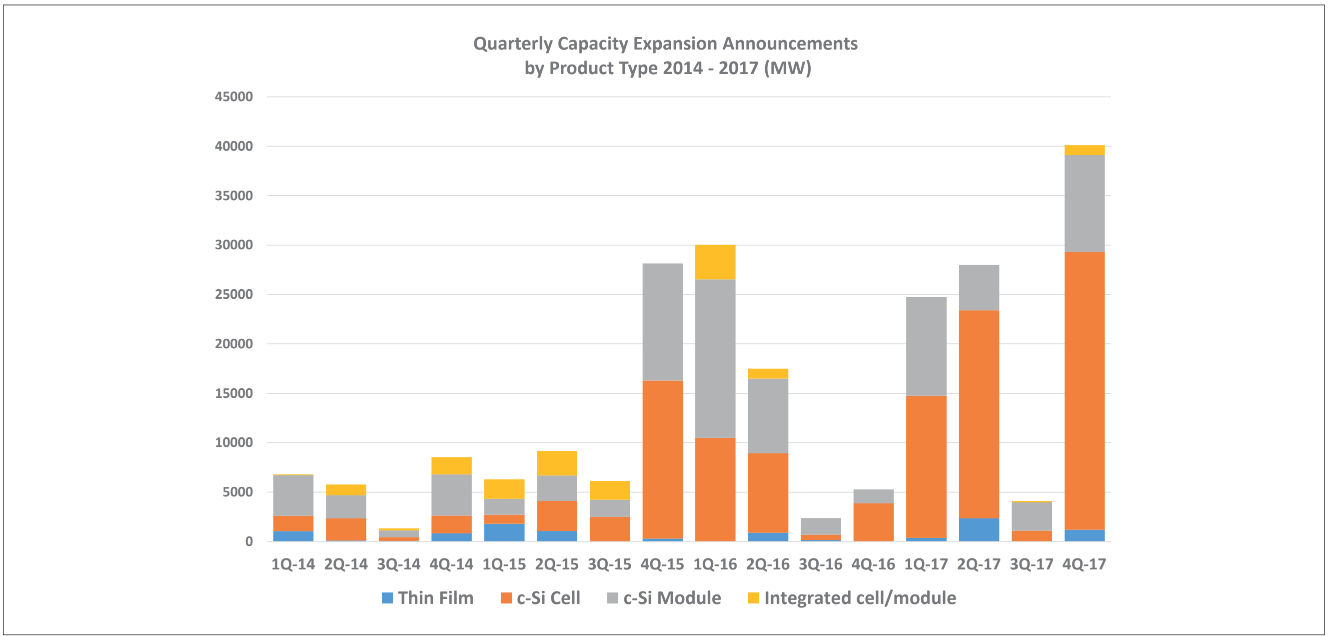


Figure 3 (top). Quarterly capacity expansion announcements by product type 2014-2017 (MW).

Figure 2 (bottom). Total monthly capacity expansion announcements in 2017 (MW).

highly likely but the degree of the collapse in the third quarter was a still a surprise.

Indeed, with October lacklustre the magnitude of the rebound in November and December making the fourth quarter (40.1GW) a new quarterly record was also unexpected.

Segment review

Twenty-seventeen was notable for the revival in thin-film activity, with prominent pronouncements relating to CdTe via First Solar and CIGS via Avancis and Manz partners in China leading to 4GW of thin-film planned expansions announced in 2017. Importantly none of the announcements in this segment are seen as speculative.

But the major trend was the aggressive new wave of c-Si solar cell expansions, which topped 64.6GW, far outpacing c-Si module assembly plans that exceeded (27.2GW) in 2017. More than 80% of the c-Si plans related to high-efficiency monocrystalline PERC technology, accounting for around 52GW of the total.

New plans for n-type mono c-Si (IBC) and heterojunction (HJ) technology expansions almost reached 3GW in 2017 with the wild card HJ technology expansion plans being Tesla and its manufacturing partner Panasonic, which has kept a shroud over the actual ramp at its plant in Buffalo NY state.

Integrated cell and module plans just topped 1GW in 2017. However, several announcements through the year could actually be classified as integrated once construction and start of operations in 2018 happens and further information becomes available.

Geographical review

The key geographical trend in a record but volatile year was the major resurgence of China as the dominant destination for capacity expansion announcements in 2017.

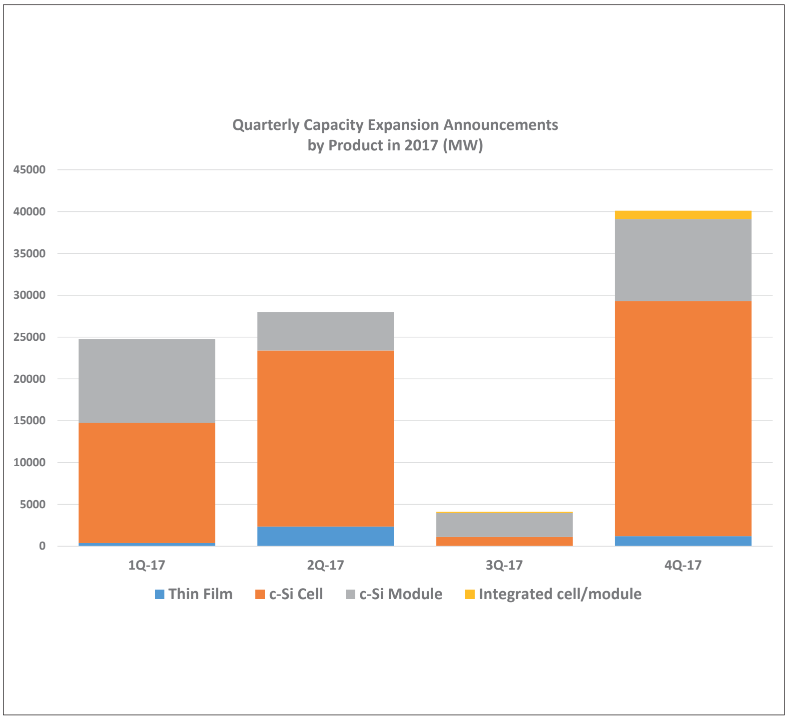


Figure 4. Quarterly capacity expansion announcements by product in 2017 (MW).

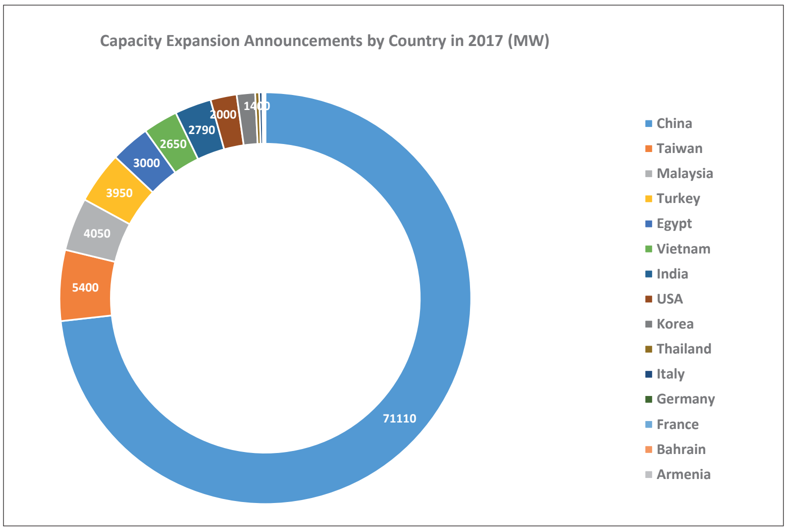


Figure 5. Capacity expansion announcements by country in 2017 (MW).

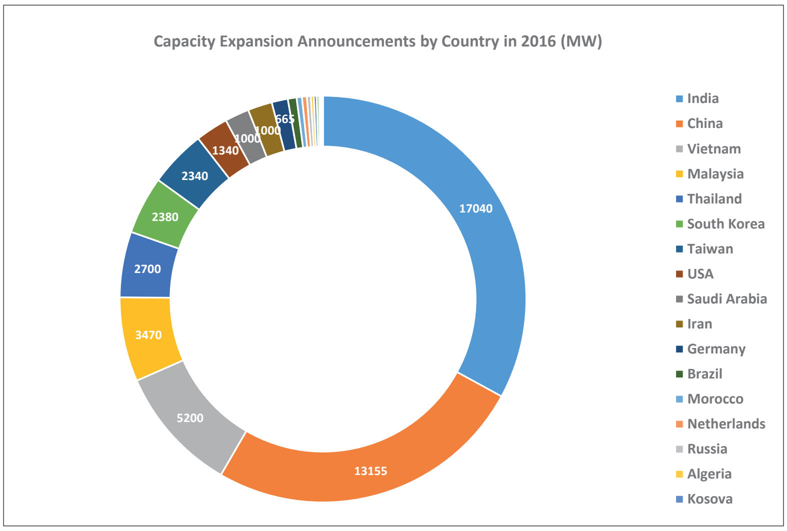


Figure 6. Capacity expansion announcements by country in 2016 (MW).

China accounted for over 71GW of total combined expansion plans in 2017, accounting for around 72% of the total, compared to 13GW or 25% of plans in 2016. It should also be noted that on a segment basis, high-efficiency mono c-Si PERC as well as n-type mono IBC cell expansion plans dominated after years of relatively balanced cell-to-module capacity expansion plans.

The dominance of China should also be looked at in the context of downstream solar module demand hitting a record 53GW in 2017, accounting for around 50% of total global demand.

India had surpassed China in 2016 with combined plans totalling over 17GW and accounting for 33% of the total. But with very few plans from 2016 actually turning into effective capacity in 2017, not surprisingly India mustered only around 2.8GW of plans in 2017, accounting for just 3% of the total and with much of this lower total in 2017 remaining speculative.

China's resurgence also impacted previously highly attractive destinations for Chinese manufacturers in 2017, such as Thailand, which accounted for only 300MW of new expansions, compared to 2.7GW of new expansion plans in 2016.

Vietnam also experienced a significant decline in 2017, despite First Solar's 1.2GW plans announced in December. Vietnam attracted a combined total of over 2.6GW of planned expansions, compared to 5.2GW in 2016.

However, Malaysia held its own with just over 4GW of new capacity plans, compared to around 3.5GW in 2016. However, no new announcements were made in the second half of the year related to Malaysia.

Emerging downstream markets such as Turkey and Egypt also attracted upstream manufacturing attention in 2017. Turkey attracted almost 4GW of new plans throughout the year, up from zero in 2016. Egypt attracted 3GW of manufacturing plans in 2017, up from zero in 2016.

As with many emerging downstream PV markets, speculative upstream manufacturing follows; Egypt outweighed Turkey in that respect in 2017.

The European region also suffered from fewer announcements and smaller expansions in 2017, compared to the previous year. Germany, the largest location for cell and module production in Europe only had 100MW of new expansion plans announced in 2017, compared to nearly 700MW in 2016.

Conclusion

The year set a number of new planned expansion announcement records with a global combined total of over 97GW, up from over 55GW in 2016, or nearly an 80% increase year-on-year.

With China's destination resurgence and domination of high-efficiency c-Si solar cell expansion plans, only Malaysia and potentially Taiwan held their own year-on-year.

News

Polysilicon consumption to decline below 4g/W in Q3 2018

Credit: Getty/iStock

PV Tech's market research team will now track the polysilicon demands of the industry as cell and module technology evolves.

Consumption of polysilicon used by the solar industry will decline to below 4g/W during 2018, hitting 3.92g/W at the end of Q4'18, according to a new value-chain model developed by the in-house market research team at PV Tech.

Just a few years ago, the industry was accustomed to levels of 5-6g/W, but all this has changed recently, driven by several factors running concurrently.

The market research team at our publisher, Solar Media, has developed a new model, which factors in every key aspect of material efficiency, and allows for highly accurate forecasting going forward.

At the heart of the new analysis is our bottom up tracking of manufacturers throughout the entire c-Si value-chain, and allocation of cell technologies across all variants that affect module efficiency and wafer thickness. This unprecedented detail is then backed up through wafering, ingot production and finally arriving at polysilicon g/W levels that can be compared to legacy top-down back-of-envelope estimates undertaken in the industry.

The analysis pulls out actual cell production, cell-to-module interconnection losses by technology, mono/multi usage (including n-type and p-type cell variants), diamond-wire saw adoption, kerf losses and many other factors that influence the ongoing reduction in polysilicon (g/W) used by the industry as a whole.

For a full report on our new polysilicon modelling, please see page p.15

LONGi signs major US$1 billion polysilicon supply contract with OCI

Leading integrated high-efficiency monocrystalline module manufacturer and 'Silicon Module Super League' (SMSL) member LONGi Green Energy Technology has signed a three year deal to purchase polysilicon from Korean-headquartered polysilicon producer OCI Co worth around US$1.02 billion.

LONGi said in a financial filing that the contract would last three years and would entail the purchase of around 64,638MT for its subsidiaries that produce monocrystalline silicon ingots and wafers locate in Yinchuan, Baoshan, Lijang and Ningxia, China.

The polysilicon contract between LONGi subsidiaries is with OCI in Korea and its Malaysian operations, acquired in 2017 from Japan's Tokuyama.

Recently, PV Tech reported that LONGi was tripling ingot/wafer capacity through 2020. The new strategic plan includes taking ingot/wafer capacity to 28GW by the end of 2018 and 36GW by the end of 2019.

PV Tech also recently reported that OCI was expanding its production of high-purity polysilicon to meet greater demand for P-type monocrystalline wafers used with PERC (Passivated Emitter Rear Cell) technology. The company said that its South Korean production of high-purity polysilicon for mono wafers, which stood at around 42% of capacity - would be increased to around 60% of production capacity in 2018.

OCI has around 52,000MT of polysilicon capacity in South Korea and its average product mix in 2017 for mono-quality polysilicon was said to be only around 35%

LONGi tripling monocrystalline wafer capacity to 45GW

Leading fully integrated, high-efficiency monocrystalline module manufacturer and 'Silicon Module Super League' (SMSL) member LONGi Green Energy Technology has set a strategic plan to triple monocrystalline ingot and wafer capacity to 45GW in 2020.

LONGi said in a financial filing that it achieved 15GW of monocrystalline wafer nameplate capacity by the end of 2017, up 2GW from previous plans as the company accelerated production ramps to meet demand.

The new strategic plan, which is not a commitment to investors that it would action the plans and commit to the significant capital expenditures required, includes taking wafer capacity to 28GW by the end of 2018 and 36GW by the end of 2019. LONGi also said that the plan was to achieve 45GW by the end of 2020.

PV Tech had previously reported that LONGi was fast-tracking various ingot and wafer expansion plans currently under construction and pulling in projects nearing completion where possible.

In 2017, LONGi was undertaking the construction of a 5GW ingot production plant in Lijiang, China. The company also announced in early 2017 that Trina Solar and Tongwei, via its polysilicon subsidiary, Sichuan Yongxiang were to form a joint venture (JV)

Credit: Photowatt

A proposed deal with Canadian Solar could help Photowatt increase its cell manufacturing capacity.

to own and operate the facility. LONGi also planned a 5GW ingot/wafer plant in Baoshan, China.

The company had also expected to complete and have begun operating a 1GW wafer plant in Kuching, Malaysia at the end of the year.

A 1GW ingot production plant in Ningxia was also expected to have started production in the fourth quarter of 2017.

As a result, LONGi's target of 28GW of ingot/wafer nameplate capacity by the end of 2018 looks highly plausible. The tripling of capacity to 45GW would require a significant round of investments in the multi-billion dollar range.

EDF Energies Nouvelles and Canadian Solar could form JV wafer production plant

'Silicon Module Super League' (SMSL) member Canadian Solar could become a partner with small-scale PV manufacturer in France, Photowatt, a subsidiary of EDF Energies Nouvelles in establishing a manufacturing plant producing next-generation silicon ingots and wafers.

Photowatt said in a statement that it was in talks with Canadian Solar and ECM Greentech, a Grenoble-based company that has pioneered low-carbon silicon crystallisation technology in partnership with the French National Solar Energy Institute (INES) in regards to the possible joint venture.

The move is in response to Photowatt having only around 50MW of module and cell production capacity in France and the French government's PV project tendering that stipulates a level of low carbon content requirements to be eligible.

The plan would be to increase nameplate capacity to over 500MW, supported by Canadian Solar.

A new company has been proposed, dubbed 'Photowatt Crystal Advanced' with ownership split between EDF Energies Nouvelles via Photowatt (60%), 30% owned by Canadian Solar and 10% owned by ECM Greentech.

EDF recently announced major plans to increase its reliance on renewables. The EDF Solar Power Plan lays out its goal to develop and build 30GW PV projects in France over the period of 2020 to 2035.

Daqo's long-term CEO resigns

China-based polysilicon producer Daqo New Energy announced that its long-term CEO, Dr. Gongda Yao would step down from all executive positions and leave the company at the end of March, 2018.

The unexpected exit of Dr. Yao, regarded as an innovator in low-cost polysilicon production, will lead to search of a replacement and in the interim, Guangfu Xu, founder and chairman, will become acting CEO.

"For the past nine years, it has been a privilege to work with the wonderful team of Daqo New Energy on its journey to become a world-leading low-cost and high-purity polysilicon manufacturer. I am proud of the achievements that we have accomplished together. Now as the company has been performing very well both operationally and financially, I think it's time for me to step down from my position and spend more time with my family and pursue personal interests," said Dr. Yao.

"I will still stay on the board of directors until the end of March 2018, and work closely with Chairman Mr. Guangfu Xu and other board members to achieve a seamless leadership transition."

Guangfu Xu added: "I sincerely regret Dr. Yao's decision to leave, however I fully understand and respect his decision. We are extremely grateful for Dr. Yao's contribution to the company in the past nine years, as Dr. Yao has built a world-class company with a leading position in the industry in terms of product quality and cost structure."

There have been very few executive changes for many years within Daqo and the polysilicon sector in general that were not been related to bankruptcies or market exits.

Wuxi Suntech ramping diamond wire and MACE texturing production

China-based integrated PV manufacturer Wuxi Suntech Power Co has started initial mass production of P-type multicrystalline wafers using its in-house developed metal assisted chemical etching (MACE) texturing process (black silicon) for diamond wire sawing.

Metal assisted chemical etching is regarded as quite a simple, low-cost method for fabricating various nanostructures on the wafer surface with the ability to control shape, and orientation.

Wuxi Suntech said that its optimized nanostructured processing technology had provided an additional absolute efficiency gain of up to 0.3%, compared with the additive direct texturing process.

The company's R&D team were said to be developing higher efficiency PERC (Passivated Emitter Rear Cell) technology better capable of being integrated with its black silicon process for higher efficiency gains and lower production costs.

Wuxi Suntech expects to ramp its diamond wire sawing and MACE production to approximately 500MW in 2018, after starting development work on the technology in June 2017.

Diamond wire process monitoring

Fabrice Coustier, Roland Riva, Mathieu Debourdeau, Nicolas Velet, Jérémy Bounan & Amal Chabli, CEA-LITEN at INES, Le Bourget du Lac, France

Abstract

Major progress has been made in the PV industry in the last five years as a result of the extensive use of diamond wire during silicon wafering operations. Productivity has increased and costs have fallen to the point where the price of a monocrystalline wafer cut with diamond wire is approaching the price of a multicrystalline wafer cut using slurry. Since multicrystalline silicon still dominates the PV market, it is essential that this area quickly adopt diamond wire technology; however, because of the intrinsic inhomogeneity of this material its precise characterization, as well as a characterization of the diamond wire cutting process, will be required in order to fully reap the benefits. In this context, the monitoring of the cutting process will become mandatory to ensure both the expected productivity and the required wafer quality at an industrial level.

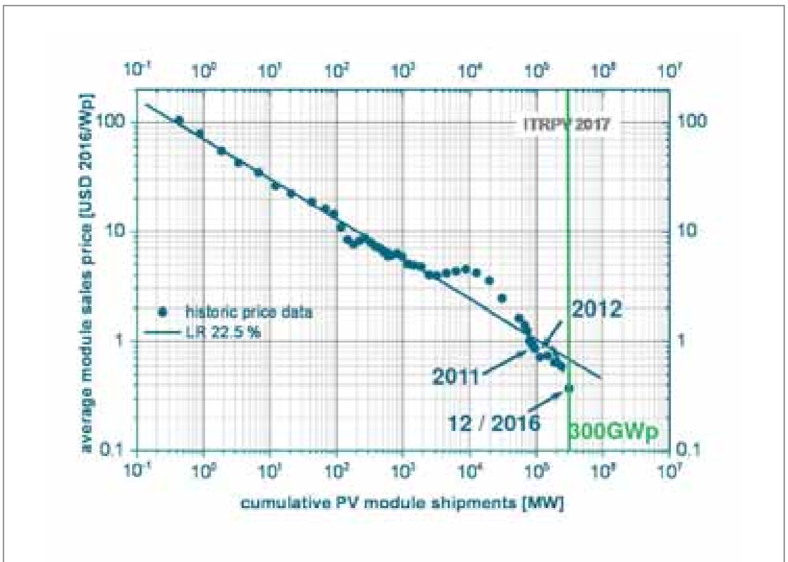
Introduction

As was rightly anticipated in a previous article by CEA-LITEN in 2012 [1], diamond wire technology has made significant progress in the PV industry in the past five years, mainly for cutting monocrystalline silicon. The main reason for this is its higher cutting ability than conventional wafering technology, namely steel wire and slurry, which is still the main technology used today in the industry for cutting multicrystalline silicon wafers [2–4].

The rapid market share progression of diamond wire wafering technology for monocrystalline silicon since 2012 has happened as a result of many favourable factors coming into play:

- The official price of diamond wire was around \$150/km in 2012, whereas today it is around \$45/km when bought in large quantities.
- The wire diameter used in 2012 was 120µm, whereas now it is often 70µm.
- The cutting time using slurry was approximately five to seven hours, whereas the cutting time using diamond wire is currently close to two hours.
- The total thickness variation (TTV) of the slurry wafers was typically between 20 and 30µm, whereas the TTV of wafers cut using diamond wire is typically between 5 and 15µm using state-of-the-art wafering equipment.
- The equipment cost used to be close to \$1m, whereas for high-end diamond wire cutting equipment it is now half of that, and even less for the low-cost equipment that has swiftly been developed in recent years.

Figure 1. Average module sales price vs. cumulative PV module shipments.



Courtesy of ITRPV 2017

In consequence, the production costs associated with monocrystalline wafers have fallen by more than 30% in the past five years. Since the PV market cost reductions are still following the same trend as in the past 50 years (Fig. 1), and because some of the above-mentioned advantages have appeared much more quickly than anticipated (in particular, the decreases in diamond wire price and diameter), the reductions in wafer thickness forecast by the industry roadmap have not really materialized, because kerf loss has already been reduced by 40%.

Diamond wire technology has been particularly well suited to monocrystalline silicon, since such high-quality material does not present defects, such as grain boundaries and/or inclusions. The fast-growing diamond wire technology in the wafering industry for monocrystalline silicon has driven the market to the point where around 90% of this material is now cut using diamond wire. The cost of monocrystalline wafers cut using diamond wire is very close to the cost of multicrystalline wafers cut using the slurry process; this is driving the PV industry (where 70% of the market is still multicrystalline silicon) to use diamond wire technology as well. While some issues – such as the problematic compatibility of the surface obtained using diamond wire and acidic texturization used for multicrystalline – are on their way to being resolved, the inhomogeneity of the multicrystalline material remains intrinsic to its particular crystallization process.

This paper discusses why, in the authors' opinion, the monitoring of the diamond wire cutting process is extremely important for further improvements of this technology, for all types of material, namely monocrystalline, mono-like [5–9] and multicrystalline silicon. As a reminder, mono-like silicon ingots are obtained in directional solidification system (DSS) furnaces by melting silicon above monocrystalline seeds sitting at the bottom of a crucible. The goal is to only melt a portion of the seeds and begin directional solidification from the bottom to the top. Ultimately, a full monocrystalline G6 ingot is obtained. Such material offers an electrical performance close to that of monocrystalline silicon, but with the high-productivity advantage from the use of DSS furnaces.

"An increase in productivity cannot happen without a highly controlled wafering process."

Why process monitoring?

As explained in the introduction, major improvements in the diamond wire wafering process have been made in the past five years; those process enhancements have mainly been possible by improvements in wire performance and decreases in diamond wire diameter, as well as by higher wire speeds, which allow a higher cutting speed. As always, PV roadmaps predict that further improvements will be necessary in the future.

A 30 to 40% increase in wafering productivity is expected/needed by 2027. The authors believe that for the multicrystalline silicon wafers producers to remain competitive, they will quickly need to master the diamond wire process in order to reap the same benefits that the monocrystalline silicon wafers producers already enjoy. An increase in productivity demands further reductions in wire diameter, reductions in wafer thickness and improvements in wafer quality, which cannot happen without a highly controlled wafering process.

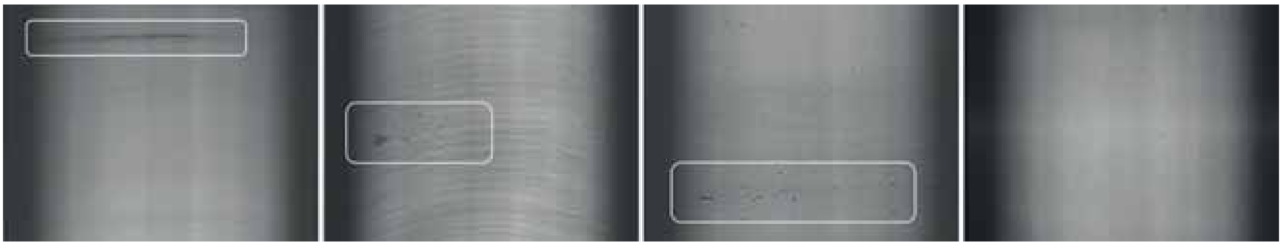
Even today, wafer specifications are given mainly in terms of wafer geometry, electrical characteristics and relative cleanliness; there is no mention of wafer surface morphology, subsurface damage (SSD), mechanical behaviour and morphological defects.

As the trend of the PV market is to move towards thinner wafers, it is very important to determine what level of wafer quality can be achieved today. First, while the monocrystalline silicon crystallization process prevents precipitates from forming in the material (making it fairly easy to cut using diamond wire), the nature of the multicrystalline silicon crystallization process makes it difficult to completely avoid certain contaminations. Silica crucibles coated with silicon nitride produce impurities that diffuse into the silicon at high temperatures and might precipitate in the form of silicon nitride. The graphite environment of the solidification furnaces leads to saturation of the silicon with carbon, which can precipitate at the solid–liquid interface during directional solidification, thus creating SiC inclusions. It is well known that diamond wire can be used to cut hard materials, such as silicon nitride or silicon carbide [10,11]; however, it is not possible for a diamond wire designed and used for cutting silicon to efficiently cut small inclusions of silicon nitride or carbide that are present within the silicon.

With the use of high-resolution infrared characterization equipment developed by the French company B.E.A, the presence of large precipitates can be observed in 156mm × 156mm silicon bricks (Fig. 2). As can also be seen in the infrared images, very large differences in size and density of precipitates in the material can occur, depending on the crystallization conditions and/or the brick position in the crucible. Clearly, the wafering operation should not be driven using identical processes on those silicon bricks. If tempted to do so, the cut would result in poor wafer quality at the locations where excessive precipitate density is visible on the infrared images [12]; moreover, wire breakage could even occur due to more rapid damage to the wire.

Apart from using different processes, another solution would be to allow excessive wire consumption in order to find a process that gives satisfactory results in all cases (which would therefore lead to a smaller potential cost reduction of the cutting step). Fig. 3 shows different precipitates that can be observed in the silicon using a scanning electron microscope (SEM).

As a result of the use of graphite-rich heating elements in the furnaces, and of the use of silicon-nitride-coated silicon crucibles, the technology



Courtesy of B.E.A

Figure 2. Infrared images of a selection of silicon bricks. Precipitate-rich areas are identified by the white rectangles.

used in the PV industry to produce G6 ingots makes the formation of precipitates in the silicon inevitable. Furnace and process optimization have a tendency to cause the precipitates to appear in zones that will ultimately be removed from the ingot (sides, bottom-part/red zone, top-part/segregated impurities); however, the difficulty in producing precipitate-free ingots tends to demonstrate the need for a precise understanding of wire behaviour and process monitoring in order to cut those ingots efficiently using diamond wire.

What sort of monitoring?

During diamond wire cutting, the main consumable is the wire itself, in contrast to the slurry process, in which different consumables assure the success of the process, specifically steel wire, SiC abrasive and polyethylene glycol (PEG) lubricant. The quality of the diamond wire is therefore extremely important.

Over the past six years the team at CEA has developed diamond wire characterization techniques in order to help the French company Thermocompact in the development of diamond wires for silicon applications, and to gain knowledge about the diamond wire cutting process. Optical microscopy and/or SEM are always useful tools for getting an idea of the precise wire morphology (see Fig. 4); on the other hand, these tools also present the inconvenience of only being able to inspect local/small areas. Typical diamond wire spools are about 50km long, and a lack of diamonds over just a few centimetres of the wire can be disastrous to the cut should the steel wire make contact with the silicon. Thus, microscopy is not the most appropriate tool for studying diamond wires.

Bidirectional optical micrometres make it possible to study the wire morphology along two different axes at 90° to each other. High acquisition frequencies allow very precise morphology studies, while lower acquisition frequencies allow very long portions of the wire to be studied – eventually the entire spool. The measurement principle is illustrated in Fig. 5, and typical data obtained from the micrometer are given in Fig. 6.

After further interpretation, such measurements yield a lot of the information needed to anticipate the wire behaviour inside a wire saw; this information is reported in Table 1, along with what the consequences might be if the studied factor is out of specification. Some other wire characteristics are mentioned, along with the possible monitoring techniques.

From the authors' own experiences, it is known that if the longitudinal homogeneity is poor (a lack of diamonds over a few centimetres of wire), then the risk of wire breakage is high. The same conclusion is drawn if the radial homogeneity is poor (a lack of diamonds around the periphery of

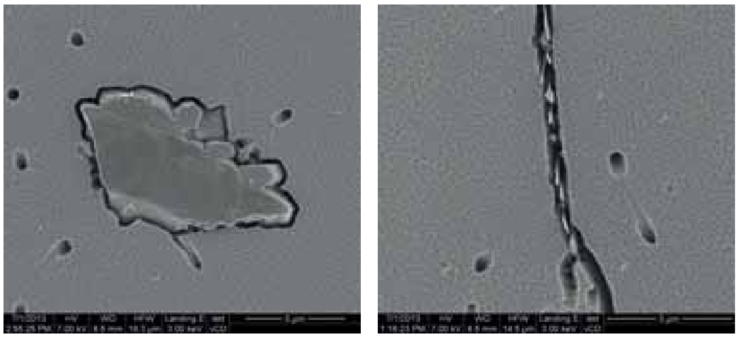
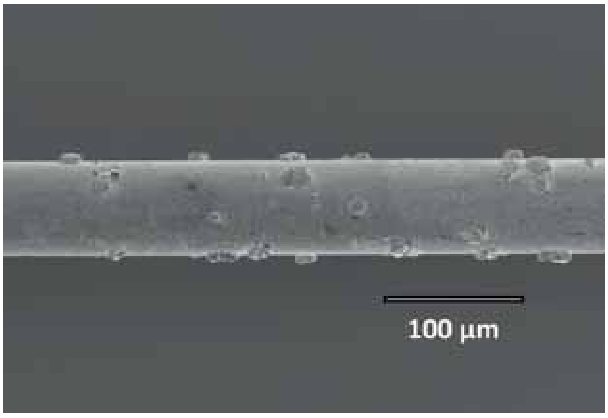


Figure 3. SEM images of SiC (left) and Si_3N_4 (right) precipitates inside the silicon matrix.



Courtesy of Thermocompact

Figure 4. SEM image of a diamond wire typical morphology.

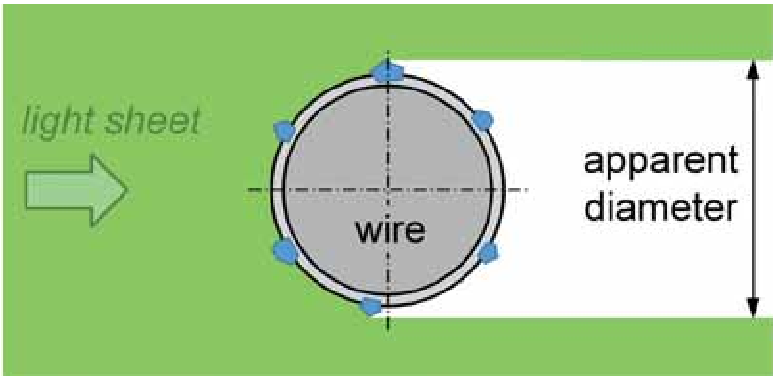


Figure 5. The measurement principle using an optical micrometer to characterize diamond wire.

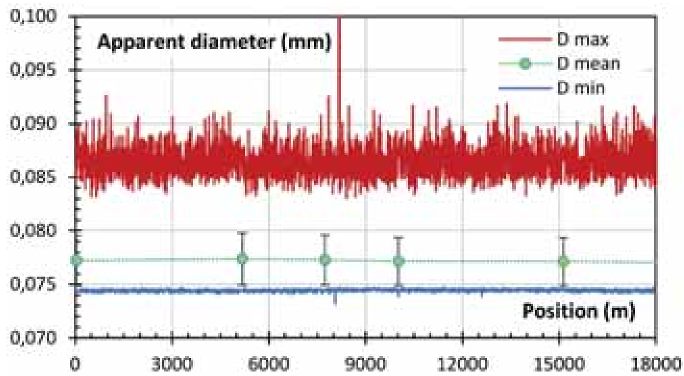


Figure 6. Optical micrometer inspection of new diamond wire.

Wire characteristic	Consequence during a cut	Possible monitoring	Wafers characteristic
Longitudinal homogeneity	Lack of diamonds results in wire breakage	Wire inspection	Poor wafer quality (TTV and mechanical)
Radial homogeneity	Lack of diamonds results in wire breakage	Wire inspection	Poor wafer quality (TTV and mechanical)
Diamond size	Larger diamonds allow faster cutting but create more surface damage	Wire inspection Bowing sensors in the wire saw	Wafer quality (TV, TTV and mechanical)
Number of diamonds/mm	The smaller the number of diamonds, the more pressure put on them and the more material removed	Wire inspection	Wafer quality (mechanical)
Diamond shape	The more angled the shape, the more material removed but the greater the surface damage	Microscopy, SEM	Wafer quality (TTV, roughness, SSD)
Binder thickness	The thinner the coating, the more the diamonds stick out and the more material removed	Wire inspection	
Binder composition	The higher the abrasion resistance, the longer the wire life	Chemical analysis	
Mechanical resistance	The higher the mechanical performance of the wire, the greater the wire tension that can be used and the less the bowing during the cut	Pulling test and fatigue test	Wafer quality (TTV)

Table 1. Important wire characteristics for predicting the cutting behaviour of diamond wire.

the wire). It is also well known from the literature that larger diamonds remove more silicon material [13]; a faster process can therefore be used, but large diamonds create more damage to the surface and subsurface. In addition, large diamonds increase the kerf loss created by the wire, and rougher surfaces decrease the mechanical properties of the wafers. A compromise invariably has to be found by weighing these advantages and disadvantages.

The number of diamonds/mm at the surface of the wire is very important. For a given cutting process, a low density of diamonds results in more pressure on each individual diamond; this leads to larger silicon chips being removed by a diamond, resulting in a higher cutting efficiency of the wire, which can be observed by less wire bowing in the wafering equipment. However, as the diamonds machine the silicon their cutting ability decreases (crushing, polishing) and the force applied to them increases; this force can exceed the mechanical bond between the diamond and the binder, in which case the diamond will be removed from the surface of the wire. The subsequent deficiency in diamonds results in wire breakage. A compromise therefore also has to be found between the initial number of diamonds present at the surface of the wire, the cutting process that can be used, and the final number of diamonds present at the surface of the used wire after cutting. A greater initial number of diamonds may reduce the cutting efficiency, but it will ensure the longevity of the wire and/or lower wire consumption [14].

Rounded diamonds allow cutting in a ductile mode under certain conditions; this results in a very good surface quality but the cutting process is extremely slow [15]. In contrast, sharp diamonds remove silicon in a fragile mode, creating chipping at the silicon surface but allowing a fast cutting process.

The thinner the binder, the greater the protrusion of the diamonds, which results in fast cutting (or in the removal of large chips of silicon), but increases the risk of diamond detachment from the wire surface.

The more resistant to silicon abrasion the binder the better, but most diamond wire manufacturers today use electrodeposited nickel. (Resin-bonded diamond wires also exist but are not discussed in this paper [16].)

As diamond wire has seen a rapid decrease in diameter in recent years, the mechanical characteristics of the steel used in this type of wire have improved, and so wire tension can be kept as high as possible during the cut. The higher the tension, the smaller the bow; the smaller the bow, the better the wafer quality. As an example, a wire tension of 12N is used on 70μm diamond wire, whereas 28N is used on 120μm diamond wire.

As explained in an earlier section, the development of a technique that allows the determination of most of the important characteristics of a diamond wire has been extremely fruitful in understanding the correlation of wire behaviour and its morphology. In order to determine the characteristics, in situ monitoring of the cutting process was necessary.

"A characterization method that makes it possible to follow the bowing of the wire during the cut has been developed."

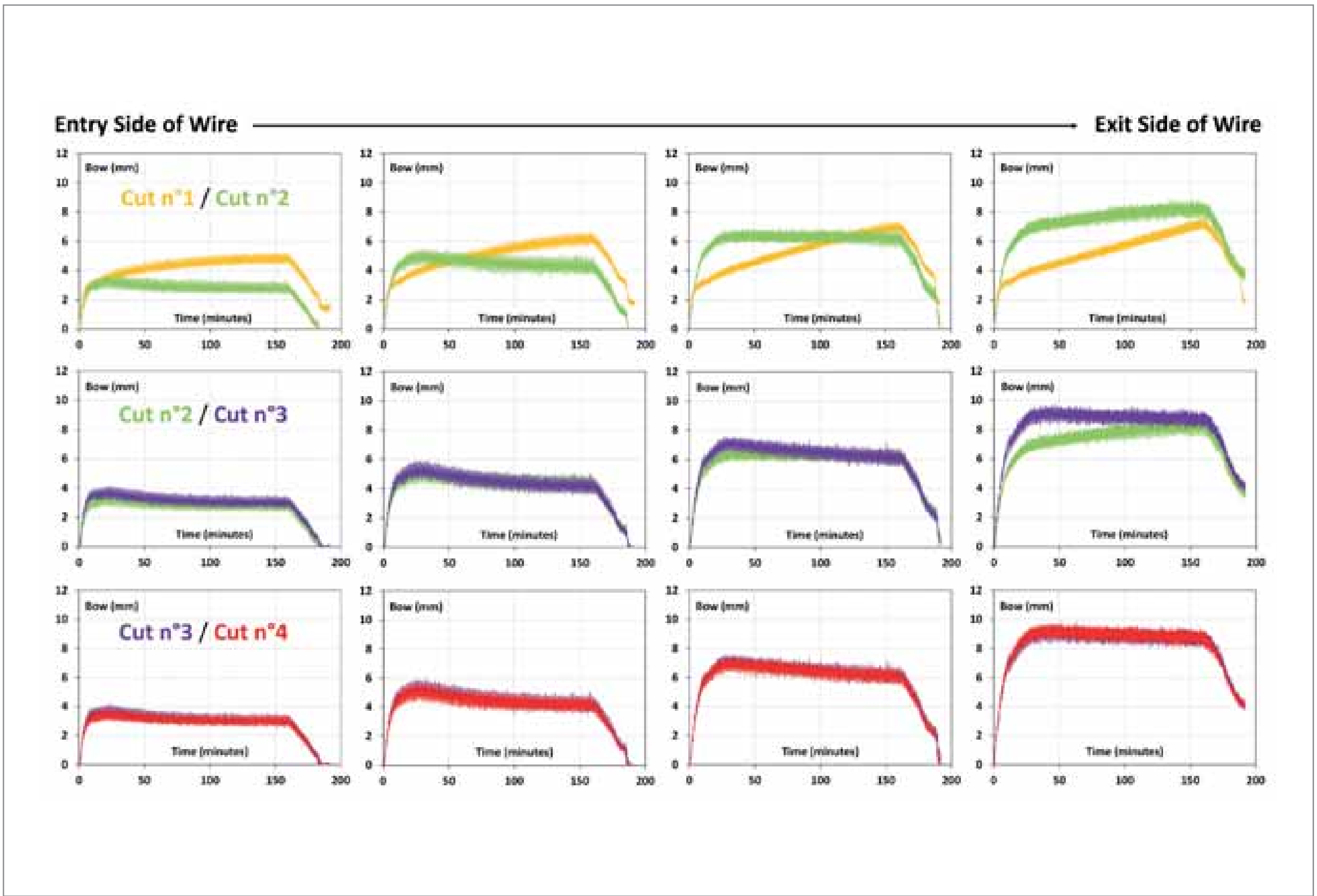


Figure 7. Evolution of the bowing along the wire web during four consecutive cuts.

A characterization method that makes it possible to follow the bowing of the wire during the cut has been developed by the team at CEA-LITEN. As many sensors as required can be distributed along the wire web in order to study the cutting behaviour of different wires and/or different processes. In the example shown in Fig. 7, four sensors monitor the bowing of the wire web from the entry side of the wire (new wire) to the exit side of the wire (used wire). These results were obtained using a state-of-the-art Meyer Burger DW288+S3 wire saw and 500mm-long monocrystalline silicon ingots.

During the experiments, a somewhat relaxed process was used: 1m/wafer using 70μm-diameter diamond wire and a process time of 180min. As usual during a diamond wire process, the wire runs back and forth from one working spool to the other, with a small amount of fresh wire feeding in on the entry side of the web during each back and forth movement.

Under these particular conditions, it was observed that, since the process began with a completely fresh web of diamond wire, the wire bowing increased during the entire first cut, as the wire in contact with the silicon began to wear. During the first cut, in which 1m/wafer of wire was used, about two-thirds of the web was being replaced, and therefore two-thirds of the wire web reached a stabilized state of wear as fresh wire was constantly coming in from the entry side. Consequently, it was only under the fourth sensor located at the exit side of the wire web that the wire continued to wear during the second cut, as the other three sensors showed that the bowing had stabilized at different values, depending on the sensor position and on the wire wear. Finally, the behaviours of the third and fourth cuts were identical, as the bowing curves were perfectly aligned when superimposed. This proves that the

Figure 8. In situ force measurement set-up.

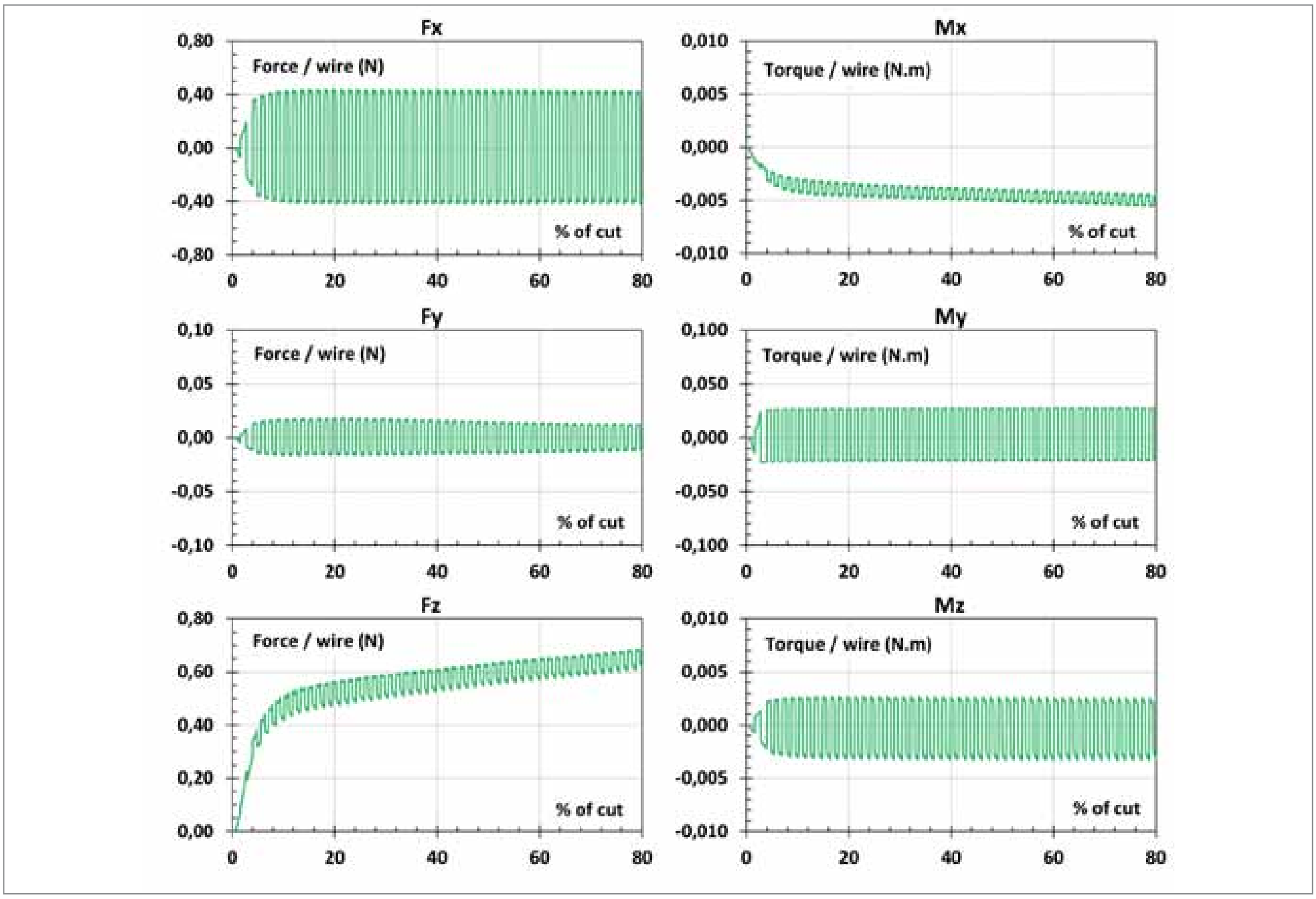


Figure 9. Force and moment components measured along three axes during silicon brick slicing.

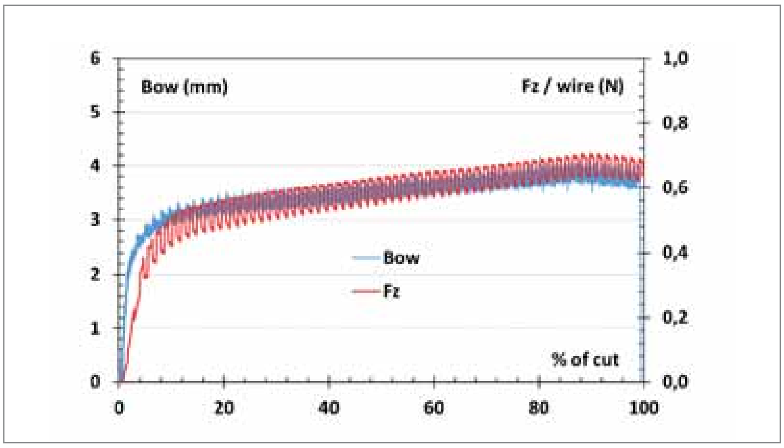


Figure 10. Force and bow measurements during the same cutting experiment.

wire quality is constant, the material is identical and the equipment process is constant as well.

Monitoring the bowing provides precious live information about wire behaviour. Wire defects or wire jumps, which can result in faster wire wear, will induce greater bowing during the cut; this can quickly be identified if monitored properly. For example, adjusting wire consumption during the cut could avoid wire breakage.

Other parameters of the cutting process, such as in situ force measurement (Fig. 8), can be monitored. As an experimental set-up to study the cutting behaviour of wire, half-height (78mm) silicon bricks, 100mm long, attached to a three-axis force sensor were used. A small wire web was created in order to cut 80mm of silicon. The device allows the monitoring of the forces F_x, F_y and F_z as well as the moments M_x, M_y and M_z during a cut. The six measurements taken from the slicing of the silicon bricks are reported in Fig. 9.

Typical oscillations are visible on the plots of the forces and/or torque during the cutting process, since a back-and-forth motion of the wire is used. Along the *y* axis (i.e. along the brick axis), the force and moment values are very small; as the movement of the wire is 90° to that direction, this is expected. For one wire, the force along the *x* axis oscillates around ±0.5N (along the wire direction). The vertical force applied by the wire web to the silicon brick increases as the cut progresses and the wire wear increases.

From these data, the friction coefficient and the cutting efficiency of the wire can be determined and correlated with the wire specification determined previously using the optical micrometer. It is interesting to note that if the bow and the vertical force are plotted on the same graph (Fig. 10), the correspondence of the curves is almost perfect. With the aid of such measurements, it can be determined in advance whether or not a diamond wire will cut silicon efficiently.

The experiments make it possible to establish the link between the wire morphology and the cutting behaviour of a new wire; however, they do not yield information about the state of the wire after cutting and the damage to the wire created by the cutting. The same optical micrometer technique mentioned earlier was therefore quickly implemented in order to study the used wires after the cuts (Fig. 11). Typical results obtained using commercial wire, for example, are given in Table 2.

When the quality of the wire is adequate, the decrease in bump height (diamond + binder) is around 40%; this decrease is due to the abrasion of the binder layer on top of the diamonds as well as to a certain amount of erosion/wear of the diamonds. In addition, approximately 20% of the initial quantity of diamonds present at the surface of the wire are removed during the cutting process.

As explained earlier, the cutting behaviour of monocrystalline silicon is almost solely dependent on the wire and the process being used (coolant is an important part of the process). Although it is fairly easy to empirically develop a wafering process for monocrystalline silicon, it is not the case for other materials being crystallized in DSS furnaces, such as high-performance (HP) multi or mono-like silicon. In those cases, it is extremely important to adapt the cutting process to the silicon morphology. To this end, a software package has been internally developed which allows the determination of the risk associated with the presence and density of precipitates inside the silicon bricks, in order to help predetermine the most appropriate cutting parameters for the wafering operation. Early results are encouraging and demonstrate that mono-like and/or multicrystalline silicon can be successfully cut.

In addition, the implementation of in situ diamond wire characterization during the wafering process is currently under way. One can imagine that in the near future, the cutting parameters of the wafering equipment might be made self-adaptive according to the in situ process monitoring information obtained, in order to guarantee and/or optimize wafer quality, cutting yield and wire consumption, depending on the needs of the wafer manufacturer.

Conclusions and perspectives

CEA-LITEN at INES, as a research laboratory, has developed over the last eight years an abundance of know-how, characterization techniques and data analysis methods that have helped French companies (e.g. B.E.A and Thermocompact) to design state-of-the-art equipment, such as a high-productivity closed-loop cropping machine, infrared characterization equipment and high-quality diamond wire for various applications.

As the PV industry gains maturity, wafers become thinner and cell efficiency increases, it is highly probable that wafer manufacturers will need to know and/or guarantee the detailed characteristics of the wafers they produce. These characteristics may include roughness, subsurface damage and mechanical properties, which are all extremely important in cell and module manufacturing. In order to ensure the best wafer quality, wafer manufacturers will need to carefully monitor their wafering process during the cut in order to optimize the cutting time and the wafer surface and mechanical properties; moreover, this process will need to be adapted to the material and/or the wire. This is extremely important for guaranteeing success in cutting multicrystalline and/or mono-like material efficiently in the near future.

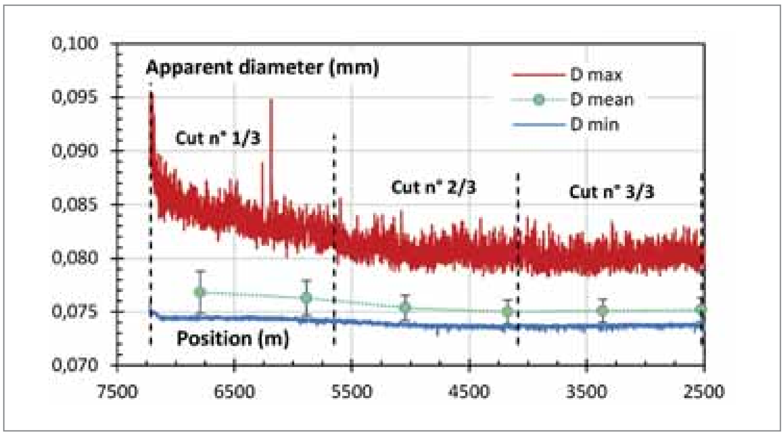


Figure 11. Optical micrometer inspection of used wire.

	New wire	Used wire	Difference [%]
Longitudinal homogeneity [%]	>95	>95	
Radial homogeneity [%]	>95	>95	
Diamond linear density [mm^{-1}]	100	80	–20
Maximum bump height [μm]	8.5	4.9	–42
Binder thickness [μm]	3.0	2.5	–17

Table 2. Typical results obtained after wire inspection before and after cutting using commercial wire.

"In order to ensure the best wafer quality, wafer manufacturers will need to carefully monitor their wafering process during the cut."

Acknowledgements

We gratefully acknowledge our colleagues B. Marie for the SEM images of precipitates (Fig. 3) and V. Brizé for the SEM image of diamond wire (Fig. 4). A special thank you is extended to B.E.A for having consigned CEA to develop/optimize high-cutting speed, closed-loop diamond wire silicon cutting equipment since 2010, as well as infrared silicon brick characterization equipment. We would also like to especially thank Thermocompact for entrusting us with the study of diamond wire and silicon cutting for their development of high-quality diamond wire since 2011.

References

[1] Coustier, F. et al. 2012, "Diamond wire wafering: State of the art and perspectives", *Photovoltaics International*, 15th edn, pp. 40–45.
[2] Wu, H. 2016, "Wire sawing technology: A state-of-the-art review", *Precis. Eng.,* Vol. 43, pp. 1–9.
[3] Bidiville, A. et al. 2015, "Wire-sawing processes: Parametrical study and modeling", *Sol. Energy Mater. Sol. Cells,* Vol. 132, pp. 392–402.
[4] Anspach, O., Hurka, B. & Sunder, K. 2014, "Structured wire: from single wire experiments to multi-crystalline silicon wafer mass production", *Sol. Energy Mater. Sol. Cells,* Vol. 131, pp. 58–63.
[5] Kutsukake, K. et al. 2015, "Characterization of silicon ingots: Mono-like versus high-performance multicrystalline", *Jpn. J. Appl. Phys.,* Vol. 54, 08KD10.
[6] Jouini, A. et al. 2012, "Improved multicrystalline silicon ingot crystal quality through seed growth for high efficiency solar cells: Improved mc-Si ingot crystal quality through seed growth", *Prog. Photovolt: Res. Appl.,* Vol. 20, pp. 735–746.
[7] Tsoutsouva, M.G. et al. 2015, "Mono-like silicon ingots grown on low angle misoriented seeds: Defect characterization by synchrotron X-ray diffraction imaging", *Acta Mater.,* Vol. 88, pp. 112–120.
[8] Camel, D. et al. 2017, "The crucible/silicon interface in directional solidification of photovoltaic silicon", *Acta Mater.,* Vol. 129, pp. 415–427.
[9] Oliveira, V.A. et al. 2016, "Recombination activity of 2D extended defects in monolike silicon", *Energy Procedia,* Vol. 92, pp. 755–763.
[10] Hardin, C.W. 2003, "Fixed abrasive diamond wire saw slicing of single crystal SiC wafers and wood", M.S. dissertation, NC State University, Raleigh, North Carolina, USA.
[11] Li, S., Wan, B. & Landers, R.G. "Surface roughness optimisation in processing SiC monocrystal wafers by wire saw machining with ultrasonic vibration", *J. Eng. Manuf.,* Vol. 228, pp. 725–739.
[12] Wu, H. 2012, "Fundamental investigations of cutting of silicon for photovoltaic applications", Ph.D. thesis, Georgia Institute of Technology, Atlanta, Georgia, USA.
[13] Chung, C. 2012, "Abrasive distribution of the fixed diamond wire in wire sawing process", *Adv. Mater. Res.,* Vol. 579, pp. 145–152.
[14] Doyeon, K. et al. 2016, "Characterization of diamond wire-cutting performance for lifetime estimation and process optimization", *J. Mech. Sci. Technol.,* Vol. 30, pp. 847–852.
[15] Goel, S. et al. 2015, "Diamond machining of silicon: A review of advances in molecular dynamics simulation", *Int. J. Mach. Tools Manuf.,* Vol. 88, pp. 131–164.
[16] Tsai, P.-H. et al. 2013, "A comparison of wafers sawn by resin bonded and electroplated diamond wire – from wafer to cell", *Proc. 39th IEEE PVSC*, Tampa, Florida, USA, pp 0523–0525.

About the Authors

Fabrice Coustier has been working on silicon squaring, cropping and wafering since 2002. He joined CEA-LITEN in 2010 and currently leads the silicon-shaping activity in the Laboratory for Materials and Processes for Solar Energy. Before joining INES he worked at AMAT Switzerland, Photowatt International and the University of Minnesota.

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Nicolas Velet has spent all of his professional career working in PV, for fifteen years as a maintenance technician at Photowatt and on industrial projects. He has been participating in research activities at CEA-LITEN for seven years, making headway in this field full of novelty and change.

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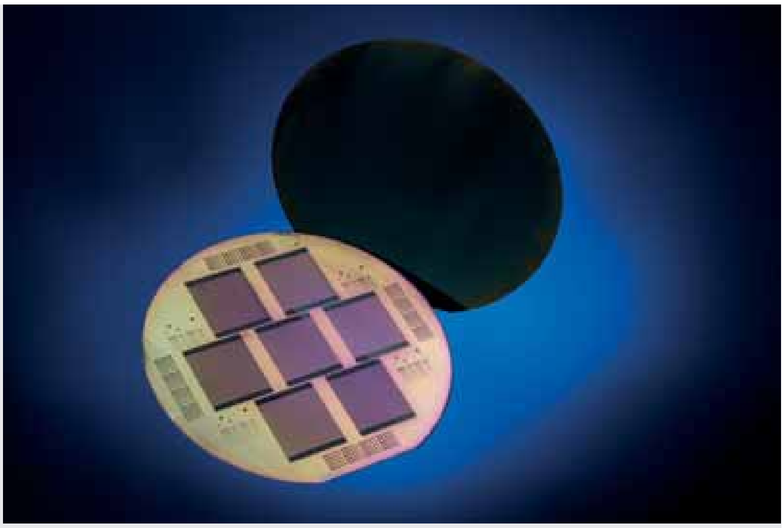
News

ISFH pushes p-type mono cell to record 26.1% conversion efficiency

The Institute for Solar Energy Research Hamelin (ISFH) and the Leibniz Universität Hannover have produced lab cells using polysilicon on oxide – POLO – junctions, in an interdigitated pattern on the rear side and a specially treated p-type monocrystalline wafer to record a cell conversion efficiency of 26.1%.

The record cell was described as using a passivating electron-selective n+-type polysilicon on oxide (POLO) junction at the minus contact of the cell and a hole-selective p+-type POLO junction at the plus contact.

The high selectivity of POLO junctions are a key factor in generating the high efficiencies, which are being applied in an interdigitated pattern on the rear side, minimizing the parasitic absorption in the poly-Si and avoids shading by front side metallization.



Credit: ISFH

ISFH has achieved a record 26.1% conversion efficiency in a p-type mono solar cell.

The n+-type and p+-type poly-Si are separated from each other by an intrinsic poly-Si region that is doped using lab-type processes. ISFH noted that the dielectric rear-side reflector was created local laser ablation and similar to current production techniques.

The record cell, which was tested and verified at ISFH-CalTeC, a ISO 17025-accredited Calibration and Test Center had an open circuit voltage of (726.6 ± 1.8) mV, short circuit current density of (42.62 ± 0.4) mA/cm2 and a fill factor of (84.28 ± 0.59) % on a designated cell area of 4 cm2.

"Replacing photolithography by laser contact opening is a first important step towards industrialization as it enables screen-printing-based metallization," Professor Robby Peibst, the leader of the workgroup.

CELL EFFICIENCY RECORDS

LONGi hits record 23.6% conversion efficiency for mono PERC solar cells

LONGi Solar, a subsidiary of LONGI Green Energy Technology, has hit a 23.6% conversion efficiency with its p-type monocrystalline passivated emitter rear contact (PERC) solar cells – a new industry record.

The results were certified by China's National Centre of Supervision and Inspection on Solar Photovoltaic Product Quality (CPVT).

An increasing number of manufacturers worldwide are migrating towards toward higher efficiency mono PERC cells.

Dr. Li Hua, vice president of research and development at LONGi Solar, said: "Since October 2017, LONGi Solar has broken the world record three times in terms of conversion efficiency of monocrystalline solar cells. The company achieved a new world record of 23.6% in efficiency at the beginning of 2018... This achievement is another testament to LONGi Solar's leading technology in monocrystalline cells."

Trina Solar takes n-type mono IBC cell to record 25.04% conversion efficiency

Trina Solar has set a record 25.04% conversion efficiency for an n-type monocrystalline IBC (interdigitated back contact) solar cell at its State Key Laboratory (SKL) of PV Science and Technology (PVST).

The record was independently certified by Japan Electric Safety and Environmental Technology Laboratory (JET).

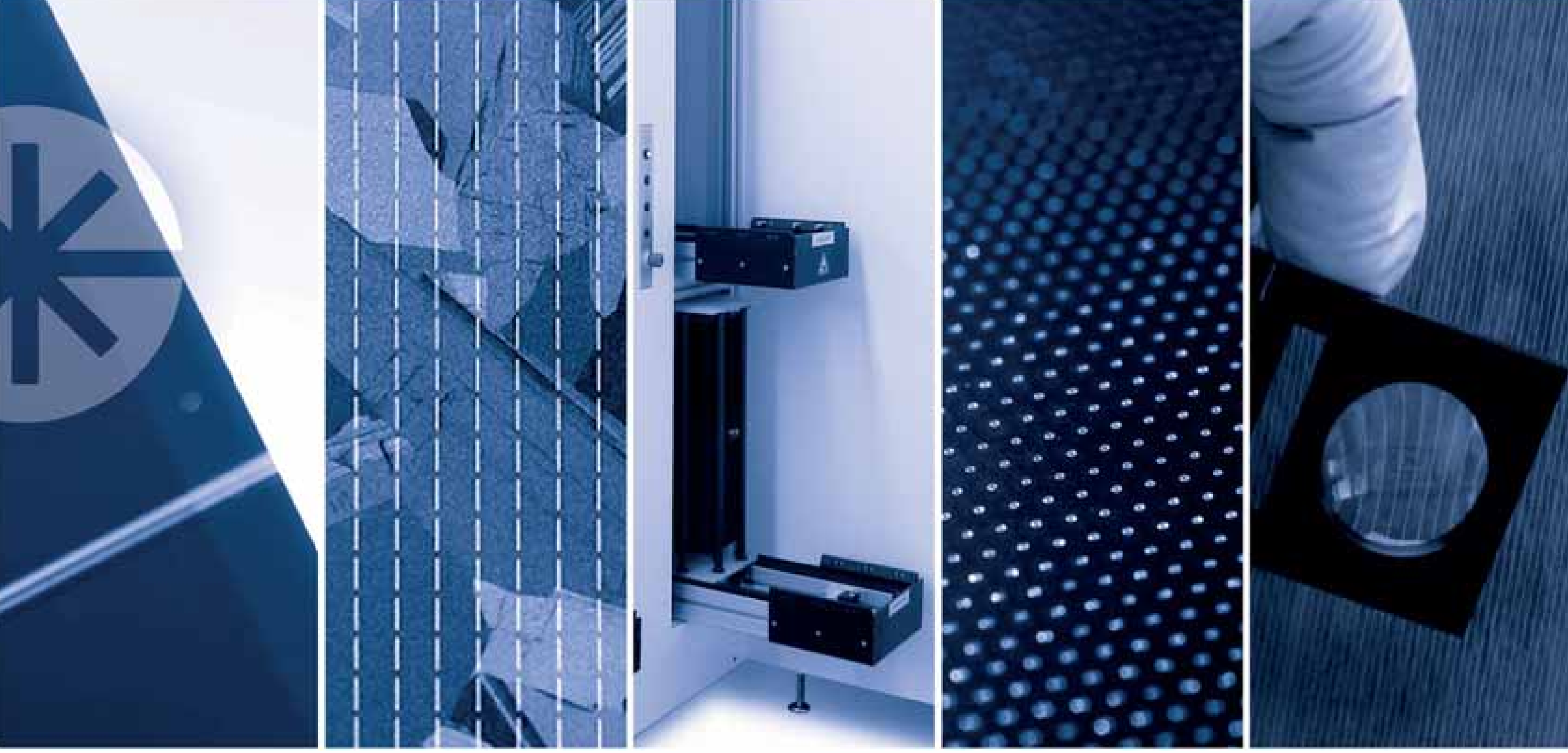
Trina Solar said the n-type mono IBC cell used a large-area (243.18 cm2) 6-inch n-type monocrystalline silicon wafer, with a low-cost industrial IBC process, featuring conventional tube doping technologies and fully screen-printed metallization.

Trina Solar noted that it was also the first single-junction c-Si solar cell developed in China to attain a conversion efficiency above 25%, and also has been demonstrated to be the highest efficiency c-Si single junction solar cell based on a 6-inch large-area c-Si substrate.

Hevel achieves heterojunction cells with 22.8% efficiency as plant ramps

Russian integrated PV manufacturer Hevel Group, which has switched production from amorphous silicon thin-film technology to silicon heterojunction (HJ), has said it has been successful in ramping to its 160MW nameplate capacity and achieving cell conversion efficiencies of 22.8%.

Hevel Group noted that having converted to HJ technology it was able to produce more than 323,000 HJ solar modules, equivalent to around 95.25MW in the July to December 2017 timeframe. At the end of the year the company said it was producing cells of 22.8% conversion efficiency.



HETEROJUNCTION TECHNOLOGY

Aurora collaborating on heterojunction and Industry 4.0 initiatives

Aurora Solar Technologies said that it had recently made major progress in developing its infrared measurement technology to support heterojunction (HJ) cell processing quality control. AST has teamed with with the Solar Energy Research Institute of Singapore (SERIS), which has strong expertise in HJ R&D.

"SERIS places great value on working with innovative industry partners such as Aurora," said Dr. Armin Aberle, SERIS' CEO. "With our scientific expertise in PV cell design and performance, and our advanced fabrication and analysis facilities, we can assist Aurora in the sophisticated technology development necessary to quickly and effectively address high-growth market segments such as HJT."

Dr. Thomas Mueller, head of SERIS' heterojunction R&D activities, added: "We appreciate the opportunity to work with Aurora on developing rapid inline metrology tools to analyze solar cell doped layer carrier concentrations using infrared technology. The ability to gather this information at a large sampling rate in a non-destructive way will lead to much faster process optimization, tighter process control, and higher yield in PV production than is possible with today's probing techniques."

INDEOtec gains tool acceptance from R&D facilities for next-gen heterojunction cells

Swiss PV manufacturing equipment specialist INDEOtec has gained acceptance for its PECVD process tools from both Fraunhofer ISE and the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia for next-generation heterojunction solar cells.

INDEOtec noted that the important acceptance test milestones have been completed for both projects ahead of expected deadlines and had surpassed the expectations especially for the intrinsic and doped a-Si:H layers.

Jochen Rentsch, head of department for PV production technology at Fraunhofer ISE said: "Our team is excited about the process results and the system quality. We are now really looking forward to do our research work with the new tool."

"For our research team here in Saudi Arabia the high system quality and the timely, on-the-spot process qualification is indeed convincing and confirmed the capabilities of INDEOtec," added Prof. Stefaan de Wolf from KAUST.

RESULTS, ORDERS AND SHIPMENTS

Meyer Burger beats revenue guidance for 2017

PV manufacturing equipment supplier Meyer Burger has exceeded its revenue guidance as it discloses preliminary financial information for fiscal year 2017.

The company reported net sales of CHF473 million (US$492.2 million), exceeding guidance of sales in the range of CHF440-460 million and up 4% year-on-year.

Meyer Burger said that its previous EBITDA guidance at CHF5-15 million (US$5.2-15.6 million was unchanged, while it expected a small reduction in its net loss for the year, compared to a net loss of CHF97.1 million in 2016. The company has been undertaking a range of restructuring activities in 2017.

The company reported that incoming orders reached around CHF560 million (US$582.7 million in 2017, an increase of 23% compared to the previous year and its highest order intake for the past six years.

The company has been benefiting from a new wave of capacity expansions and a technology buy cycle, driven by a major migration to diamond wire and 'Black Silicon' texturing of p-type multicrystalline wafers, PERC technology and next-generation n-type heterojunction cell migration at a select number of PV manufacturers.

Aurora Solar Technologies expects orders to reach record levels in 2018

Inline solar cell measurement equipment specialist Aurora Solar Technologies (AST) is expecting 2018 to be a record year for new orders, as major PV manufacturers continue to migrate and ramp high-efficiency solar cells technologies such as monocrystalline PERC and bifacial.

Michael Heaven, Aurora's chief executive, said: "We continue to see strong traction of our systems for monocrystalline PERC and bifacial applications and have already exceeded last year's revenue by 35%. While there were some delays on order decisions pending the Section 201 Solar trade case in the United States, we continue to track new order opportunities from current and new customers of between 40 and 80 systems which would position Aurora with a record level of backlog heading into our next fiscal year."

AST highlighted a number of customer engagements that could turn into significant new orders in 2018.

Tongwei increases merchant solar cell shipments 75% in 2017

Chinese integrated and merchant PV manufacturer Tongwei Group has said it will report full-year 2017 profits to be in the range of 80-100% higher than in 2016, due in part to its capacity expansions of both polysilicon and solar cells and higher average selling prices (ASPs) in the year.

Tongwei said in a financial filing that it expanded polysilicon production by 5,000MT in 2017, bringing nameplate capacity to 20,000MT. The company benefited from a rise in polysilicon ASP's as well as lower production costs. In general, polysilicon ASPs topped US$20/kg in 2017, double production costs.

The company also benefited from its expansion of solar cell capacity in 2017. Tongwei had shipped around 1GW of solar cells in 2016, having reached a nameplate capacity of around 2.4GW at the end of the year.

ECN's IBC solar cells in mass production environment: rise of a competitive back-contact module concept

Antonius R. Burgers, Ilkay Cesar, Nicolas Guillevin, Arthur W. Weeber and Jan M. Kroon, ECN Solar Energy, Petten, The Netherlands

Abstract

We present an n-type bifacial IBC solar cell that uses a simple process comparable to our industrially proven n-type cell process for conventional H-grid front- and rear-contacted n-PERT cells. The process is based on tube diffusion and a simultaneous single-step screen-print of the contacts to both polarities, and has been demonstrated on an industrial line at pilot scale. These IBC cells have been successfully integrated in foil-based modules, even using cells with thickness just below 100µm, enabling a route to significant reduction of silicon use. Further cost reductions with foils using cheaper aluminium instead of copper as conductor are described. The technology has huge potential to realize cost-effective PV electricity, for applications with both monofacial and bifacial illumination. Although the peak efficiency of 21.1% is currently modest, the process was embraced due to its inherent process simplicity.

The Mercury cell: enabler for low cost IBC

The Mercury Interdigitated Back Contact (IBC) cell [1] is a diffused screen printed IBC cell. The cell structure comprises an interdigitated boron-doped emitter and a phosphorous-doped back surface field (BSF) on the rear-side. A key feature is the boron-doped front floating emitter (FFE) on the front-side. The resulting Mercury IBC cell structure is shown in Figure 1 in comparison to an n-PERT cell. The analogy is clear, and the opportunities to apply the same process as much as possible to both architectures will be discussed below.

The core of the IBC process is the same as in the n-PERT process, comprising single step BBr_3 and $POCl_3$ tube diffusions, identical SiN_x layers and screen printed fire-through metallisation. The tube diffusion processes used are designed to be suitable for industrial throughput, i.e. with lower cycle time and high load density. While the boron diffusion has been pivotal for the development of n-PERT, the competitiveness of an IBC cell with FFE is even more empowered by this process step. The FFE and the rear emitter are formed in the same, and single, diffusion step.

Structuring of the rear-side diffusion regions is based on conventional screen-printing processing. This patterning and diffusion approach greatly simplifies processing of the device and reduces manufacturing costs compared to complex and costly high resolution patterning techniques such as lithography or laser ablation processes. In addition, this approach offers a great flexibility in implementing different diffusion pattern designs and matching metallization and interconnection designs. Front-side and rear-side surface passivation and anti-reflecting coatings can be realized with industrial ALD (Atomic Layer Deposition) and PECVD (Plasma Enhanced Chemical Vapour Deposition) equipment respectively. The metallization consists of a firing-through Ag paste deposited in a single step, for both emitter and BSF, by screen-printing, and features an open grid design suitable for thin wafers and bifacial applications.

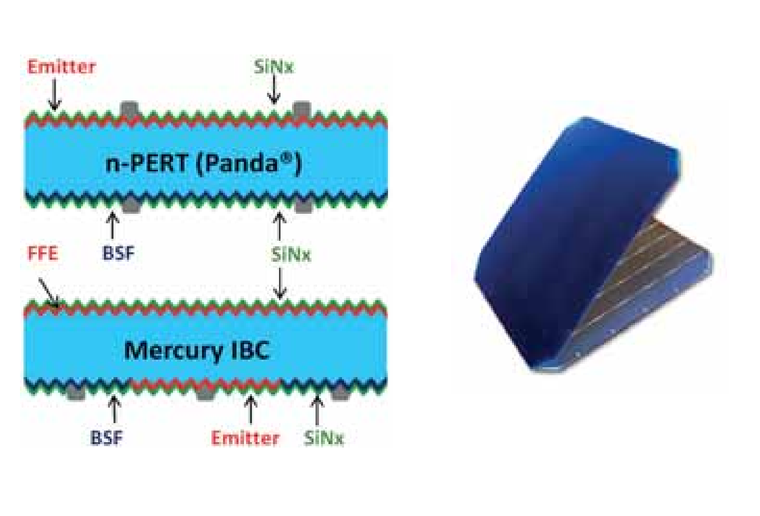


Figure 1. a) cross section of an FFE IBC cell; b) picture of front and rear side of an IBC cell.

The case for n-type cells

p-type Al-BSF and PERC

The PV market is presently dominated by cells and modules with p-type multi- and monocrystalline front-to-back contacted solar cells [2], as we can see in Figure 2. The trusted p-type Al BSF cells are to date still the workhorse of the PV industry, explained in a large part by the low cost and the simplicity of the process. Over recent years p-type Passivated Emitter and Rear Cell (PERC) cells have been successfully making a dent in the Al BSF cell dominance. The key innovation in the PERC cell over the Al-BSF cell is improving the passivation and light trapping of the rear side by means of a dielectric, making openings with laser processing in that dielectric, and then realizing local Al contacts. Although the PERC cell shares major process characteristics with the Al BSF steps, it does add to the complexity and cost of the process.

The Al-BSF cell and its modules are monofacial, because of the full aluminium metallization at the rear side. The basic PERC process also uses a full aluminium rear metallization as source for the local rear contacts, and hence is not bifacial. The PERC+ cell [3] addresses this by applying a partial aluminium metallization. Because of the lower conductivity of an open Al metallization, the integration of the cell with the interconnection and module technology becomes very important, in particular when aiming for bifacial modules.

Towards n-type cells

Solar cells based on n-type materials are generally considered and expected (See Figure 3) to enable significantly higher conversion efficiencies, and hence open a route to modules with lower cost of ownership. The potential for high efficiency is well documented and demonstrated, e.g. by Sunpower [4] and Panasonic [5].

The high conversion efficiency potential makes the n-type-based cells most attractive for back-contact concepts requiring high-quality material, such as IBC cells. In high-efficiency cells the collection efficiency for charge carriers is high, independent of whether they are generated at the front or rear side of the cell, thus enabling excellent bifaciality of the cells. High-efficiency n-type modules have the benefits of a better temperature coefficient, and converting a larger fraction of the incoming light to electricity instead of heat, leading to better kWh/kWp energy yield [6, 7]. Additionally, the higher module output power of the same size module reduces also the area-related costs of a PV system.

A bifacial module will, in addition to light impinging on the front side, also convert light that enters through the back side of the module into power. This brings about a gain of 10-30% [8] in power compared to a monofacial module. There is a large range in these bifacial gains, because they depend on a multitude of factors, such as the albedo of the surroundings, the elevation of the modules over the ground plane, the separation between modules, to mention just a few. Exploiting the bifaciality effectively increases the cell efficiency at little cost, reducing the area related system cost.

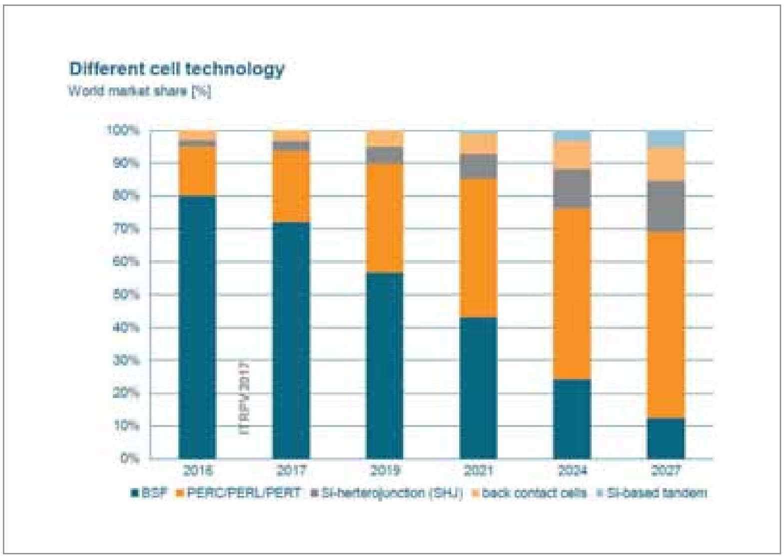


Figure 2. The actual and projected market shares of different cell types, ITRPV 2017.

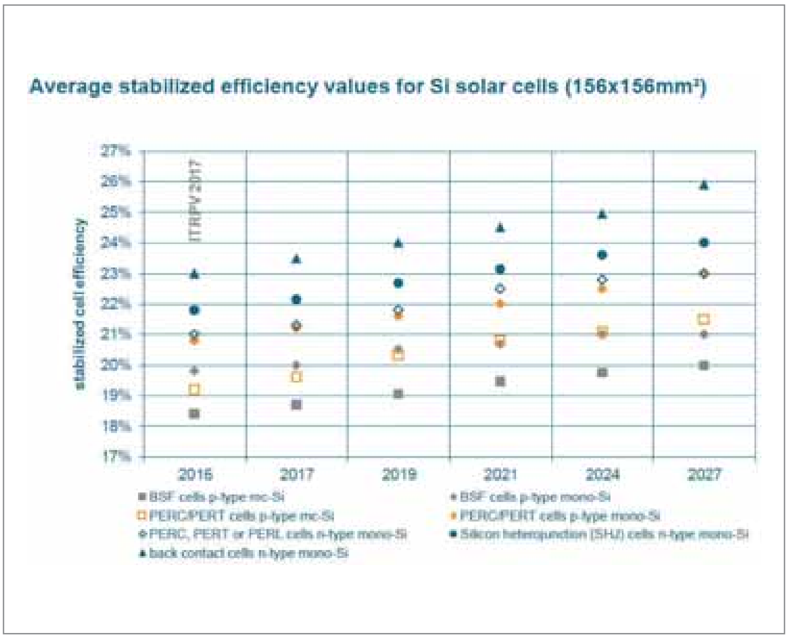


Figure 3. Projected development of the efficiency of different cell types, ITRPV 2017.

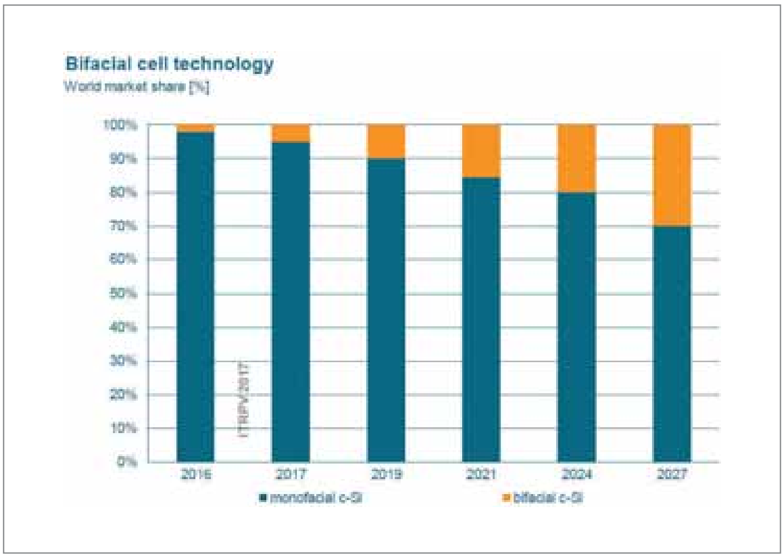


Figure 4. Actual and projected market share for mono- and bifacial modules, ITRPV 2017

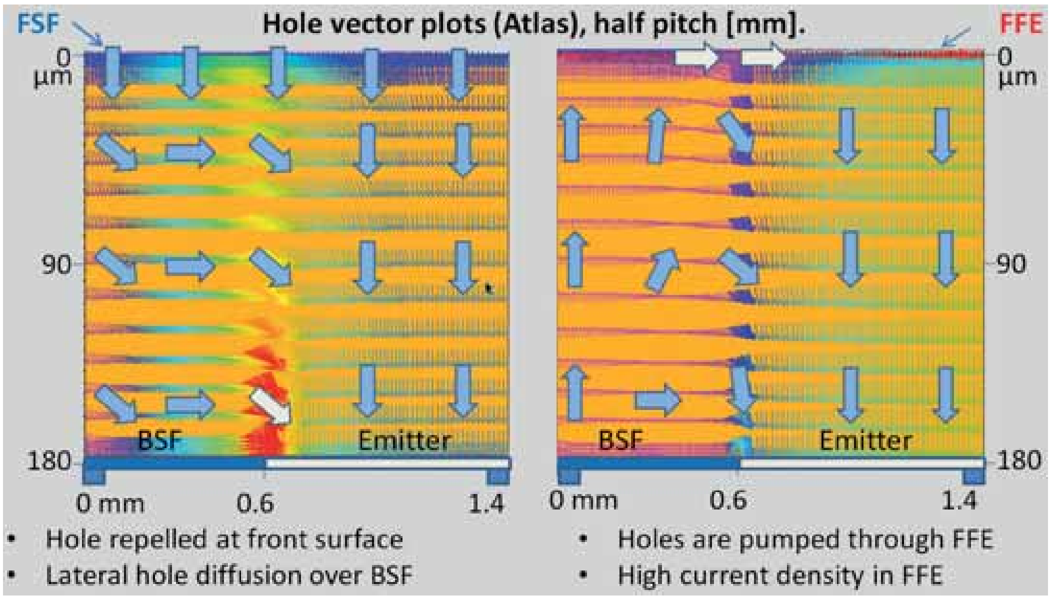


Figure 5. Comparison of hole current flow in a) FSF and b) FFE IBC structures

Front floating emitter for low cost IBC

Traditionally, IBC cells use a front surface field (FSF). If not properly designed, an FSF IBC cell can suffer from high recombination losses over the rear BSF, an effect referred to as "electrical shading". To mitigate the effect of electrical shading two approaches are available:

1. High-resolution processing: in an FSF cell the primary approach is to reduce lateral transport distances, in particular by realizing narrow

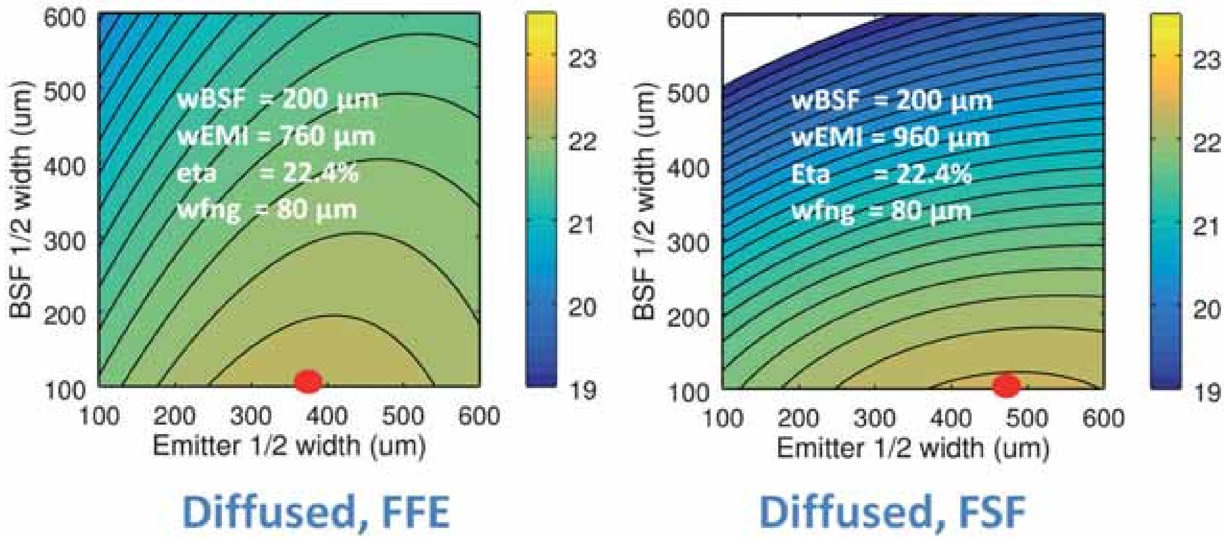


Figure 6. Cell efficiency as a function of emitter and BSF width for a) with an FFE and b) with an FSF. The white text gives the device parameters at the spot of the optimum (indicated by a red dot).

BSFs. This can be achieved by high-resolution patterning steps, which in general comes at a cost.

2. Using a front floating emitter (FFE) we mitigate electrical shading with the FFE. This enables low-resolution processing, and hence opens up a route to lower cost processing.

Electrical shading and these two approaches will be explained in more detail in the next section.

Mitigating electrical shading with an FFE

In FSF IBC cells the p-n junctions are present only on the rear side of the cells. Hence minority carriers generated above the rear BSF need to diffuse laterally towards the nearest p-n junction (Figure 5a). Lateral transport distances are governed by the pitch in the rear cell geometry. If the distance towards the nearest p-n junction is relatively large, that increases the risk of recombination of the carriers on their way. Secondly, in order to drive the diffusion, a concentration gradient is required, with a high concentration of minorities above the BSF. This increases the injection level, and increases chances of recombination.

In an IBC cell with an FFE, a p-n junction is also formed at the front side, which is never more than a wafer thickness away for any carrier. Once collected in the FFE (see Figure 5b) carriers can travel laterally as majorities, without recombination losses. Over the rear emitter the majorities are re-injected into the base as minorities, and once again only need to cross the thickness of the wafer. This process of collection over the BSF and subsequent re-injection back into the base over the rear p-n junction results in a "pumping effect": transport of minority carriers from regions above the BSF to the rear emitter through the FFE with very little recombination losses.

To illustrate this, Figure 6 shows contour plots of the efficiency as a function of the unit cell design. The cell efficiency in IBC cells depends much more strongly on unit cell design than in conventional front rear contacted cells, such as the Al BSF cell and n-PERT cells, due to the importance of lateral transport of minority carriers in the base. Device simulations were done for multiple BSF-emitter width combinations, using J_0 values for a diffused IBC with firing through metallization, and the results were used to derive the contour plots. What we observe is that for FFE cells the efficiency holds up much better than for FSF cells as we move up along the y-axis and the BSF width is increased. For instance for the case of both BSF and emitter having a width of 1mm we observe an efficiency of well >21% for the FFE case, where the FSF case is already <20%.

Even with the FFE there are of course limits on the lateral transport distance, because of resistive losses in the FFE. However an FFE radically expands the design space of IBC cells, thereby offering ways to reduce process complexity and thus cost. In addition, being able to increase the pitch size on the rear side reduces the metal coverage on the rear side, and in turn enhances the bifaciality of the IBC cell. If p-n junctions would have an adverse effect, an FFE allows their impact to be reduced, by reducing the number of p-n

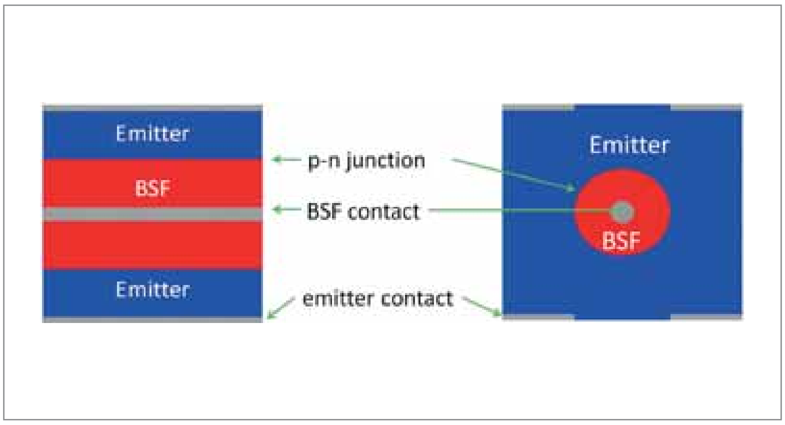


Figure 7. Changing from linear diffusion to island geometry.

Processing step	*Mercury IBC*	*n-PERT*
diffusions	boron/phosphorous	
diffusion patterning	screen-printed patterning	no
edge isolation	no	yes
surface passivation	wet chemical and dielectrics	
metallization	all-in-one paste single print	1. Ag/Al front print 2. Ag rear print

Table 1. Comparing major process steps in n-PERT and Mercury IBC.

junctions.

Synergy and simplicity in process flows

The continuing success of the Al-BSF cells makes one wonder what can be learnt from this process, and how these lessons can be applied to new technologies. A key factor is the very simplicity of the process. At the core of the process, one diffuses a phosphorous emitter into the future light receiving front side, deposits a hydrogen rich silicon nitride (SiN_x:H) film at the front, prints the rear side fully with aluminium paste, and applies an H-grid pattern with Ag paste on the front side.

Then during the firing step near magic occurs. The Ag paste fires through the SiN_x:H film and makes an ohmic contact to the emitter. The temperature occurring during the firing makes the hydrogen in the SiN_x:H film mobile, and allows the hydrogen to improve both bulk and surface passivation. At the same time the aluminium dissolves some of the silicon, leaving a BSF passivating the rear side on cooling down and forming an ohmic contact to the rear.

The Mercury IBC cell was conceived with this success in mind, the boron diffusion serving similarly as an important multifunction process step:

1. The developed diffusion process results in passivation of the emitter – BSF junctions at the rear side, as well as a perfectly passivated wafer edge. Both process features circumvent a laborious and expensive gap and edge isolation process [9].
2. It is a one step process preparing the front and rear emitters for surface passivation and rear contact formation.
3. The entire surface with all its diffused layers, including the rear BSF-emitter junctions, can be passivated using regular wet chemistry steps and dielectric layers. Because of the presence of diffused layers, inversion layers have less impact on the surface passivating quality, and a wide range of passivation options is available and suitable for passivation of polarities at the same time.
4. A conductive FFE is realized that enables large pattering feature sizes for ease of manufacturing and more freedom in module integration, which will be discussed in the module section of this paper. The large feature size in turn enables high bifaciality, and renders the cell less prone to hi-hi p-n junction issues.

The patterning of the rear-side diffusions is an extra step, but this is offset in other steps, as shown in Table 1. The presence of all contacts on the rear side allows for all-in-one print of the metallization, ready for soldering.

Demonstration in a pilot line setting

Because the process is close to existing n-PERT processing, and the requirements on resolution for the FFE IBC cells are lower, the cell concept maps well to industry-scale screen-printed processing. Similar process equipment as well as process parameters are used without increasing the number of major manufacturing steps, making the Mercury process compatible with an industrial-scale production and throughput. Pilot processing in an industrial environment therefore offers a great opportunity for the Mercury IBC technology to gain in maturity by rapidly acquiring knowledge on manufacturability. Yingli has successfully implemented this process [10, 11]. First working cells were achieved within three months of the start of the project.

Cell efficiency results

In Table 2 the I-V parameters of our best IBC cell are shown. The bifaciality factor reaching 83% here is excellent, considering this is an IBC cell. In an IBC cell all metallization is on one side of the cell, the rear side, limiting the bifaciality. If for example the metallization coverage on the rear side is say 12%, the bifaciality factor cannot exceed 88%. On encapsulation the bifaciality can increase, by virtue of trapping of the light reflected diffusely off the metallization at the glass-air interface.

Note that ISC Konstanz has developed a similar concept, the Zebra cell (12). For the Zebra cell efficiencies up to 21.9% [13] have been reported.

Performance limitations in current cells

By measuring the recombination losses at surfaces and interface we determined that the efficiency of our IBC cell is to a large extent limited by recombination at the screen printed contacts, in particular the emitter contact, and at the passivating quality of the BSF, as can be observed from Table 3.

We have seen that for pastes for phosphorous emitters and boron emitters huge improvements have been realized over the years, realizing better J_o and r_c values on these emitters with increasing resistivity. Current development of the Mercury design has been limited by the performance of the all-in-one paste. We think there is ample room for improvement in the short term for all-in-one pastes that contact both phosphorous and boron diffusions. Since developing novel pastes needs more effort, we investigate alternative routes like so called BSF islands.

BSF island: Mercury IBC cells with localized BSF diffusion

The recombination activity in the cell is dominated by the emitter contacts and the heavily doped BSF area. Therefore, reducing both the BSF area and the emitter contact fraction is a route to decrease the recombination in the cell and therefore enhance the cell performance.

Depending on the contact width and the screen printing tolerances, a minimum width of the passivated BSF area is required, which is typically more than 300 µm. In a one-dimensional interdigitated finger design (Figure 7a) the only option to reduce the BSF area fraction further is then to increase the emitter width, but this induces large transport losses. Therefore, we reduced the BSF length within the unit cell [14], and in this way we created "islands" of BSF surrounded by the rear-side emitter, as shown in Figure 7. The BSF area reduction will mainly improve the passivation of the cell, and increase the voltage, and increase current by avoiding recombination. In the Mercury IBC cell case, electrical shading is not a major issue due to the collecting and transporting front floating emitter, hence reducing the BSF area is not required from a standpoint of electrical shading.

In Table 5 the breakdown in J_o contributions between the two different geometries is compared. In particular the contribution of the emitter contact to the recombination has reduced.

In the longer term, passivated contacts open a route to higher efficiencies. For n-PERT the so called PERPoly cell has been developed. In the PERPoly cell the rear phosphorous BSF is replaced with an industrial rear poly silicon BSF [15, 16], that achieves markedly lower J_o values for the contacts while still using firing through contacts, (See Table 6) and has resulted already in a 0.5% absolute efficiency gain for PERPoly cells compared to n-PERT references.

Because the IBC Mercury process is very close to the n-PERT process, improved contacts for n-PERT can be transferred to n-IBC with relative ease.

IBC cell-based modules

Flexibility of the diffusion pattern and metallization grid designs offers freedom when it comes to the choice of module interconnection technology. Based on the current metallization grid design, which includes interconnection pads, the cells can be readily processed into modules using ECN's foil-based interconnection technology [17, 18]. ECN's module manufacturing technology is based on an interconnection foil with integrated conductor layer (e.g. copper or aluminium), on which the cells are electrically contacted using an electrically conductive adhesive (ECA). Compared to a tabbed interconnection technology, the interconnection foil allows reduction of the module series resistance by using more interconnect metal (more cross-sectional area) and thereby reduces the cell-to-module FF loss [19]. Also, the module manufacturing based on integrated back-foil can be done with higher yield and reduced interconnection-process-related stress, allowing use of (much) thinner cells and therefore offering additional cost reduction possibilities. This type of module has passed full IEC testing [20].

Full size 60 cell – thin wafer – IBC cell module

To prove that we are ready for the future silicon wafer thickness, we have processed modules with cells nearly half as thick as today's standard. These fragile wafers are incompatible with current standard tabber-stringer processes, because the process yield is low.

A batch of 156 thin wafers (starting thickness 120um, final thickness 95um) has been processed to Mercury IBC cells at ECN. The best 60 cells of this batch have been integrated

Area	J_{sc} (mA/cm²)	V_{oc} (mV)	*FF* (%)	Eta (%)	Bifaciality factor
239	41.2	653	78.4	21.1	83%

Table 2. I-V parameters of the best Mercury IBC cell measured at ECN. Short circuit current is corrected for spectral mismatch.

	J_o corrected for area fraction (mA/cm²)						V_{oc} @300K (mV)
bulk	FFE	emitter		BSF		total	
J_o	J_o	J_o	$J_{o,contact}$	J_o	$J_{o,contac}$t	J_{ototal}	
11	40	22	149	89	45	357	658

Table 3. Area weighted J_o breakdown for IBC cell.

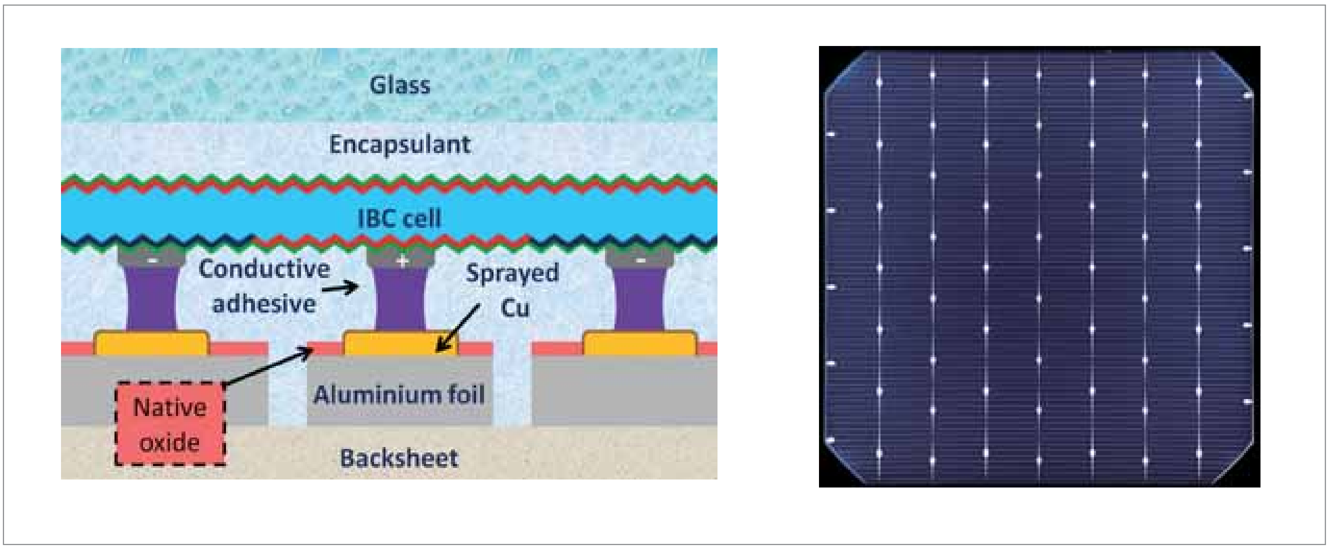


Figure 8. a) Interconnection by means of the Cu cold spray method (schematic); b) 62-pad cell interconnect pattern.

Figure 9: the pick and place stage for the cells on the foil. Picture taken at Eurolab BV, NL.

	J_{sc} [mA/cm^2]	V_{oc} [V]	FF [%]	Efficiency [%]
Reference	38.9	0.653	79.1	20.1
BSF islands	39.9	0.663	77.9	20.6

Table 4. I-V results for the BSF island geometry.

in a foil-based module using copper as the conductor layer, without any breakage. The one-sun power output of this module was measured at 277W, while the summed power of the individual cells was 278W. Hence the cell-to-module loss was <1%. This is a good number, considering that:

- The foil-based approach allows close packing of the cells, with little spacing between the cells. The white space in a conventional tabbed module actually contributes significantly to the module current.
- In a front metallized cell, after encapsulation, light reflected diffusely off the metallization is trapped in the front glass and encapsulant and can re-impinge on the non-metallized cell, contributing to the current of the cell, and hereby effectively reducing the metal grid shading. This effect is absent in IBC cells.

Noting that the silicon wafer comprises about 40% of the cost of the module in 2017 [2], being able to integrate thin cells with high yield in a module opens a route to saving on wafer cost. A paper describing this module and module technology in more detail, and its cost benefits will be presented at the WCPEC-7 [21].

		J_o corrected for area fraction (mA/cm^2)						V_{oc} @300K (mV)
case	bulk	FFE	emitter		BSF		total	
	J_o	J_o	J_o	$J_{o,contact}$	J_o	$J_{o,contac}$t	J_{ototal}	
linear	11	40	22	149	89	45	357	658
BSF island	11	40	30	60	60	19	220	670

Table 5. J_o breakdown for IBC cell.

polySi thick (nm)	n-poly j_o (fA/cm^2)	n-poly/Ag paste $j_{o,c}$ (fA/cm^2)	p-poly j_o (fA/cm^2)	p-poly/AgAl paste $j_{o,c}$ (fA/cm^2)
100	1.3	1084 (461)	5.6	796 (103)
200	2.7	386 (22)	5.7	319 (40)

Table 6. J_o values for n-type and p-type polysilicon layers with firing-through contacts.

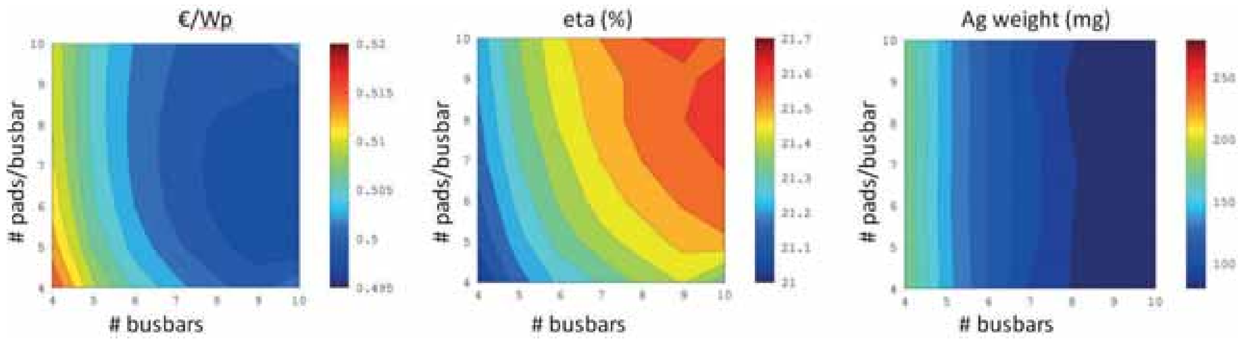


Figure 10: Interconnect design and Ag consumption a) €/Wp; b) efficiency; c) Ag used per cell based on cost levels in 2016.

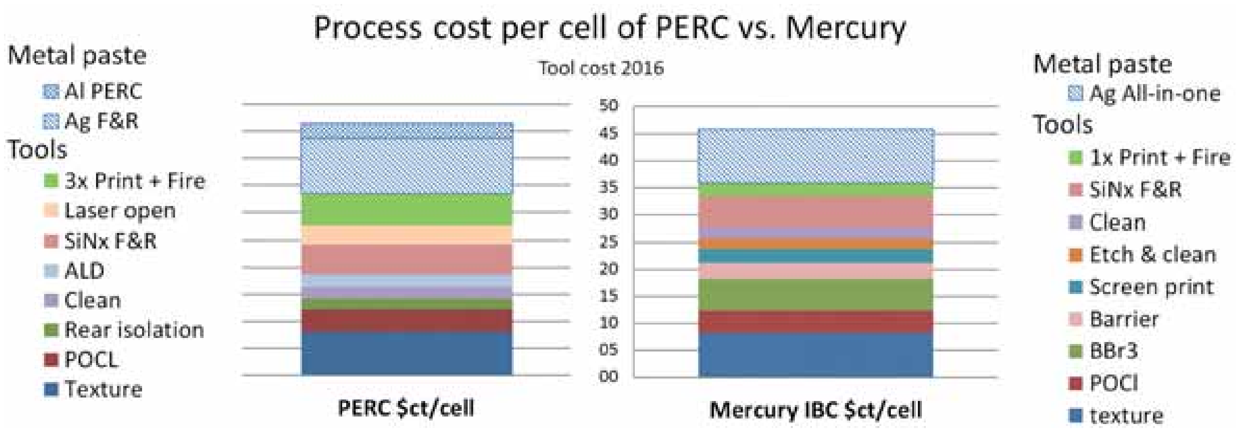


Figure 11. Cost breakdown of the cell processing cost for PERC and Mercury.

Aluminium based rear foils

Replacing the Cu conductor layer with Al can result in a cost saving of about 2% on module level. However it is much more difficult to make an electrical contact with ECA to Al than to Cu, because of the native oxide that is present on Al. The copper cold-spray method [22, 23] is a method to deposit copper particles on aluminium conductive foil, while opening the oxide, and allows to establish a both mechanically and electrically good and stable localized contact between the solar cells and the aluminium, as illustrated in Figure 8a.

Figure 8a is a schematic in the sense that connections are not made directly to the individual fingers. Instead in Figure 8b we show that the cell has an interdigitated finger pattern, with busbars of alternating polarity. On the busbars there are in this case 62 pads (~30 per polarity) provided for application of ECA. The corresponding positions on the rear foil are the locations where Cu needs to be present.

Several IBC four-cell mini-modules using cold-sprayed aluminium as the conductive back foil were fabricated and passed selected IEC 61215 tests (damp heat at 85°C/85% RH and thermal cycling between -40 and 85 °C), demonstrating the large potential of this cost reduction approach. An upcoming paper describing this method and the benefits of the back contact module technology will be presented in more detail at the WCPEC-7 [21].

Foil design and cell Ag cost

The foil-based approach is an enabler to reduce Ag cost, by moving conduction from Ag on the cell to the metal on the rear foil. By increasing the number of interconnects, the average distance of any point on the cell to nearest interconnect decreases, reducing the requirements on Ag conductivity.

The requirement on Ag consumption is illustrated in Figure 10. For each combination of the number of busbars and the number of pads/busbar, the unit cell design (BSF width, emitter width) was picked that gives the best €/Wp. The amount of ECA required per interconnect was assumed to be fixed. The best cell efficiencies are reached in the upper right corner, for a high number of busbars (short fingers) and a high number of interconnects (short busbars). For lower numbers of busbars, the fingers become long, and much Ag is required to maintain a sufficient FF. For high numbers of pads/busbar the ECA cost comes into play, leading to an optimum in this case of around nine busbars and seven interconnects per busbar. The Ag consumption at that point is in the order of 100mg. [10] reports our evolution in cell and processing from a design with ~30 contact pads to ~81 pads currently, allowing us to reduce the Ag consumption.

Cost comparison Mercury IBC with PERC

In Figure 11 a breakdown is shown of the processing cost for PERC and Mercury per wafer. The boron diffusion is a relatively expensive step; however in the Mercury process we prevent other costly steps, such as laser opening and multiple print steps, ending up with comparable cost.

Conclusions

Mercury cells open up a route to manufacturable n-type IBC cells, building upon existing n-PERT technology, enabling high efficiency and good bifaciality. The cells feature a simple process, a well passivated gapless rear p-n junction, without need for edge isolation. The progress is currently limited by the performance of the silver paste. For monofacial application the combination with foil-based modules with aluminium as the main conductor allows significant cost reductions. We demonstrated Technology Readines Level 6 processing of ultra-thin silicon wafers in to IBC modules without yield loss. We look forward to advancing these concepts with our partners.

Acknowledgements

We are grateful for the financial support from the Dutch government through the Topsector Energy Subsidies of the Ministry of Economic Affairs of the Netherlands and the European Commission via the funded project Cheetah (GA nr. 609788).

References

[1] Cesar, I. et al. 2104, "Mercury: A Back Junction Back Contact Front Floating Emitter Cell with Novel Design for High Efficiency and Simplified Processing", Energy Procedia, Volume 55, 633-642.

[2] International Technology Roadmap for Photovoltaic (ITRPV), Eighth Edition 2017.

[3] Dullweber T. et al, 2018, "Industrial implementation of bifacial PERC+ solar cells and modules", *PV international*, Edition 38, page 46.

[4] Smith, D. et al. 2014, "Towards the Practical Limits of Silicon Solar Cells", Proc. 40th IEEE PVSC.

[5] "Panasonic HIT solar cell achieves world's highest energy conversion efficiency of 25.6% at research level", Public Relations Development Office, Panasonic Corp., Osaka, Japan, April 2014.

[6] Smith, D. et al. 2012, "Generation III high efficiency lower cost technology: Transition to full scale manufacturing", 38th IEEE Photovoltaic Specialists Conference, Austin, TX, 001594-001597.

[7] "Panasonic HIT Solar Module Achieved World's Highest Output Temperature Coefficient at -0.258%/°C", Public Relations Development Office, Panasonic Corp., Osaka, Japan, May 2017.

[8] Janssen, G., Van Aken, B., Carr, A., Mewe. 2015, "Outdoor performance of bifacial modules by measurements and modelling", Energy Procedia 77, 364-373.

[9] Spinelli, P. et al. 2017, "Quantification of p-n junction Recombination in Interdigitated Back-Contact Crystalline Silicon Solar Cells", IEEE Journal of Photovoltaics, Vol 7, 1176.

[10] Guillevin, N. et al. 2017, "Pilot line results of n-type IBC cell process in mass production environment", 33rd EU-PVSEC, Amsterdam.

[11] Liu, D. et al. 2018, "Development of Large-Area Bifacial Interdigitated-Back-Contact (IBC) Solar cell with Industrial Production Environment", submitted to WCPEC-7: 45th IEEE PVSC, 28th PVSEC, 34th EU PVSEC, Hawaii.

[12] Mihailetchi, V., Chu, H., Galbiati, G. 2015, "A comparison study of n-type PERT and IBC cell concepts with screen printed contacts", Energy Procedia 77, 534 – 539.

[13] Galbiati, G. et al. 2106, "Large area IBC Zebra solar cells in pilot production: the results of FP7 Hercules project", 32nd EU-PVSEC.

[14] Mewe, A. et al. 2017, "BSF islands for reduced recombination in IBC cells", IEEE PVSEC-44, Washington DC.

[15] Stodolny, M. et al. 2016, "n-Type Polysilicon Passivating Contacts for Industrial Bifacial n-PERT

Cells", EU-PVSEC, 2016.
[16] Çiftpinar, H., Stodolny, M., Wu, Y., Janssen, G., Löffler, J., Schmitz, J., Lenes, M., Luchies, J-M., Geerligs, L. 2017, "Study of screen printed metallization for polysilicon based passivating contacts", Energy Procedia, Volume 124, 851-861.
[17] Bennett, I.J., Eerenstein, W., Rosca, V. 2013, "Reducing the cost of back-contact module technology", Energy Procedia 2013; 38:329-33.
[18] Bende, E.E., Van Aken, B.B. 2015, "The effect of reduced silver paste consumption on the cost per Wp for tab-based modules and conductive-foil based modules", Energy Procedia 2015; 67:163-74.
[19] Van Aken, B., Slooff-Hoek, L. 2016, "Positive cell-to-module change: Getting more power out of back-contact modules", *Photovoltaics International*, Vol. 33, 97-105.
[20] Eerenstein, W. et al., 2010, "Climate chamber test results of MWT back contact modules", 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion, Valencia, Spain.
[21] Newman, B., Kroon, J., Guillevin, N., Okel L., Sommeling, P., Goris, M., Eerenstein, W., Gonzalez. J. 2018, "Materials Development and Increased Module Efficiency for 15% Cost Reduction of Reduction of Back Contact Modules". Submitted to WCPEC-7: 45th IEEE PVSC, 28th PVSEC, 34th EU PVSEC, Hawaii, 2018.
[22] Goris, M., Bennett, I., Eerenstein, W. 2014, "Aluminium Foil and Cold Spray Copper Technology as Cost Reduction Process Step in Back-contact Module Design", Energy Procedia Volume 55, 342-347.
[23] Goris, M.J.A.A., Kikkert, B.W.J., Kroon, J.M., Rozema, K., Bennett, I.J., Verlaak, J. 2016, "Production of low cost back contact based PV modules", 32nd European Photovoltaic Solar Energy Conference, Munich, Germany, p. 99-104.

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‘Less is more’: Ultrathin heterojunction cells offering industrial cost reduction and innovative module applications

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Abstract

Because of its symmetrical a-Si/c-Si/a-Si structure, silicon heterojunction (SHJ) cell technology offers the possibility to use much thinner wafers, and thus to reduce material and production cost. In order to evaluate the industrial feasibility of these thinner heterojunction cells, wafers from the standard thickness of 160μm down to 40μm were processed on the heterojunction pilot line at CEA-INES. It was found that no major modifications to the line were required to maintain stable cell performance down to a thickness of 80μm. For thicknesses below 80μm, wafers had to be processed in a semi-automatic/manual mode. The sweet spot in terms of cell performance, line compatibility and production cost was found at a thickness of around 90μm, roughly half that of the current mainstream thickness. These 90μm cells, with dimensions 156mm × 156mm, were then assembled into 60-cell modules, both glass–glass (bifacial) and glass–backsheet (monofacial) configurations, without changes to the interconnection and lamination process or to the bill of materials. A cell-to-module (CTM) performance above 99% was obtained, and the symbolic target of 1Wp per gram of silicon was reached. The thinner wafers also made it possible to manufacture ultralightweight (< 1kg/m^2) and semi-flexible modules for product-integrated PV (PIPV).

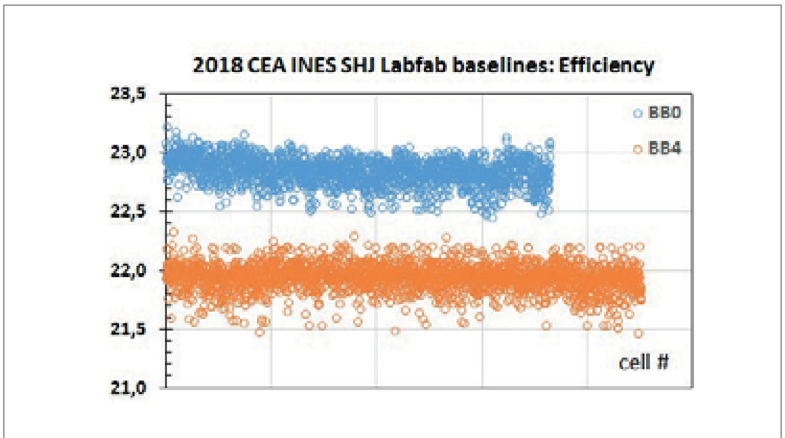
Introduction

As now widely recognized, the amorphous/crystalline silicon heterojunction (a-Si:H/c-Si, SHJ) is one of the most attractive solar cell architectures, combining high performance and industrial compatibility. The low-temperature, high-throughput and cost-effective processes involved, the bifaciality, and the option of a rear-contact cell design are the competitive advantages of SHJ technology over other cell architectures [1,2]. Because of such advantages, an SHJ market is currently emerging, with a 5GW production capacity forecast in around 2020 [3]. The SHJ cell concept currently holds a world-record efficiency of 26.7% in its back-contact configuration [4].

CEA-INES has been exploring heterojunction cell technology for over 10 years, and an industrial pilot line has been in operation since 2011. The pilot line offers a turnaround time of <8h from as-cut wafers to electrical cell testing and sorting, at a nominal capacity of 2,400 wafers per hour, in combination with flexible R&D activities for each individual process step [5,6]. In 2016 and 2017, a hundred thousand wafers per year were fed into the pilot line to respond to industrial partner requests and to develop SHJ process know-how at CEA-INES. The production baseline performance during the first quarter of 2018 is shown in Fig. 1.

Work at the CEA-INES SHJ cell pilot line is complemented by an automated module pilot line to develop encapsulation and interconnection options. This notably includes bifacial modules and low-temperature cell interconnection options, such as the Meyer Burger SmartWire Connection Technology (SWCT) concept [7]. SWCT is especially suited to thinner cells, as the mechanical stress peaks generated on the cell are lower than in the case of standard ribbon interconnection. Moreover, SWCT is a redundant interconnection concept, with the impact of cell cracks on module power being lower. The module pilot line is supported by indoor testing facilities (climate chambers and mechanical test benches) and diagnostic tools for evaluating long-term module reliability, as well as by outdoor testing facilities [7].

This paper describes the work carried out on processing ultrathin (70–100μm) 156mm × 156mm wafers. The goals are twofold: 1) to reduce cell production costs; and 2) to enable innovative module designs, such as lightweight modules, either flexible



The CEA-INES Labfab SHJ process baselines in 2018 for thousands of wafers with standard thickness. Busbarless cells average efficiency is 22.8% thanks to lower sensitivity to metal finger resistivity and less shadowing. Best cell at 23.8% on record process batch. The 2018 process baseline of four-busbar cells is 21.95% with best cell at 23.0% from record process batch.

> "The need for cost reduction is driven by the fact that current wafer production costs still represent as much as 35% of the total costs of an industrial PV module."

or rigid in nature. The need for cost reduction is driven by the fact that current wafer production costs (including material and sawing) still represent as much as 35% of the total costs of an industrial PV module [3].

The second goal, relating to innovative module architectures, is driven by the PV application potential in areas such as aerospace, vehicles, boats or building integration, where non-planar shapes and weight reduction (including that of the cells) can be a key requirement. Figs. 2 and 3 show examples of such lightweight modules integrated in unmanned aerial vehicles for observation and telecommunication. In these two particular cases, the targeted module weight is less than 700g/m^2, in contrast to the weight of 12kg/m^2 for standard glass–backsheet modules, and to the weight of standard 180μm silicon cells, which already amounts to 450g/m^2.

The potential for reducing the thickness of the SHJ cell is based on some of the following key characteristics. The SHJ cell design is symmetrical with respect to the front and back sides (see Fig. 4), and all steps of the cell and module process operate at moderate temperatures below 250°C (compared with about 800°C for most other cell designs). This makes the cell much less sensitive to bowing/warping during cell metallization, which are bothersome phenomena for thin wafers [8]. Most importantly, surface recombination mechanisms generally become more important as wafer thickness is reduced. Here, the SHJ cell offers a competitive advantage over other cell designs, as the thin a-Si layer provides an outstanding surface passivation of the c-Si. Thinning the wafer leads to enhanced electron–hole pair generation as well as to reduced recombination in the c-Si bulk, effectively resulting in an increase in open-circuit voltage V_{oc}, as will be demonstrated in the following sections.

In the following discussion, the way in which the cell production process of the pilot line has been adapted to deal with wafers of thicknesses down to 40μm will be described. Standard wafers from three different commercial suppliers were used; for evaluation purposes, these wafers were chemically thinned. It will be demonstrated how the mechanical and electro-optical characteristics of SHJ cells appear better suited to cell thinning than other cell architectures. The key process steps for the module assembly of these thin cells will be discussed,

Figure 2. A solar-powered drone co-developed by CEA-INES, commercialized by SUNBIRDS in 2017. The PV module weighs 640g/m^2.

Figure 3. Artist's impression of STRATOBUS, the solar-powered high-altitude pseudo-satellite (HAPS) under development by Thales Alenia Space, with industrialization foreseen in 2020.

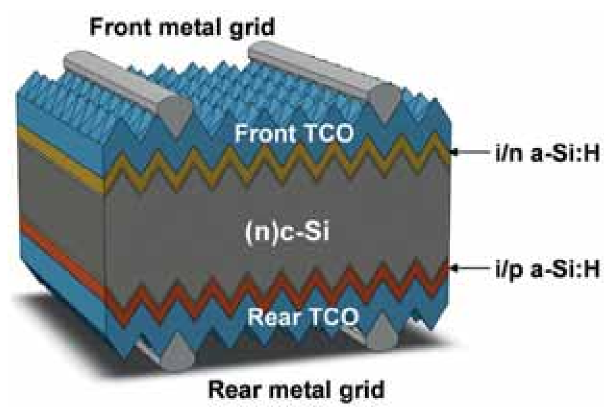


Figure 4. The symmetrical bifacial structure of the silicon heterojunction (SHJ) cell.

and some prototypes presented. Finally, it will be indicated how these characteristics contribute to an overall cost reduction when an optimal cell thickness of around 90µm is chosen.

Dealing with thin wafers in an SHJ cell production environment

The CEA-INES 'LabFab' pilot line has a standard capability of producing 130 to 160µm SHJ cells at a processing rate of 2,400 wafers/hour. The global breakage rate on the line is well below 1.5% for this standard thickness. The breakage rate as a function of wafer thickness has been monitored along the whole process chain (Fig. 5), revealing wafer automation (transfer/load/unload) during deposition and metallization to be the main cause of breakage [9]. Wafer flexion tests demonstrate that thin wafers are initially no more fragile than the reference wafers (Fig. 6). An initial integration with standard line settings has allowed an identification of the main issues for the production of thin wafers on the SHJ production line. The significant increase in breakage rate below 100µm appeared to be mostly related to the handling between deposition chambers and cassettes, the wafer stiction during wet processing, and the metallization screen printing.

Several line adjustments have been performed to reduce breakage rate and global cell defectivity. This iterative line optimization includes automation tuning

No breakages were observed during *I–V* testing or sorting, for either busbarless or 4BB cells on wafers >60µm. With these straightforward line adjustments, a reduction in the total line breakage rate was obtained during 2017 (Fig. 7). Although line throughput is currently affected for wafers <100µm (slower wafer robotics, fewer wafers per carrier), processing of wafers down to 80µm could be maintained at nominal throughput using simple modifications of cassettes or pickers. On the other hand, for thicknesses below 70µm the current production line and equipment would require major upgrades (such as single-side wet etch and cleaning tools, and new transfer systems) to maintain a high throughput and a low breakage rate. Cells have therefore been processed from 70 to 40µm wafers in a semi-automated/manual mode.

SHJ cell performance for thicknesses down to 40µm

Sets of wafers with different thicknesses down to 90µm were processed with no modification of the current production flow. As an illustration, Fig. 8 shows the effect of wafer thickness on the increase in the number of wafers obtained from an ingot, compared with the 160µm reference thickness: at a wafer thickness of 90µm there is a 40% increase in the number of wafers. With the cost of silicon material contributing 24% to the final module costs [3], a reduction of 10% in module cost for 90µm wafers is implied.

Results for one batch of 4BB bifacial cells are

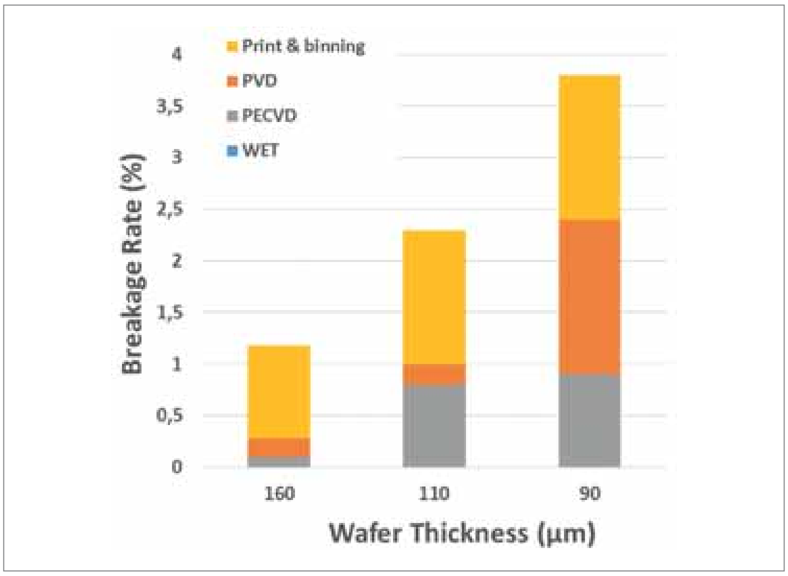


Figure 5. Impact of wafer thickness on breakage rate (without modification of the current production flow).

Figure 6. Flexibility of a 60µm SHJ bifacial cell (156mm × 156mm).

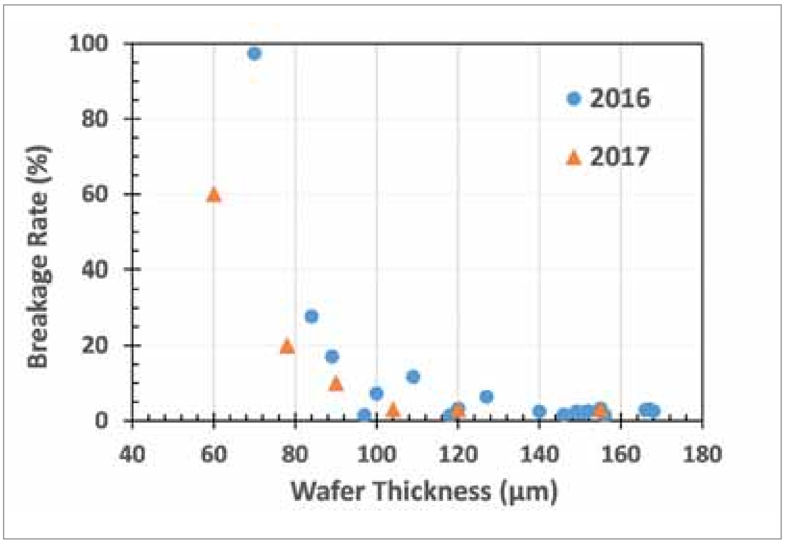


Figure 7. Improved breakage rate with specific line adjustments.

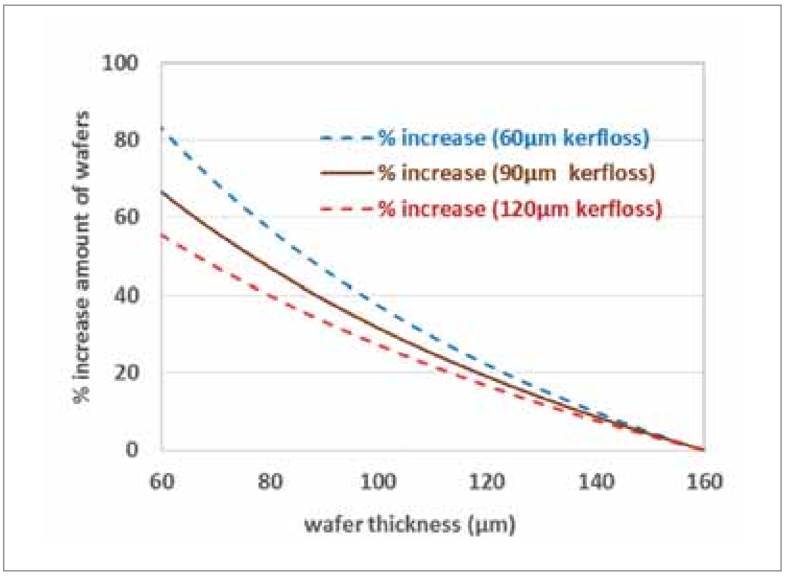


Figure 8. Increase in the number of wafers from an ingot as a function of wafer thickness, for three different values of kerf loss.

presented in Fig. 9. For cell thicknesses ranging between 160µm and 90µm, the final cell efficiency remains approximately the same. For all the batches, with a typical size of 30 to 200 wafers, it was noticed that record efficiencies in the 90–100µm range are very close to those for the reference wafers at 160µm, namely 22.1% versus 22.3%, proving the compatibility of such thin wafers with very high efficiencies. Average efficiency is more affected than record efficiency, which implies that process defectivity is slightly higher for the thinner wafers. This defectivity seems not to be due to handling-related wafer damage, but rather to wafer misalignment during PVD TCO deposition, causing edge isolation issues (i.e. shunts), as shown in Fig. 10.

The good overall efficiency performance of the thin cells is mostly due to the increase in V_{oc} for thinner cells, as shown in Fig. 11. This V_{oc} gain is in turn due to the outstanding surface passivation of the c-Si wafer by the a-Si layers. This wafer thinning, however, comes at the expense of a lower short-circuit current (I_{sc}), attributed to reduced photon absorption in the infrared (IR) region of the solar spectrum. In practice, the gain in V_{oc} does in fact almost offset the loss in for wafers below 100µm, which is represented in Fig. 12. The IR response of thin cells can be increased by specifically optimizing the electro-optical properties of the rear TCO layer in order to improve internal reflection and IR light trapping [10]. Other options for optimizing the cell current, such as the use of a back reflector at the cell rear side or a module with a white reflective backsheet, would be at the expense of bifaciality.

Figs. 10, 11 and 12 show the results for three different wafer providers, used to evaluate the impact of the incoming wafer quality/purity. Fig. 12 shows how these three wafer qualities have a similar J_{sc} loss behaviour of around 0.01mA/cm^2 per micron thickness. Interestingly, Fig. 11 reveals that the lower wafer quality of provider 3, with the lowest V_{oc} at 160µm thickness, is seen to improve the most with wafer thinning, achieving a V_{oc} at around 90µm thickness, which is similar to that obtained with the higher wafer quality counterparts. A transition to thinner wafers would therefore allow the use of lower-quality wafers, and thus offer an additional reduction in wafer cost.

Finally, the feasibility of integrating wafers of thicknesses down to 40µm was evaluated on the pilot line; the results are given in Fig. 13 and Table 1. Wafers below 80µm were processed on the line operated in a semi-automatic mode with manual loading, unloading and *I–V* testing to avoid breakage by the wafer-transfer conveyor used in the automatic mode. On the other hand, this manual handling introduces additional defectivity issues. The current pilot line encounters its limits at a wafer thickness of 40µm, at which point the breakage rate rapidly approaches 100%.

Module assembly of thin SHJ cells

The feasibility of a module assembly incorporating 90µm SHJ cells was evaluated on the module pilot line at CEA-INES. Full-size 60-cell modules and 4-cell mini-modules were fabricated; these included monofacial (glass–backsheet) and bifacial (glass–glass) module designs, using ribbons or SmartWire technology as cell interconnection. The module assembly was performed without any changes to the standard bill of materials (BOM) used for the assembly of 160µm cells. An industrial laminator was used for cell encapsulation, as well as an industrial tabber/stringer for the ribbon interconnection using conductive adhesives (ECA). The electroluminescence (EL) images in Fig. 14 reveal defect-free modules after lamination and subsequent thermal cycling in accordance with IEC 61215. The power loss of these modules after the 200 thermal cycles is shown in Fig. 15 and appears to be less than 3%, well below the 5% criterion of the IEC 61215 certification standard.

On the basis of these encouraging results for 4-cell mini-modules, full-size 60-cell modules were assembled, for both glass–backsheet (monofacial) and glass–glass (bifacial) architectures. The EL image and performance of an example of a 60-cell glass–backsheet module is shown in Fig. 16: the module features a cell-to-module (CTM) ratio of 99.1% and a very low massic module power (Wp per gram of silicon), achieving the symbolic target of 1Wp/g Si.

Another example, given in Fig. 17, shows a 24-cell module assembled with 115µm-thick SHJ cells and intended for semi-flexible applications on a stratospheric airship (or HAPS: high-altitude pseudo-satellite) for telecommunication, under development by Thales Alenia Space. The module efficiency is 18% and the power loss is less than 5% after 500 thermal cycles. The thin cells also contribute to the very low specific weight of only 600g/m^2, which allows a higher effective payload of the airship.

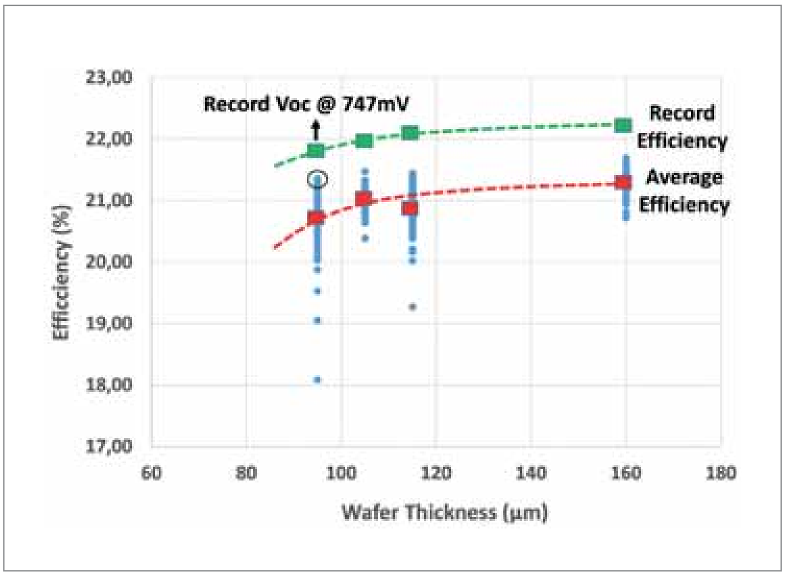


Figure 9. Impact of cell thickness on efficiency, for one batch of wafers based on 2016 process of reference.

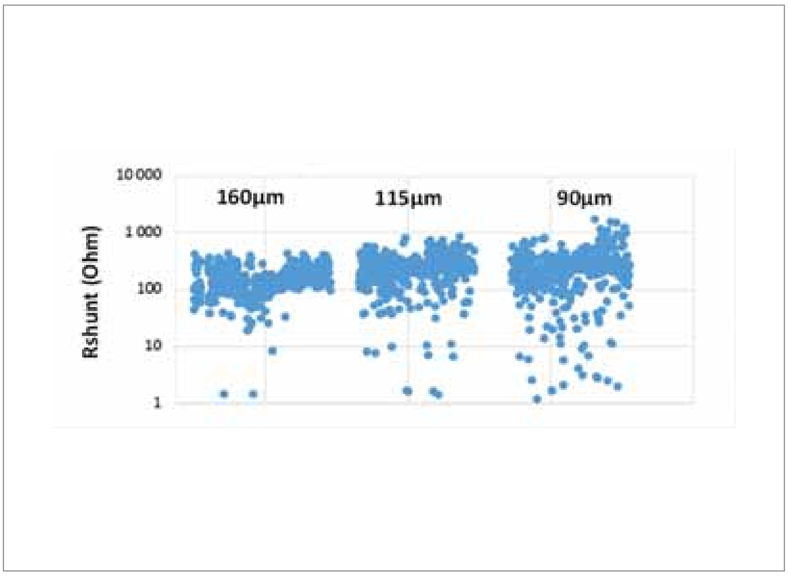


Figure 10. Dispersion in shunt resistance (R_{sh}) increases below 90µm wafer thickness.

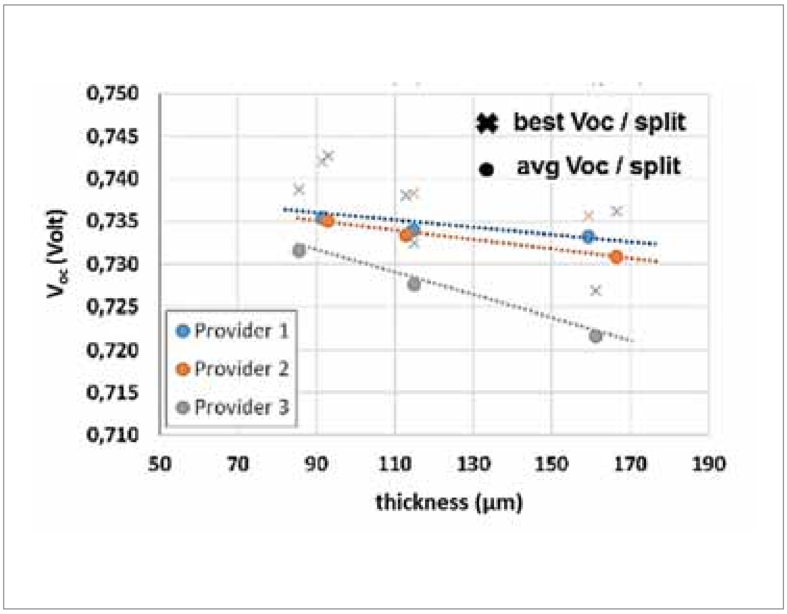


Figure 11. Impact of wafer thickness on V_{oc} for three wafer providers.

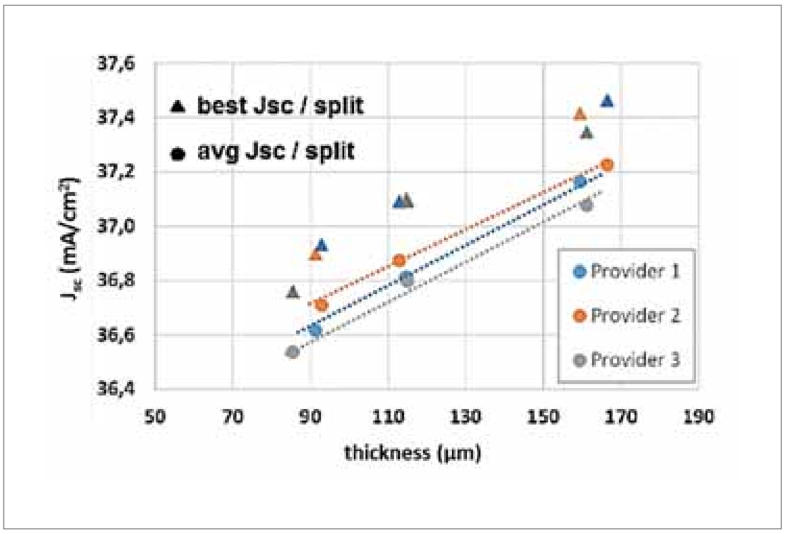


Figure 12. Impact of wafer thickness on short-circuit current density (J_{sc}) for three wafer providers.

"The optimal cell thickness was estimated between 90µm and 100µm."

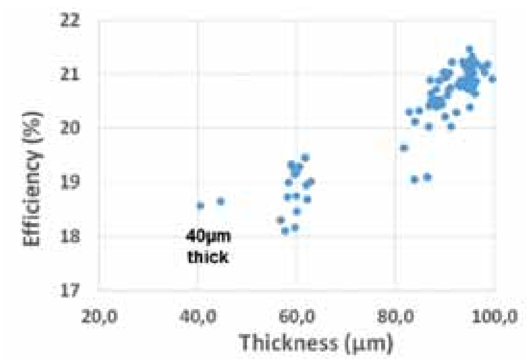
Cost considerations

The potential cost reduction thanks to the use of thinner wafers in an SHJ industrial production line (80MW nameplate capacity, 4BB cell configuration) was evaluated using an internal cost model similar to that given in Louwen et al. [11]. On the basis of the current pilot line results obtained, the optimal cell thickness was estimated between 90µm and 100µm (Fig. 18). For even thinner wafers, the main challenges for the future are the likely decrease in efficiency and increase in breakage rate, which might no longer be offset by the lower substrate costs.

Complementary to these cost considerations versus wafer thickness, it is interesting to note that analytical calculations of cell performance as a function of thickness also gave an optimal value of around 100µm, as illustrated in Fig. 19 [12]. These calculations were based on a similar approach to that reported in Richter et al. [13], but with additional defect-induced recombination mechanisms and using characteristic values for recombination and resistivity of the SHJ cells, as measured on the CEA-INES pilot line.

Conclusion and outlook

The industrial compatibility of thinner wafers for the manufacturing of heterojunction cells has been demonstrated down to a thickness of 80µm and even further, down to 40µm, on the semi-industrial LabFab pilot line at CEA-INES; at 90µm thickness, an average cell efficiency of 20.8% has been achieved, with a record efficiency of 22.1%. The optimal thickness range, with respect to performance, production cost and compatibility with the current pilot line layout, was identified



Thickness [μm]	J_{sc} [mA/cm^2]	V_{oc} [mV]	*FF* [%]	η [%]
40	34.7	730	73.3	18.6
45	35.1	732	72.7	18.7

Figure 13. SHJ cell efficiencies obtained for ultrathin wafers of thicknesses down to 40μm, fully processed on the CEA-INES pilot line based on a 2016 process of reference

Before lamination | After lamination | After 100 TCs (−40°C/+85°C) | After 200 TCs (−40°C/+85°C)

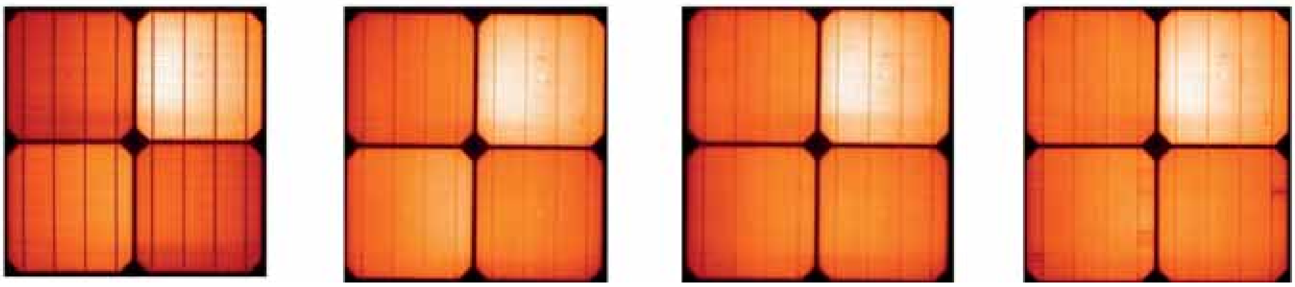


Figure 14. EL inspection of 4-cell glass–backsheet mini-modules with 110μm SHJ cells, after lamination and IEC thermal cycling (100 and 200 thermal cycles).

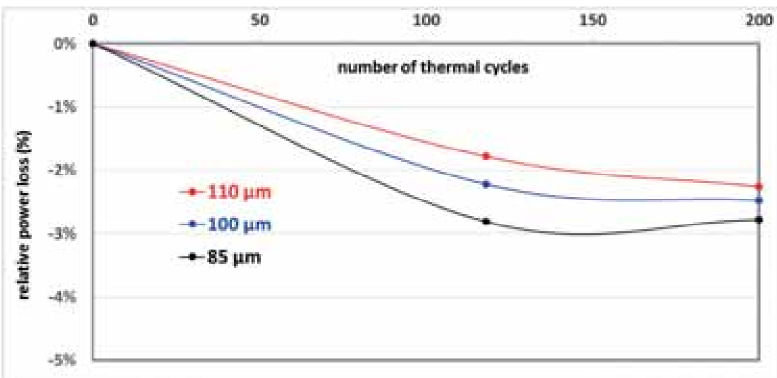
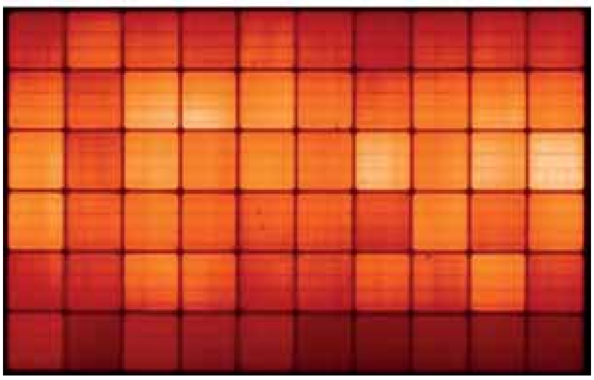


Figure 15. Relative power loss during 200 thermal cycles of SHJ glass–backsheet modules with cell thicknesses of 110, 100 and 85μm.



Thickness [μm]	P_{mpp} [W]	I_{sc} [A]	V_{oc} [V]	*FF* [%]
Total cells	315.6	8.8	44.3	80.1
Module	312.7	9.1	44.2	77.8
CTM	99.1%	103.2%	99.8%	97.1%

Figure 16. EL image and performance of a 60-cell glass–backsheet module with 93μm cells, yielding a massic module power of 0.98Wp per gram of Si.

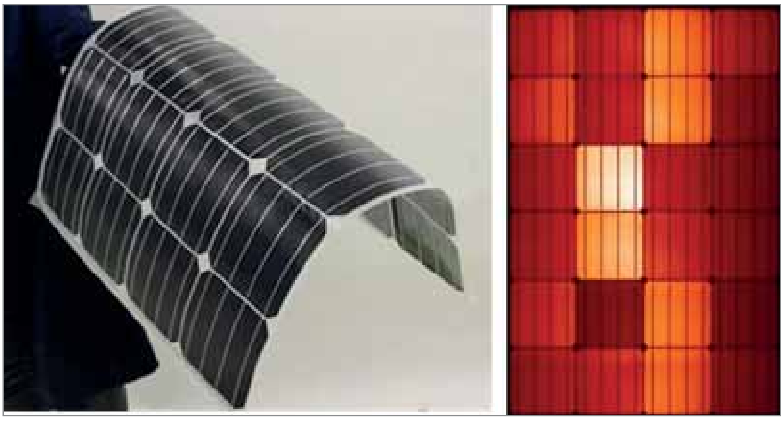


Figure 17. A 24-cell semi-flexible module incorporating 115μm SHJ cells, for the Thales Alenia Space HAPS application.

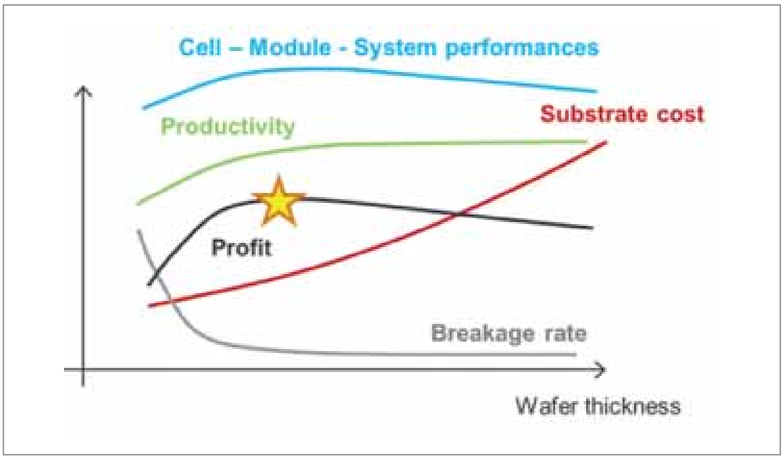


Figure 18. Cost, productivity and performance trends in reducing wafer thickness. The optimum thickness is estimated to be in the 90–100μm range for maximizing the final product earnings before interest and taxes (EBIT).

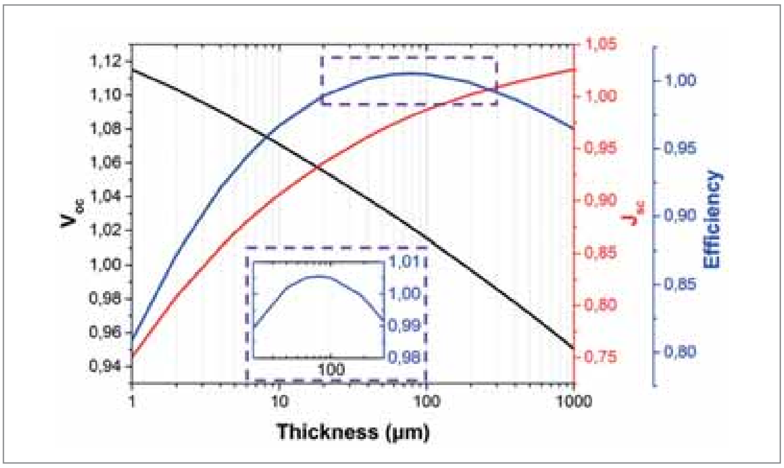


Figure 19. Simulated performance (V_{oc} in black, J_{sc} in red, efficiency in blue) of SHJ solar cells as a function of thickness. Values are given relative to those for 180μm thickness. The inset shows the simulated SHJ cell efficiency in the range 20 to 300μm. [13].

to be around 95μm. Modules incorporating these thin 95μm cells were successfully assembled, which allows a leveraging of the reduced mass and increased flexibility of these cells, targeting lightweight or semi-flexible module applications. Module performance measurements and reliability testing yielded CTM ratios beyond 99%, a massic output of 1Wp per gram of silicon, and full compliance with IEC certification standards during thermal cycling tests. It was found that a stable high efficiency for thin cells sets higher standards in process control of the production line (defectivity, monitoring, etc.).

Ultrathin heterojunction cells offer industrial cost reduction, high performance and innovative module applications, ultimately demonstrating that 'less is more'.

Acknowledgements

The results reported here were obtained through the collaborative effort of all members of the heterojunction pilot line and PV module platform at CEA-INES. Part of this work was performed within the framework of the European CHEETAH project (**C**ost reduction through material optimization and **H**igher **E**n**E**rgy outpu**T** of sol**A**r p**H**otovoltaic modules) through FP7 EC grant 609788; our thanks to all partners within the CHEETAH project. Meyer Burger, 3SUN/ENEL and Thales Alenia Space are gratefully acknowledged for joint development efforts, technical discussions and support.

References

[1] Taguchi, M. et al. 2014, "24.7% record efficiency HIT solar cell on thin silicon wafers", *IEEE J. Photovolt.*, Vol. 4, pp. 96–99.

[2] Wolf, S.D. et al. 2012, "High-efficiency silicon heterojunction solar cells: A review", *Green*, Vol. 2, pp. 7–24.

[3] ITRPV 2017, "International technology roadmap for photovoltaic (ITRPV): 2016 results", 8th edn (Mar.) [http://www.itrpv.net/Reports/Downloads/].

[4] Yoshikawa, K. et al. 2017, "Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%", *Nature Energy*, Vol. 2, p. 17032.

[5] Danel, A. et al. 2015, "Recent progress on the CEA-INES heterojunction solar cell pilot line", *Proc. 31st EU PVSEC*, Hamburg, Germany.

[6] Danel, A. et al. 2017, "A versatile pilot line to support heterojunction solar cell industrial development", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.

[7] Colin, H. et al. 2017, "Energy Yield Field Data of Heterojunction-Smartwire PV Modules", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.

[8] Yoon, P. et al. 2014, "Numerical simulation of bowing phenomenon in ultra-thin crystalline silicon solar cells", *Solar Energy*, Vol. 105, pp. 705–714.

[9] Harrison, S. et al. 2016, "How to deal with thin wafers in a heterojunction solar cell industrial pilot line: First analysis of the integration of cells down to 70 μm in production mode", *Proc. 32nd EU PVSEC*, Munich, Germany.

[10] Holman, Z. et al. 2013, "Infrared light management in high-efficiency silicon heterojunction and rear-passivated solar cells", *J. Appl. Phys.*, Vol. 113.

[11] Louwen, A. et al. 2016, "A cost roadmap for silicon heterojunction solar cells", *Sol. Energy Mater. Sol. Cells,* Vol. 147, pp. 295–314.

[12] Gerenton, F. et al. [forthcoming].

[13] Richter, A. et al. 2013, "Reassessment of the limiting efficiency for crystalline silicon solar cells", *IEEE J. Photovolt.*, Vol. 3, pp. 1184–1191.

About the Authors

Eric Gerritsen studied physics at Twente University (Netherlands) before joining Philips Research Labs (Eindhoven, NL) in 1985 to work on ion implantation, for which he received his Ph.D. from Groningen University in 1990. He then held various positions at Philips (Lighting, Semiconductors) in Germany, The Netherlands and France, before joining CEA-INES in 2008 to work on PV module technology and applications.

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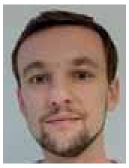

Julien Gaume received his Ph.D. in 2011 in physical chemistry from Clermont-Ferrand University (France), for his investigations on the photochemical behaviour of polymer/clay nanocomposites used as organic solar cell encapsulants. He joined CEA-INES in 2012 to work on the development of lightweight and flexible c-Si photovoltaic modules.

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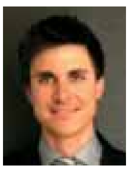
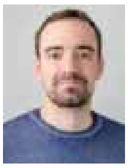


Jordi Veirman studied semiconductor physics at the National Institute for Applied Sciences (INSA) in Lyon, France, where he graduated with an engineering degree and a master's in microelectronics in 2008, followed by a Ph.D. in 2011. Since then, his main focus at CEA-INES has been the interaction between silicon properties and solar cell performance.



Felix Gerenton graduated from the Grenoble Institute of Technology in 2013, and received his Ph.D. from the University of Lyon in 2016, working on thin-film crystalline silicon solar cells. He is currently a postdoctoral researcher at CEA-INES, where he is involved in the optimization of silicon heterojunction solar cells of reduced thickness.

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Bifacial solar products light new pathway to future PV

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Abstract

Relatively few experimental and academic studies about bifacial p-type PERC cells have been published to date. This paper looks at the experimental findings from JinkoSolar's large area, industry-grade bifacial monocrystalline silicon PERC (biPERC) cells. These cells are manufactured using mass production tools and in a continuous running condition. The average batch efficiency of these biPERC cells is over 21.8%. Detailed analysis of the electrical parameters and cross sectional microscopic images of these cells will be shown.

As the solar photovoltaic market and technology have improved over the past years, there has been an impressive drop in global PV electricity generation cost. One of the major contributors is the continuous increase in solar cell and module conversion efficiencies. For example, at JinkoSolar, average efficiency for p-type PERC solar cells has reach over 21.8%. At the same time, concerns have also been raised that crystalline silicon PV products efficiencies are approaching a ceiling. As a result, the PV market is eagerly looking for new frontier innovations that could help maintain the current development trend. Bifacial solar cell technology and bifacial modules, which collect light energy from both the front and rear side of the panel, can be this new frontier. Bifacial cell and module technologies use most of the available panel surface area and effectively increase overall power generation efficiency.

JinkoSolar as one of the world's largest solar module manufacturer has been at the forefront on the development of high-efficiency bifacial technologies. Existing data has shown that the output power of a bifacial PV module is significantly higher than standard PV modules. Bifacial module standard test condition power can reach over 320W in a 60-cell module form factor and reach over 380W in a 72-cell module form factor. When applied in an environment with a white painted background, the effective efficiency of bifacial modules can reach as high as 27.3%. When paired with an appropriate tracking system, the power generation capacity of bifacial modules can be over 40% greater than that of conventional modules. In addition, as our bifacial modules utilizing JinkoSolar's Eagle Dual PERC production infrastructure, JinkoSolar's p-type bifacial products solutions greatly improve the module performance while keeping the marginal price increases at a competitive level. Our p-type bifacial PERC solar cell can reach a bifaciality of over 80% in lab environments and over 70% when mass produced.

Bifacial solar cell performance

P-type passivated emitter rear contact (PERC) is a mainstream high-efficiency solar cell technology, where a rear-side passivating dielectric layer is used to reduce the surface recombination power losses and to improve the internal reflection [1]. PERC technology has made huge strides in the market, and is an area where JinkoSolar has also invested in R&D efforts. JinkoSolar's p-type PERC bifacial cell is based on our existing PERC structure. Localized rear contacts are formed through laser ablation on the passivation layer and subsequent screen-printing process. Instead of full area Al contacts, Al fingers and busbars can be screen printed on the rear surface so that reflected light can also be absorbed for higher current output. PERC solar cells have the potential to achieve an average mass production efficiency of >22%. Additionally, bifacial p-type PERC solar cells require less metal on the rear side and different processing recipes, enabling the potential for further future cost reduction.

Surprisingly, despite these advantages, few experimental and academic studies about bifacial p-type PERC cells have been published to date [2]. In this paper, we provide a glance at the experimental findings and understandings for JinkoSolar's large area, industry-grade bifacial monocrystalline silicon PERC (biPERC) cells. These cells are manufactured using mass production tools and in a continuous running condition. The front-side structure of the test samples uses a homogenous junction design rather than the selective emitter technique. The average batch efficiency of these biPERC cells is over 21.8%. Detailed analysis of the electrical parameters and cross sectional microscopic images of these cells will be shown.

Boron-doped Czochralski-grown Si wafers were used in this study. The wafers used have a dimension of 156x156 mm^2, resistivity of 1.5-1.8 Ohm-cm, and thickness of ~200µm. Conventional mass production processes were used as follows: the wafers are first textured with alkaline and cleaned with acid/DI water. Emitter formation was than carried out through $POCl_3$ diffusion. Next, phosphosilicate glass (PSG) and rear phosphorus diffused layers were etched away by a HF/HNO_3 solution. Fourthly, the wafers were coated with surface passivation. Fifthly, anti-reflection layers were deposited by plasma enhanced chemical vapour deposition (PECVD) and atomic layer deposition (ALD). Then, rear surface passivation layers were etched open by a nanosecond laser. Afterwards, front surfaces were screen printed with Ag fingers and busbars. Lastly, Al fingers and busbars were screen printed on rear surface for bifaciality.

A schematic of the bifacial PERC structure is shown in Figure 1.

Figure 2 shows the cross section SEM images at the local rear Al contacts for both the biPERC and PERC cells. The rear contacts consist of (i) screen printed Al (ii) alloyed Al-Si eutectic and (iii) the Al doped p+ layer (Al-BSF). The mechanism of the rear contact formation in a typical PERC cell is described as follows [3]: At the start of the firing process, high temperature ramping causes the printed Al paste to melt. This melted Al also dissolves Si on the wafer surface. At peak firing temperature, a high solubility causes Si to saturate in the melted Al paste. As the temperature decreases, a reduction in the Si solubility causes a large amount of Si to be rejected from the melt until an Al-Si eutectic concentration of ~12.6% wt is reached. This rejected Si will recrystallize at the wafer/melt interface and will be incorporated with a small amount of Al from the melt. This Al is usually in the range of 10^{18} to 10^{19} cm^{-3} and will act as a p-type dopant, forming the so-called high-low p+/p junction known as the back surface field (BSF) [3]. The Al-BSF acts as minority carrier reflectors, which prevent the loss of photo-generated carriers at the rear surface [4-9].

Interestingly, from the SEM images in Figure 2, biPERC cells exhibit a much thinner Al-BSF layer of ~1µm than the PERC cells of ~4µm. The thinner Al-BSF layer may explain the drop in Voc as observed in the biPERC cells. A thinner Al-BSF layer can degrade its effectiveness in passivating and improve the recombination velocity of the rear surface [10]. As observed under SEM, the thinner Al-BSF is believed to be a result of the misalignment between the screen-printed rear Al fingers and the laser opening. This misalignment limits the concentration of available Al dopants during firing, resulting in the thinner Al-BSF. The lack of Al atoms participating in the rear contacts formation can also been seen from the thinner Al-Si eutectic in rear contacts of biPERC cells compared with that of the baseline PERC cells, as illustrated in Figure 3. Further experiments have shown that through improving the alignment and quality of the printing process, higher efficiencies can be achieved.

As a summary, we report industrial

Table 1. Cell parameters of bifacial PERC used in this study.

Parameters	Batch average bifacial PERC (front)	Batch average bifacial PERC (rear)
Efficiency	21.81%	16.58%
FF	80.47%	80.53%
Voc	675mV	666mV
Isc	9.80A	7.55A

Figure 1. Schematic of a bifacial PERC cell used in this study.

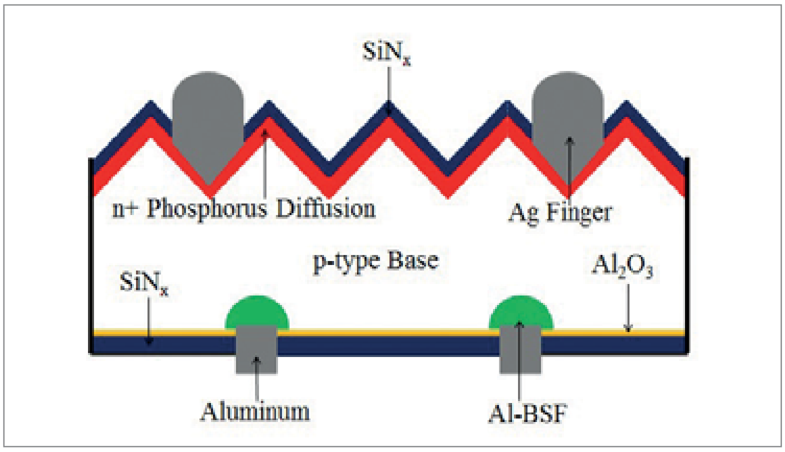
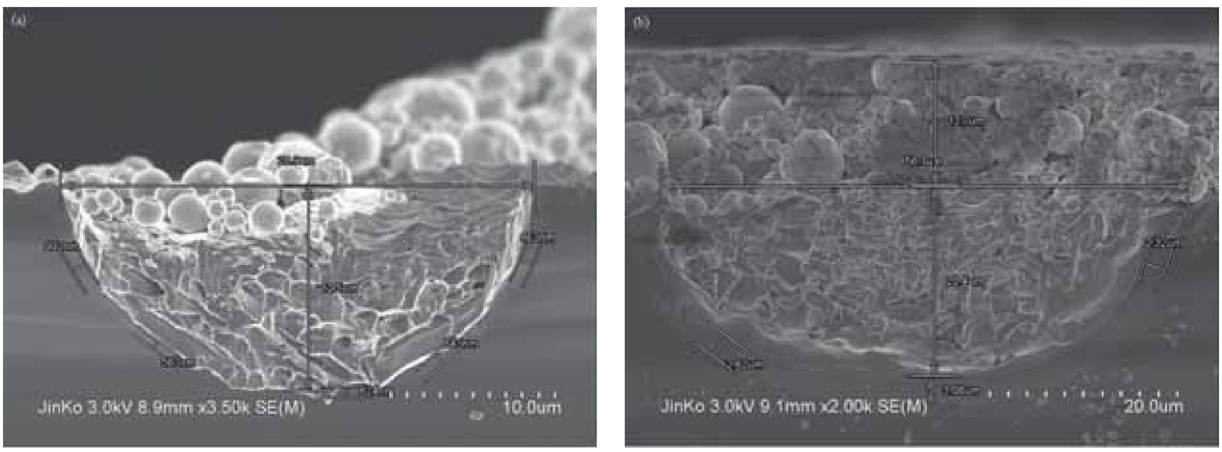


Figure 2. SEM images at the local rear Al contacts for the (a) bifacial PERC cells (b) baseline mono-facial PERC cells.



monocrystalline p-type bifacial PERC cells with an average batch efficiency of >21.8%. Eighty percent of Al paste can be saved from the rear contacts of the PERC cells. Further developments have been applied into the production with improvement in: printing alignment, rear contact design and Al paste contact formation. The average front side-efficiency of biPERC cells can reach more than 21.8% and is expected to reach over 22% when techniques such as selective emitter and rear surface texturing are applied. Additionally, with a bifaciality of 76%, it is expected to have a large room for either improving the front side efficiency or enhance the bifaciality.

Bifacial solar module performance

Depending on the albedo of the installation environment, JinkoSolar's bifacial products can reach an effective power output of 360W in a 60-cell form module. In addition, the Eagle Dual module, utilizing double-glass encapsulation, provides a better reliability with 30-year linear power degradation guarantee. Thus the significant gain in lifetime power generation makes it a tremendously attractive product for the PV market. Highlights of the bifacial products include:

Significant rear side power contribution

The bifaciality factor φ, which is the ratio of the maximum rear surface power and the maximum front surface power under standard test conditions, is a good indicator of the overall power generation performance. Generally, the bifacial p-type PERC module has an average bifaciality value in the range of 65-70%. JinkoSolar's bifacial PERC product applies fine finger technique to reduce the optical shading and the internal resistance. Combining the fine finger technique with a low resistivity welding ribbon, the overall module electrical loss is significantly reduced, allowing for a higher generation capacity. Bifaciality of 80% has been achieved in lab environments and an average bifaciality value of >70% has been measured for the JinkoSolar's bifacial modules in mass production.

Low temperature coefficient and outdoor operating temperature

Two-and-a-half millimeter ultra-thin patterned encapsulation glass is applied on both sides of the bifacial cells to create the bifacial module. With thinner glass, the heat dissipates to the surrounding air more easily compared to conventional modules. In addition, the pattern on the inner side of the glass is designed to scatter incident lights, effectively increasing light trapping and reducing solar-thermal conversion. Based on field test results, the Eagle Dual Module has a temperature coefficient of -0.38%/°c, lower than standard unilateral module of -0.41%/°c. The practical

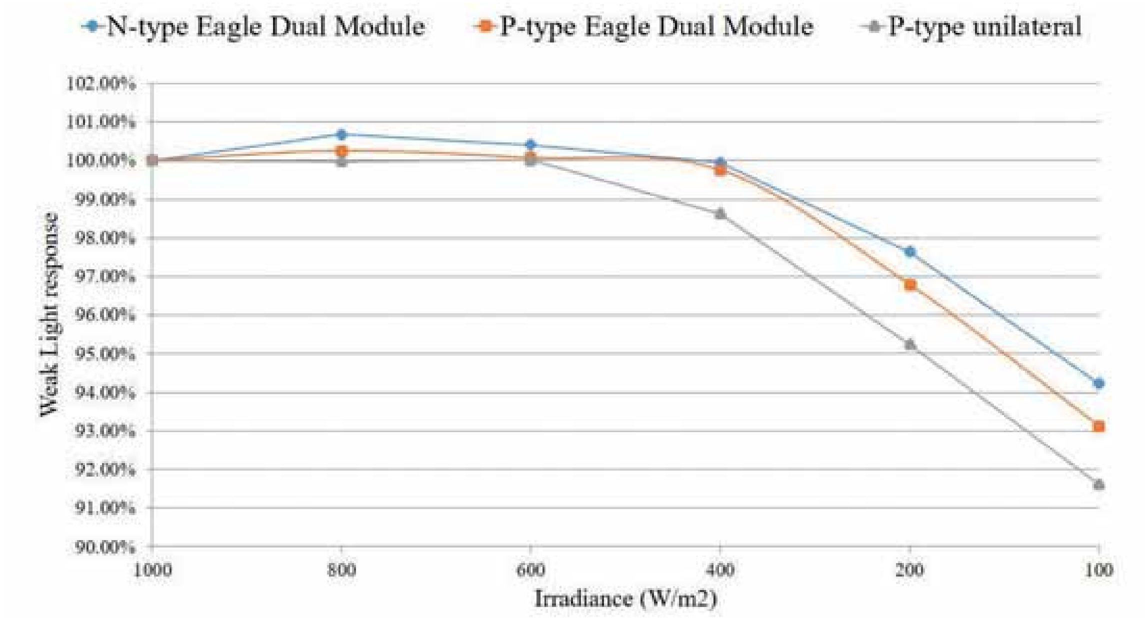


Figure 3. Weak-light response for different modules.

operating temperature is measured to be 1-3°c lower than standard modules. These results indicate that bifacial modules perform better at limiting thermal related losses, considering all other circumstances are the same.

Module type		T_{MAX}/°c	T_{MIN}/°c	T_{Ave}/ °c
Standard unilateral P-PERC	Rear	66.30	63.70	65.60
	Front	61.60	49.00	58.70
The Eagle Dual Module	Rear	67.90	50.30	62.20
	Front	59.60	52.60	57.80

Table 2. Operational temperature for different module types under same conditions.

Excellent weak light response

By adopting a passivation process and antireflection coating on both sides, the p-type biPERC modules are able to capture even more photons. Meanwhile, the thin 2.5mm glass provides better optical transmittance and lower refraction loss. Bifacial products have shown good performance in weak light environments. In-field test data collected at an irradiance level down to 100W-200W/m^2 is shown in Fig.4; significant advantages of bifacial products have been observed over monofacial panels.

Degradation Test	DH3000	TC600	TC150-HF30
P-type Eagle module	3.85%	3.43%	3.62%
Degradation Test	DH1000	TC200	TC50-HF10
P-type standard unilateral module	3.92%	3.89%	3.73%

Table 3. Degradation results for different modules.

Improved module reliability

The double-glass structure utilized in our bifacial products protects the panel from infiltration of oxygen and ambient moisture. This protection enables higher reliability, increasing the outdoor operational lifecycle to 30 years. Frameless design is adopted to eliminate potential-induced degradation of the panel, while durable encapsulation materials are used with high tenacity to protect panels from mechanical stress. Table 3 lists typical degradation test results for PERC bifacial modules. As shown in Table 3, compared to standard module, bifacial modules can endure test conditions three times more strict than standard tests. The dynamic load test for JinkoSolar bifacial PERC modules has shown outstanding performance results with minimal cell cracks. Damp-heat (DH) 3000 test has also shown an excellent result with less than a 5% degradation rate. As a summary, biPERC products have significant advantages of module quality and reliability.

Excellent outdoor generation capacity

All the above mentioned characteristics, such as high bifaciality value, low temperature coefficient, low operational temperature and excellent weak light response, comprehensively contribute to the outdoor performance of JinkoSolar p-type biPERC modules. Field tests on ground surfaces with different albedos show that the Eagle Dual Module

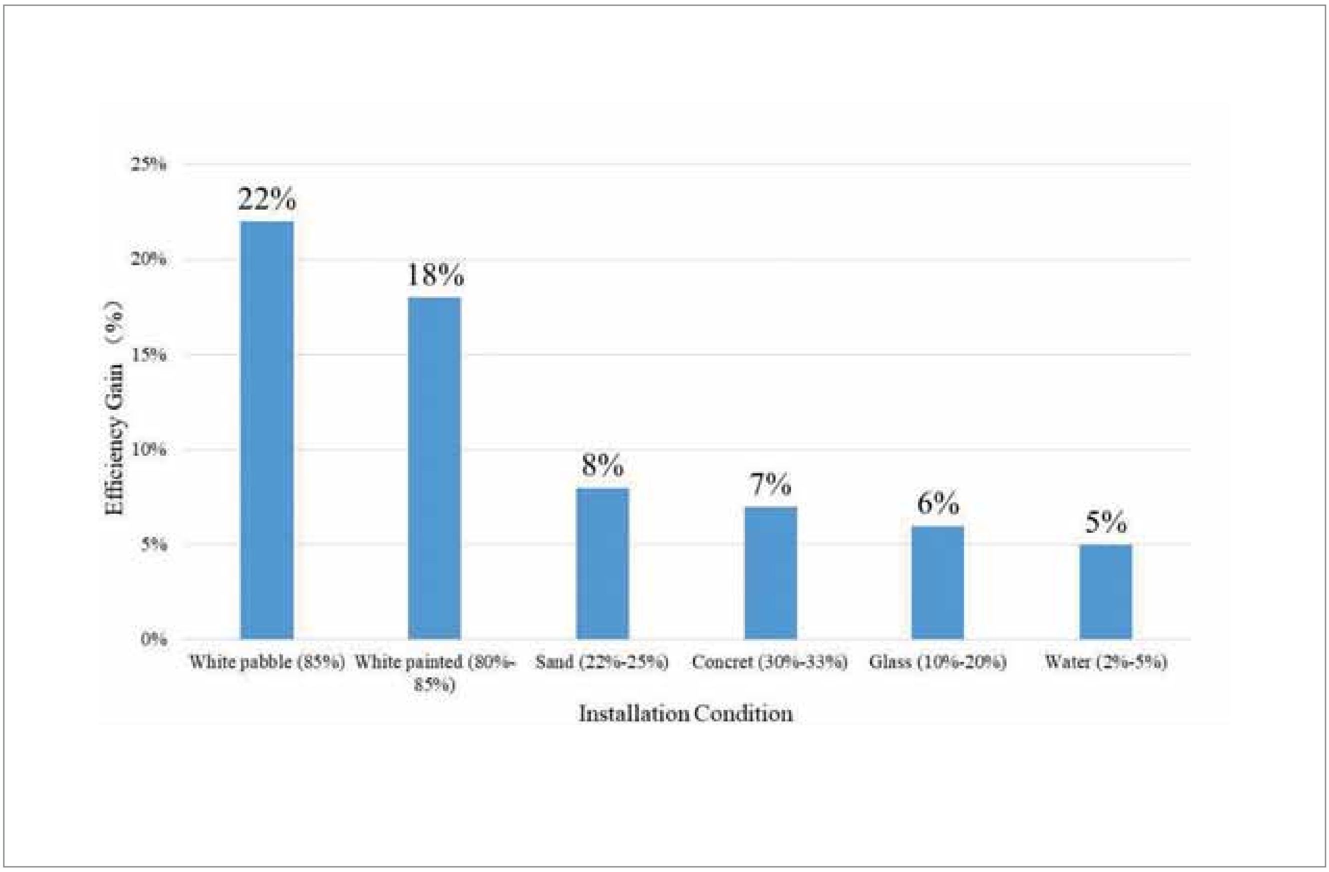


Figure 4. Efficiency gain of p-type Eagle (bifaciality=0.70) in different installation places

enables a 5-25% increase in output when compared to that of a standard unilateral module in a fixed mounting system. In a smart tracking PV system, the output increase is expected to be >40%.

Conclusion

With an excellent panel power generation performance, bifacial technology opens up a new frontier for PV technology. The enhanced PV module efficiency will lead to reductions in levelized cost of electricity. JinkoSolar's bifacial products, both p-type and n-type series, show that cell and module technology upgrades can be achieved at a competitive cost. Increasing market interest for bifacial products, especially from agricultural/fishery solar farms and PV projects in regions with high snowfall or long daylight hours, is writing this new chapter in PV technology.

References

[1] B. AW, A. M. A Wang, J. Zhao and M. Green, 1989, "22.8% efficient silicon solar cell", Applied Physics Letters, vol. 55, p. 1363–1365.
[2] T. Dullweber, 2015, "Prog. Photovolt: Res. Appl.", EU PVSEC PAPER.
[3] T. Lauermann, B. Fröhlich, G. Hahn and B. Terheiden, 2013, "Diffusion-based model of local Al back surface field formation for industrial passivated emitter and rear cell solar cells", Progress in Photovoltaics: Research and Applications, vol. 23, pp. 10-18.
[4] J. D. Alamo, J. Eguren and A. Luque, 1981, "Solid-State Electron," vol. 24, p. 415.
[5] C. Khadilkar, S. Kim, A. Shaikh, S. Sridharan and T. Pham, 2005, "Tech. Digest of International PVSEC- 15".
[6] A. Kaminski, B. Vandelle, A. Fave, J. Boyeaux, L. Q. Nam, R. Monna, D. Sarti and A. Laugier, Solar Energy Materials & Solar Cells, vol. 72, 2002, p. 373.
[7] S. Narasimha, A. Rohatgi and A. W. Weeber, IEEE Trans. on Electron Devices, vol. 46, 1999, p. 1363.
[8] F. Huster and G. Schubert, in 20th European Photovoltaic Solar Energy Conference and Exhibition , Barcelona, 2005.
[9] C. Lin, S. Y. Tsai, S. P. Hsu and M. H. Hsieh, "Solar Energy Materials & Solar Cells," vol. 92, 2008, p. 986.
[10] B. Sopori, V. Mehta, P. Rupnowski, H. Moutinho and Aziz Shaikh, "Studies on Backside Al-Contact Formation in Si Solar Cells: Fundamental Mechanisms," in MRS Online Proceeding Library Archive 1123, 2011.

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News

Solar Frontier breaks thin-film efficiency record with lab-scale cell

Credit: Solar Frontier

The record was verified by the National Institute of Advanced Industrial Science and Technology (AIST).

PV manufacturer Solar Frontier has set a new thin-film cell efficiency record of 22.9%.

The result, on a $1cm^2$ cell, was achieved in partnership with Japan's National Research and Development Agency's New Energy and Industrial Technology Development Organization (NEDO).

The record was verified by the National Institute of Advanced Industrial Science and Technology (AIST) and is 0.3% higher than the previous record set by Germany's ZSW.

The cell uses Solar Frontier's Copper, Indium and Selenium (CIS) architecture with enhancements via "absorber engineering and enhanced surface treatment of the absorber layer".

The company claimed it was further evidence of the ongoing potential of CIS technology improvements.

The company has also sold its 66MW Midway I project in California. The buyer is Spanish developer and operator X-ELIO, which is owned by giant private equity firm KKR.

"We have partnered with Solar Frontier's expert team since May, and worked hard in creating an extremely competitive capital structure," said Jorge Barredo, CEO, X-ELIO. "We are now ready to deploy capital at any stage of the project lifecycle, from development to operation and we rely on a growing team of highly experienced people to develop our pipeline, forge partnerships with other development companies, and become a major player also in the United States."

FIRST SOLAR

First Solar mulls US manufacturing expansion in wake of Trump tax boost

First Solar could establish new US-based manufacturing capacity after citing President Donald Trump's corporate tax reforms as the key enabler.

The company is establishing production of its large-format Series 6 module across five facilities in Ohio, Vietnam and Malaysia.

CEO Mark Widmar, while adding plenty of caveats, acknowledged that the option was back on the table – noting: "As we look at the tax reform and what's happening now with the US corporate tax rate, when you look at immediate expensing, there's optionality potentially or there's scenarios I guess maybe is a better way to say that we would look to in the US to add additional manufacturing as part of our overall scenario analysis across the global production platform.

"Looking at the US has a different lens than it would have otherwise before tax reform," said Widmar adding that any additional capacity would be in the order of hundreds if MWs rather than the GW scale.

Corporate tax in the US was cut from 35% to 21% by the President.

First Solar is sold out till 2020 and more than three-quarters of the 6.8GW potential bookings flagged in its results are in North America where it has been buoyed by the Section 201 tariffs on overseas crystalline silicon-based PV competitors.

First Solar ramping Series 6 capex as R&D spending declines

The major manufacturing transition by First Solar to its large-area Series 6 CdTe thin-film module format is well underway and has increased its tempo slightly, not least due to updated spending plans for the second time in a few months.

The company had entered 2017 with capex guided to be in the range of US$525 million to US$625 million, but ended the year with capex of US$514.4 million. There were a lot of moving parts in relation to the Series 6 early phase transition, but the main reason behind the lower than guided spending was a holding back on planned equipment spending as the company retained more Series 4 production in Malaysia to meet increased demand on the back of the pending US Section 201 trade case outcome.

However, with capex topping US$300 million in the first nine months of 2017, running at around US$100 million per quarter, spending significantly increased in the fourth quarter.

Capex in the fourth quarter of 2017 reached almost US$200 million (US$199.3 million), as building the second fab in Vietnam (Vietnam S6 Factory 2) started (with a name plate capacity of 1,200MW), coupled the completion of facilities at Vietnam S6 Factory 1.

First Solar also completed the plant fit-up at Malaysia S6 Factory 2, as well as around 50% of 'front-end' equipment installation, accounting for around 25% of total tool installs required for the 1,200MW nameplate capacity of the facility.

PEROVSKITE

Skanska to test perovskite solar modules from start-up Saule Technologies

Multinational construction firm Skanska AB is to test semi-transparent perovskite solar modules from start-up Saule Technologies on commercial office buildings with the first applications planned to be installed in Poland in 2018.

Skanska has yet to specify the module form factor for the modules but it could be in the 1 metre squared. Saule uses an ink-jet printing technique for fabricating free-form perovskite solar modules.

The company also noted that it has secured a number of research grants valued at over €20 million and was working on a large-scale, prototype production line.

Oxford PV is in the "final stage" of commercializing its technology.

Credit: Oxford PV

Oxford PV collaborates with new HZB lab on perovskite optimisation for HJ cells

Perovskite solar cell developer Oxford Photovoltaics said it was working with scientists at the new Helmholtz-Zentrum Berlin (HZB) innovation lab to further the optimisation of its perovskite cell materials for silicon heterojunction solar cell technology.

Oxford PV, one of the leading pioneers in perovskite cell material development had previously established a lab-to-fab facility in Brandenburg an der Havel, Germany, to speed the commercialisation of its perovskite technology as a tandem layer to conventional silicon solar cells.

The new partnership with HZB intends to further that effort with greater leverage of HZB's silicon cell material knowledge and specifically heterojunction cells.

Chris Case, chief technology officer, at Oxford PV, said: "Oxford PV is now in the final stage of commercialising its perovskite photovoltaic solution, which has the potential to enable efficiency gains that will transform the economics of silicon photovoltaic technology globally."

The start-up is expected to commercialise its perovskite materials under a licensing model.

New perovskite ageing measurements offered for standardization by EPFL

The École polytechnique fédérale de Lausanne (EPFL) is proposing the standardization of aging measurements of perovskite solar cells after developing a range of new methods that are claimed to best represent some of the unique characteristics of perovskite materials.

New perovskite ageing measurements were developed by Prof. Michael Grätzel and Prof. Anders Hagfeldt at EPFL in Switzerland and recently published in the journal, Nature Energy.

Rapid degradation of perovskite solar cells has been a major barrier to commercialization, despite record conversion efficiencies and the potential for low cost manufacturing.

Researchers at EPFL acknowledged that degradation and stability issues have hampered developments, not least in the ability to measure aging when standardized measurements and testing have not been established.

The researchers investigated the effects of different environmental factors on the ageing of perovskite solar cells, looking at the impact of illumination (sunlight-level light), temperature, atmospheric, electrical load, and testing a systematic series of combinations of these.

European Investment Bank awards €15 million to commercialise Oxford PV's perovskite technology

The German subsidiary of UK firm Oxford Photovoltaics (PV) has been awarded €15 million (~US$18 million) by the European Investment bank (EIB) to support the commercialisation of the company's perovskite photovoltaic technology.

Oxford Photovoltaics Germany was awarded the financing last month to further develop its perovskite on silicon tandem solar cell technology.

Frank P. Averdung, chief executive officer at Oxford PV, said: "The funding will allow Oxford PV to continue to invest in its demonstration line infrastructure, in Brandenburg, Germany, enabling the company to continue the rapid transfer of its perovskite on silicon tandem solar cell technology from the lab to an industrial scale process in collaboration with our joint development partner – a large scale manufacturer of solar cells and modules."

The EIB funding is the first financing in Germany under the InnovFin - EU Finance for Innovators' Energy Demonstrator Projects, which seeks to facilitate and accelerate access to finance for innovative businesses and other innovative entities across Europe.

The finance initiative, which has a particular focus on R&D funding, also has the backing of the European Union under the Horizon 2020 programme.

Volume production of customized organic photovoltaics

Sri Vishnu Subramaniam, Grzegorz Andrzej Potoczny and Tobias Sauermann, OPVIUS GmbH, Kitzingen, Germany

Abstract

To realize power generation everywhere, customers and designers are eager for PV solutions offering total design freedom for seamless integration into everyday life. This trend becomes even more important if the 'mega city' development is taken into account: more and more people will live in city environments in the future while classical PV technologies do not offer proper solutions for this context. Accordingly, the next wave of renewable energies will not be standalone products like today but will rather be a kind of integrated functionality. Organic photovoltaics (OPVs) already broaden applications as they are manufactured on polymer foil where the final product is thin, flexible and semi-transparent. However, OPV modules are commonly printed/coated in form of stripes that limits their design layout and integration. Therefore, the current state of the OPV manufacturing process needs to be modified to allow fabrication of free patterns and fully customized devices. In this contribution we present the approach pioneered by OPVIUS in the evolution of OPV towards customization in large volumes to meet customer expectations. Starting with modifications on the slot-die, we also describe advances in patterning and printing technologies that allow realization of free shapes on devices. For the first time we also present a three-dimensional (3D) OPV module produced using mass production techniques.

Introduction

OPV is a renowned solar technology for its thin and semi-transparent properties. Organic polymer materials allow easy formulation and empower OPV to be realized in roll-to-roll (R2R) formats by printing or coating. This gives OPV several advantages over conventional photovoltaic technologies in terms of upscaling toward serial and high-volume production. Moreover, the flexibility of OPV allows easy integration into any structure or product. This enables photovoltaic power generation to be no longer limited to open field or rooftop installations and could potentially save acres of land for the future or give access to environments where no open space is available by definition, such as big cities. This is further backed by the capability of adding aesthetic value to products and structures, which is a highly desirable property especially if it comes down to emotional products like buildings including facades.

The state-of-the-art organic (semiconductors) materials allow a wide range of coating and printing technologies to be implemented toward fabrication of OPV. Reports suggest improved device performances using novel polymer blends to the most widely used P3HT:PCBM heterojunction [1, 2]. Besides the performance, the polymers also possess unique characteristics of being able to reflect a different colour at different angles. This makes the OPV portfolio quite vibrant in comparison to other photovoltaic technologies.

With regard to the OPVIUS approach for functional processing, slot-die coating has proven to deposit functional OPV layers with a very high cross-directional uniformity [3-6]. However, unlike the printing methods the slot-die coatings are incapable of producing patterns as they are a highly unidirectional process. Therefore, OPV development studies using slot-die coating technique are also carried out in layouts that are unidirectional or otherwise termed as 'stripes'. Most of today's publications are based on this very standard on which the cells are produced and evaluated. Only recently there have been reports about OPVs being produced in free-form patterns/designs, but only OPVIUS is currently operating its production on this scheme [7, 8]. Besides slot-die, printing technologies are also currently in discussion – like among others inkjet printing, which gained industrial interest due to the possibility of being able to print free shape forms as printing is based on drop-on-demand principle. The inkjet process allows printing ink in the desired place on the moving web [9-12]. However, it faces several issues related to ink rheology and morphology of printed layers and finally also reflects a much higher initial investment if compared to slot-die. In this contribution, we expand the potential of the OPV by accompanying slot-die coated layers with suitable additional patterning and printing techniques [13-17].

"The process of mass producing custom-designed OPV has been greatly simplified and realized at a serial production level. By integrating state-of-the-art patterning, printing and 3D conforming technologies along with the slot-die coated layers it is possible to make cells and consequently modules in a free-form design."

Evolution of customized OPV

Based on the pioneering work done at OPVIUS, OPV layouts produced via R2R process is shifted from stripes toward uniform flood coat at full web width. This is possible by modifying and developing the slot-dies to coat wide areas and with a high uniformity. In addition to the slot-die modifications, selective laser patterning with

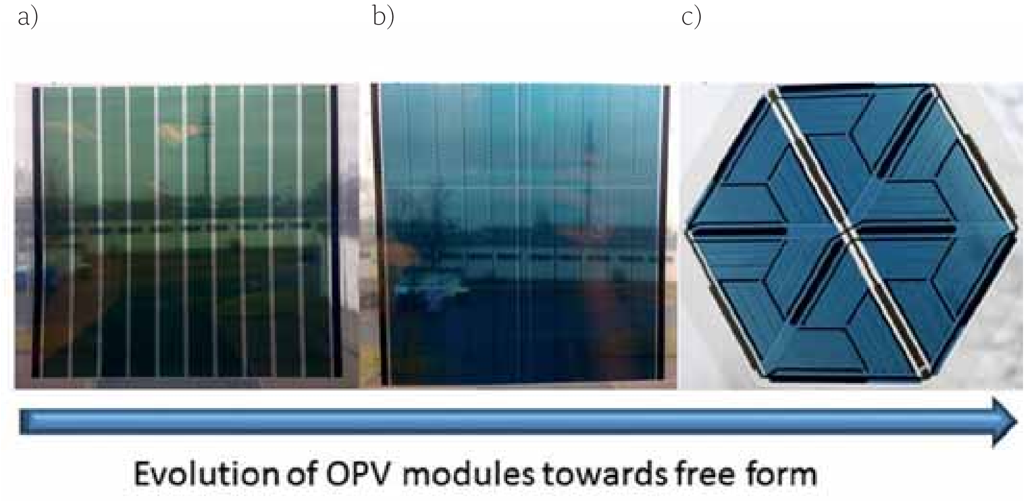

Figure 1. Evolution of large area R2R fabricated OPV applications towards free shape and customization based on laser scribing; a) module with separated stripes, b) module with uniform colour across web width and c) free-form module.

precise registration techniques is integrated into the production process. The laser patterning process allows the creation of patterns and digital shapes that are limited only by the imagination of the designers. Figure 1 shows the evolution of OPV modules from lines to free shape and pattern based on laser patterning technology. Based on continuous evaluation, the process of mass producing custom-designed OPV has been greatly simplified and realized at a serial production level. By integrating state-of-the-art patterning, printing and 3D conforming technologies along with the slot-die coated layers it is possible to make cells and consequently modules in a free-form design. This opens the door to new product applications where other photovoltaic technologies might not be suitable.

Being able to selectively remove the coated layers overcomes the need to make deposition based on stripes. This many-a-time also increases the total active area of the device. This is because each stripe is conveniently placed to prevent the wet films from merging during the coating and allow a serial connection to be made without electrical short circuit. This can be observed in Figure 1a where the area between two coloured stripes is quite visible as they are designed to be couple of millimetres apart to prevent the merging. This zone between the stripes is often considered as 'Aperture loss' as there is no charge generation in this region [18]. However, in a patterned layout, the already deposited and cured layers are selectively removed using a fine laser scribing tool. Many technical lasers used for scribing are capable of delivering cuts that are few micrometres in width. Therefore, very fine structures can be created by separating coated

Figure 2. Mass produced window curtain product based on 3D shaped OPV panels.

Figure 3. OPV tree that mimics banana leafs and fits into natural surrounding (chameleon effect).

layers into multiple cells. In Figure 1b the area between any two cells is hardly visible as it is very finely structured thereby allowing the stripes to be wider in comparison.

The ratio of the device active area to its total size is technically termed as Geometrical Fill-

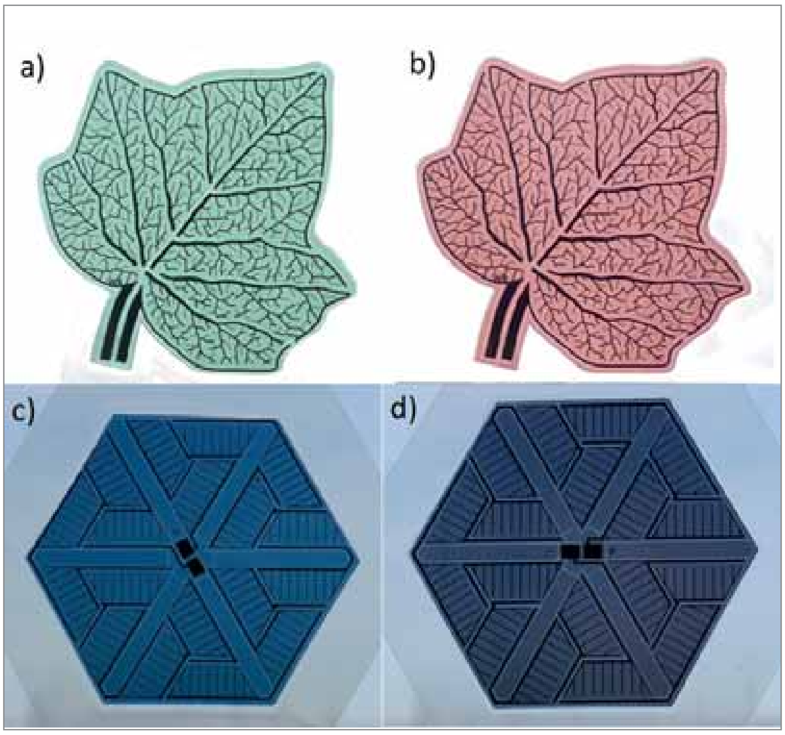

Figure 4. Colours of OPV modules based on different photoactive compounds currently available in large scale production without additional colour filter; a) green, b) red, c) blue and d) grey/purple.

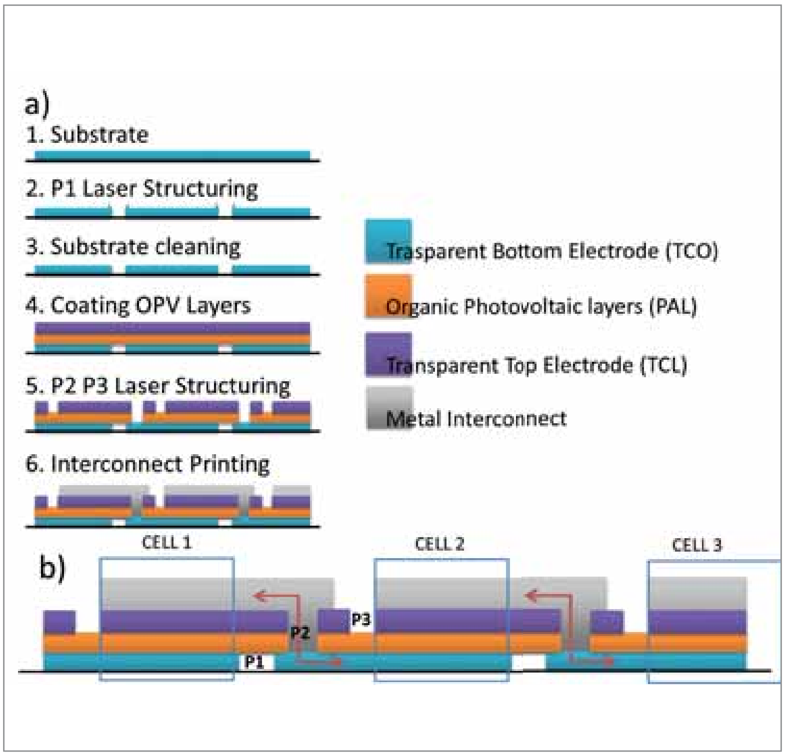

Figure 5. Schematic illustration of the patterning technique; a) a cross-sectional step-by-step laser structuring process and b) cross-section view of the OPV serial interconnection indicating the charge flow after the Z connection is established.

Factor (GFF). The GFF of a module could be raised from approximately 70% in the case of stripes to >90% for a free-form laser patterned layout [19]. Accordingly, the generated power output of the module can also be increased by 20%.

Taking one step further we obtain the free-form. Instead of connecting the cells merely linearly (Figure 1a and Figure 1b), the module shown in Figure 1c consists of cells that are connected planarly across the two-dimensional plane of the coated layers [20].

Conforming printed electronics in 3D shape is a natural next step and recently this process began to take off from the ground in volume production of OPV applications (www.suncurtain.solar). Figure 2 shows a window curtain product based on 3D shaped panels.

Another attribute influencing the product design is its colour. Semi-transparent OPVs are desired in vibrant colours to extend their integrity to the final product and allow it to blend in with its surroundings - for example, OPV trees that mimic real banana leafs and perfectly fit into green urban areas exhibiting the chameleon-like effect (see Figure 3).

Currently, OPV modules in green, red, blue and grey can be produced in large volume without any colour filters, as Figure 4 presents.

Free-patterning methodology

OPVIUS GmbH has developed and demonstrated fully free-form modules with different colours being produced at large scale. Based on the developed process, custom-shaped module designs are created to meet customer requirements for successful applications. The key behind the process is to produce patterned OPV modules without compensating the overall device voltage.

Structuring the layers to disconnect them becomes essential for semi-transparent large-area OPVs to improve device performance and obtain high voltages. The reason behind the performance loss is because the conventional transparent metal oxide electrodes (e.g. indium tin oxide (ITO)) as well as the printed top electrode are not capable of transporting charges over large distances, which results in ohmic losses. These conductivity issues are overcome by separating the electrodes and extracting the charges from smaller areas or cells. Multiple cells are interconnected in series to comprise a module. A serial interconnection will increase the device voltage whereas parallel connection will add the currents to provide increased amperage. The technology developed at OPVIUS uses the freedom of the laser ablation process over a fully coated wide web, where cells are realized in virtually any customized shape and position. An overview of this process is presented in Figure 5. The cells are scribed digitally by laser and then are interconnected within the 2D plane to bring out the desired device shape. From that step, modules can be formed in a 3D shape too.

A step-by-step process diagram for a serial interconnection using the process developed at OPVIUS is shown on Figure 5a. The laser step "P1" is structuring the bottom electrode (typically referred to as "TCO" – Transparent Conductive

Oxide). The P1 cut also separates each cell of the device. This step is carried out prior to actual coating on the manufacturing line.

A large area coating covering almost the entire substrate width is carried out over the structured bottom electrode. By coating wide areas, the freedom is provided to produce modules of varying sizes. Alterations were made on the slot-die setup to enable them to coat wide areas. The challenges of uneven ink distribution inside the channel are overcome by suitably designing the meniscus flow guides.

The cut made during the P1 process is a very crucial part of the device and must be isolated from any conductive material, especially the top electrode. This is to maintain a high parallel resistance and prevent shorting of the device. The architecture of the OPV device enables separation of the top electrode and the P1 as a series of semi-conducting layers are coated prior to the top electrode. In other words, the top electrode is separated from the P1 cut – i.e. from open TCO flanks – by the organic layers that are coated earlier. After the layers are coated, the next stages of patterning are carried out. In the later patterning stages, "P2" and "P3" are subsequently performed. The P2 is carried out adjacent to the previously made P1 cut. It removes all coated layers and exposes the bottom electrode of the adjacent cell. The role of P2 is to form a contact area for a serial interconnection with adjacent cell. The P3 is carried out to interrupt the top electrode (TCL). This reduces the parallel shorting.

By contacting the top electrode of a cell with the P2 cut of the adjacent cell a "Z" connection is established, as Figure 5b shows. This so-called, "Z" connection between the opposite poles of adjacent cells establishes the serial interconnection. As the contact is made available by the action of P2 structuring, the electrodes need to be connected depositing a conductive layer. A patterned deposition is crucial to prevent any electrical short circuiting and to only connect the said electrodes. This is achieved by depositing using a screen printing technique. The conductive ink is pressed through a screen based on the desired form. Screen printing is very versatile as it allows 2D patterned depositions to be made seamlessly. By changing the layout of the screen, various shapes can be made as desired. The process is also highly scalable and by modifying the mesh and/or printing specifications a wide range of ink viscosities can be handled to produce high quality prints [21, 22].

Challenges in process development

The production environment is quite dynamic and distinctive in comparison to the laboratory process. Constantly varying heat profiles as well as large-scale handling of the materials make the production process difficult to control toward precise reproduction of quality and performance of devices. Therefore, determining the process window and process steps for large-scale production is a challenging task as direct benchmarking with lab devices often doesn't go hand-in-hand.

To achieve highly functional devices, the deposited OPV layers need to be carefully cured to create the right morphology. In a controlled laboratory process this exact same curing can be reproduced on consecutive modules as they are separately handled in sheets. In the R2R process the drying dynamics are slightly different since the web is constantly moving. Hence, reproducing the exact same conditions as that of a lab process is a quite complex task. A cold web upon entering the oven has already passed a certain distance before the right curing temperature is obtained. This ramp-up time can be compensated either by increasing the oven temperature or reducing web speed. The latter is not desirable as it slows the production.

Alternatively, the polymer-based web (e.g. polyethylene terephthalate (PET)), used as a substrate for printed electronics, undergoes deformation at elevated temperatures used for drying printed or coated layers when handled under tension during the R2R process. This introduces a dimensional inaccuracy on the material that hinders registration of the subsequent steps thereby forcing the production to follow a strict heat budget [23].

In high volume material processing that involves extended production times, the ink

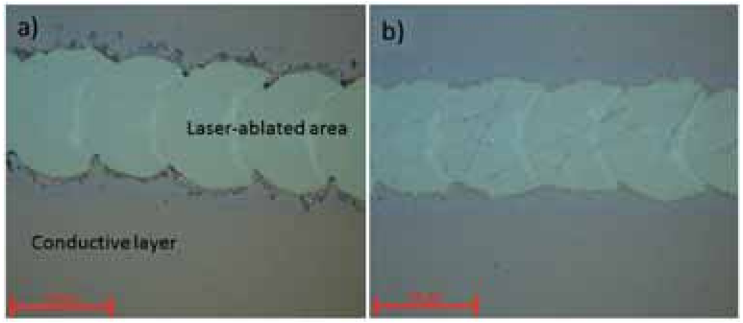

Figure 6. Optical microscopy image of P1 cut separating the TCO; a) before cleaning, b) after cleaning.

"The production environment is quite dynamic and distinctive in comparison to the laboratory process. Constantly varying heat profiles as well as large-scale handling of the materials make the production process difficult to control toward precise reproduction of quality and performance of devices."

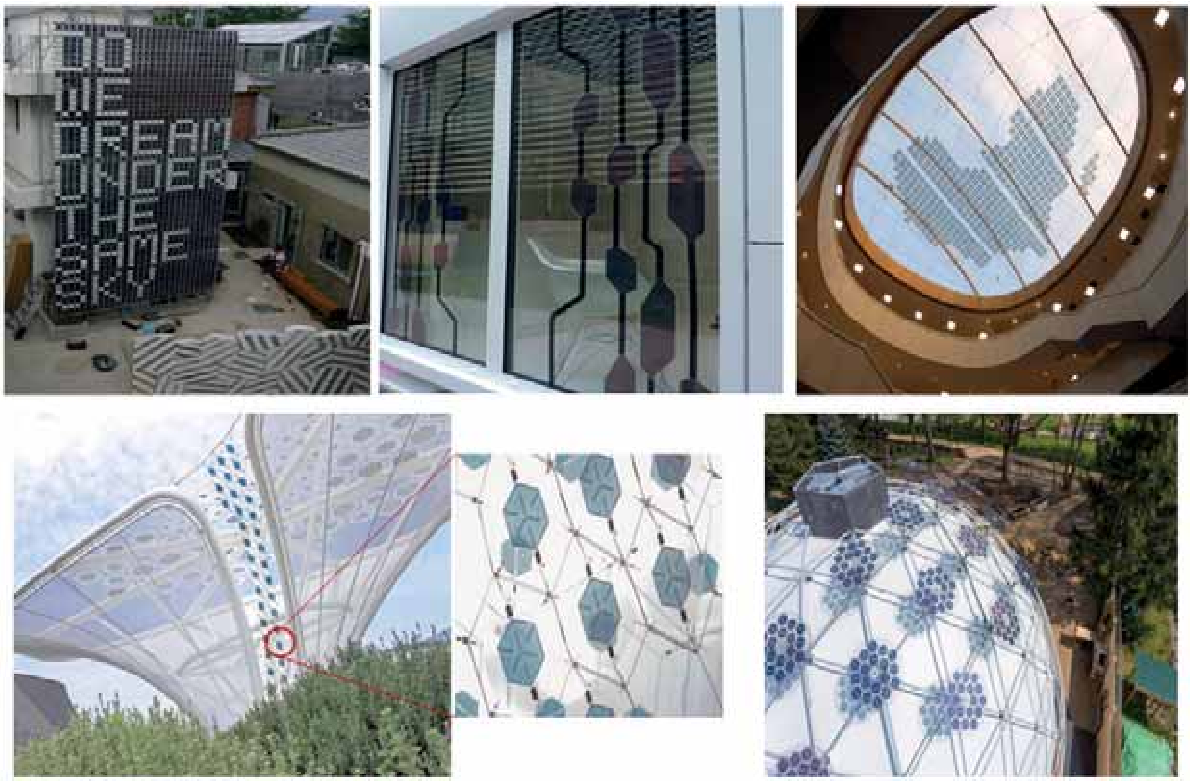

Figure 7. High volume custom designed free shape OPV modules and integrated to urban architecture.

consistency can vary over time and this could lead to a changed morphology of the coated layers. Factors such as particle agglomeration or changes in material viscosity can be caused by extended periods where the ink remains loaded in the reservoir. This could lead to a difference in the coated layer and identifying such effects on produced material requires careful analysis of devices from various parts of the roll.

Additionally, debris and warping at the edges of the ablated spot are created due to the laser ablation of the TCO. Depending on the level of contamination a subsequent cleaning step is required. The difference in the laser flanks prior and after the cleaning process is presented in Figure 6a and 6b, respectively. The debris is cleaned from the substrate before the coating. This minimizes particle accumulation and hence defects during the coating process. The cleaning however requires mechanical force to be applied on the substrate as the debris on the laser flanks are melt residues that are stuck onto the substrate after the ablative process of the laser. If the cleaning is not performed with care and in a controlled manner scratches can be made which will influence the performance of the fabricated devices.

To realize free-patterning, registration between each successive step to that of the previous is a key criterion. The P1 structuring being the first of the process steps, will determine the origin for further registration steps to be based upon. Offsets between P1, P2 and the P3 discussed in the 'Free-patterning methodology' section are introduced to reproduce the registration made during P1 until the final conductive layer is printed to make interconnection. The total interconnection zone is the area between the P1 and P3 as shown in Figure 5. The so-called, interconnection zone is inactive and does not contribute toward charge production. As discussed earlier, this region does not belong to the active are as there is no charge generation. The challenge is to minimize the offsets and increase the active area of the module. To produce a market-competitive OPV module, these offset distances must be less than 1mm. The registration accuracy within this regime falls into few micrometres. Achieving precise registration in this regime on multiple instances makes the process quite demanding.

Overcoming major challenges and integrating laser structuring to a large-area manufacturing process allowed the creation of customized and complex structures. Figure 7 shows customized OPV products fabricated by OPVIUS integrated in large urban architectural structures that are installed around the globe.

"It is expected that in the near future it will be possible to produce more complex 3D shapes and patterns for OPV devices. In order to realize that, new, more conformable materials, equipment and process steps need to be incorporated into high volume production processes."

Future trends

The current state of OPV production has been expanded and developed toward making OPVs that don't hinder the expectations of designers. The OPVIUS OPV technology uses standard off-the-shelf equipment to realize the production allowing CAPEX to appear generally low. As discussed in the earlier sections the production does come with challenges. They can be overcome by reducing the complexity of the problem. Development is being carried out at OPVIUS to reduce the current back-forth processing between the laser and the coating machine by being able to carry out all the laser stages (P1, P2 & P3) within one single step after all the functional layers are coated. This potentially broadens the OPV catalogue without having to hinder the existing production setup. The methodology to structure the product at the late stage ensures a constant stockpile of coated OPV films made at an increased throughput. The process also reduces the production time as cleaning the substrate might not be necessary.

Alternatively, development studies are also being carried out to find an alternative to the currently used TCO material. The present TCO material comprises rare earth metals, which could mean high material scarcity and increased costs in the future. Alternatives to such materials are developed and tested using production conditions and equipment.

Free-shape OPVs can be integrated into other manufacturing technologies of plastics, like injection moulding. This will widen the application area and allow better integration with manufactured parts, for example for gadgets or consumer electronics.

It is expected that in the near future it will be possible to produce more complex 3D shapes and patterns for OPV devices. In order to realize that, new, more conformable materials, equipment and process steps need to be incorporated into high volume production processes. A higher level of integration with our surroundings (nature, urban furniture, etc.) is expected when new colours of photoactive materials will be available for large-scale production. Currently, it is possible to apply colour filters; however they can reduce the PCE of the devices. Furthermore, modules with different colours can relate to each other in a form of mosaic giving a more attractive look.

References

[1] Chen, W., & Zhang, Q. 2017, "Recent progress in non-fullerene small molecule acceptors in organic solar cells (OSCs)", J. Mater. Chem. C, 5(6), 1275–1302, https://doi.org/10.1039/C6TC05066B.

[2] Kutsarov, D. I., Rašović, I., Zachariadis, A., Laskarakis, A., Lebedeva, M. A., Porfyrakis, K., … Silva, S. R. P. 2016, "Achieving 6.7% efficiency in P3HT/Indene-C70Bisadduct solar cells through the control of vertical volume fraction distribution and optimized regio-isomer ratios", Advanced Electronic Materials, 2(12). https://doi.org/10.1002/aelm.201600362.

[3] Lin, C. F., Wong, D. S. H., Liu, T. J., & Wu, P. Y. 2010, "Operating windows of slot die coating: comparison of theoretical predictions with experimental observations", Advances in Polymer Technology, 29(1), 31–44, https://doi.org/10.1002/adv.20173.

[4] Jakubka, F., Heyder, M., MacHui, F., Kaschta, J., Eggerath, D., Lövenich, W., Brabec, C. J. 2013, "Determining the coating speed limitations for organic photovoltaic inks", Solar Energy Materials and Solar Cells, 109, 120-125, https://doi.org/10.1016/j.solmat.2012.10.007.

[5] Kutsarov, D. I., New, E., Bausi, F., Zoladek-Lemanczyk, A., Castro, F. A., & Silva, S. R. P. 2017, "Fabrication of air-stable, large-area, PCDTBT:PC70BM polymer solar cell modules using a custom built slot-die coater", Solar Energy Materials and Solar Cells, 161, 388–396, https://doi.org/10.1016/J.SOLMAT.2016.12.019.

[6] Sandstrom, A., Dam, H. F., Krebs, F. C., & Edman, L. 2012, "Ambient fabrication of flexible and large-area organic light-emitting devices using slot-die coating", Nature Communications, 3. https://doi.org/10.1038/ncomms2002.

[7] Välimäki, M., Apilo, P., Po, R., Jansson, E., Bernardi, A., Ylikunnari, M., … Hast, J. 2015, "R2R-printed inverted OPV modules – towards arbitrary patterned designs", Nanoscale, 7(21), 9570–9580. https://doi.org/10.1039/C5NR00204D.

[8] Eggenhuisen, T. M., Galagan, Y., Biezemans, A. F. K. V., Slaats, T. M. W. L., Voorthuijzen, W. P., Kommeren, S., … Groen, W. A. 2015, "High efficiency, fully inkjet printed organic solar cells with freedom of design", J. Mater. Chem. A, 3(14), 7255–7262. https://doi.org/10.1039/C5TA00540J.

[9] Hoth, C. N., Schilinsky, P., Choulis, S. A., & Brabec, C. J. 2008, "Printing highly efficient organic solar cells", Nano Letters, 8(9), 2806–2813. https://doi.org/10.1021/nl801365k.

[10] Gokhale, P., Mitra, D., Sowade, E., Mitra, K. Y., Gomes, H. L., Ramon, E., … Baumann, R. R. 2017, "Controlling the crack formation in inkjet- printed silver nanoparticle thin-films for high resolution patterning using intense pulsed light treatment", https://doi.org/10.1088/1361-6528/aa9238.

[11] Mitra, K. Y., Mitra, D., Kasania, K.,

Hammerschmidt, J., & Baumann, R. R. 2016, "Influence of the process workflows on the electrical properties of a UV-curable polymeric dielectric for all-inkjet-printed capacitors", Journal Name Journal of Wearable and Flexible Electronics, 1(11), 1–10.
[12] Sowade, E., Mitra, K. Y., Ramon, E., Martinez-Domingo, C., Villani, F., Loffredo, F., … Baumann, R. R. 2016, "Up-scaling of the manufacturing of all-inkjet-printed organic thin-film transistors: Device performance and manufacturing yield of transistor arrays", Organic Electronics: Physics, Materials, Applications, 30, 237–246, https://doi.org/10.1016/j.orgel.2015.12.018.
[13] Kong, S., Application, F., & Data, P. 2011, (12) United States Patent, 2(12), 12–15. https://doi.org/10.1016/j.(73).
[14] Bian, Q., Yu, X., Zhao, B., Chang, Z., & Lei, S. 2013, "Femtosecond laser ablation of indium tin-oxide narrow grooves for thin film solar cells", Optics and Laser Technology, 45(1), 395–401. https://doi.org/10.1016/j.optlastec.2012.06.018.
[15] Proefschrift, V. S., Elektronica, E. V., & Voorzitter, I. 2015, "Selective Ablation for Patterning Organic Electronics Sanjeev Naithani. Faculty of Engineering and Architecture", retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.708.7258&rep=rep1&type=pdf
[16] Xiao, S., Fernandes, S. A., & Ostendorf, A. 2011, "Selective patterning of ITO on flexible PET Substrate by 1064nm picosecond Laser", Physics Procedia (Vol. 12, pp. 125–132), https://doi.org/10.1016/j.phpro.2011.03.114.
[17] Röttinger, S., Schwarz, B., Schäfer, S., Gauch, R., Zimmermann, B., & Würfel, U. 2016, "Laser patterning of vacuum processed small molecular weight organic photovoltaics", Solar Energy Materials and Solar Cells, 154, 35–41, https://doi.org/10.1016/j.solmat.2016.04.032.
[18] Krebs, F. C., Tromholt, T., & Jorgensen, M. 2010, "Upscaling of polymer solar cell fabrication using full roll-to-roll processing", Nanoscale, 2(6), 873–886, https://doi.org/10.1039/B9NR00430K.
[19] Lucera, L., Machui, F., Kubis, P., Schmidt, H. D., Adams, J., Strohm, S., … Brabec, C. J. 2016, "Highly efficient, large area, roll coated flexible and rigid OPV modules with geometric fill factors up to 98.5% processed with commercially available materials", Energy Environ. Sci., 9(1), 89–94. https://doi.org/10.1039/C5EE03315B.
[20] Berny, S., Blouin, N., Distler, A., Egelhaaf, H. J., Krompiec, M., Lohr, A., … Wilson, H. 2015, "Solar trees: First large-scale demonstration of fully solution coated, semitransparent, flexible organic photovoltaic modules", Advanced Science, 3(5), n/a-n/a. https://doi.org/10.1002/advs.201500342.
[21] Gilleo, K. 1989, "Rheology and surface chemistry for screen printing", Screen Printing, 128–132. Retrieved from http://et-trends.com/files/paper_uploads/Rheology and Surface Chemistry for Screen Printing.pdf
[22] Kim, J., Duraisamy, N., Lee, T.-M., Kim, I., & Choi, K.-H. 2015, "Screen printed silver top electrode for efficient inverted organic solar cells", Materials Research Bulletin, 70, 412–415. https://doi.org/10.1016/j.materresbull.2015.04.052.
[23] Macdonald, W & K. Looney, M & A. MacKerron, D & Eveson, R & Adam, Raymond & Hashimoto, K & Rakos, Karl. 2007, "Latest Advances in Substrates for Flexible Electronics", Journal of The Society for Information Display - J SOC INF DISP. 15. 10.1889/1.2825093.

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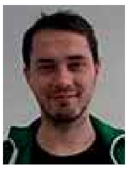

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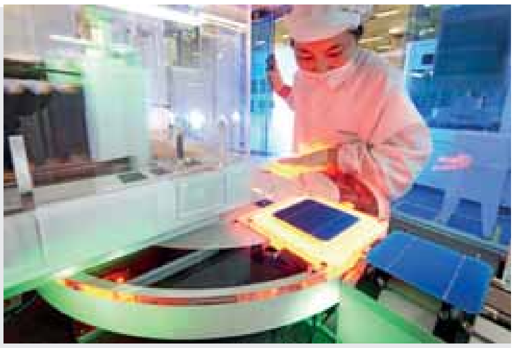
News

Wuxi Suntech providing half-cut cell modules to European customers

China-based integrated PV module manufacturer Wuxi Suntech Power Co has started supplying high-performance multicrystalline half-cut cell modules to European customers, offering power classes of 295/290W.

The addition of the half-cut multi c-Si cell technology comes on the back of production in 2017 of its in-house developed metal assisted chemical etching (MACE) texturing process (black silicon) for diamond wire sawing, which was claimed to provide an absolute efficiency gain of up to 0.3%, compared with the additive direct texturing process.



Credit: Suntech

The company is now offering higher power classes to European customers.

Wuxi Suntech's half-cut cell technology enabled module power outputs of 5W to 10W higher than standard 156mm x 156mm multi c-Si, 60-cell module formats, reducing system costs with higher module efficiency.

Module performance was also said to have been improved because of cell current losses by 50% with half-cut cell technology and cell temperature operation dropping by 20~25% compared to conventional modules, according to the company.

The half-cut cell modules also use a distributed junction box design, with power loss reduced, due to a cross layout installation, noted Wuxi Suntech.

Shuangquan He, President of Wuxi Suntech said: "In the past 18 years, Suntech focused on cutting-edge technology innovation and provided high-quality and cost-effective products to our global partners. Now, we have cooperated with VDE for quality inspection certificate, VDE-QT, and continue to monitor the quality in quarterly mass production."

The company also noted that it offered WEEE recycling solutions for European customers.

Hanwha Q CELLS making mono-PERC half-cut cell module available in Europe

'Silicon Module Super League' (SMSL) member Hanwha Q CELLS has launched its most advanced module series to the European market.

Hanwha Q CELLS Q.PEAK DUO-G5 module and Q.PEAK DUO BLK-G5 version use monocrystalline half-cut PERC (Passivated Emitter Rear Cell) technology in a six-busbar design, enabling module power classes up to 330Wp and 320Wp, respectively.

The advanced module design also features round wires, which cast less shadows on the cells and are designed to reflect some light back onto the cell, boosting efficiency.

Hanwha Q CELLS´ proprietary 'Q.ANTUM' PERC technology also controls the degradation effects of LID (light induced degradation) and LeTID (light and elevated temperature induced degradation) that can reduce the performance of conventional PERC solar modules.

"The Q.PEAK DUO-G5 series sets the new benchmark for achieving lowest LCOE for the customers. In order to reach that, the module combines our latest technological innovation, both on cell and on module level," said Daniel JW Jeong, Global CTO of Hanwha Q CELLS.

The company is providing a 12-year product warranty and a performance warranty of 98% in the first year, a minimum of 93% within 10 years and 85% of initial performance after 25 years.

JinkoSolar adds name to ARENA project intended to reduce solar cell conversion losses

A research project to identify solar cell conversion losses and provide commercial solutions, which was initiated in December 2017 by the Australian Renewable Energy Agency (ARENA), has attracted 'Silicon Module Super League' (SMSL) leader JinkoSolar.

The project, which is being lead by the Australian National University (ANU) and The University of New South Wales (UNSW) has attracted AU$29.2 million in funding and includes BT Imaging, Fraunhofer Institute for Solar Energy Systems, US National Renewable Energy Laboratory (NREL), Sinton Instruments, Norwegian Crystals, Topsil Global Wafers, MiaSole Hi-Tech Corp and Tesla.

Although much is known about cell-to-module losses, the research programme will include the entire supply chain, from silicon ingot growth, wafer, cell and module production. Also, new methods for detecting and eliminating defects in silicon modules are expected to be developed and then applied in manufacturing.

ACQUISITIONS

Ayala buys controlling stake in flexible module firm Merlin Solar

Ayala Corporation, part of Filipino conglomerate Ayala Group, has acquired a controlling stake in Silicon Valley-based firm Merlin Solar Technologies, which produces flexible, mobile and wearable crystalline silicon solar modules.

ACI Solar Holdings, a subsidiary of AC Industrial Technology Holdings, which is itself a wholly owned subsidiary of Ayala Corp, carried out the transaction for a 78.2% stake, having originally made a minority investment in Merlin Solar back in 2016.

Headquartered in San Jose, California, Merlin Solar claims that its products are suited to installation on metal roofs, auxiliary power for transportation and military applications among others. The firm is also partnered with QFlex-Ayala from the Philippines and Waaree Energies an India-based manufacturer.

Merlin has manufacturing facilities in Thailand, but intends to start manufacturing within the Philippines in partnership with Integrated Microelectronics, another ACI subsidiary.

For its part, Ayala's strategy is to invest in what it calls disruptive technologies, having already built up a portfolio of innovative technologies in electronics manufacturing, vehicle assembly and vehicle retail.

Ayala Corporation and AC Industrials chairman Jaime Augusto Zobel de Ayala said: "Merlin is highly complementary to various Ayala businesses, such as the renewable energy generation under AC Energy. We strongly believe that Merlin's solar technology has the potential to profoundly impact people's lives in the coming years."

Tomark-Worthen acquires Madico's PV technology

Backsheet producer Tomark-Worthen (TW) has acquired the products, technology, and trademarks of backsheet and solar insulation firm Madico.

TW, a joint venture between Tomark Industries and US-based adhesives, films and sheets specialist Worthen Industries, was formed in 2012 to produce co-extruded (HP-CoEx) backsheets.

The new acquisition includes all of Madico's certifications and intellectual property for its PV backsheet and solar panel insulation products. TW will be adding all of the former Madico PV products, such as the Protekt, to its own HP-CoEx backsheet products and speciality PV encapsulation materials.

Production started being migrated from Woburn, Massachusetts, to the TW facility in Nashua, New Hampshire, on 1 January 2018.

David Santoleri, president of TW, said: "This acquisition will enhance our Tomark-Worthen product offerings while building on Madico's significant brand name recognition and allowing customers to continue to purchase the Madico products."

Mark Fehlmann, VP of technology and engineering, said "We are happy to see the Madico line of PV products go to the very capable team at Tomark-Worthen. It's comforting knowing the products we created will continue to be used in the industry."

Prior to forming TW, Tomark Industries represented Madico for almost 20 years and helped to develop many of the Madico products during that time.

TECH SELECTIONS

REC to use Meyer Burger's 'SWCT' module technology for next-gen cell and module migration

Leading PV manufacturing equipment supplier Meyer Burger is to supply its SmartWire Connection Technology (SWCT) to integrated PV module manufacturer REC Group.

REC Group has pioneered volume production (1GW plus nameplate capacity) of p-type multicrystalline PERC (Passivated Emitter Rear Cell) half-cut cell technology in recent years with its 'TwinPeak' series modules, which are produced in Singapore.

The SmartWire technology would be used in the manufacturing of REC's 'newest high efficiency solar modules' with equipment delivered and installed starting in the second quarter of 2018. Actual capacity and financial details of the order were not disclosed.

However, the SmartWire technology could be used with half-cut cells. The company had highlighted its third generation of SmartWire technology at the inaugural PV ModuleTech conference in Malaysia last year, highlighting step-function improvements for high-volume manufacturing and production cost savings of over US$5 million per 100MW production line.

The technology is designed to reduce cell-to-module power losses, compared to standard busbar technologies, notably in high-performance modules driven by the migration to p-type monocrystalline PERC and heterojunction (HJ) cells and reduce silver content to support lower manufacturing costs.

Panasonic offering AC modules with Enphase IQ 7X microinverter in US

Major electronics firm Panasonic Corporation of North America is to offer an AC version of its heterojunction modules using the newly launched IQ 7X microinverter from Enphase Energy in the US.

Enphase has already secured high-performance module manufacturer LG Electronics for its AC module microinverters and leading 'Silicon Module Super League' (SMSL) member JinkoSolar.

Panasonic, which has less than 1GW of cell and module capacity and significantly less than LG and JinkoSolar, said that it would be making its N Series PV module series 'HIT' (Heterojunction with Intrinsic Thin layer) N325/N330 (96-cell), AC module available to US distributors with the

REC will use Meyer Burger's SmartWire technology on its 'newest high-efficiency solar modules'.

Credit: Meyer Burger

320W Enphase IQ 7X microinverter from May 2018 onwards.

"The N series PV Modules are manufactured for peak performance, making them an ideal partner for the Enphase IQ 7X Microinverter," noted Mukesh Sethi, group manager, Panasonic Residential Solar Group. "With a unique heterojunction technology and advanced bifacial cells, these high-efficiency panels offer homeowners state-of-the-art features and maximum solar production."

The IQ 7X Micro will support 96-cell PV modules up to 400W with peak AC output power of 320W and a Maximum Power Point (MPP) tracking range of 53-64V.

SHIPMENTS AND RESULTS

Risen Energy sets new revenue record in 2017

Major China-based PV module manufacturer Risen Energy's operating income exceeded RMB10 billion (US$1.56 billion) in 2017, a new record for the company.

Preliminary 2017 revenue and profit results showed net profit would be in the range of approximately RMB645 million to RMB705 million (US$100 million to US$110.1 million in 2017, down by 8.54% to 0.17% from 2016.

The company had an operating income of around RMB 7.0 billion in 2016, indicating sales increased around 45% in 2017.

Despite the significant increase in module shipments and revenue year-on-year, Risen Energy noted that PV module average selling price (ASP) declines and higher operating costs, due to opening new markets for the company impacted net profits in 2017.

However, the increase in polysilicon prices would have also impacted margins and profitability.

The company recently signed a framework agreement to build and operate a 5GW monocrystalline cell and module plant in Changzhou City, Jiangsu Province, China.

The JV framework agreement calls for Risen to provide RMB1.5 billion (60% stake) and its partner RMB 1.0 billion (40% stake) towards establishing the new manufacturing facilities.

JA Solar touts 50% product shipment increase in 2017

'Silicon Module Super League' (SMSL) member JA Solar has raised its 2017 full-year shipment guidance for cells and modules, including shipments to its downstream PV project business, representing close to a 50% year-on-year increase.

The SMSL has remained cautious about its business outlook throughout 2017 but has revised total cell and module shipments to be in the range of 7.5GW to 7.8GW, up from 7.0GW to 7.2GW.

In issuing third-quarter 2017 financial results late last year, JA Solar was on track to almost reach a 50% increase just in PV module shipments, compared to 2016.

The SMSL member has not split cell and module shipments in its latest guidance nor provided an update to its downstream project completions. As a result, PV Tech's 'Top 10 Module Manufacturers in 2017' remains unchanged with both Canadian Solar and JA Solar vying for the third ranked position.

Trina Solar surpasses 9GW of solar module shipments in 2017

'Silicon Module Super League' (SMSL) member Trina Solar shipped over 9GW of PV modules globally in 2017, confirming its second place position in PV Tech's Top-10 Module Suppliers annual ranking.

Module shipments for the first three quarters of 2017 were 1,966MW, 2,481MW and 2,092MW, respectively. As a result fourth quarter shipments would have peaked at over 2,500MW. Accumulated module shipments had exceeded 32GW.

Key markets for Trina Solar in 2017 were China, India and the US, while its global footprint is one of the broadest in the industry, highlighted by the fact it had shipped and distributed products to more than 100 countries.

Trina Solar also retains its in-house solar power projects business, which constructs, operates and has sold projects in China, the UK, the US and other European and Asian countries.

Trina had shipped over 3GW of modules to India in recent years, accounting for more than a 25% market share.

However, the China market has remained its largest market in the last few years. In August 2017, it launched its residential PV brand – 'TrinaHome' in China, which has quickly taken a leading market position in the Distributed Generation market.

Trina was implementing the 'One-Million Rooftop Plan' over the course of the next five years to provide the Trina residential PV system installation service for more than one million households.

Key markets for Trina Solar in 2017 were China, India and the US.

Credit: Trina Solar

Guidelines for accurate current-voltage measurement of high-efficiency c-Si solar cells

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Abstract

The market for commercial crystalline silicon (c-Si) solar modules has been ruled for decades by the well-established ribbon-interconnected Al-BSF solar cells, making their metrology and in particular the current-voltage measurement well defined and reproducible. The recent appearance of high-efficiency technologies at mass production level, such as PERC, PERT, heterojunction or back-contacted, coupled to advanced module designs like multi-wire or shingle interconnection, sometimes in bifacial configuration has raised some metrological concerns. In most cases, no norms were in place, leaving manufacturers free to rate the power of their devices by a procedure of their choice. As the pricing of solar cells is based on their energy conversion efficiency in standard test conditions, such a situation is not suitable either for manufacturers or for customers. Indeed, without a well-defined framework for the measurement, the module manufacturer and of course, the final customer, might pay a wrong price. The present contribution aims at giving an overview of the new challenges that high-efficiency c-Si solar cells are facing when it comes to assessing their optical and electrical performances, as well as providing guidelines for their accurate measurement.

Introduction: from Al-BSF design to high efficiency solar cells

The first diffused-junction silicon solar cell was developed by Pearson, Fuller and Chapin on n-type silicon in 1954 [1] and featured an energy conversion efficiency of 6%. It took then decades of development to master the mass production and achieve interesting efficiencies with the Al-BSF structure in the early 80s. This cell architecture has set the standard in industry for three decades but has now reached its physical limits, with up to 20.3 % efficiency demonstrated [2]. It represented about 90% of the global PV production in 2013 and down to 70% in 2017 with a decay expected to continue until this technology only marginally exists in about 10 years [3].

The main driver for this market change is the progressive upgrade of the production lines toward PERC cell designs that enable cell efficiencies well over 20% at competitive costs. In this respect, LONGi recently demonstrated record efficiencies of 23.6% on monofacial PERC [4]. In parallel, alternative Si-based technologies featuring higher conversion efficiencies combined with a more important room for improvement are appearing. The more important ones are silicon heterojunction (SHJ) and back-contacted (BC) solar cells encompassing interdigitated contacted (IBC) and metal wrap through (MWT) cell designs. Unlike the PERC design, IBC, MWT and SHJ designs cannot be manufactured on existing production lines as they involve different fabrication processes. For this reason, their aggregated market share does not exceed 5%, despite very high conversion efficiencies: 23.1% on SHJ MWT [5], 25.1% on both-side contacted SHJ [6] or 26.7% on SHJ IBC [7]. Note that these technologies are becoming more and more mature and cost-competitive and should significantly increase their market share in the coming years according to ITRPV annual report [3].

New metrological challenges

High-efficiency solar cells have come with optical and electrical challenges for the measurement of their performances. In particular, bifaciality, higher intrinsic capacitance or new metallization/interconnection patterns have brought complexity and currently available cell testers are no longer able to assess the power accurately. Interestingly, even the guidelines framing the data processing of IV curves are no longer sufficient for devices featuring too high fill factors.

Bifaciality

One of the most striking features is that all the above-mentioned cell designs (with the notable exception of Al-BSF) are intrinsically bifacial, i.e. their back metallization can be opened to enable light absorption from both sides. From a metrological point of view, this property raises serious questions such as: how to account for bifaciality? How to handle the parasitic optical feedback from the contacting unit? What can be reasonably measured in a production line? How to value the bifacial gain to the final customer? How to ensure standardized and comparable IV measurements?

These interrogations will soon be answered by the new IEC standard that defines the measurement procedure and requirements for bifacial cells and modules [8]. Unlike monofacial devices, IV measurement is performed on front and rear sides successively to extract the bifaciality coefficients. Optical feedback on the rear-side induced by the contacting unit should not exceed

$3W/m^2$, i.e. 0.3% of the incident power. To do so, two valid approaches are suggested:

- Use a rear-contact unit that fulfills the $3W/m^2$ recommendation, typically a non-conductive and non-reflective material with local contacting areas.
- Use a set of rear-contact units featuring different reflectivities. Then, the intrinsic short-circuit current can be extracted with a linear regression [9].

Once the two sides are measured, the front- and rear-side parameters allow the extraction of the bifaciality parameters **φ** for I_{sc}, P_{max} and V_{oc} according to the formula:

$$\varphi_X = \frac{X_r}{X_f} \qquad (1)$$

Where X stands either for I_{sc}, P_{max} or V_{oc} and f and r, for the front and rear side configurations, respectively.

In a second phase, the bifacial gain is highlighted by flashing the device in field-equivalent conditions, where 10% to 20% of additional irradiance is collected from the surrounding albedo. To mimic these situations, the device is flashed at minimum three irradiances. Two approaches are suggested:

- ***The "G_E – method" (or equivalent irradiance method)***
  To achieve an effective rear irradiance G_r [W/m²], the front side is flashed with an equivalent irradiance G_E defined as:

$$G_E = 1000\left[{}^{W}/_{m^2}\right] + \varphi\, G_r \qquad (2)$$

G_r is usually comprised between 0 and 200 W/m_2 and **φ**=min (**φ** I_{sc}, **φ** P_{max}) is the device bifaciality.

- ***The dual illumination method***
  Here, the front light source flashes either at 1,000 W/m² (front side configuration) or at 0 W/m² (rear side configuration). For the higher irradiances, i.e. 1,000 + G_r [W/m²], the front light source flashes at 1,000 W/m² and the rear one at G_r [W/m²].

For the device labelling, the values of P_{max} at STC with G_r = 100 W/m² and G_r = 200 W/m² must be indicated and are labelled $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$, respectively.

Beside hardware differences, the two methods feature different injection profiles for the configurations at irradiances higher than one sun, as in the first approach the light is absorbed from the front side only. For the short-circuit current, one could expect than nonlinear cells might suffer from this anisotropic injection. However, a study from Fraunhofer has shown that such a nonlinearity has no detectable impact on I_{sc} determination and the two approaches are fully equivalent [10].

Regarding the fill factor (FF), more discrepancies can be observed when comparing front and rear-side illuminations. If one considers low quality bifacial PERC solar cells, the situation might become noticeable. For light incident on the back surface field side (rear side), the carrier transport to the emitter side is driven by diffusion and leads to an important accumulation of charges at the interface and therefore to an enhanced recombination. For poor lateral conductivities or badly conductive fingers, I_{sc} and FF might be affected. Conversely, for light incident on the emitter side (front side), carrier transport through the structure is driven by the internal electric field, making the carrier distribution more flat through the structure and fewer charges accumulate at interface [11]. This asymmetry is real and should be reported as such in the bifaciality coefficients, as recommended by the norm. The question that arises is the equivalence between the GE-method and the dual-side illumination at higher injections, i.e. the 1000 + G_r case. No conclusive study has been conducted so far on cells (some are ongoing), but it is expected that the two methods are equivalent as the cell is already under "high" injection when the irradiance is increased from the 0 to 200 W/m² on the rear side.

In production lines, it might not be necessary to go through the full sequence that requires five flashes and eventually one cell flipping in case only one lamp is used. It would make sense to flash all cells in standard test conditions on the front side and use a non-reflective chuck or use dual-side flashing, taking great care that no parasitic light can hit the rear side of the cell, in agreement with IEC norm [8]. The information related to bifaciality, i.e. **φ**, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$, would be given on a statistical basis, as for the thermal coefficients. Keeping the number of flashes per cell at its minimum will maintain a high throughput and costs at a lower level.

Advanced metallization

Contacting quality can be challenging for new cell technologies as they do not necessarily follow well-defined standards for metallic patterns. Metallization has become a fantastic playground for manufacturers to improve their cell efficiency and lower their costs: square cells with few busbars arranged in the so-called H-pattern is not anymore the only way to go. New patterns and cell configurations are appearing and calling for dedicated metrological solutions and standards. In the following, we list the recent trends in cells manufacturing.

Back-contacted cells

An interesting approach towards high cell efficiencies is to decrease the optical losses occurring at the front of the device by placing all terminals on its rear side. For instance, IBC cells are completely metal-free on front side and feature a dense comb-pattern alternating p and n polarities at the rear-side. MWT cells explore non-standard metallic geometries on front side optimized to reduce the optical and resistive losses. The generated current is then collected at the backside through metallic pads.

In both cases a careful attention must be paid to the bifaciality. Moreover, as n and p polarity terminals are located at the rear-side they cannot be measured with a conventional contacting units or bars. A dedicated contacting layout with distributed current and voltage probes must be set up. Among them, we can cite the two following approaches:

- ***The pin-based approach***
  This approach consists of using a non-conductive contacting unit where spring-loaded pins probing the voltage and the current are inserted. This approach is very convenient if the cell metallic design is fixed. In case of frequent variation of the metallic pattern, the rear contacting unit must be replaced each time.

- ***The PCB approach***
  If the rear side pattern of solar cells is frequently evolving over time, it is important that various metallic patterns can be measured without the need for expansive setup modification. This idea of flexibility at low costs is possible with the PCB approach, like the PCB^{TOUCH} developed and patented by PASAN [12]. The base contacting system is always the same, only the PCB is replaced from one cell pattern to another.

New patterns for advanced module designs

Beside back-contacted technologies, it is also very interesting to see how the module designs have dictated new rules for metallization. The most striking current applications are new interconnections like multi-busbars, multi-wires, shingles or cut cells [13].

Multi-busbar and multi-wire

H-patterned Al-BSF cells with two or three busbars require a lot of costly metallic paste and induce important shadow losses. The trend today is to further increase the busbar number to four, five or six but with reduced widths. Narrower tabs and finger lines reduce the metal usage while decreasing the shadow losses and also improving the aesthetics of the module. The multi-busbar approach from SCHMID pushes this trend to an extreme by implementing 12 (or more) narrow "busbars", typically thinner than 0.5 mm [14]. IV measurements might become problematic due to the increased projected shadowing during the contacting. Such configuration might not be representative of the field application. CSEM is currently evaluating the impact of irradiance spatial inhomogeneity during IV measurement that could potentially affect FF and V_{oc}.

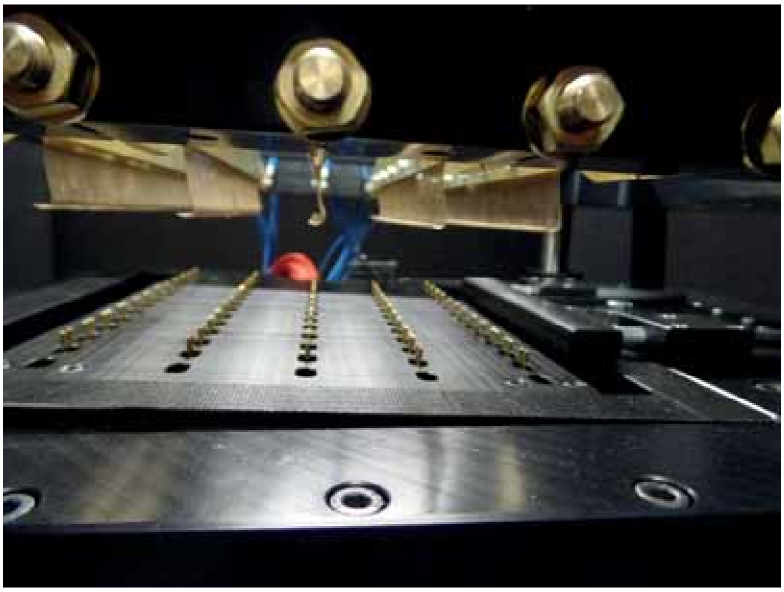

Figure 1. h.a.l.m. contacting unit for busbarless solar cells.

When further increasing the busbar number, it might no longer be cost-effective to print them. The multi-wire approach involves removing them completely. Instead they will be replaced by soldered interconnectors during lamination. This is achieved with the SmartWire Connection Technology (SWCT) [15]. When the number of extracting lines N increases, the finger losses decrease as $1/N^2$ and become completely negligible when N > 15 or 20 (depending on the line resistivity). As the finger electrical losses no longer impact the FF, ultra-fine lines can be printed which considerably lowers the silver usage and costs but also decreases the shading. From a metrological point of view, ensuring a 100% rate of contact on such shallow lines is a real challenge. Nowadays, two competitive approaches are available:

Approach 1: Finger contacting with hooks

This solution (see Fig. 1) has been developed by h.a.l.m. and consists in five contacting bars, each of them containing one metallic hook per finger. This approach ensures a one-to-one contact and a good measurement reproducibility [16].

Approach 2: Finger contacting with wires

The so-called Grid^{TOUCH} (see Fig. 2) developed and patented by PASAN [17] from the Meyer Burger group (that developed the SWCT technology) consists of 30 wires for current extraction and five wires for voltage measurement [18]. The rear contacting is either ensured by wires with the same configuration or by a PCB. A slightly bent plateau ensures a homogeneous contact. The certification institute CalLab (Fraunhofer ISE) is following this approach.

Once the busbars have been removed and replaced by interconnecting wires at the module level, the cell-to-module (CTM) loss analysis is no longer defined for the grid losses. The reason is very simple: grid losses depend on the mean distance travelled by electrons through the metallic grid. For busbarless cells, this value is fixed at the module level only. As the cell measurement geometry does not necessarily correspond to the extraction geometry at the module level, IV cell parameters must be corrected to allow a one-to-one comparison between cell and module, like for standard cells where the busbar number equals the ribbons number.

In the first approach, only five arrays of hooks are present and in the second approach, 30 wires serve the same goals. Typically, the number of wires in the module is close to 15 depending on their diameter. It is clear that both methods are not giving FF corresponding to the final application. Figure 3 shows how the grid losses will contribute to the device losses depending on the number of bars or wires used for current extraction. Clearly, for a standard busbarless module design containing 15 to 20 wires, the approach with hooks (five measuring bars) underestimates the FF, whereas the wire approach (30 measuring wires) overestimates it.

Beside the electrical mismatch between cell and modules, busbarless cells are measured without the impact of shadowing as the irradiance is adjusted to compensate the contacting unit shadowing. Whereas this effect is fully accounted for in the CTM analysis of standard cell with busbars, the IV cell parameters must be corrected to account for the presence of interconnectors. Otherwise the cell efficiency would be artificially too high and no fair comparison could be made with identical cells featuring a standard print with busbars.

Correcting the electrical and optical losses does not impact in any way the final module power but only the attribution of losses between cell and module. The CTM analysis will in the end contain the exact same terms but some of the module losses are transferred to the cell ones via the effective efficiency approach that sets busbarless and standard cells on equal footing. The corrections requires the following inputs:

- ***Optical correction:*** Cell size L, wire number Nw and diameter Dw
- ***Electrical correction:*** Grid resistance of front and rear sides, GRf and GRr [Ohm/cm], respectively

The effective IV key parameters are given by the following set of equations [19]:

$$I_{sc,eff} = I_{sc,meas}(1-s) \quad (3)$$

$$I_{mpp,eff} = I_{mpp,meas}(1-s) \quad (4)$$

Where $s \approx \frac{N_w D_w}{L}$ is the shadowing due to interconnectors in the final module. To apply this

$$V_{oc,eff} = V_{oc,meas} + \frac{kT}{I_{sc,eff}q} ln(1-s), \quad for\ s < 5\% \quad (5)$$

$$V_{mpp,eff} = V_{mpp,meas} + \frac{kT}{q} ln(1-s) - \frac{L}{12N_w^2}(GR_f + GR_r)I_{mpp,meas} \quad (6)$$

approach, the cell tester manufacturer must also provide a grid resistance diagnostic, which is the case for the products of two previously mentioned companies: h.a.l.m. and PASAN.

Cut cells and shingles

The module industry is also innovating by modifying the cell shape with the goal of achieving higher efficiency by increasing the voltage and decreasing the current. Doing so, the resistive losses are reduced but optical gains are also expected [13]. One approach is to dice the cells parallel to the fingers into halves or quarters. With this approach, the interconnection strategy is unaltered as well as the cell contacting. The second popular approach is to cut the cells perpendicularly to fingers along the busbars. Cell interconnection is trickier as it no longer involves metallic contacts: the cells are stacked on top of each other with electrically conductive adhesives. These so-called "shingles" would be more challenging to measure, in particular if made bifacial, as a single busbar would lie along the cell border. In practice, these cells are measured on the full wafer, prior to laser cutting for economic reasons: segmenting the cells in N parts would decrease the throughput by the same factor.

Capacitive effects

Solar cell capacitance has two main origins: the junction capacitance Cj in the depletion layer and the diffusion capacitance Cdiff. For an abrupt junction, the former term reads [20]:

$$C_j = A\sqrt{\frac{q\varepsilon_S}{2(V_{bi}-V)}\left(\frac{N_A N_D}{N_A+N_D}\right)} \quad (7)$$

Where A is the cell area, q is the elementary charge, ε is the semiconductor permittivity, V_{bi} is the built-in potential, V is the voltage applied to the capacitor, N_A and N_D are the acceptor and donor impurity concentrations. This term represents the accumulation of charges in the depletion layer and dominates the cell capacitance in reverse and low bias conditions. Under forward bias, the charge distribution of minority charge carriers in the bulk of the cell increases exponentially with the applied bias voltage. This charge is compensated by an equal distribution of excess majority carries at the other side of the junction. The associated capacitance reads [21]:

$$C_{diff} = C_0 e^{b\frac{q}{kT}V} \quad (8)$$

Where b is a fitting parameter, k is the Boltzmann constant and Co is the base capacitance given in the wide base diode limit by:

$$C_0 = \frac{q}{kT}\frac{qn_i^2}{N_A}L_n = \frac{q}{kT}\tau I_0 \quad (9)$$

L^n is the base diffusion length, τ is the minority carrier lifetime and I_o is the diode saturation current. In reality the exponential term is no longer valid above the maximum power point (MPP) because of interface states and another relation should be used to account for the Gaussian decrease of the capacitance [20]. Looking at equation 9, it is clear that technologies featuring low lifetime, and low base doping, will suffer less from capacitive effects. It is thus not surprising that Al-BSF cells are not limited by capacitive measurement artefacts, PERC only weakly and n-PERT more severely [22]. The situation gets even worse for IBC and HJT devices [Virtuani2012].

In case the sweep goes from short circuit (SC) to open circuit (OC) during the IV measurement, the carrier concentration raises, leading to an underestimation of FF and V_{oc}. Conversely, if the sweep goes from OC to SC conditions, the carrier concentration has to be lowered, leading to an overestimation of FF and VOC. [22]. The magnitude

Figure 2. Grid[TOUCH], PASAN's contacting unit for busbarless solar cell.

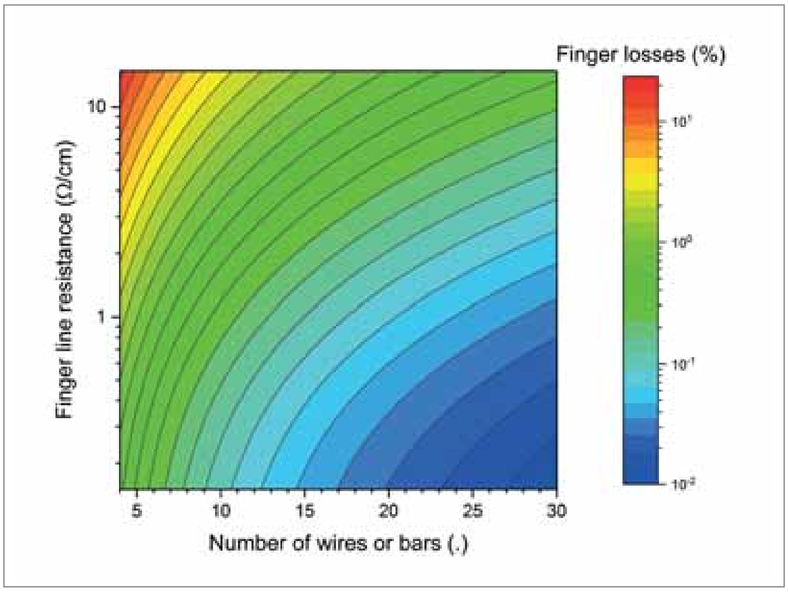

Figure 3. Contribution of grid losses depending on the finger line resistance and on the number of contacting bars or wires.

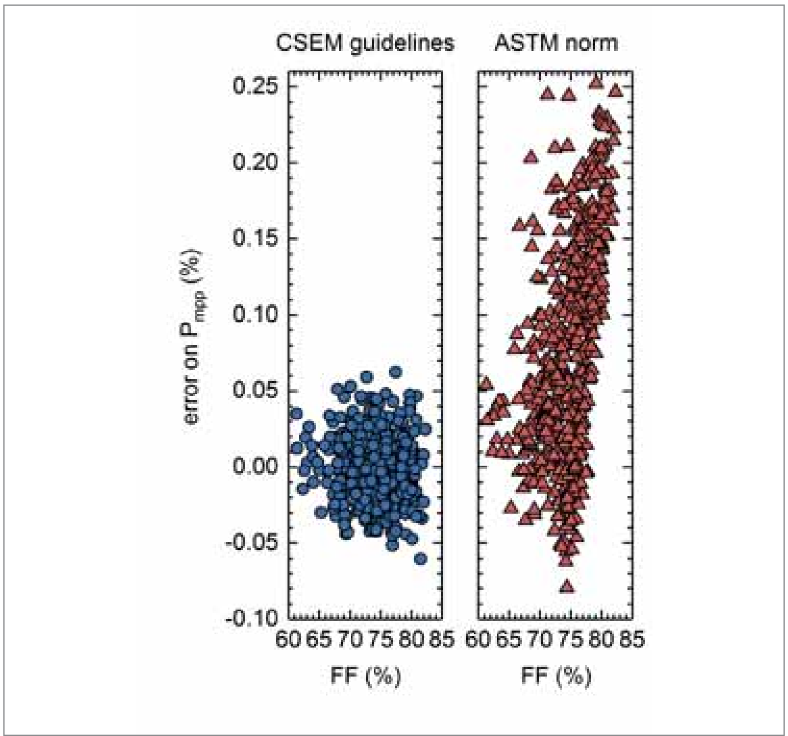

Figure 4. Comparison of the error on Pmpp as a function of the FF of the device under test when applying the ASTM norm (right) and the CSEM guidelines (left).

of the measurement error mainly depends on two parameters: the cell capacitance and the sweeping time. The shorter the sweeping time, the higher the cell capacitance, the higher is the measurement error. On the other side, the measurement time must be kept as short as possible to prevent undesired errors induced by radiation heating of the device. For this reason, the IV measurement must be carefully designed for high efficiency solar cells. Multiple approaches exist:

- ***Multi-flash***
  Increase of measurement time by flashing the device multiple times over segmented voltage ranges and reconstruct the IV curve in post-processing. Such approach can be very time-consuming and is not suited for the high throughput of industry.
- ***Optimized voltage ramp***
  Optimization of voltage ramp by slowing down acquisition time around MPP condition (or where the cell capacitance is limiting the cell response time). Such an approach allows flashing very capacitive solar cells with times compatible with industry standards.
- ***Photo and Dark Analysis (PDA) technology***
  The PDA method developed by KOPEL [23] is based on a comparison between a 50ms light-IV and a three-step sequence of dark-IV curves. The method assumes that light and dark IV have the same response with the exception of the series resistance contribution. The impact of cell capacitance is removed by calculating the internal cell resistance. The full measurement sequence does not cause any important heating of the device but requires an important measurement time for high capacitance devices.
- ***Hysteresis measurements***
  Hysteresis-based approaches rely on the fast sweeping of IV curves in forward and reverse biases. The resulting IV curves feature exotic shape because of the parasitic contribution of the voltage dependent cell capacitance. Nevertheless, these curves can be used to extract the cell capacitance and the true IV curves can be calculated with a proprietary algorithm based on an equivalent circuit. H.a.l.m. has implemented this approach on its cell tester to measure cells with high capacitance [24]. The main advantage is that the measurement is very fast and suited for the high throughputs of the industry but the generated IV curves are calculated from the measured ones and rely modelling.
- ***DragonBack***
  The 'DragonBack' technology has been developed by PASAN together with SUPSI [25]. It applies voltages above the set-point for each point on the IV-curve to accelerate capacitance loading. Then the voltage is reduced to the set-point value and kept stable until the current becomes stable. Fewer points are measured in the final IV curves, typically 15 to 20 but this has no impact on the accuracy of IV key parameters, i.e. I_{sc}, Voc and Pmpp, provided the voltages of these data points are carefully chosen [26].
- ***Voltage modulation***
  In this approach patented by Sinton Instruments [27], the voltage at the cell terminals is modulated by a small signal correction in order to suppress the measurement artifact produced by the cell capacitance.

Data processing

In addition to several practical details known to alter the accuracy of IV curves measurements (most prominently fluctuations of the spectrum and the irradiance of the light source), the methods and the algorithms used to extract Pmpp from a given IV curve have been shown to lead in themselves to errors up to 2-3% [28, 29, 30]. To date, the ASTM E948-09 standard [31] is the only international norm specifically providing guidelines for Pmpp extraction. However, neither an estimation of the residual error on Pmpp, nor suggestions on how to adapt these guidelines to the performances of the device under test are provided. Based on numerically generated IV curves, we demonstrated that for devices with FF >75 %, the ASTM norm clearly overestimates Pmpp due to an inappropriate fit range, with errors as high as 0.25% (see Fig. 4 and Fig. 5). In contrast, adjusting the fit boundaries to the FF of the device under test eventually results in a three to fourfold reduction of the Pmpp error. Importantly, our new guidelines apply equally well on high and low density IV curves. Further details can be found in [26] and [32].

Improved UV and infrared response and new light sources

The market of cell testers relies on well-established norms and standards. The light sources used to assess the performance of solar cells feature collimated light and continuous spectra, usually produced by Xenon flashes. As high-efficiency solar cells come along with higher capacitances, it is clear that the flash duration has become an important parameter that can be hardly tuned with Xenon tubes. For this reason, LEDs have recently attracted a lot of attention due to their high versatility in term of light pulse duration, irradiance control and spectral availability. The other important advantage of LEDs is their low maintenance costs, as they are relatively cheap and offer very long lifetime. The price of LEDs is however strongly dependent on their wavelength as different materials are involved: from blue to red they are really inexpensive but the situation changes for the near UV (<400 nm) and near-infrared ranges (>900nm) where availability, price and radiative efficiencies become limiting. However, the prices are going down and it is nowadays possible to achieve A+ spectra (according to the IEC60904-9:2007) at competitive costs. The availability and the prices of infrared LEDs is of paramount importance in the case of high-efficiency solar cells as they all feature improved quantum efficiencies in these spectral ranges: probing the UV ranges allows to probe surface recombination and parasitic absorption in the front layers whereas probing in the infrared gives an insight into rear surface recombination and light trapping efficiency. At the moment of the writing, many LED-based light sources are available for modules (MBJ, PASAN, Wavelabs, ECOPROGETTI, J. v. G. Thomas, Gsolar Power etc.) and cell testers (Wavelabs, Gsolar Power etc.). Alternative concepts are also emerging and combine the benefits of LED and conventional light sources. For example, PASAN SpotLIGHT is using a Xenon lamp for the I_{sc} measurement and the calibration of red LEDs which are used during the voltage sweep. Alfartec is using a hybrid concept mixing LEDs and Halogen lamps to extend the spectral range in the infrared. More developments are expected in a near future that will enable cost reduction and a better compatibility with high efficiency solar cells.

Conclusion

The prime goal of solar cell testers is to accurately assess the power of solar cells. For this reason, their architecture and mode of functioning must be constantly challenged, upgraded and validated. With the recent evolution of new solar cell designs at the commercial level, the needs for accuracy in the current-voltage measurement has become critical. The current lack of norms and directives framing the power rating of photovoltaic devices is problematic and the community has to rely on good practices and guidelines but also on reliable hardware compatible with all cell designs. The potential uptake of alternative technologies such as perovskite or perovskite-silicon tandem cells will very likely come with new requirements and problems. The validity of the measurement must therefore constantly be questioned, even in the (provisory) absence of metrological standards.

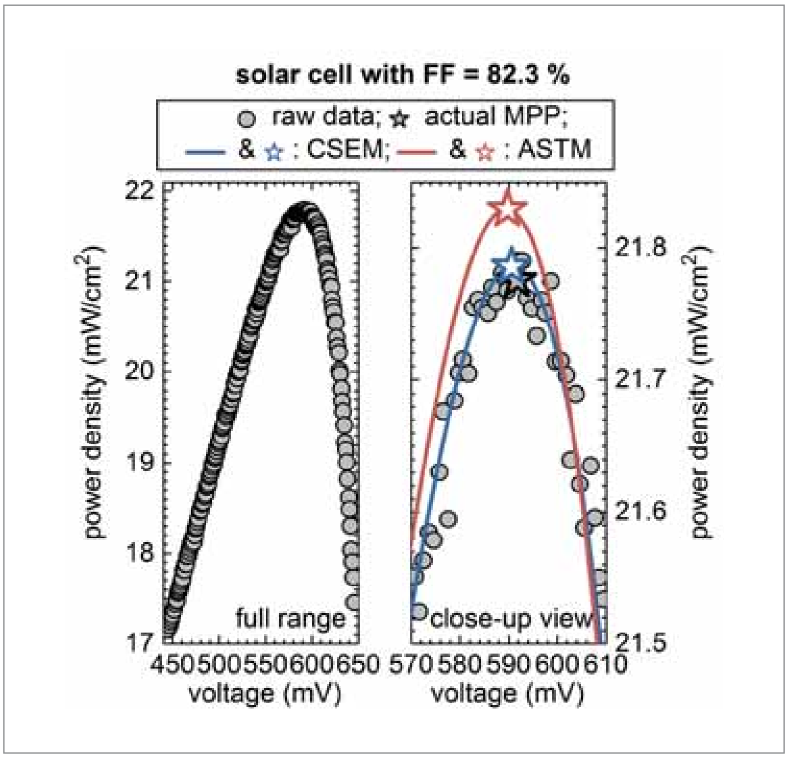

Figure 5. Illustrative example of a solar cell with a high FF. The close-up of the MPP region clearly reveals that the ASTM norm leads to an overestimated Pmpp, whereas the CSEM guidelines prove much closer to the actual MPP.

References

[1] DM Chapin et al. 1954, "A new silicon p-n junction photocell for converting solar radiation into electrical power", *Journal of Applied Physics* 8, 676.

[2] Ki Hyung Kim et al. 2017, "Record high efficiency of screen-printed silicon aluminum back surface field solar cell: 20.29%", *Jpn. J. Appl. Phys.* 56 08MB25.

[3] ITRPV report, http://itrpv.net/Reports/Downloads/

[4] Press release by LONGi, "LONGi hits record 23.6% conversion efficiency for mono PERC solar cells", 28 February 2018.

[5] Press release by Japanese solar-PV manufacturer Choshu and Dutch energy research institute ECN, "New world record efficiency for large area metal wrap through silicon heterojunction solar cells", 15 June, 2016.

[6] D. Adachi et al. 2015, "Impact of carrier recombination on fill factor for large area heterojunction crystalline silicon solar cell with 25.1% efficiency", *Appl. Phys. Lett.* 107, 233506 (2015).

[7] K. Yoshikawa et al. 2017, "Silicon heterojunction

solar cell with interdigitated back contacts for a photoconversion efficiency over 26%", *Nat Energy*. 2(5):17032.
[8] IEC 60904: Photovoltaic devices, Part 1-2: Measurement of current-voltage characteristics of bifacial photovoltaic (PV) devices (in its approval phase at the time of writing).
[9] J. Hohl-Ebinger, W. Warta. 2010, "Bifacial Solar Cells in STC Measurement", *Proc. 25th EU-PVSEC*, Valencia.
[10] M. Rauer et al. 2017, "Bifacial Solar Cells und Single- and Double-Sided Illumination: Effect of Non-Linearity in Short-Circuit Current", *4th bifi workshop*, Konstanz.
[11] Ingrid Romijn 2017, "Bifacial solar cells - a brief overview", *4th bifi workshop*, Konstanz.
[12] J. Rochat, J. Hiller, N. Rebeaud, A. Ambühl. 2017, "Testing device", *Patent EP3126859*.
[13] R. Witteck et al. 2016, "Optimized Interconnection of Passivated Emitter and Rear Cells by Experimentally Verified Modeling", *IEEE Journal of Photovoltaics* 6, 432-439.
[14] J. Walter et al. 2014, "Multi-wire interconnection of busbar-free solar cells", *Energy Procedia* 55, 380 – 388.
[15] T. Söderström et al. 2013, "SmartWire Connection Technology" *Proc. of the 28th EU-PVSEC*, 495-499.
[16] S. Dauwe et al. 2017, "Precise IV-measurement of busbarless solar cells including process control methods for production", *6th Workshop on Metallization & Interconnection for Crystalline Silicon Solar Cells*, Konstanz.
[17] D. Bätzner, C. Clerc, E. Neto, P. Volluz, P. Beljean, B. Albers, P. Papet. 2015, "Testing device", *Patent EP2875366*.
[18] N. Bassi et al. 2014, "Grid^{TOUCH}: Innovative Solution for Accurate IV Measurement of Busbarless Cells in Production and Laboratory Environments", *29th EU PVSEC*, 1180 - 1185 (2014).
[19] P. Papet et al. 2017, Effective Efficiency of Busbarless solar cells", *6th Workshop on Metallization & Interconnection for Crystalline Silicon Solar Cells*, Konstanz.
[20] C. Monokroussos et al. 2006, "The Effects of Solar Cell Capacitance on Calibration Accuracy When using a Flash Simulator", *Conference Record of the IEEE 4th WCPEC*.
[21] G. Friesen and H.A. Ossenbrink 1997, "Capacitance effects in high-efficiency cells", *Solar Energy Materials and Solar cells* 48, 77-83.
[22] T. Roth et al. 2011, "In-depth analysis of transient errors of inline IV measurements", *Energy Procedia* 8, 82-87.

[23] J. Abe et al. 2014, "Accurate and Rapid Measurement of High-Capacitance PV Cells and Modules using Dark Current Characteristics", *Proc. of 29th EU PVSEC*.
[24] K. Ramspeck *et al.* 2014, "Accurate Efficiency Measurements on Very High Efficiency Silicon Solar Cells Using Pulsed Light Sources", *Proc. of 29th EU PVSEC.*
[25] A. Virtuani et al. 2012, "Fast and accurate methods for the performance testing of highly-efficient c-Si Photovoltaic modules using a 10 ms single-pulse solar simulator and customized voltage profiles", *Meas. Sci. Technol*. 23, 115604.
[26] B. Paviet-Salomon et al. 2016, "Accurate Determination of Photovoltaic Cell and Module Peak Power from Their Current-Voltage Characteristics", *IEEE JPV* 6(6), 1564-1575.
[27], R.Sinton, R. Pauley 2005, "Measurement of current-voltage characteristic curves of solar cells and solar modules", *Patent US7309850B2.*
[28] K. A. Emery and C. R. Osterwald 1990, "PV performance measurement algorithms, procedure and equipment," *Proc. 21st IEEE Photovoltaic Spec. Conf.,* 1068–1073.
[29] R. Gottschalg et al. 1999, "The influence of the measurement environment on the accuracy of the extraction of the physical parameters of solar cells," *Meas. Sci. Technol.,* vol. 10, no. 9, 796–804
[30] H. Qasem et al. 2011, "Analysis of key performance parameter extraction from current voltage measurements of photovoltaic devices " *Proc. 37th IEEE Photovoltaic Spec. Conf.,* 002283–002288
[31] Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight, ASTM Int. Std. E948-09, 2009
[32] B. Paviet-Salomon *et al.* 2017, "New guidelines for a more accurate extraction of solar cells and modules key data from their current-voltage curves", *Progress in Photovoltaics: Research and Applications* 25, 623-635.

Acknowledgements
This project has received funding from the Swiss KTI program within the COMET project and from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No. 745601

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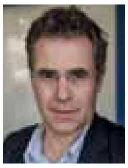

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Bifacial PV: comparing apples with apples sometimes does not make sense

Radovan Kopecek & Joris Libal, ISC Konstanz, Germany

Abstract

Bifaciality can be implemented by varieties of architectures for solar cells, modules and in addition there are even many more applications on system level. This makes bifaciality a complex technology. Currently there is some confusion in the PV community what bifacial gains can be expected and how these transfer to the cost reduction and lowering the LCOE of the system. In this article we will describe how bifacial gains are defined, what bifacial gains can be expected and what this means for real applications.

Bifacial systems offer a very promising possibility to reduce the levelized cost of energy (LCOE) for many PV system applications. There is a huge application field for this new upcoming technology – such as large ground-mounted systems, flat reflective rooftops, sound blocking systems, floating systems or even in utility-scale systems using trackers. The last application is very interesting, these days achieving the lowest LCOE for many cases. The lowest bid ever for a PV system was announced recently in Saudi Arabia, offered by EDF and Masdar for first time below US$0.02/kWh and most likely using bifacial technology in conjunction with trackers [1].

Not only are there many potential application fields, there are also various mounting geometry possibilities: from standard slanted systems, to horizontal to even vertical bifacial installations with almost zero ground coverage. Three prominent examples are depicted in Figure 1.

Definition of bifacial gain

An obvious way to visualize the benefits of bifaciality is to analyse the "bifacial gain", which means the difference in the energy yield if bifacial and monofacial devices with identical installation configurations are compared. The comparison can either include single modules or larger units of one or both device types, because typically the energy yield in kWh/kWp ratio is analysed. The kWp data usually reflects the STC front-side measurement of the bifacial module(s). In the most direct form, devices of similar type and with the same front-side efficiency are compared, for example if bifacial modules with covered rear sides are used as reference.

The bifacial gain is usually defined as:

$$g_{bifacial}\,[\%] = \left(\frac{(e_{bifacial} - e_{monofacial})}{e_{monofacial}} \right) \times 100$$

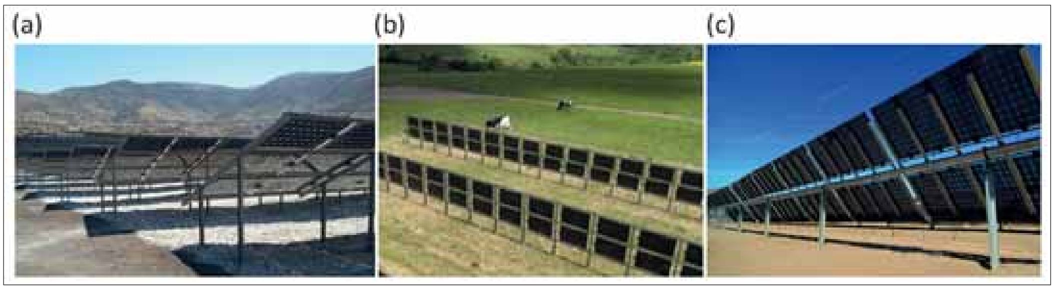

Figure 1. (a) La Hormiga fixed tilt bifacial PV plant in St Felipe, Chile (b): vertical bifacial PV plant by Next2sun in Germany and (c) a tracked bifacial PV plant in La Silla, Chile

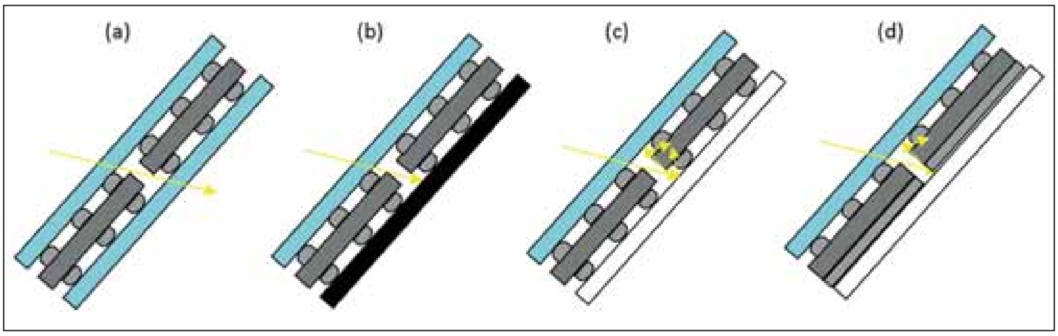

Figure 2. Schematic cross section of a (a) bifacial module and three possible monofacial reference modules with (b) bifacial cells and black backsheet, (c) bifacial cells and white backsheet and (d) monofacial cells and white backsheet

With
• $e_{bifacial}$: specific energy yield (kWh/kWp) of the PV system with bifacial modules
• $e_{monofacial}$: specific energy yield (kWh/kWp) of the PV system with monofacial modules on the same site, with the same configuration and during the same time period

As the bifacial gain is another way to indicate the energy yield, it is the metric that determines – together with the total cost of installing and operating the bifacial PV system – the LCOE (€/kWh) and therefore the economic viability of bifacial PV.

The above mathematical definition of bifacial gain is quite simple – however there are different possibilities in terms of what module type can be chosen for the monofacial reference. Therefore sometimes the reported bifacial gains already differ there – even if at a first glance identical conditions are applied. Figure 2 depicts in (a) the bifacial module and three different monofacial references (b) to (d) which are very often used.

Many groups use standard white backsheet modules with monofacial cells for reference (Figure 2 (d)), some use monofacial white backsheet modules with the same bifacial cells (Figure 2 (c)) and some monofacial black backsheet modules with the same bifacial cells (Figure 2 (b)). All three references will lead to different results, as the white backsheet is causing additional reflection of the front-incoming light into the solar cells. Even if the monofacial solar cell has similar properties as the bifacial (e.g. front-side power, voltage and temperature coefficient) the front side power of the module is increased by ca. 2% at STC (standard test conditions: 25°C, 1,000 W/m2, AM 1.5 spectra) because of the additional reflection of light to the front side and during field measurements the energy harvest is increased more. An increased level of power can also be seen in the case of the bifacial cell and white backsheet: the total additional energy yield (kWh/kWp), also due to the scattering of the light into the solar cell rear side, can be up to 5%, as observed, for example, in LG NeON modules.

Therefore: if you want to observe bifacial gain only, as a reference the same bifacial cell in a module with a black rear cover or black backsheet is required.

This comparison reveals precisely what additional energy is provided by the rear side only. If you take for example a monofacial module with a bifacial solar cell and white backsheet as a reference, you will underestimate the bifacial gain by ca. 5%, as the rear side is already contributing

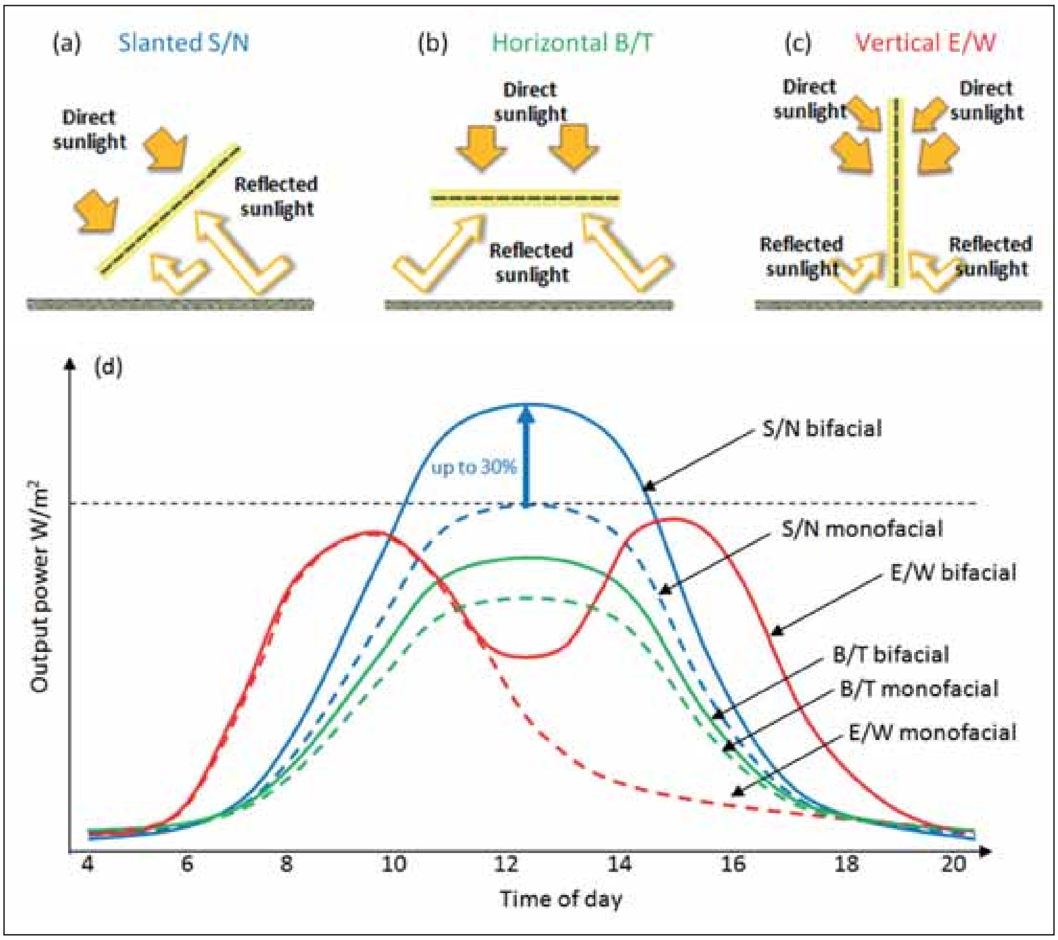

Figure 3. (a)-(c) Possible applications for bifacial modules and (d) resulting daily power generation curves compared to monofacial ones in the same configuration.

in field measurements. Therefore the choice of different references leads already to different results reported in various publications.

Another important point is that the temperature coefficient of the monofacial reference module should be in the same range as for the bifacial ones. Otherwise, for example when comparing bifacial heterojunction modules (temperature coefficient for Pmpp around 0.30%/°C) with standard monofacial aluminium back surface field (Al-BSF) c-Si modules (temp coeff around 0.45%/°C), a significant part of the gain attributed to bifaciality will be due to the reduced temperature losses of the HJT module. Here, as a reference, the same HJT module with a black back cover would be the best choice leading to an "apple to apple" comparison.

Examples of bifacial gains: comparison of apples with apples

Not only the choice of different references, but also different mounting geometries will lead to different bifacial gains – and as we will show, these can be even more than 100% in some cases. Figure 3 depicts different mounting geometries: (a) slanted S/N (south/north) oriented mounting, (b) horizontal B/T (bottom/top) and (c) vertical E/W (east/west) oriented mounting.

The slanted S/N-oriented mounting leads to the highest powers of the applied bifacial modules as the front side produces the highest possible power and the rear, depending on the albedo of the ground, can contribute up to 30% additional electricity. Here, a 300Wp module can behave as a module with an effective power of close to 400Wpe ('peak effective'). This relationship can be seen in Figure 3 (d) between the dotted and solid blue curve.

Horizontal B/T-oriented installations, used in car ports, for example, demonstrate very similar behaviour, only that the absolute energy production is reduced, as the module is – apart for sites located nearby the equator – not oriented at an optimal angle towards the sun. The monofacial and bifacial generation curve is demonstrated by the green dotted and solid lines respectively. The shape for all installations so far discussed is very similar, having a peak intensity around noon.

A completely different form (camel and dromedary curve) is generated by a vertical E/W-oriented installation. When you install a bifacial module with a high bifacial factor (b: rear power/front power >0.9, for example an nPERT BiSoN (Bifacial Solar Cells on N-type) or "HJT module" from Sunpreme) you end up with the solid red line. Much more electricity is generated during morning and evening as compared with the S/N-oriented case. During midday there is a generation dip, as the direct sunlight is shining on the frame and only diffuse light is hitting the module front and rear side. However, due to the ground coverage ratio close to zero and due to the broader generation peak this installation geometry is very interesting. Now: if you install a monofacial module in such a mounting geometry the generation peak moves to a dromedary-like (red dotted line) shape with generation energy less than 50% compared to the bifacial one. Here the bifacial gain is therefore higher than 100%. However such a comparison does not make much sense as installing a monofacial module vertically with an E/W orientation is highly improbable. In this case the vertical bifacial modules have to be compared with a slanted monofacial equator-oriented module. Depending on the installation latitude the bifacial gain can be even negative – in this case, if modules are installed vertically in sun-

Bifacial module	Bifacial installation geometry and latitude	Installation geometry of monofacial reference	Albedo	"Bifacial gain" (rounded to 5% steps)
nPERT BiSoN (b>0.9)	slanted fixed tilt in San Felipe, Chile (32° south)	slanted fixed tilt	25%	15% [2]
nPERT BiSoN (b>0.9)	slanted fixed tilt in San Felipe, Chile (32° south)	slanted fixed tilt	65-75%	30% [2]
nPERT (b>0.9)	Vertical installation, USA	vertical installation	unknown	100+% [3]
nPERT BiSoN (b>0.9)	Vertical installation in Winterthur, Switzerland (47° north)	slanted fixed tilt	25%	10% [4]
nPERT (b>0.9)	Vertical installation in Saar, Germany (49° north)	slanted fixed tilt	25%	10% [5]
nPERT BiSoN (b>0.9)	Vertical installation in el Gouna, Egypt (27° north)	slanted fixed tilt	25%	-5% [6]
nPERT BiSoN (b>0.9)	Single-axis tracked in La Silla, Chile (29° south)	Single-axis tracked	25%	15% [7]

Table 1. Bifacial gains for nPERT modules (mostly BiSoN) with various installation geometries

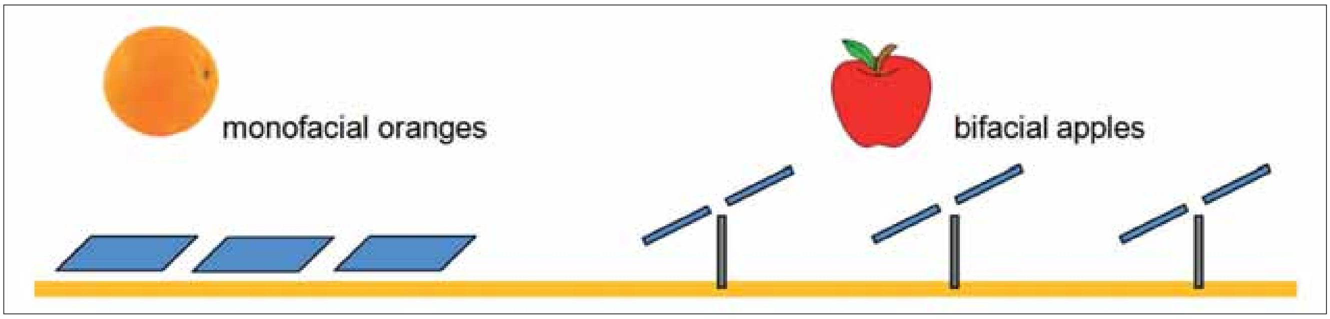

Figure 4. Schematic drawing of (a) a monofacial S/N oriented system and (b) an E/W-oriented bifacial single-axis tracked system.

belt regions. However this might make also sense in some cases, if the soiling can be reduced by the vertical installation.

Table I summarizes several examples of various installation geometries and resulting 'bifacial gains' for BiSoN nPERT modules. Because in the large bifacial systems in Chile standard monofacial modules with white backsheet are used as a reference by developers MegaCell and Enel, the real physical bifacial gains would differ from there slightly.

In the case of the fixed-tilt S/N module system there are already many cases reported all around the world with different albedi. Depending on the ground albedi (25% for natural sand and 75% for white stones) bifacial gains from 15-30% can be achieved.

When it comes to vertical E/W systems things become more complex and also not so many reference systems exist. In these cases, not only are the module type and albedo of importance but so are the mounting geometry of the reference module and the installation latitude. If you compare with a vertical installed monofacial module, a bifacial gain of more than 100% can be observed. This comparison makes only little sense – here a comparison with a slanted equator-oriented monofacial module is more interesting as well. If you install such systems at high latitudes, where the amount of diffuse sunlight is higher and where the vertical mounting is less far away from the optimum slanted angle, an electrical gain of 10% is observable – however at low latitudes even an electrical loss of -5% was observed. Still this application remains interesting because of several reasons: the ground coverage is close to zero, the generation peak is broader and vertical installations have less soiling problems. However also some challenges have to be solved as the wind loads are high using this mounting configuration.

Within the last few months bifacial systems using single-axis tracking have gained more and more attention, as experimental results in large systems showed that the bifacial gain in those cases is also very high. This is because many tracking mounting systems are almost ideal for bifacial modules as they are mounted high from the ground with high row spacing. Therefore the bifacial gains – in this case, the gains compared to monofacial single-axis tracking – are very similar as for the fixed-tilt systems. The first one to report this behaviour was Enel in la Silla [7].

A combination of single-axis tracking with bifacial modules in systems with high albedo result in electrical gains of over 40% compared to fixed-tilt monofacial modules [8].

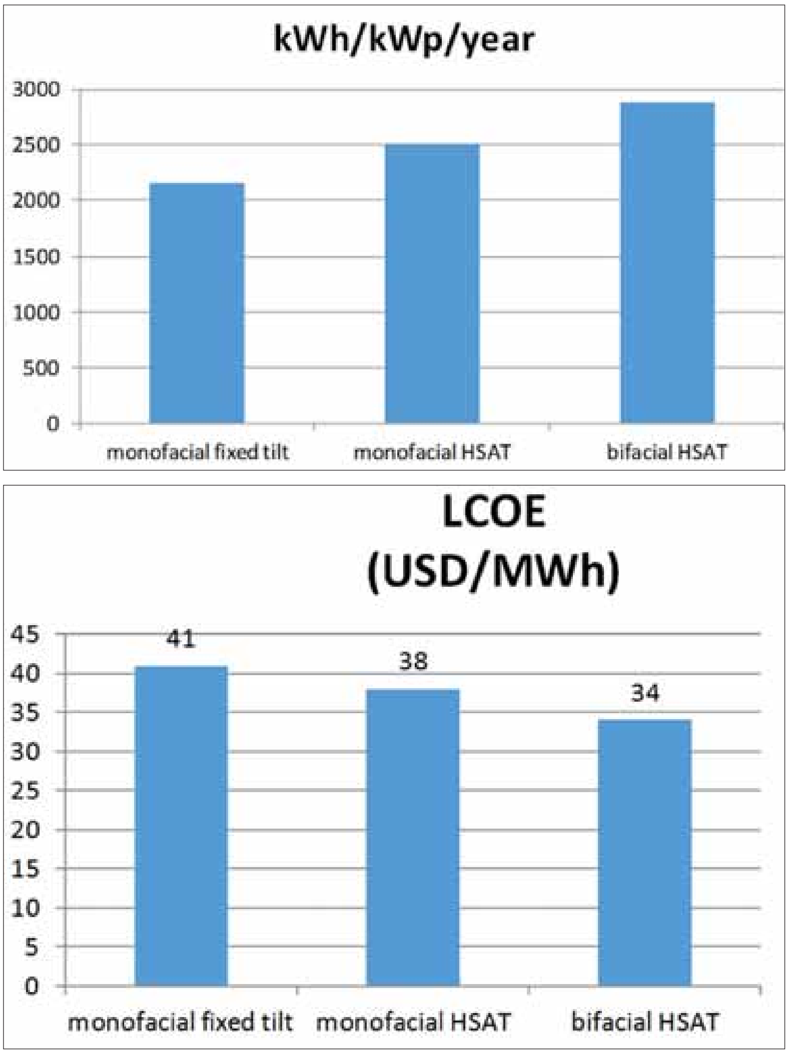

Figure 5. Examples of a) calculated energy yield and b) resulting LCOE for different module and system technologies when installed in Chile (assumption for monofacial installed fixed-tilt system cost: US$0.92/Wp and US$1.00/Wp for monofacial and bifacial horizontal single-axis tracker) with a ground albedo of 25%. In this case the tracking gain (monofacial horizontal axis tracking compared with monofacial fixed tilt) is 17%. Using bifacial instead of monofacial modules on the HSAT system results in an additional 14.7% (rel.) gain, leading to a combined gain (tracking + HSAT) of 34%.

More and more large companies have realized this incredible increase and the companies building single-axis trackers are optimising their systems for bifaciality.

Bifacial applications in reality: comparison of apples with oranges

We have learned that bifacial gains, as they are defined, can reach values of more than 100%. However, this information is not very practical for system designers. The only interesting question for them is: how can a PV system with the lowest LCOEs be designed? Then the best possible monofacial installation has to be compared with the best bifacial one, as depicted, for example, in Figure 4.

Many PV system designers are using PVsyst for this purpose which is a simulation software generating bankable results. With all the necessary import parameters such as module properties, system geometry and data for specific local conditions, the energy output can be calculated which at the end leads to values for LCOE. PVsyst is also since September 2017 capable of running reliable bifacial simulations – however for systems with fixed-tilt mounting only. At ISC Konstanz we have developed a simulation program (MoBiDiG: Modeling of Bifacial Distributed Gain) which is capable of conducting reliable simulations for bifacial tracked systems as well. Figure 5 depicts the result of three different systems at the same location in Chile.

Summary

Bifacial gains show how bifacial modules increase the electrical performance of a system when bifacial modules instead of reference monofacial modules are mounted. Depending on the choice of reference modules these values can differ by more than 5% (rel.), even when choosing the same installation configuration for the bifacial and the monofacial system. If you want to know the real bifacial gain – the additional power that the rear side is generating – then the easiest way is to use the bifacial module covered by a black sheet for reference. Bifacial gains are also dependent on module bifacial factor, b. Bifacial PERC modules at the moment have b<80%, nPERT and HJT b>90%. Therefore it has to be also stated which modules with which b were used in corresponding modelling or experiment.

In special configurations, bifacial gains of more than 100% can be measured, when e.g. bifacial vertical installations are compared with monofacial vertical installations. However in practice, for the optimal design of PV systems, it makes only sense to compare the energy output for an optimized monofacial versus an optimized bifacial system and at the end compare the resulting LCOEs. The meaning of "optimized" can be influenced by restrictions imposed by the specific application and by the available installation site.

In the bifacial area more standards and more advanced simulations programs are needed. Therefore we organize yearly bifacial workshops where the newest results are presented - this year in September 10/11 in Denver. BifiPV2018: www.bifiPV-workshop.com

References

[1] Parnell, J. 2017. "Bifacial technology was likely reason world's lowest ever solar bid was rejected", PV-Tech.org https://www.pv-tech.org/editors-blog/bifacial-technology-was-likely-reason-worlds-lowest-ever-solar-bid-was-reje

[2] Kopecek, R. and Libal, J. 2017. "Complex problems require simple solutions: how to measure bifacial devices correctly?" *Photovoltaics International 37*, pp.105-112.

[3] https://www.solarchoice.net.au/blog/news/bifacial-solar-cells-the-two-sides-of-the-story-050515

[4] https://www.slideshare.net/sandiaecis/5-hartmut-nussbaumer-bifi-psda-antofagasta-chile-2015

[5] Next2sun, internal presentation

[6] Shoukry, I. 2015. "Bifacial Modules - Simulation and Experiment", Master thesis, University of Stuttgart.

[7] Di Stefano, A. et al. 2017. "La Silla PV Plant as a utility-scale side-by-side test for innovative module technologies", 33rd EUPVSEC Amsterdam.

[8] Yong, L. 2017. "nPERT technology and its application", Bifacial PV workshop, Konstanz.

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The PV-Tech blog

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Solar Media Ltd

China doesn't need US polysilicon for solar industry

In President Trump's statement imposing a 30% import duty on all foreign made crystalline silicon solar cells and modules reference was made to renewed efforts that would be made to resolve the trade war with China over polysilicon duties on US producers, effectively locking them out of the market.

Both Hemlock Semiconductor and REC Silicon campaigned to highlight the significant impact the last trade war has had on their companies with significant production curtailment and the loss of hundreds of jobs already.

Although REC Silicon is headquartered in Norway it produces both conventional 'Seimens' process polysilicon and FBR (Fluidized Bed Reactor) bead polysilicon for multicrystalline ingot/wafer production in the US and is running plants at only around 50% utilization rates.

REC Silicon has been unable to supply customers in mainland China since polysilicon anti-dumping duties were imposed.

In a statement addressing the issue after new 30% duties were imposed, impacting key market leaders from China, such as 'Silicon Module Super League' members JinkoSolar, Trina Solar and Canadian Solar, which are major suppliers to the US market, Tore Torvund, REC Silicon's CEO commented:

"It is imperative that the US Administration take constructive steps to resolve this prolonged harmful dispute in the near term. In times of rising global polysilicon demand, opportunities for US polysilicon manufacturers, the industry's technology leaders and the most competitive producers in the world, should be experiencing healthy expansion, not rapid contraction. This Administration was elected to support US workers, and we encourage the US Trade Representative to conclude an agreement to protect our dedicated and innovative US employees. REC Silicon can out-compete our foreign rivals and we can do it from our manufacturing locations here in the United States. We simply need access to the global market, which can be achieved by the discussions provided for in the President's announcement."

Torvund was right to point out that US-based polysilicon producers have been technology leaders with Hemlock well known to produce some of the highest quality polysilicon at large-scale serving both leaders in the semiconductor manufacturing industry such as Intel and high-efficiency solar cell producers in China, Asia and Europe.

REC Silicon has been leading low-cost polysilicon producers through its successful development and volume production of FBR technology, the only company to have achieved the feat.

Credit: Trina Solar

The US-China solar trade spat is harming US polysilicon producers, with China looking to bolster local production.

Indeed, REC Silicon is in a joint venture in China to build a second-generation FBR plant to circumvent Chinese duties and could be operational in 2018.

The biggest challenge facing Hemlock and REC Silicon is that US negotiations with China face an uphill task as China has supported local polysilicon producers to build new and expand existing plants to meet current and future demand for its growing solar industry so that imports are not required.

This blog post first appeared on www.pv-tech.org

"China has supported local polysilicon producers to build new and expand existing plants to meet current and future demand for its growing solar industry so that imports are not required"