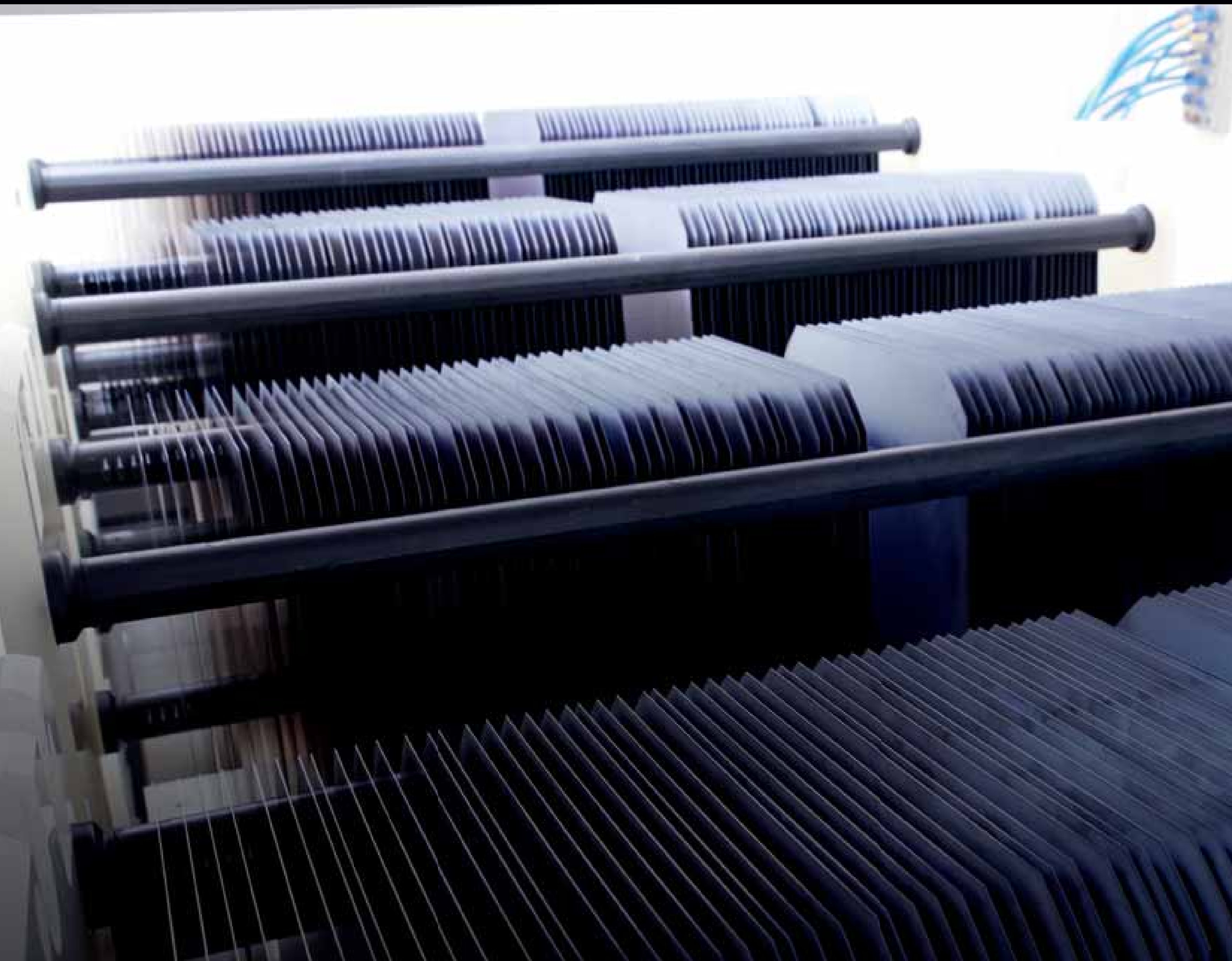
Thirty Seventh Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS



PV Tech/Solar Media Technologies driving the new 100GW annual PV solar world

ISC Konstanz Complex problems require simple solutions: How to measure bifacial devices correctly?

CSEM Metallization techniques and interconnection schemes for high-efficiency silicon heterojunction PV

Fraunhofer THM Optimization potential of the wire sawing process for multicrystalline silicon

Imec Epitaxial Si lift-off technology: Current status and challenges

Fraunhofer ISE High-efficiency solar cells on n-type HP mc-Si

Third Quarter, September 2017

www.pv-tech.org

Photovoltaics International

Published by:
Solar Media Ltd.,
3rd Floor, America House, 2 America Square
London EC3N 2LU, UK
Tel: +44 (0) 207 871 0122
Fax: +44 (0) 207 871 0101
E-mail: info@pv-tech.org
Web: www.pv-tech.org

Publisher: David Owen

Head of Content: John Parnell
Managing Editor: Ben Willis
Commissioning Editor: Adam Morrison
Sub-Editor: Steve D. Brierley
Senior News Editor: Mark Osborne
Reporter: Tom Kenning, Andy Colthorpe

Design: Tina Davidian
Production: Daniel H Brown, Sarah-Jane Lee

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

Cover image: Production of bifacial solar cells.

Image courtesy of MegaCell, Italy.

Printed by Buxton Press

Photovoltaics International
Thirty Seventh Edition
Third Quarter, September 2017
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 latest edition of *Photovoltaics International*. While our flagship upstream title is now on its 37th volume, this quarter we welcome a new member to our family of events.

PV ModuleTech takes place in Kuala Lumpur on 7-8 November. It is recognition of the vast array of emerging module technologies and configurations and will look to demystify the bold claims proponents of these make. The importance of equipment, materials choices and testing and certification will be demonstrated by CTOs and research heads from the majority of the top 20 module suppliers.

Essentially we'll be connecting major players from the downstream with the latest technology updates from their key suppliers to help them navigate the increasingly complex module landscape. This is the only way to ensure technological improvements are captured by the finance community that backs deployment. Conference chair and head of market research at PV Tech and Solar Media Finlay Colville, looks at the make-up of PV manufacturing as it approaches its first 100GW year and demonstrates just how quickly things have been changing in recent years (p.14).

As always we have a selection of technical papers from some of the industry's leading minds. Radovan Kopecek and Joris Libal from ISC Konstanz tackle one of the biggest issues impeding the rollout of bifacial cell and modules, how to standardise their measurement (p.105). As long as there is no commercially available means to measure their gain, bifacial modules will struggle to improve their market penetration.

The materials section includes an excellent paper from Fraunhofer THM examining the optimization of diamond wire sawing (p.37). The method is becoming increasingly predominant with some equipment manufacturers shelving their slurry-based tools. Here Fraunhofer assesses how to squeeze even more efficiency out of diamond wire saws.

CSEM meanwhile explores the required metallization and interconnection process changes required to enable a production-scale shift to silicon heterojunction PV (p.61).

Mark Osborne provides his latest capacity expansion report as upgrades to higher efficiency lines continue to drive planned investments.

We hope to see you at PV ModuleTech in November!

John Parnell
Head of Content
Solar Media Ltd

Photovoltaics International

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

Editorial Advisory Board

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

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

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

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

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

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

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

Dr. Wei Shan, Chief Scientist, JA Solar

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

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.

About LONGi Solar

A world leading mono-crystalline solar module manufacturer for achieving best LCOE (levelized cost of electricity) solutions.

LONGi Solar is a world leading manufacturer of high-efficiency mono-crystalline solar cells and modules. The Company is wholly owned by LONGi Group. LONGi Group (SH601012) is the largest supplier of mono-crystalline silicon wafers in the world, with total assets above $2.7 billion. (2016)

Armed and powered by the advanced technology and long standing experience of LONGi Group in the field of mono-crystalline silicon, LONGi Solar has shipped approximately 2.5GW products in 2016. The Company has its headquarters in Xi'an and branches in Japan, Europe, North America, India and Malaysia.

With Strong focus on R&D, production and sales & marketing of mono-crystalline silicon products, LONGi Solar is committed to providing the best LCOE solutions as well as promoting the worldwide adoption of mono-crystalline technology.

en.longi-solar.com

LONGi Solar

Contents


MEYER BURGER
Just imagine: photovoltaics got it off the ground.
Flying around the globe powered only by solar energy! We are proud to be part of a project which achieved such impressive success.
We invest all our efforts into clean, sustainable technologies. Our ambitious people make a better future come true for all mankind. We know how to efficiently turn the infinite power of the sun into energy by spanning the entire process chain from the wafer through cell production to the complete solar module.
“Meyer Burger is on track into a decarbonized future.”
André Borschberg & Bertrand Piccard, co-founders of Solar Impulse
Meyer Burger provided the premium technology, which was used to connect the over 17,000 high-efficiency solar cells to the 269.5 m² wing panel of the Solar Impulse airplane, which collects up to 340 kWh of solar energy per day.
www.meyerburger.com
SOLARIMPULSE
www.solarimpulse.com
© Solar Impulse | Revillard | Rezo.ch

Contents

Product Reviews

Eyelit

Eyelit's Version 5.3 MES adapts to both R&D and manufacturing

Product Outline: Eyelit Inc., a manufacturing software provider for visibility, control and coordination of manufacturing operations, has launched version 5.3 of its Manufacturing Execution System (MES) software suite.

Problem: Traditional MES software was designed for volume manufacturing and other difficult to integrate operations such as R&D and engineering activities that required prototyping and small batch production.

Solution: 'Eyelit Manufacturing' version 5.3 is a major software release that includes extensive enhancements across the entire product line. Eyelit's customer base has expanded into various segments of both hybrid and repetitive discrete manufacturing. The core MES system includes new features and improvements to manage diverse processing techniques and support a tremendous variety of innovative products and composite materials in both R&D and manufacturing.

Applications: Streamlining the methods for managing materials in discrete manufacturing operations.

Platform: The version 5.3 MES offers new quality control features to help customers handle discrepant material and its impact on work in process. Eyelit quality management and Special Processing/SWR improvements make quality management processes and experimentation management faster for new product introduction. Extensions to the ad hoc processing functions will help customers improve yields and reduce costs. Furthermore, new rules are now available in the Advanced Dispatching module to factor in tool-specific capabilities, batch sizes, dedications, inhibitions, and reservations for improved quality and throughput.

Availability: Available since June 2017.

Isovoltaic

Isovoltaic launches co-extruded polypropylene PV backsheet for high-performance and reliability

Product Outline: Isovoltaic has launched the 'ICOSOLAR CPO 3G', a co-extruded polypropylene solar PV backsheet, which was developed in collaboration with Borealis, a provider of polyolefin solutions for the global energy industry.

Problem: PV modules are exposed to a wide range of stress conditions that can have a significant impact on the backsheet material such as temperature, UV, moisture, thermal cycling and internal voltage. Over time, PET-based backsheets can show signs of yellowing, delamination and cracking in field.

Solution: The ICOSOLAR CPO 3G backsheet is designed to enhance the performance as well as extend the lifetime of PV modules and ensure greater operational reliability. The backsheet provides increased module output, due to the higher reflectivity. Improved reliability is provided by its superior water vapour transmission rate and acetic acid permeability, as well as its hydrolytic stability and insulation properties. Because there are no adhesive layers, the risk of inner-layer delamination is eliminated. Furthermore, co-extruded polypropylene, as a single-step production technology, provides the highest production quality and homogeneity, and reduces manufacturing complexity.

Applications: Co-extruded polypropylene solar PV backsheet for high-efficiency modules.

Platform: The new ICOSOLAR CPO 3G backsheet is manufactured using Borealis' solar-grade 'Quentys' polypropylene produced in Schwechat, Austria. These polypropylene grades form the core layer as well as the outer layers of the backsheet.

Availability: Available since June 2017.

J.v.G. Thoma

J.v.G. Thoma's tabber-stringer offers high speed and reliability

Product Outline: J.v.G. Thoma GmbH has introduced a new tabber-stringer to its product portfolio, which includes its 'Endless String Technology' to work at a speed that is claimed to be twice as fast as other stringers on the market.

Problem: Increasing throughput and a high uptime are key demands for PV module assembly. Reducing cell breakage rates and the ability to upgrade tabbing and stringing tools to ever-increasing busbar numbers means flexibility and serviceability are required.

Solution: The J.v.G. Thoma tabber-stringer uses the newly developed Endless String Technology that is said to enable the stringer to reach up to 1,300 cells per hour with a very high precision of ribbon alignment with an option handle 2,600 cells/h. Compared to other high-end stringers on the market, the price per speed (cells/h) is very competitive, according to the company. The tool also provides less tension in the cell, meaning less stress and resulting in a reduction in the cell breakage rate. Using the company's patented DESERT+ soldering solution, the system can process cells down to 120 micron thickness.

Applications: Tabbing and stringing of all types of solar cells.

Platform: The J.v.G. Thoma Stringer is designed to be low maintenance and have ease of operation. The new model has been thoughtfully designed so that it can be easily repaired with compatible replacement parts - even from suppliers other than J.v.G. Thoma. It is also possible to upgrade to new technologies when needed – giving the model a longer working life when migrating to new multiple-busbar configurations.

Availability: Currently available.

Market Watch

News

China boom expected to lift 2017 global solar forecasts beyond 90GW

Credit: Sungrow

A boom in China is expected to push global PV deployment in 2017 to over 90GW.

Significantly higher than expected solar PV installation in China is driving global installation forecasts for 2017 to be revised upwards.

One of the first market research firms to update global forecasts for the solar industry has been IHS Markit, which expects 90GW of global PV installations in 2017, a 14% growth rate over the previous year.

Recently, China's National Energy Administration (NEA) had stated that in the first half of 2017 a total 24.4GW of solar was grid connected. Soon after, China Electric Council (CEC) reported that 2017 cumulative installations had reached 34.9GW by the end of July.

IHS Markit said it estimated that 26GW of installations were completed in China in the first half of 2017 and that it expects a further 12GW to be installed in the third quarter of 2017. For the full year, IHS Markit is forecasting China to install a total of 45GW in 2017.

Previous expectations of a slowdown in demand from China in the second half of the year had not materialised as 'Top Runner' and 'Poverty Alleviation' programmes replaced to some extent the first half year demand for utility-scale projects ahead of regular mid-year feed-in tariff reductions.

Indian manufacturing

India initiates solar anti-dumping investigation

India has officially started an investigation into the import of solar cells and modules from China, Taiwan and Malaysia.

The Directorate General of Anti-Dumping & Allied Duties (DGAD) received a petition from the Indian Solar Manufacturers Association (ISMA) in June calling for the investigation into anti-dumping to take place, followed by the imposition of anti-dumping duties.

Consultancy Bridge to India understands that the introduction of anti-dumping duties is not the only option being considered. Indeed DGAD is also looking at the possibility of bringing in safeguard duties. The difference is that safeguard duties can be brought in far quicker if it is proved that there has been a significant increase in imports that may be causing harm to domestic manufacturers. No evidence of unfair trade practices is required. Furthermore, safeguard duties are country agnostic and are imposed on all imports.

Indian manufacturers Indosolar, Websol, Jupiter Solar Power and Jupiter International led the petition. DGAD will consider a 15-month period from April 2016 to June 2017 to probe dumping and three-year financial data of the petitioning companies to analyse injury to domestic manufacturers.

China warns against Indian 'abuse of trade remedy measures' on solar

China has responded to India's initiation of an anti-dumping investigation relating to solar cells and module imports from China, Taiwan and Malaysia, labelling it an "abuse of trade remedy measures", but also seeking to cooperate in resolving the trade issue.

Wang Hejun, director of the Trade Relief Investigation Bureau of China's Ministry of Commerce, said in a statement that the Chinese government was highly concerned about the investigation, which relates to both thin-film and crystalline solar cells, including those within modules.

Hejun noted the importance of solar in addressing climate change, promoting rural electrification and eradicating poverty. Futhermore, as solar is an emerging industry, states should be working together to promote its sustainable growth rather than disrupting normal trade order, he added.

Hejun noted how India's impressive 370% growth in solar deployment over the last three years had benefitted from the price of Chinese equipment coming into India, adding: "The adoption of trade restrictions on photovoltaic cells and components is not conducive to the development of [the]photovoltaic industry in India."

Problems with India's newest domestic PV manufacturing support idea

India has proposed a new strategy of supporting its domestic solar manufacturers by allocating 7.5GW of local content tenders to Central Public Sector Undertakings (CPSUs), but analysts have identified a number of limitations.

India's original Domestic Content Requirement (DCR) policy is set to fully end on 14 September this year – following a World Trade Organization ruling – and Indian manufacturers are eager for other support schemes to take its place.

A report presented to a Lok Sabha committee reviewing India's 100GW by 2022 PV target stated: "Ministry of New and Renewable Energy (MNRE) has initiated a 2nd phase of CPSU scheme of 7,500MW, which provides for installation of entire capacity of solar projects based on domestically manufactured solar PV cells and modules. The scheme is under process of approval."

While clearly at preliminary stages, analysts at Bridge to India, Mercom Capital Group, and Gensol Solar, all said that CPSUs have struggled in the past to match solar tariffs offered by private developers and are often unwilling to buy power at a higher price.

Jasmeet Khurana, associate director, consulting at Bridge to India, said that the inclusion of a local content requirement would simply make CPSU-related projects even more uncompetitive, making it harder to find off-takers.

The Indian government's new support mechanism for domestic PV manufacturers has received a lukewarm response.

Credit: Tata Power Solar

Final US government grid report neuters support for renewables

The final US Department of Energy (DoE) report into the impact of renewables on the grid has tempered its backing for solar and wind compared to an earlier, leaked draft.

The 'Staff Report to the Secretary on Electricity Markets and Reliability,' released in late August, recommends investment in new coal, nuclear and hydropower generation. It echoes President's Trump's recent infrastructure mantra regarding the paring back of regulations and permitting requirements.

The report was commissioned by Energy Secretary Rick Perry in April with the objective of investigating the impact of increasing variable generation on the stability of the grid and electricity pricing. An earlier draft, leaked in July, appeared to allay concerns about the growing volume of deployed renewables.

"One of the benefits of renewable energy is that it can serve as a hedge for more volatile fossil-fuelled generation. Many customers seek a steady bill payment because it's easier to budget for and manage than a bill that varies by month. To the degree that renewable energy stabilizes the cost of an overall energy portfolio (or even just a customer's bill), that affects perceived affordability."

This paragraph has now been removed.

A section observing that technical studies have repeatedly found that high penetrations of variable generation sources can be integrated into the grid is now qualified with the following: "However, these studies (particularly those examining high VRE levels) may often assume (or ignore) modelled conditions that could be difficult and/or costly to achieve in practice, such as a large transmission buildout that may face siting or other obstacles, ability of non-wind and solar plants to remain financially viable and thus available, institutional changes, or, for one study, synchronization of all three interconnections."

Europe's solar manufacturing vacuum needs urgent action, says R&D and trade groups

The significant decline in the solar PV manufacturing supply chain in Europe in recent years has reached a critical condition, according to a string of R&D and trade groups in the region.

The European Technology and Innovation Platform for Photovoltaics (ETIP PV), EUREC – the Association of European Renewable Energy Research Centers – and Solar United, the global solar PV technology and industry association, as well as equipment manufacturers, materials providers and PV manufacturing companies have published an 'Open Letter from the European PV Community' to European policymakers to take urgent action to support the industry.

Although not a new claim, the recent bankruptcy of Europe's largest integrated manufacturer, SolarWorld AG, and the failure of anti-dumping duties on Chinese producers to maintain a minimum import price (MIP), due to circumvention by establishing production outside China and even in Europe, was a major concern to energy independence in the region, according to industry groups.

Marko Topič, ETIP PV Chairman stated: "Photovoltaics is transforming Europe's and the world's energy system. It is strategically important for Europe to maintain strong involvement in this technology and contribute to the energy union and sustainable energy independence in Europe."

The letter went on to highlight that the solar sector was of 'strategic importance for the EU economy, providing energy independence, industrial jobs and economic growth.'

Spain awards 4GW solar and 1GW wind in auction surprise

Spain has awarded 3,909MW of solar PV capacity and 1,128MW of wind capacity to 40 companies in its latest auction, which was originally set to be only a 3GW tender.

Spain's energy ministry noted that high demand from developers caused it to enact a clause allowing it to offer out more than the original 3GW. It said the extra awards would allow the country to "move definitively" towards meeting its 20% renewable energy targets in 2020, since all the projects must be completed by then.

All the capacity was awarded with the maximum discount available, proving that solar really did have a better chance in this second auction compared to the previous one. In the last auction, if there was a tie between wind and solar (both bid for maximum discount), the capacity would be awarded to wind.

The ministry stated: "The discounts obtained guarantee that the energy produced will be remunerated exclusively by the market – i.e without cost to consumers."

With both major auctions combined, Spain has now awarded 8,037MW of renewable energy capacity evenly spread across wind (4,107MW) and solar (3,910MW), with 20MW going to other technologies.

Australian regulator dumps solar tax proposal to avoid 'death spiral'

The Australian Energy Market Commission (AEMC), responsible for regulating the energy market, has dropped a proposal to let power network companies charge rooftop solar owners for feeding their electricity to the grid in a form of 'solar tax', after facing resistance from communities.

Shani Tager, senior solar campaigner at PV support group Solar Citizens, said: "It was an outrageous proposal to begin with and has been rightly taken off the table. 2,500 solar owners across Australia made it very clear to the AEMC that this was an unacceptable approach and they should not be charged for exporting their clean solar power to the grid.

"The big power stations don't have to pay to export the energy they generate to the grid and solar households shouldn't have to pay either."

Tager said this is the second time that the AEMC has attempted to introduce similar charges and withdrawn after facing opposition from solar owners.

Technologies driving the new 100GW annual PV solar world

Finlay Colville, Head of Market Research, PV-Tech & Solar Media Ltd.

ABSTRACT
The solar industry is on track to produce and ship 100GW of solar modules during 2017, reaching this landmark achievement many years ahead of previous industry consensus. With no sign of capital investments slowing down in 2018, this article takes a close look at the factors that have propelled 2017 solar production levels to the 100GW mark, in addition to the companies and technologies that make up mainstream module supply today. Data and graphics are presented also, to help explain what to expect from PV manufacturing over the next 12 to 18 months.

During 2017, the PV industry is forecast to produce and ship close to 100GW of solar modules, reaching this key milestone well ahead of all market forecasts previously projected. Furthermore, the explosive growth of solar PV shows no sign of abating, despite the constant threats and barriers imposed by ongoing trade import restrictions.

This article examines the key factors driving the industry to 100GW in 2017, analysed both from the supply and demand sides, with a focus on the technologies being used in manufacturing today. This is compared to estimates of technology market shares when the industry first moved through the 10GW mark.

The focus on technology improvement is explained also, in particular the factors behind the strong capital expenditure (capex) levels being seen this year, including the constant need for upgrades and efficiency enhancement.

How did the solar industry get to 100GW of module production?

Just a few years ago when the solar industry was moving towards 50GW of annual production (see for example, "Global PV demand to exceed 50GW in next 12 months, says NPD Solarbuzz", as reported on PV-Tech.org in April 2014), many observers considered this forecast alone to be highly ambitious, given the legacy challenges with demand-constrained and government-adjusted feed-in tariff schemes in Europe.

During 2014, and indeed up until quite recently, forecasts for annual module supply in 2017 ranged anywhere from 50GW to about 80GW, with many suggesting the China market would contract possibly creating negative growth projections.

When historians look back at the solar industry of 2017 and 2018, and the reality

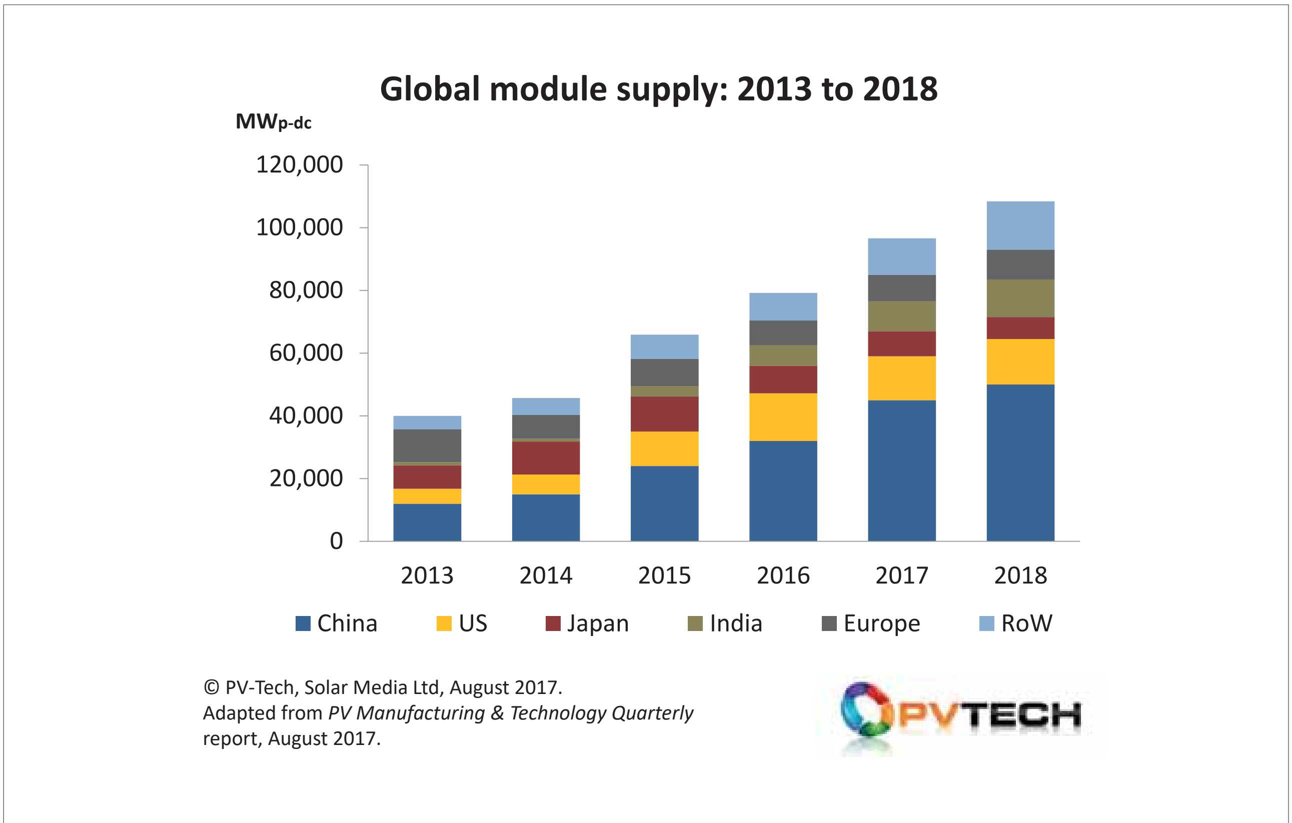


Figure 1: Solar PV module production and shipments during 2017 are expected to approach the 100GW level, double the levels seen just three years ago. This is mainly being stimulated by manufacturing and deployment in China that remains largely supply-driven in a self-contained climate.

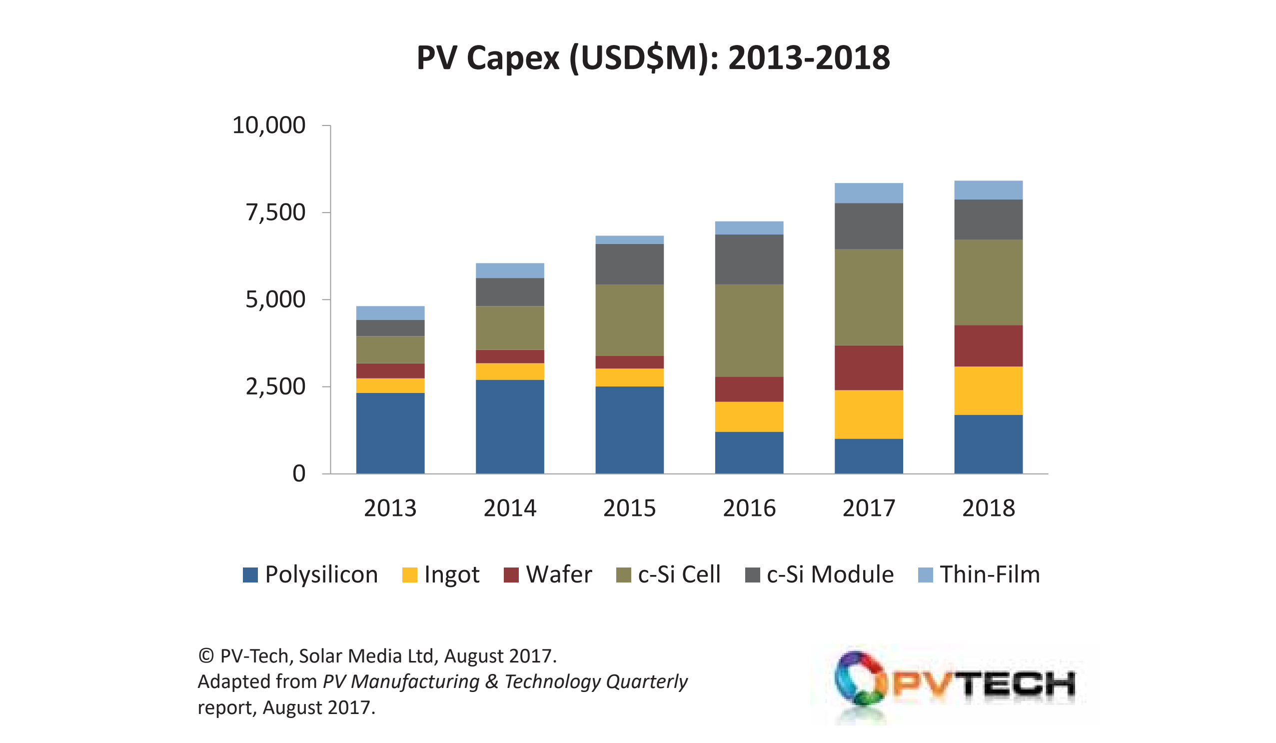


Figure 2: Capital expenditure, or capex, has been increasing strongly since 2014, with investments going into each stage of the value-chain at different periods. Recently, capex has seen greater contributions from technology upgrades, including diamond wire saws and tools for PERC cell lines (deposition and laser based).

of a 100GW module production climate has sunk in, perhaps the single driving factor in moving from 50GW to 100GW annually will be China: both from a manufacturing standpoint and as the route of module shipments and site deployment.

Figure 1 shows the current forecast from the in-house market research team at PV Tech and Solar Media Ltd., as it relates to geographic module shipments. This type of forecast is one of the most accurate currently for the solar industry, as the legacy (somewhat academic) route of waiting for government data on grid interconnection data has been shown to be misleading, out of synch and inaccurate.

Module supply is likely to exceed 95GW in 2017, with actual module production close to the 100GW mark. Incredibly, almost half of all module shipments will be for the Chinese market, and virtually all of these modules (including ingots, wafers, and cells) manufactured domestically. This is equivalent to the entire solar industry of just three years ago (2014) being placed inside one country during 2017.

The implications of this are only starting to be felt by all key stakeholders across both upstream and downstream channels of the solar industry, and it is unlikely that the dust will have settled by the time we enter 2019 or 2020.

The remainder of this article now looks more closely at the impact on PV manufacturing, technology and the factors behind the strong push to new cell concepts, high-efficiency performance and increased module power ratings.

Capital expenditure trends confirm investment confidence

Capex is known as one of the key leading indicators behind investor and manufacturer confidence, and current profitability levels. Manufacturing capex broadly has a few components, and each of these is typically important when viewing new site investments and technology improvements.

When PV manufacturers go through downturns that impact cashflow, capex is normally one of the first operating metrics to be cut to a minimum. This is actually in contrast to adjacent technology sectors (most notably semiconductor), when this phase will spur increased investments for next-generation tools and fabs. For solar manufacturers, capex during downturn phases is largely based on maintenance-only spending, with recently minor upgrades to include the move from three to five busbars, adding automation or general debottlenecking of process tools. This environment permeated PV manufacturing between 2012 and 2013, prior to the onset of the 50GW-plus annual industry demand climate.

As shown in Figure 2, the growth in capex from 2014 has been particularly strong, and this reflects the main two components of capex that have been instrumental not just in enabling the supply of approximately 100GW of modules in 2017, but also in moving module offerings to higher efficiencies and larger panel sizes.

These two elements of capex are new capacity and technology upgrades. All of the leading ingot-to-module producers in the PV industry today have made significant investments in each of these areas.

The mono-PERC transition is only the beginning

Until just last year, the solar industry was dominated by the supply of c-Si modules (mostly 60- or 72-cell configuration) assembled from p-type solar cells, produced with a full-aluminium back surface field. This 'standard' cell design was popularized some 10 years ago by the two countries that pushed cell production to the multi-GW level (China and Taiwan). Wafer supply was controlled by GCL-Poly, and the low-cost structure of this value chain was critical to the rate that module suppliers could expand shipment levels globally.

The fact that mono wafer use leads inherently to higher cell efficiencies and increased panel power levels comes as no surprise to anyone. The issue always however was supply related, and the existence of major multi-GW ingot pulling plants, located in low-cost regions. This all changed during 2016, when the very real ambitions of LONGi Solar and Zhonghuan Semiconductor became clear.

The other driver for increased mono use has come from the cell producers, and the desire to change rear surface processes and materials to allow for the increased cell efficiencies from the passivated emitter and rear contact (or

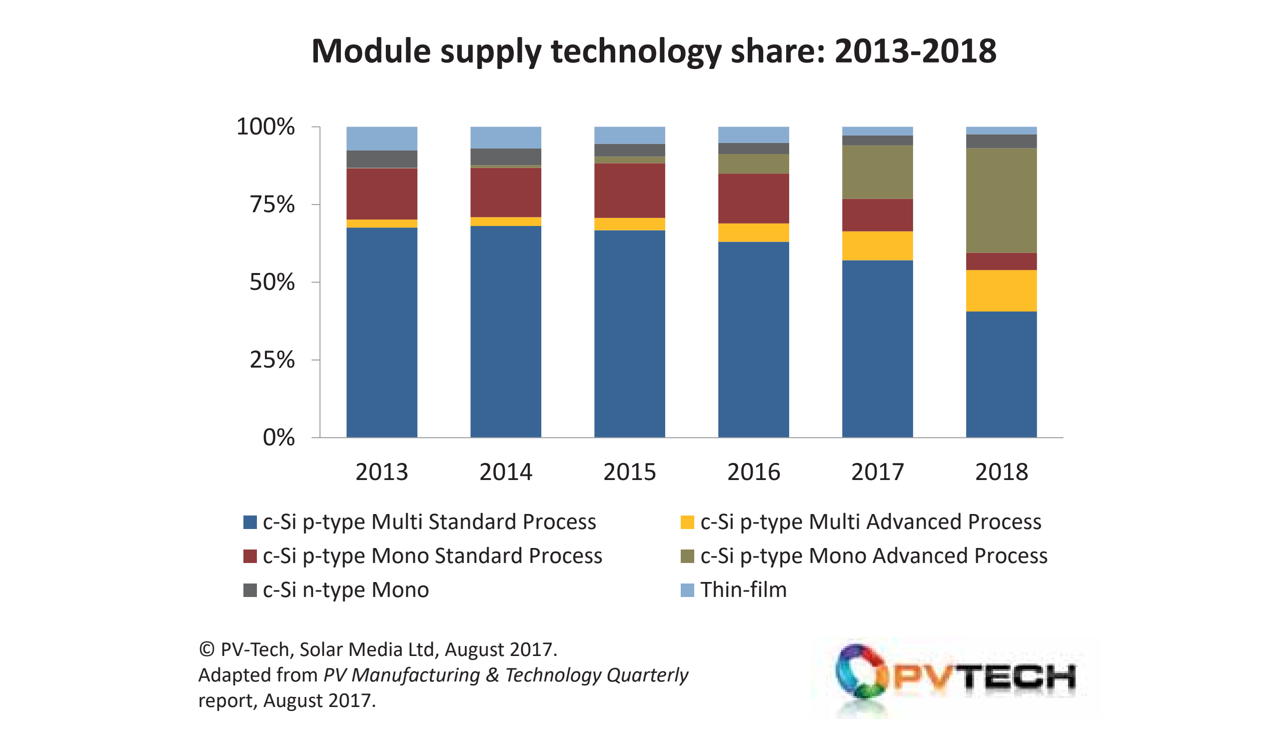


Figure 3: Until recently, most modules being shipped were based on standard p-type multi cells, assembled in 60- and 72-cell module sizes. During 2017 and 2018, the migration to mono-PERC based modules will become more visible, with glass/glass and bifacial designs lined up as the next potential technology node for c-Si suppliers.

PERC) structure that had been pioneered at the University of New South Wales (UNSW) back in the 1980s.

The twist to this story however is that the cell/module producers that drove this change in the industry for mono cell producers actually came from the first two companies to offer volume supply of PERC modules, Hanwha Q CELLS and REC Solar, both of whom were loyal p-multi manufacturers and as such developed the PERC recipe to work on multi, not mono.

As with almost every cell line change, mono has increased processing windows compared to multi, and this is largely what has driven the Taiwan and Chinese cell makers to adopt mono-PERC as the go-to next-generation cell technology for 2017 and 2018. This is shown in Figure 3, where the 'Advanced' categories for both p-multi and p-mono are dominated by PERC upgrades or new capacity specified from the start at p-mono PERC.

Currently, there are a couple of factors holding back mono-PERC from being the main technology used in module supply to the industry. First, wafer availability is still limited, despite the multi-GW of new mono pullers being installed by both LONGi Solar and Zhonghuan Semiconductor in China. The other issue is cell related and the time it is taking most companies to work out how to ramp up PERC-based tools for desired yield, quality and performance levels.

PERC upgrades will continue to dominate the industry during 2017, 2018 and most likely through to the end of 2019. By this time, it is likely that all p-type solar cells (both mono and multi) will have rear surfaces comprised of passivation layers and local contact openings. If this transpires, then PERC will be seen as the catalyst to opening up bifacial module capability, and glass/glass being standard on ground-mounted solar sites. This change however is not expected until 2019-2020, with downstream developers and EPCs also needing to go through a rapid learning curve regarding the energy yield levels that can be predicted and realized in practice.

Which companies are leaders in module supply in 2017?

Solar module supply remains highly fragmented, with still a few hundred module suppliers seeking to sell products globally. Consolidation remains largely non-existent, with no meaningful mergers or acquisitions having taken place yet in the industry. The closest the solar industry has come to this has been some of the cell makers in Taiwan being consolidated in the past few years.

Rather, if anything, the industry continues to see new module producers being added to the mix, largely in China but also across Southeast Asia as a working vehicle to avoid the made-in-China/made-in-Taiwan labels on shipments headed for Europe and the US.

However, when we look at the leading module suppliers by volume in 2017 (and indeed 2018), there is certainly a divide opening up between the top few and all the rest. This comes over most notably in the categorization we created at PV Tech a few years ago, under the banner of the Silicon Module Super League (SMSL). This was done as a means of segmenting those module suppliers expected to ship in excess of 4GW each during 2017, a figure well ahead of any other module supplier. This grouping (all c-Si and almost exclusively p-type) is largely a Chinese affair, comprised of Canadian Solar, GCL Systems Integration, JA Solar, JinkoSolar, LONGi Solar and Trina Solar. The final member of this grouping is Korean-run Hanwha Q CELLS, a company that started life as Chinese cell/module manufacturer Solarfun.

Figure 4 shows our module supplier rankings for 2016, with most of these companies likely to be included in 2017 also. For interest, we have also shown our estimate of the top-10 module suppliers of 2016, once we exclude all shipments to the Chinese market. For many of the companies with manufacturing outside China, the 'other-50GW' of global supply (excluding the Chinese market) does have a different supply-base, pricing and technologies being shipped to utility-scale solar sites.

Module changes are not without questions

With the solar industry dominated by utility-scale solar, the success of much of the 100GW of solar modules

航天机电 HT-SAAE

High-Efficiency Poly-Crystalline PV Modules

Hyper Black

Leaving The Past Behind

Black silicon cell
Nano texture method leads to higher cell efficiency
Uniformity in the cell's overall appearance

5BB cell
Lower series resistance
Higher module efficiency

Microcrack protected /PID protected
Triple EL tested for high quality control
Applied anti-PID cell and high reliability encapsulation material

280W
Output power can reach 280W and above for 60-cell module

20%
Cell efficiency level for mass production up to 20% and above

9.6%
Output power increase of 9.6% per unit area (compared with 260W)

4.8%
A 4.8% BOS reduction per Watt (compared with 260W)

*48pcs,60pcs,72pcs modules and other options available

SUSTAINING INNOVATION SINCE THE 1960s

Shanghai Aerospace Automobile Electromechanical Co., Ltd.
Web：www.ht-saae.com
E-mail：pvmarketing@ht-saae.com

FORTUNE 世界 500 | Bloomberg TIER 1

FORTUNE 世界 500	Bloomberg TIER 1	60YS Based on nearly 60 years experience in solar technology R&D by CASC	10 million+ 10 million+ USD R&D investment per year	1.8 billion+ Corporate ' s total assets is over 1.8 billion US dollars	100+ Over 100 independent intellectual property rights for cell & module	600+ Established over 600 PV power plants in China and overseas

* All above information on technical parameters is for reference only. HT-SAAE reserves the right to modify.

Leading module suppliers to the China/non-China industry of 2016

	2016 Global	2016 China Only	2016 Non-China
1	JinkoSolar	GCL-SI	Trina Solar
2	Trina Solar	JinkoSolar	Hanwha Q-CELLS
3	Canadian Solar	JA Solar	Canadian Solar
4	JA Solar	LONGi Solar	JinkoSolar
5	Hanwha Q-CELLS	Trina Solar	First Solar
6	GCL-SI	*There were more than 25 companies in the 500MW - 1.5GW level, with the top companies too close to rank with accuracy.*	JA Solar
7	First Solar		SunPower
8	LONGi Solar		SolarWorld
9	Yingli Green		REC Solar
10	Shunfeng (incl. Wuxi Suntech)		Shunfeng (incl. Wuxi Suntech)

Adapted from *PV Manufacturing & Technology Quarterly* report, August 2017.

Figure 4: Module supply in 2016 was dominated by the seven members of the Silicon Module Super League (SMSL), the exclusive grouping of companies now forecast to each ship above 4GW of modules in 2017.

produced in 2017 will be based upon their reliability over 20 years in the field. This is not a new concept, but it becomes even more critical when so many changes are being made with wafer supply, process flows and new materials used for cells and assembled modules.

In fact, it is necessary to add into the mix here the actual companies that are assembling much of the modules and the trend in recent years to outsource large portions of shipment volumes to new factories built in countries such as Vietnam and Thailand.

Whereas in the past, module makers would often cite an isolated factory audit or certification and testing based on one product type made 100% in-house, this partial means of company validation becomes somewhat questionable if more than 50% of cells and modules are made in a factory in a different country, run by a low-cost new entrant with little or no previous solar manufacturing expertise.

Unless some kind of standardization in processing, assembly, testing and certification is done, we are potentially heading for an even greater phase of risk in module supply, if we add in bifaciality or n-type cells and modules coming from China.

PV CellTech and PV ModuleTech events to capture new industry landscape

A few years ago, we recognized at PV Tech that the industry was still awash with meaningless conferences (added on to trade exhibitions), purely academic events with some blue-sky manufacturing R&D, and downstream finance gatherings where accounting metrics were typically the order of the day. Hearing about mass production technology issues from the industry's leading CTOs and heads of R&D was something many thought was confined to semiconductor or displays events.

This prompted us to organize PV CellTech, and the event will be in its third year in March 2018 in Penang, Malaysia. The focus will remain on examining the mass production trends in technology from the industry's leading wafer and cell manufacturers, and what 100GW of cell production will really look like in 2018 and 2019.

During the past couple of PV CellTech events, a great many attendees and industry stakeholders requested us to organize a 'module and downstream' equivalent of PV CellTech, where the module supply side was explained and understood in equal depth, but with the big focus being on module reliability, testing , certification, benchmarking, and field-driven analysis.

The result of this is PV ModuleTech, with the first event in Kuala Lumpur, Malaysia, on 7-8 November 2017. In addition to hearing from the silicon module super league, and most of the global top-20 module suppliers for 2018, the event will see the leading certification bodies, testing agencies, EPCs, developers and O&Ms say exactly what they are seeing in terms of module reliability for utility-scale solar, and what they need from the GW-level module suppliers in terms of the new module architectures that are set to become available in volume in the next few years.

Ultimately, the success of the industry in general comes from utility-scale return-on-investment, and this can only increase in scope when an increasing number of countries move to a subsidy-free environment where solar competes on a level playing field with other forms of renewable energy. The rate at which the solar industry moves from 100GW to 200GW will ultimately be based upon how well the investor community is satisfied that operating assets in the pre-100GW solar world have performed and what additional yields can be expected from the higher-performing module options going forward.

PV ModuleTech will be held on 7-8 November in Kuala Lumpur, Malaysia. Further information is available at moduletech.solarenergyevents.com

About the Author

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

R&D spending analysis of key PV module manufacturers in 2016

By **Mark Osborne**, Senior News Editor, Photovoltaics International

ABSTRACT
The total R&D expenditure by 12 major PV module manufacturers tracked for the last 10 years declined around 4.4% in 2016, having reached a record level in 2015. Dedicated R&D employee levels declined around 9.5%. Lower spending at five manufacturers and lower headcounts attributed to six manufacturers were behind the downward trends.

R&D spending patterns

Combined R&D expenditures of 12 major PV module manufacturers in 2016, tracked since 2007, decline by approximately 4.4% in 2016 to US$519.3 million (see Figure 1), compared to US$542.9 million in 2015. As 2015 expenditures were a new record high, 2016 becomes the second highest year of spending and 2014 the third highest. All three years highlight total combined annual R&D expenditures above US$500 million.

Interestingly, two expenditure peaks, both above the US$500 million mark have occurred in the last 10 years with 2011 standing out at US$510 million, the first time the US$500 million mark was exceeded, and five years later in 2015, when a second peak occurred.

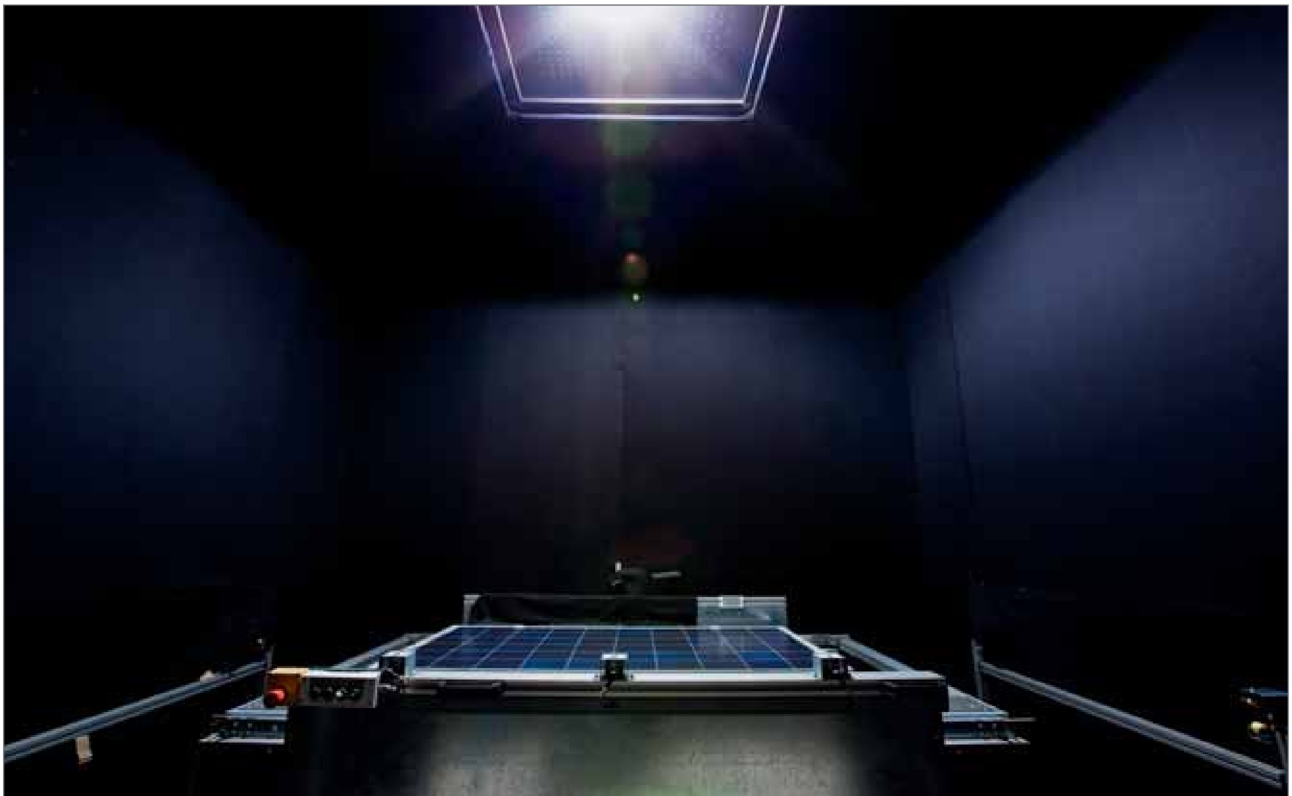
There were four manufacturers that reduced R&D spending in 2016 (see Figure 2): First Solar, Yingli Green, ReneSola and REC Group. All four had also reduced R&D spending in 2015 from 2014 levels. R&D spending bottomed in 2013, after the PV industry had been through its worst period of overcapacity in 2012; that year saw six companies reduce spending, many for the first time, with overall spending reaching a low in 2013.

Notable in the expenditure decline year-on-year were Yingli Green, ReneSola and First Solar, which reduced spending by 65.4%, 37% and 4.4%, respectively. Explanations for these companies' spending declines will be covered below in the individual company breakouts.

The overall increase in spending in 2014 and 2015 had led to more companies spending above the US$20 million mark annually, which left only two companies (Canadian Solar and REC Group) below that level. With REC Group estimated to have reduced spending slightly in 2016 and Canadian Solar making a marginal increase but below the US$20 million mark, no changes at this low level occurred in 2016.

Trina Solar was estimated to have moved into the above US$40 million to US$60 million range in 2016, which was populated by ReneSola and Hanwha Q CELLS in 2015. However, with ReneSola significantly reducing expenditure, only Trina Solar and Hanwha Q CELLS populated the US$40 million to US$60 million range in 2016.

The US$20 million to US$40 million range is now the most populated with six companies (SolarWorld, ReneSola, JinkoSolar, Suntech, Yingli Green and JA Solar). These six manufacturers are clustered tightly together with the lowest



R&D spending by some of the world's leading module manufacturers has fallen in the past year.

Credit Hanwha Q CELLS

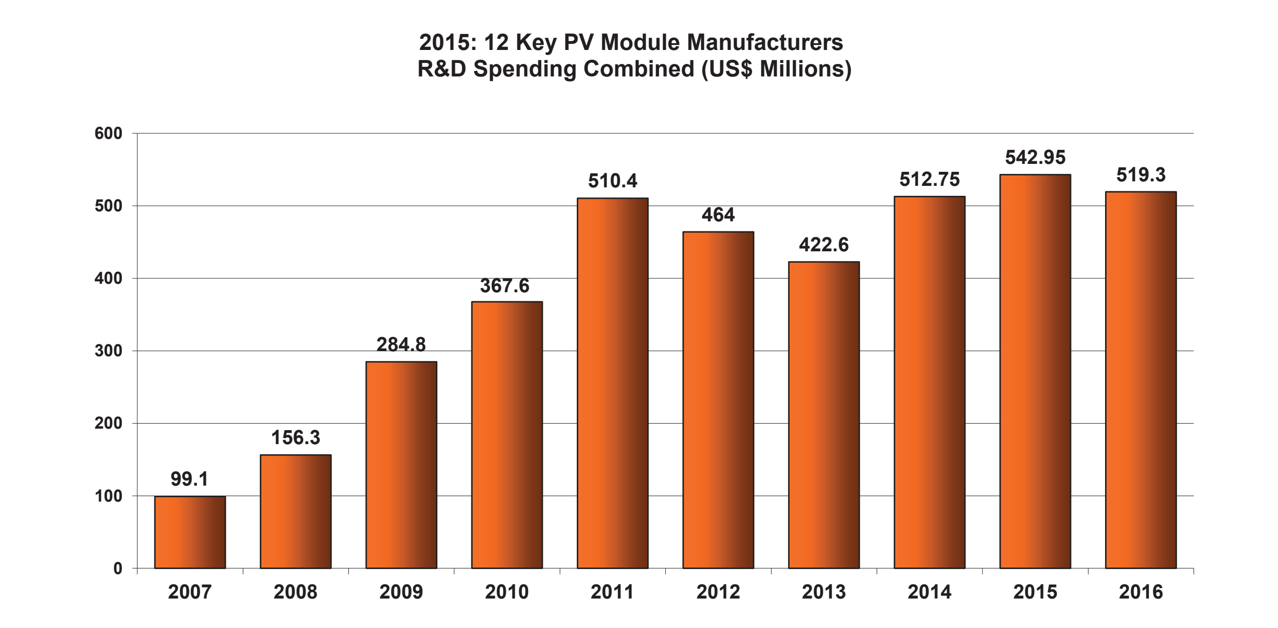


Figure 1. Combined R&D expenditures of 12 major PV module manufacturers in 2016.

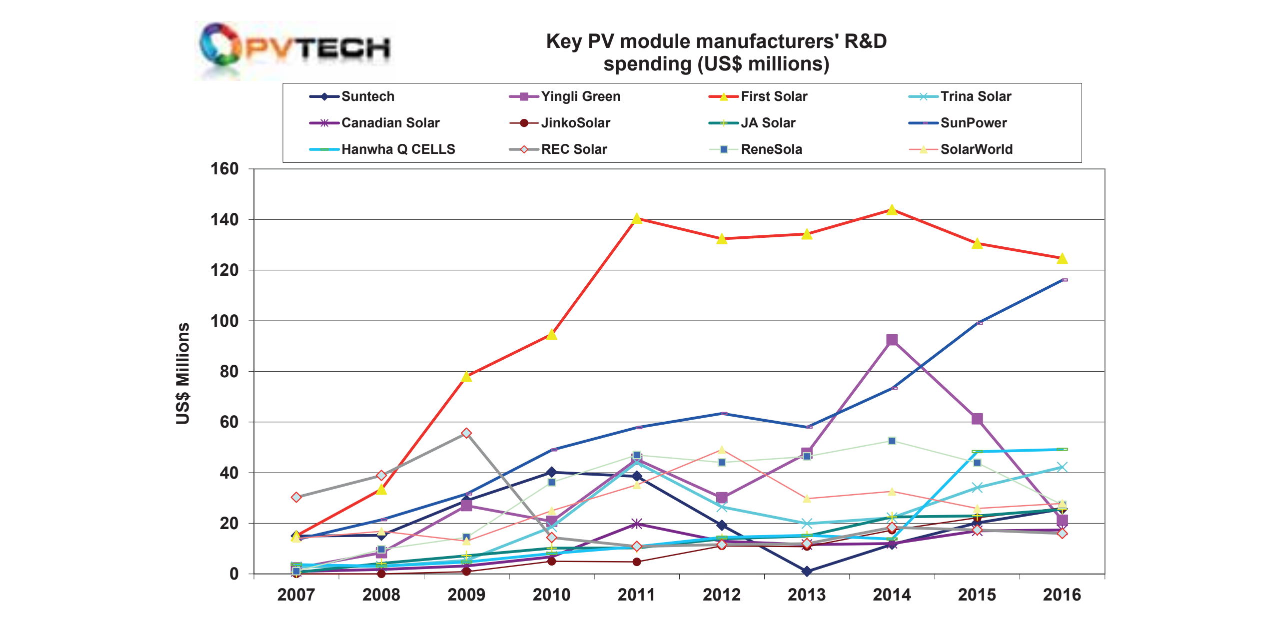


Figure 2. R&D spending levels of 12 major PV module manufacturers in 2016.

spender in this bracket being Yingli Green with US$21.2 million spent on R&D activities in 2016 and the highest, SolarWorld, spending US$27.9 million.

In relation to the two manufacturers (First Solar and SunPower) in the top echelons of R&D expenditure, the gap between the two has closed significantly for the first time. With First Solar reducing spending for two years in a row and SunPower increasing spending three years in a row the two were separated by only US$8.6 million, compared to US$31.6 million in 2015 and US$70.6 million in 2014.

Both First Solar and SunPower spent over US$100 million each on R&D activities in 2016, which was the first time for SunPower (US$116.1 million) and the sixth time (consecutively) for First Solar (US$124.7 million).

On a year-on-year R&D expenditure increase basis, Trina Solar was estimated to have increased spending by around 24%, while Suntech and JinkoSolar reported the same 17.5% increase and SunPower a 17.3% increase. Other manufacturers (Hanwha Q CELLS, Canadian Solar, JA Solar and SolarWorld) increased spending in the single-digit percentage range.

R&D staffing patterns

A key difference in 2016 to previous years covered by this report was the higher decline (9.5%) in the number of employees designated to R&D activities than when R&D expenditure also declined but at a lower rate (4.4%, see Figure 3).

After a major decline in the number of employees designated to R&D activities in 2013, staffing levels have rebounded strongly. Having reached an initial headcount peak in 2011 of 3,575, numbers declined to a low of 2,911 in 2013. With higher spending came increased staffing, as well as the previously highlighted re-designation of R&D personnel at Yingli Green in 2010 and Trina Solar in 2014, which significantly weighted overall staffing levels higher.

A total of eight manufacturers in 2015 added R&D headcount. However a total of nine manufacturers (including estimated) reduced R&D headcount in 2016 (see Figure 4). These included manufacturers (Trina Solar, JA Solar,

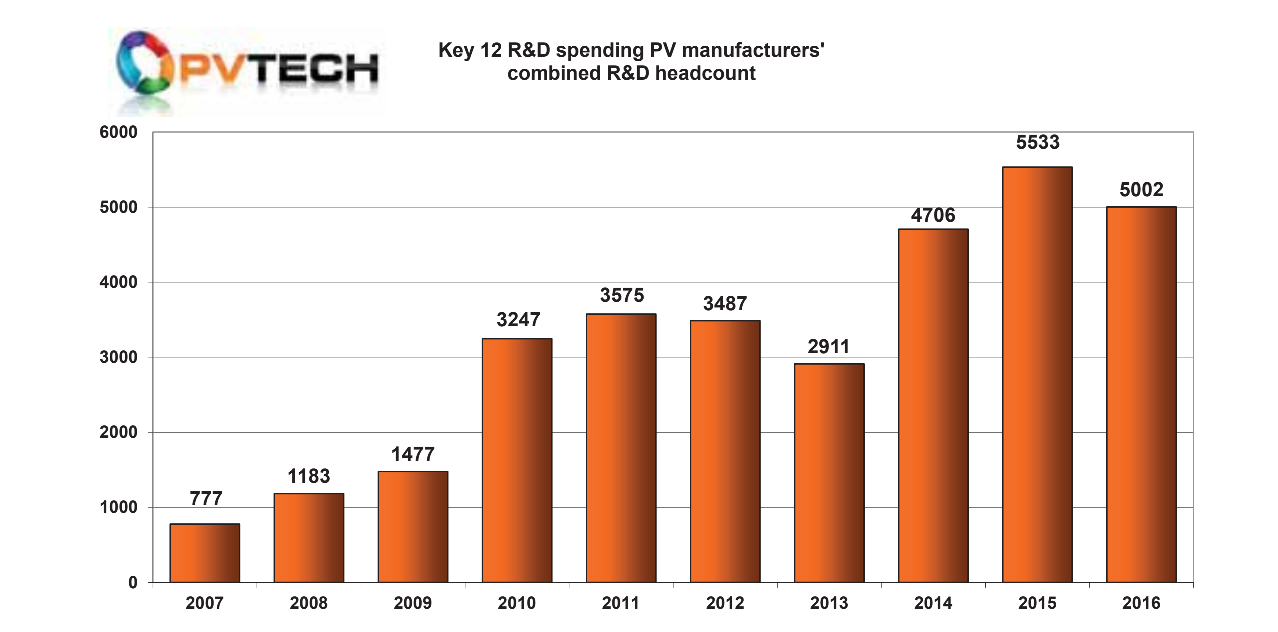


Figure 3. Key 12 R&D spending PV manufacturers' combined R&D headcounts in 2016.

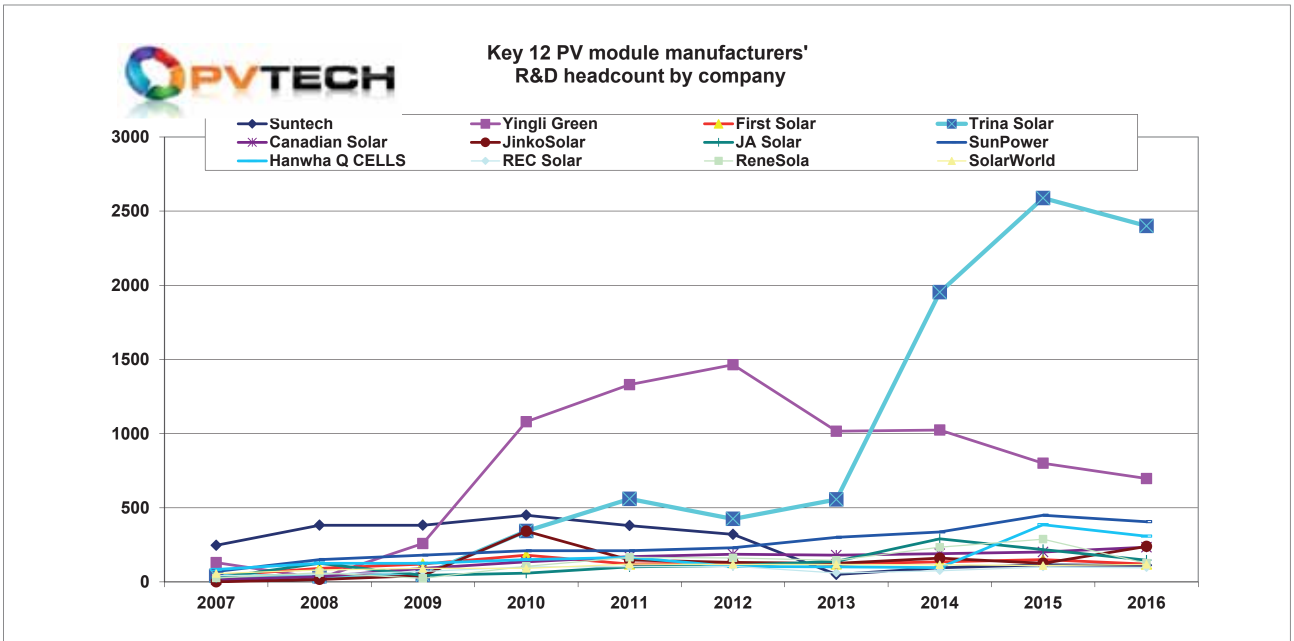


Figure 4. Key 12 PV module manufacturers' R&D headcount by company in 2016.

SunPower and Hanwha Q CELLS) that actually increased R&D spending in 2016.

The four manufacturers (First Solar, Yingli Green, ReneSola and REC Group) that reduced R&D spending in 2016 also reduced R&D headcount in 2016. It should be noted that both First Solar's and REC Group's headcounts are estimated and the reductions negligible.

The standout reductions in R&D headcount come from ReneSola (162), Yingli Green (103), Trina Solar (188 estimated), Hanwha Q CELLS (78) and SunPower (43).

The R&D headcount reductions in 2016 from the four highlighted manufacturers are generally due to restructuring, cost reductions and business transitions. In the example of Yingli Green, a major restructuring has been underway, resulting in a massive 3,908 headcount reduction by the end of 2016. A company in transition away from manufacturing, ReneSola also reduced its overall employee headcount by 524 in 2016. Ongoing cost reduction strategies at Hanwha Q CELLS led to 1,901 job losses in total in 2016.

In contrast, SunPower actually increased its overall headcount in 2016 by 1,714. However, SunPower has since closed facilities and is undergoing a major restructuring effort.

The total number of employees designated to R&D activities from the 12 PV module manufacturers tracked was 5,002 in 2016, down from 5,533 in 2015, a decline of 531 or 9.5%.

R&D spending rankings in 2016

Once again there were certain changes to the spending rankings (see Figure 5) as cuts impacted the middle cluster of manufacturers; but while the gap at the top may have closed sharply, there were no changes to the rankings for the first and second positions in 2016.

First Solar

First Solar once again has been ranked first in annual R&D spending, making it the eighth consecutive year for the CdTe thin-film module manufacturing leader, despite a second year of expenditure reductions, and confirming the view highlighted in the 2015 report that R&D spending would seem to have peaked in 2014.

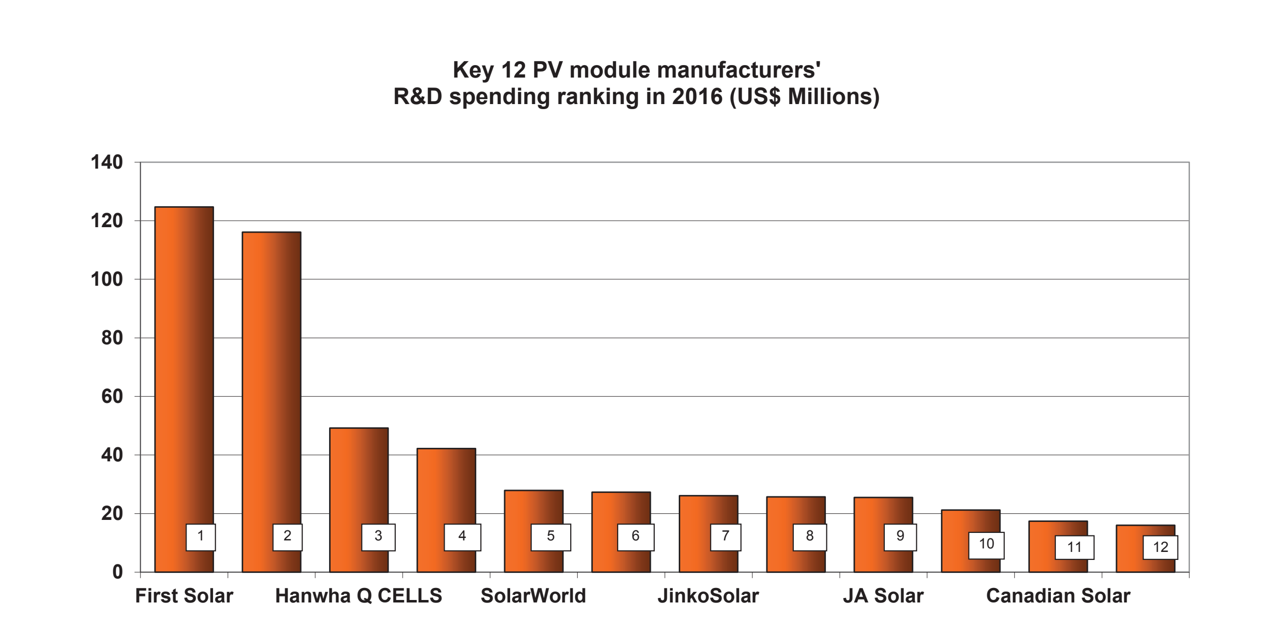


Figure 5. Key 12 PV module manufacturers' R&D spending ranking in 2016 (US$ millions).

The decrease in R&D expenditure was partially due to a lower R&D headcount but also because of the emphasis shifting to capital expenditure to completely migrate all manufacturing (including new build) to its next-generation Series 6 CdTe modules. The company is also placing less emphasis on PV system development, such as trackers, preferring to collaborate with leading third-party suppliers, especially with the Series 6 module transition.

The company is continuing to operate its 'vertical integration' R&D model from advanced research to product development through to manufacturing roll-out, which includes continued module conversion efficiency improvements, despite the large-area module format change.

SunPower

SunPower was ranked second in 2016, the second consecutive year for the company, whose IBC (Interdigitated Back Contact) cell technology still offers the highest efficiency solar cells and modules.

In fairness to SunPower, apart from one year (2014) when Yingli Green outspent it on R&D it had easily been the second highest spender since 2010. The boost in spending in 2016 does not correlate to increased R&D staffing levels; instead it relates to its P-Series module and new PV systems development and roll-out for residential, commercial and utility-scale downstream markets.

The increase can also be attributed to establishing a new R&D facility at its headquarters in San Jose, California. Only recently has SunPower said that it had invested around US$25 million in the last 12 months on the facility, which includes several high-volume production-sized manufacturing tools and automation, and specialized testing equipment, designed to support its next generation of high-efficiency n-type monocrystalline IBC solar cells and modules. The new facility was said to be housing around 100 engineers and support staff.

Hanwha Q CELLS

Despite an R&D headcount reduction, Hanwha Q CELLS moved up the rankings in 2016, after spending almost US$50 million and due to Yingli Green's continued drastic spending cuts as it restructures. The company was ranked third in the spending rankings in 2016, up from fourth in 2015.

Its R&D focus continued to be centred on p-type multicrystalline PERC and mono-PERC cell efficiency gains and production cost reduction initiatives such as migrating all capacity to the larger (156.75mm by 156.75mm) wafer size.

Average p-type multi PERC cell conversion efficiencies have reached 20% and 22% for p-type mono PERC cells. Other R&D efforts have continued on LID and PID process limitation.

Trina Solar

Increased R&D spending in 2016 helped Trina Solar jump from sixth in 2015 to fourth in 2014. The company also benefited from the spending cuts by Yingli Green and ReneSola to move up two ranking positions.

Trina Solar had increased R&D spending in the first half of 2016, compared to the prior year period. However, due to delisting from the NYSE the company was not obliged to provide further quarterly reports or a 2016 annual report.

This meant that full-year 2016 R&D spending figures and R&D headcount numbers were estimated based on the first half year, publicly reported details.

Recently, Trina Solar reported that R&D efforts with n-type monocrystalline IBC solar cells had led to a conversion efficiency of 24.13%, which was verified by the Japan Electrical Safety & Environment Technology Laboratories (JET). This was produced on 156×156mm solar cells with a low-cost industrial IBC process, featuring conventional tube doping technologies and fully screen-printed metallization. In December 2014, Trina Solar announced a 22.94% total-area efficiency for an industrial version, large size (156x 156mm^2, 6" substrate), IBC solar cell.

The company has also been developing PERC and bifacial cells in recent years and reported in 2016 that it had achieved a new world conversion efficiency record of 22.61% for a high-efficiency p-type monocrystalline PERC solar cell, independently confirmed by the Fraunhofer ISE CalLab in Germany.

SolarWorld AG

SolarWorld AG increased R&D spending to US$27.9 million in 2016, up from US$25.9 million in the previous year. Also benefiting from spending cuts at Yingli Green and ReneSola, the company was ranked seventh in 2015 but moved up two positions to fifth in 2016.

The company has focused resources on high-efficiency p-type multicrystalline and monocrystalline PERC solar cell development in recent years including bifacial cells. However, the company realigned to focus on mono-PERC and bifacial technology.

SolarWorld had achieved average efficiencies of over 22.0% with PERC cells manufactured on its high-throughput pilot line with 5BB and M2 large area 156mm x 156mm wafers. SolarWorld was working on conversion efficiencies above 24.0% that retained screen-printing PERC and other process improvements.

However, in May 2017 the company entered insolvency proceedings but its German manufacturing and R&D operations were acquired by the founder and chairman of SolarWorld AG, Frank Asbeck, which included manufacturing and R&D operations under the subsidiaries SolarWorld Industries Sachsen GmbH, SolarWorld Innovations GmbH as well as SolarWorld Industries Thüringen GmbH.

The new company, SolarWorld Industries, plans to continue to focus on mono PERC and bifacial cell R&D and production in partnership with Qatar Solar Technologies, its new 49% shareholder.

ReneSola

With ReneSola cutting both R&D expenditure and headcount in 2016, it was relegated to fifth from fourth in the rankings, spending US$27.3 million that was primarily attributed to continued development of technologies to manufacture high-conversion efficiency solar cells with improved performance.

The company was able to achieve conversion efficiency rates of 21.1% for p-type monocrystalline cells and 18.6% for p-type multicrystalline cells manufactured using its in-house-developed solar wafers.

However, ReneSola is transitioning its business to become a downstream PV project developer and in 2017 has announced a potential sale of its manufacturing and therefore main R&D operations.

JinkoSolar

Having been a perennial low spender, JinkoSolar was ranked seventh in 2016, up two ranking positions from ninth in 2015, after spending US$26.1 million on R&D compared to US$22.2 million in the previous year.

The company outstripped spending by JA Solar in 2016 and was supported by the spending cuts forced upon Yingli Green as it restructured its operations.

JinkoSolar began research on its "Eagle+" solar modules, which are expected to have multicrystalline cells that reached conversion efficiencies of approximately 20.4% in lab tests by a third party in 2016. The company has also achieved a record p-type multicrystalline cell efficiency of 21.63% in 2016.

The company also made a decision to increase p-type mono PERC R&D including migrating to diamond wire and 'black silicon' texturing.

Wuxi Suntech

Wuxi Suntech, now the PV module manufacturing arm of Shunfeng International Clean Energy (SFCE), increased R&D spending to US$25.7 million in 2016, up from US$20.2 million in 2015 after full integration into SFCE.

R&D activities have focused on continued efficiency improvements for PERC cell technology. The company has achieved an average cell efficiency of over 21%, and a champion cell efficiency of 21.3% in production.

The company continues to collaborate on a hydrogenation process with UNSW and confirmed the development and testing with Taiwan Carbon Nanotube Technology Corporation (TCNT) of a high-strength, lightweight carbon and glass fibre composite PV module frame, the first such development of its kind in the PV industry.

JA Solar

Although JA Solar increased R&D spending in 2016 to US$25.5 million, up from US$23 million in 2015, it was ranked ninth compared to eighth in 2015.

Importantly, JA Solar is the only manufacturer in the group that has increased R&D spending consecutively for the last 10 years, a remarkable feat, considering the dynamics of the PV industry.

The company has continued to develop high-efficiency multi and mono technologies having introduced its monocrystalline PERCIUM series utilizing PERC technology and its multicrystalline RIECIUM series utilizing 'reactive ion etching' texturing to enable the use of diamond wire technology on multicrystalline wafer. The technologies offer average conversion efficiencies of over 21.0% and 19.2% respectively.

A key focus in 2016 was bifacial PERC-based cell and module development, which led to new product introductions in early 2017.

Yingli Green

Major financial issues have forced Yingli Green to drastically cut costs across its entire operations in the last two years. With R&D spending cuts, Yingli Green was ranked tenth in 2016, down from third in 2015.

However, Yingli Green continued to invest in its Project PANDA, a research and development venture for next-generation high efficiency monocrystalline PV cells, established back in June 2009. The company noted that by the end of 2016, it had achieved an average cell conversion efficiency rate of 20.8% on the PANDA (n-type mono PERT) commercial production lines.

Further development is ongoing to improve n-PERT cell performance with doping, passivation and metallization enhancements. Yingli's roadmap is aiming for 22% efficiency in an n-PERT cell for production.

The company also had its PANDA bifacial module receive China's 'Front Runner certification at the end of 2016 and is aiming to develop a bifacial cell with bifaciality greater that 95%.

Canadian Solar

Canadian Solar has continued to place greater emphasis on module efficiency improvements, focused on p-type multicrystalline technology and has been a perennial low spender on R&D.

The company allocated US$17.4 million to R&D activities in 2016, up slightly from US$17.05 million in 2015. As a result the company just about traded places with estimated spending from REC Solar to be ranked eleventh, compared to twelfth in 2015.

Canadian Solar began commercializing its in-house developed black silicon 'Onyx' technology, on multicrystalline wafers to be used with PERC technology, entering mass production in March 2016.

Indeed, Canadian Solar is placing a potentially risky bet on pushing ahead with this technology combination after stating at the PV CellTech conference in early 2017 that it would continue to focus on this technology in R&D. However, the company also has small-scale initiatives on n-type bifacial and heterojunction cell development.

REC Group

REC Group was sold to Bluestar in late 2014 and delisted from the Norwegian Stock Exchange in 2016. We have estimated that the REC Group continued to tweak R&D expenditures slightly down from US$17.4 million from figures provided by the company that year to around US$16 million in 2016.

This meant it traded places with Canadian Solar, almost six times larger from a module manufacturing capacity standpoint, to be ranked twelfth in the R&D spending rankings in 2016.

With the adoption of PERC cell technology and an ongoing transition to 100% p-type multicrystalline PERC production with half-cut cells, R&D intensity into PERC was expected to slow down and therefore R&D expenditure lowered in 2016.

However, spending on PERC efficiency and production cost reductions was expected to account for a key percentage of R&D expenditure in 2016 and beyond. The company had focused on improving the light capture of PERC cells and migrating to five-busbar technology to reduce cell resistance in 2016.

R&D efforts were expected to continue in the field of diamond wire and black silicon technology ahead of the migration in 2017. Like other previously exclusive multicrystalline manufacturers, development of monocrystalline PERC product offerings would also receive investment in 2016 and beyond.

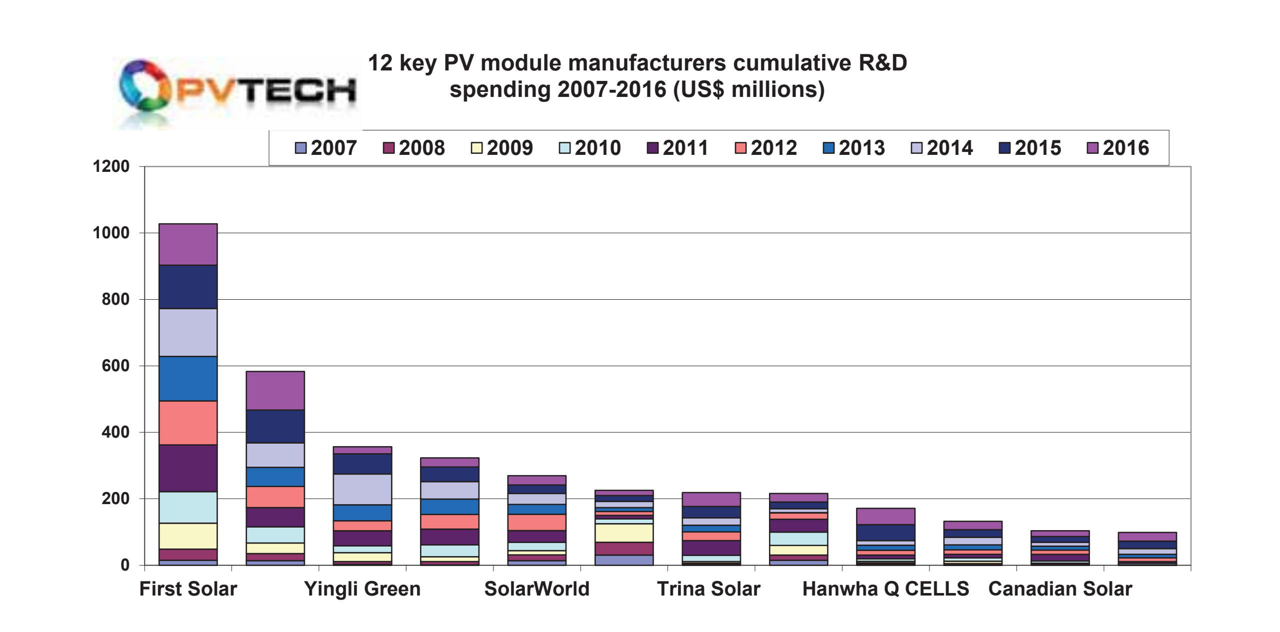


Figure 6. 12 key PV module manufacturers' cumulative R&D spending 2007-2016 (US$ millions).

Cumulative R&D spending rankings and analysis

As previously highlighted in our 2015 report, we expected First Solar to exceed the US$1.0 billion mark in cumulative R&D spending (since 2007). Indeed, First Solar surpassed that mark in 2016, reaching a cumulative US$1,027.8 million in R&D expenditure, making it the first module manufacturer to do so.

First Solar has no equal in the PV industry for investment in R&D activities over the last 10 years (see Figure 6)

Second in the cumulative R&D spending rankings is SunPower, which was expected to surpass the US$500 million market in 2016. Through much of the period, SunPower has been ranked second or third in annual spending and with its increased spend in 2016 easily surpassed that figure, reaching a total spend of US$583.2 million over the last 10 years.

SunPower is only the second company to surpass cumulative R&D spending of over US$500 million, a figure not expected to be reached by another company over the next four years or more.

Due to its previous high R&D expenditure and PV market leadership position, Yingli Green is the third ranked for cumulative R&D spending. The company reached cumulative R&D spending over the last 10 years of US$356.7 million.

In fourth place is ReneSola, having cumulative R&D spending over the last 10 years of US$322.8 million. Since 2010, ReneSola had been a consistently high investor in R&D activities, which only in 2016 experienced a significant decline, due to its business transition. R&D spending peaked in 2014 at US$52.6 million.

SolarWorld is ranked fifth with cumulative R&D spending over the last 10 years of US$269.4 million. The company has spent no less than US$25 million per annum from 2010 onwards and peaked spending just short of US$50 million in 2012.

In the middle of the field, REC Solar, Trina Solar and Suntech had cumulative R&D spending of US$225.5 million, US$218.8 million and US$215.9 million, respectively over the 10 year period.

Three companies, Hanwha Q CELLS, JA Solar and Canadian Solar had cumulative R&D spending of US$171.4 million, US$132.4 million and US$103.6 million respectively. The only company that had cumulative R&D spending below US$100 million was JinkoSolar, which achieved a total spend of US$98.3 million between 2007 and 2016.

End of an era

Reflected throughout this year's report has been the increased reliance on estimated figures. When the analysis originally began, all 12 manufacturers were publicly listed companies and therefore official and verifiable figures were available.

There have been moments when estimates had to be made, such as when Suntech was bankrupt but was soon back in action in another publicly listed company, enabling continued reporting. Problems occurred when REC split into two companies but these two companies remained public.

However, a few years later, REC's module manufacturing arm was acquired by a private Chinese enterprise and has since stopped providing the necessary figures for this report. Trina Solar, the second largest PV manufacturer in 2016, went private before having to release official figures for 2016, adding to the need to use estimates.

The issues have continued to mount in 2017. SolarWorld has entered insolvency proceedings and although back in business is no longer publicly listed, meaning estimates will likely have to be used for the next report. The same could happen with ReneSola, with its manufacturing operations potentially spun off into private hands; JA Solar and JinkoSolar could follow Trina Solar in delisting and going private as well.

Already four of the 12 manufacturers have gone private and the study has become significantly less representative of the sector than in the past. The greater dependency on estimated figures would also further undermine the value of the report and its analysis in the future.

We should all be aware of how dynamic and sometimes brutal the PV manufacturing industry can be and this report has clearly plotted some of those events over the years, not least the first major industry downturn.

However, we have been closely watching the rise of other manufacturers in the last few years, notably LONGi Solar, GCL-SI and more recently Jolywood, all publicly listed in China, meaning the possible inclusion in a new collection of companies alongside those still relevant from our original group since 2007.

The uncertainties surrounding how many companies from the original group will still be relevant to continue with and how best to integrate much newer companies mean that it is definitely the end of an era with this report but a decision on continuing but with new additions will be made at a later date.

Fab & Facilities

Tesla roof tile production at Gigafactory 2 delayed

Having just completed its first 'Solar Roof' tile system installations in the US, Tesla said in reporting second quarter 2017 financial results that production of the roofing tiles would not enter mass production at its Gigafactory 2 in Buffalo, New York until the end of 2017.

Currently, small-scale production of the tiles is being undertaken at the former SolarCity pilot production line in Fremont, Silicon Valley.

Manufacturing partner, Panasonic was previously expected to start production of its conventional high-efficiency HIT (Heterojunction with Intrinsic Thin layer) solar cells at Gigafactory 2 in the summer of 2017, to supply Tesla's tile product and conventional solar panels for the former SolarCity business.

In a letter to investors covering Tesla's second quarter results, the company touted that its solar roofing system had started to be installed.

Credit: Tesla

Tesla has delayed production of its solar roof product at its Buffalo Gigafactory 2.

New and planned fabs

President Duterte inaugurates expanded 800MW Philippines solar module factory

Filipino president Rodrigo Duterte has inaugurated the Philippines' first solar module manufacturing facility with an expanded capacity of 800MW at Santo Tomas, Batangas, owned by renewable energy firm Solar Philippines.

Solar Philippines launched the factory as a 200MW plant in March 2017 and has since then expanded the facility to 800MW.

The company already has three OEM agreements with Chinese companies for manufacturing and exporting the majority of the panels to both the US and Europe.

In both these markets there are existing tariffs against imports directly from China.

In addition, the company has also begun selling a small fraction of its panels to local distributors, and solar systems to homes and businesses using a model of zero upfront cost for installation.

The firm entered the PV manufacturing space following the closing of two factories run by US firm SunPower in the Philippines. The new factory is managed and staffed by the former team of SunPower Philippines.

Earlier this year, the firm started construction on the first utility-scale solar project to be combined with battery energy storage in the Philippines, with 150MW of PV and a 50MWh battery at Concepcion, Tarlac, using modules from the Batangas factory. Commisioning is due in the next few months.

SunPower spends US$25 million on new US R&D and pilot line facility

US-headquartered high-efficiency PV cell and module producer SunPower Corp has invested around US$25 million in the last 12-months on a new US R&D and pilot line facility located at its headquarters in San Jose, California.

The new facility includes several high-volume production-sized manufacturing tools and automation, and specialized testing equipment, designed to support its next-generation of high-efficiency n-type monocrystalline IBC (Interdigitated Back Contact) solar cells and modules, which are being designed with greater emphasis on lower cost manufacturing.

Over 30 parts suppliers and equipment manufacturers located in the US supplied the facility, which is housing over 100 SunPower engineers and support staff.

SunPower had the second highest R&d expenditure from a basket of module manufacturers analyzed in 2016, investing US$116.1 million, up from US$99 million in 2015, a US$17.1 million increase.

GCL-SI opens JV solar cell plant in Vitenam with 330MW of PERC

GCL System Integrated Technology (GCL-SI) has officially started production at its joint venture solar cell plant with Vina Solar in Vietnam as well as an unmanned module assembly pilot project in China.

The new facility has a nameplate capacity of 600MW and includes 330MW of initial PERC (Passivated Emitter Rear Cell) capacity. Germany PV systems integrator IBC Solar was being supplied 60MW of solar modules from Vietnam for projects in Europe with deliveries starting in September 2017.

GCL-SI's use of diamond wire cutting of the polysilicon wafers and wet chemical

Credit: Solar Philippines

The Philippines president Rodrigo Duterte has inaugurated the county's first PV production facility.

‘Black Silicon’ texturing of PERC cells has achieved average conversion efficiencies of 20.3%. Modules using the wafer and cell technology were producing on average 290W. The target for the fourth quarter of 2017 was to reach average cell efficiencies of 20. 5%.

Recom plots European manufacturing expansion after Sillia site acquisition

European PV firm Recom will expand the facilities of recently acquired fellow manufacturer Sillia.

Sillia’s 50MW production site in north-west France will be expanded to 150MW. The expansion will in part enable Recom to fulfil any outstanding requirements for Sillia’s 197MW project development portfolio.

Sillia went into administration in March this year and was acquired by Recom in June. Recom has guaranteed the existing commitments made to the Brittany factory’s 44 employees for the next two years. Recom will not operate Sillia’s 150MW facility in eastern France that was previously acquired from Bosch.

Tool supplier news

Meyer Burger’s new orders up 15% to US$316 million in first half of 2017

PV manufacturing equipment supplier Meyer Burger has reported a 15% increase in new orders in the first half of 2017, driven by a strong technology buy-cycle in the wafer and solar cell sectors.

A key highlight of Meyer Burger’s first half year financial results was strong incoming orders of CHF 308.5 million (US$316.6 million), a 15% increase over the prior year period.

This has been driven by the continued migration by leading solar wafer producers such as GCL-Poly in the multicrystalline sector and LONGi Green Energy in the monocrystalline sector to diamond wire technology that significantly lowers production costs, boosts throughput and overall capacity.

Meyer Burger reported net sales of CHF212.3 million (US$217.9 million) in the first half of 2017, down 2.5% from the prior period. Net financial loss was CHF 7.4 million (US$7.59 million), compared to a net loss of CHF 7.9 million in the prior year period.

Amtech’s solar orders soar

Specialist PV manufacturing equipment supplier Amtech Systems has reported its best performing quarter since a record peak in 2011, driven by a bifacial n-type technology turnkey line contract from a new customer based in China.

Amtech reported fiscal third-quarter 2017 revenue in its solar segment of US$29 million, up from US$16.6 million in the previous quarter.

New solar orders were US$54.2 million, compared to US$46.9 million in the previous quarter. This is the highest level of total orders since the first quarter of 2011.

In the June quarter, the firm’s solar subsidiary Tempress Systems received a follow-on order to n-type bifacial technology, which included PECVD and diffusion systems. Part of the major 1GW turnkey order was also shipped in the quarter.

The company returned to profitability, reporting a net income of US$3.3 million compared to a net loss of US$1.4 million in the previous quarter.

Manz guides full-year revenue to exceed €350 million

PV and electronics equipment manufacturing and automation specialist Manz AG has said it expected to generate revenue of at least €350 million in 2017, including significantly improved and positive EBIT as it starts execution of its large CIGS thin-film orders.

Manz reported revenue in the first half of 2017 of €119.6 million, compared to €124.0 million in the prior year period. Earnings before interest, tax, depreciation and amortization (EBITDA) was €12.4 million, compared to a negative EBITDA of €4.5 million in the prior year period.

Earnings before interest and taxes (EBIT) was €7.0 million, compared to a negative EBIT of €11.7 million in the prior year period. The rebound in earnings was boosted by the sale of Manz CIGS Technology GmbH for €34.4 million as part of the JV activities and large order with Shanghai Electric Group and Shenhua Group.

Martin Drasch, COO of Manz AG, said: “The realization of the large CIGS orders in the solar segment is doing well and development in the Contract Manufacturing and Service segments has met our expectations, contributing positively to our results.”

Solar segment sales in the first half

Credit: Meyer Burger

Meyer Burger’s orders were up 15% in the first half of 2017.

Credit: centrotherm

Centrotherm's profitability in 2017 is in doubt following a major cancelled tool order from Algeria.

of 2017 were €16.4 million with an EBIT of €26.1 million, due to the Manz CIGS Technology GmbH sale.

Manz reported an order book backlog of €301.8 million with around 70% related to its two major CIGS orders.

Centrotherm hit by €11 million claim for damages after losing arbitration case

Specialist solar PV equipment supplier centrotherm has warned that it is unlikely to be profitable in 2017, due to the loss of an arbitration case against a cancelled €290 million integrated wafer, cell and module plant in Algeria.

Back in June 2014, centrotherm announced a previously planned integrated production facility for energy producer, CEEG, a subsidiary of Algerian state utility Société Nationale de L'Electricité et du Gaz (Sonelgaz). Centrotherm and facilities engineering firm, Kinetics Germany had won the contract to build it, but it was cancelled.

The project suppliers sued CEEG and the case was heard at the International Court of Arbitration (ICC) in Geneva that led to total claims for damages from CEEG, including arbitration and legal costs of approximately €11 million.

According to centrotherm's 2016 annual report, the company allocated around €3.1 million to the possible negative outcome of the arbitration.

Fab closures, sales and problems

Ulbrich Solar Technologies closes ribbon interconnect plant used by SolarWorld Americas

Solar PV cell and module ribbon interconnect supplier Ulbrich Solar Technologies has closed its production operations in Hillsboro, Oregon due to operating difficulties of SolarWorld Americas after parent company SolarWorld AG went into insolvency proceedings.

The Ulbrich ribbon plant closed down on 4 August with potentially the loss of around 35 jobs.

SolarWorld Americas was attempting to operate in some capacity while its parent company and all its German subsidiaries went into bankruptcy and had previously stated that it would be receiving funds from SolarWorld AG investors.

The decision by Ulbrich to close the plant supporting SolarWorld Americas' manufacturing operations could potentially indicate production may have stopped, due to lack of recent financial support.

Although founder and chairman of SolarWorld AG Frank Asbeck highlighted that production in Germany would restart soon, which it then did, saving 500 jobs, he did not mention SolarWorld Americas in a statement.

PV Crystalox to close UK manufacturing operations

UK-headquartered multicrystalline solar wafer producer PV Crystalox Solar has confirmed plans to completely close its multicrystalline ingot/brick production facilities in Oxford, UK.

The company had previously planned to phase out the production of multicrystalline ingots using its DSS furnaces during 2017. The plan had been to purchase ingots from third parties and continue processing of ingots into bricks before supplying the bricks to its Germany-based production plant converting the bricks into wafers.

However, adverse market conditions have meant that brick processing operations will also be closed with the majority of all jobs lost. The company did not say how many jobs would be lost due to the closure of all manufacturing operations in the UK.

PV Crystalox will continue to produce finished multicrystalline wafers at its facility in Germany and source bricks from an undisclosed external supplier. All production operations in the UK are to end during the third quarter of 2017.

NSP sells former DelSolar cell and module plant in Taiwan

Taiwan-based cell and module producer Neo Solar Power (NSP) has sold the former solar cell and module assembly plant of DelSolar to specialist semiconductor manufacturer Maxchip Electronics for around NT$1,252 million (US$41.1 million).

The vacated production plant, under a recent restructuring of manufacturing operations by NSP, was built by DelSolar in 2008 and completed in October 2009 in Zhunan northern Taiwan at an estimated cost (fully equipped) of around US$280 million.

The facility had been designed under an energy saving concept and has won LEED-NC (Leadership in Energy and Environmental Design – New Construction) from the U.S. Green Building Council.

NSP has consolidated its high-efficiency manufacturing operations in Hsinchu Science Park and Tainan Technology Industrial Park as part of plans to migrate all production to monocrystalline PERC (Passivated Emitter Rear Cell) technology and a pilot line for IBC cell development.

DelSolar was merged with NSP in 2013, during a period of overcapacity and consolidation of PV manufacturers.

JA Solar reports fire at solar cell plant in China

'Silicon Module Super League' (SMSL) member JA Solar's Fab 7 solar cell plant in Yangzhou, Jiangsu province, China, had a significant fire incident overnight on 13 July 2017.

The cell manufacturing equipment was affected by a fire that lasted between 1:32AM Beijing time to around 6:00AM the same day, related to old production lines installed in 2009 and accounted for only around 6% (approximately 330MW) of its total solar cell nameplate capacity, the company said. The old lines were expected to be replaced in the next 12 months.

JA Solar had a solar cell nameplate capacity of 5,500 MW per annum at the end of 2016.

The cause of the fire had not been identified and was under investigation.

PV manufacturing capacity expansion plan announcements: Analysis for the first half of 2017

Mark Osborne, Senior News Editor, Photovoltaics International

ABSTRACT
Global solar PV manufacturing capacity expansion announcements in the first half of 2017 showed a significant increase over the second half of 2016, which was characterized by subdued activity, and almost reached the record heights set in the first half of 2016. However the resurgence was overwhelmingly driven by China and the migration to high-efficiency solar cell technologies, compared to a broader geographical split in the prior year period. Although the second quarter of 2017 surpassed first quarter announcements, major updates to previously reported activity covering the first quarter of 2017, have also been made.

Revised Q1 2017 expansion plans

As previously highlighted in the last report covering Q1 2017 capacity expansion plans, the quarter was dominated by the latest round of annual announcements from the majority of the 'Silicon Module Super League (SMSL) membership (JinkoSolar, Trina Solar, Canadian Solar, JA Solar, Hanwha Q CELLS, LONGi and GCL) which were profiled separately in the last report.

Preliminary total global PV manufacturing capacity expansion announcements in the first quarter were reported to be 17,595MW, which were ahead of levels seen in the second quarter of 2016, when total expansion plans topped 17,500MW.

On a geographical basis, planned expansions in China dominated, followed by South Korea and the Philippines. Expansions were also announced in India, Malaysia, Taiwan, Germany, Italy and the US.

However, based on the level of new announcements in the second quarter of 2017, extensive checks going back to the beginning of the year revealed a further 7GW of capacity expansion plans existed in Q1 2017, than previously reported, leading to a new total of 24.7GW.

The upward revisions primarily related to January and February, with increases to 4GW and 13.9GW, respectively. This compares to preliminary figures for January and February of 1.2GW and 11GW, respectively.

Revised figures for March were 6.8GW, compared to 5.3GW, previously reported. There was a reasonable balance between solar cell module assembly announcements in March, 3.7GW and 3.1GW, respectively.

The revised figures only reinforced the previous assessment that almost all of the solar cell expansions were for high-efficiency upgrades such as p-type multi PERC, p-type mono PERC, n-type mono heterojunction and bifacial cells as well as 2,100MW attributed to n-type mono IBC/bifacial cells, due to Jolywood (Suzhou) Sunwatt starting construction of a new cell and module production plant in February.

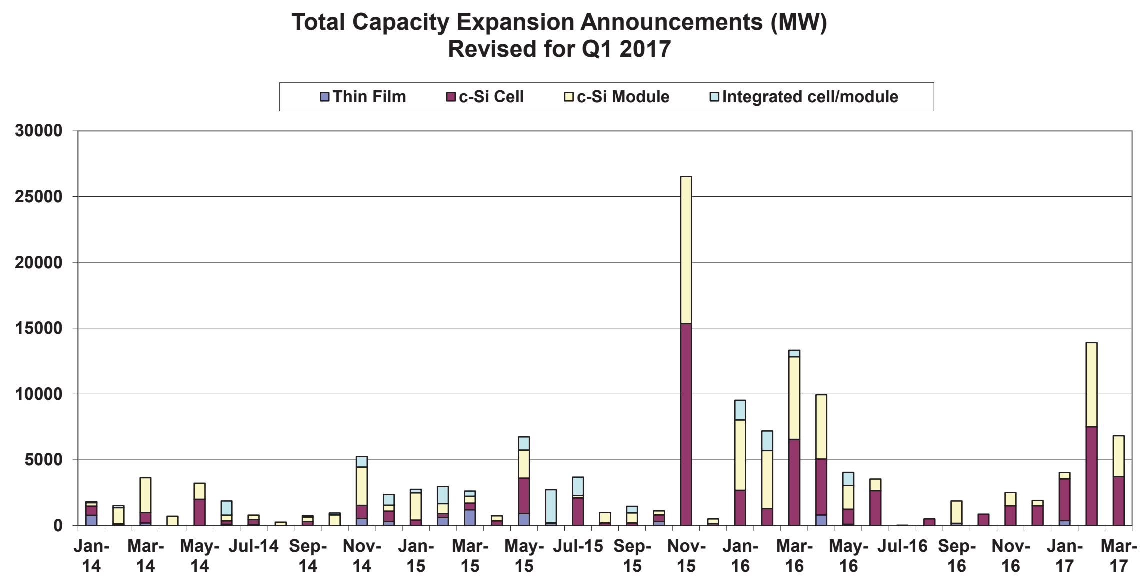


Figure 1. Revised Q1 2017 capacity expansion plans.

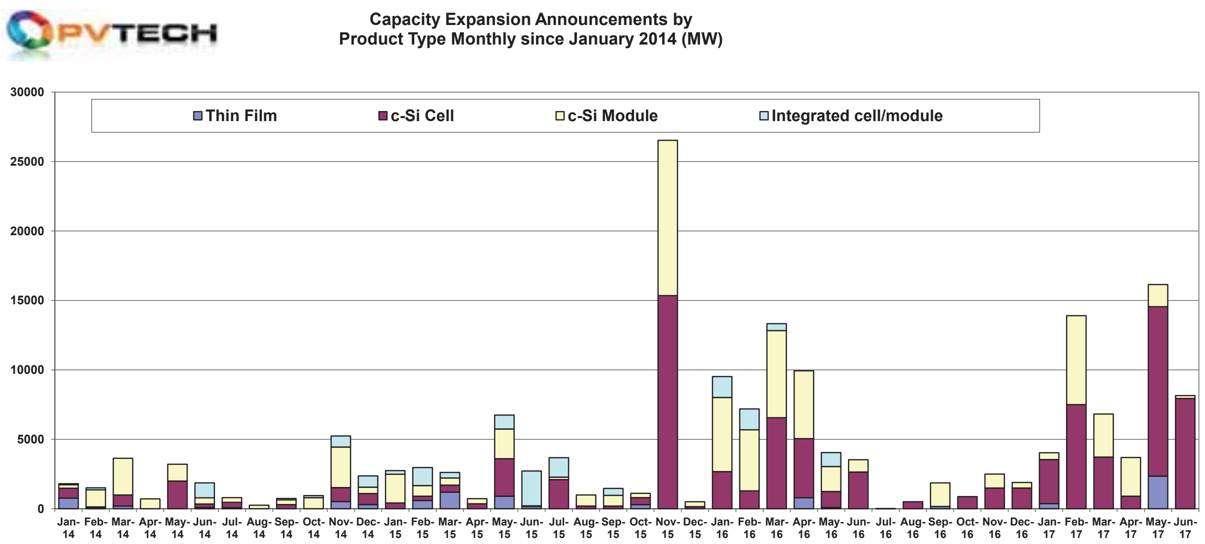


Figure 2. Capacity expansion announcements by product type monthly since January 2014 (MW).

The changes related to higher solar cell expansion plans than previously reported and an accompanying increase in module assembly expansions, although the emphasis was solar cell plans in January that outstripped module assembly and higher solar cell and module assembly plans than reported in February. On a geographical basis, the majority of the upward revisions related to China. We have therefore restated in Figure 1 data that includes these Q1 2017, updates.

April review

With such a strong first quarter, total capacity expansion announcements in April dropped significantly from the previous month's 6.8GW to 3.7GW. The high level of solar cell activity seen in the first quarter subsided significantly to just 900MW. Therefore the majority of announcements related to module assembly at 2.8GW.

However, as seen in the first quarter of 2017, large single capacity expansions that actually had multiple phases spread over multiple years continued, dominated by a new joint venture (JV) by Taiwan-based companies TSEC, Giga Solar Materials and Hou Gu Photoelectric to build a new module assembly plant in Pingtung County, southern Taiwan. Initial plans were for a 500MW plant to meet the expected increase in Taiwan's downstream PV installations, due to new government incentives and strategy to replace nuclear electricity capacity with renewables. The joint venture partners said the plans were to increase nameplate capacity to 2GW.

Keeping with the high-efficiency solar cell drive, Jinneng Clean Energy Technology (JNCEC) and its solar subsidiary, Jinergy would be starting mass production of its n-type monocrystalline bifacial heterojunction (HJ) cells and modules later in 2017, with a capacity of around 800MW.

In total only five companies announced expansion plans in April from China, Taiwan and Thailand.

May review

In contrast, due primarily to the largest annual PV exhibition SNEC in Shanghai, China capacity expansion announcements rocketed to a preliminary total of over 16GW in May 2017.

This was the second highest level of activity since November, 2015 when a total of more than 26.5GW of expansion plans were announced. There is a high probability once final checks are made that this figure could rise much further. The majority of announcements were from Chinese manufacturers in the cell and module assembly sectors.

Solar cell announcements dominated in May, totalling over 12GW, up from 900MW in the previous month and easily topping February's figure of 7.5GW. P-type mono PERC solar cell plans were high on the agenda with two notable confirmations that reinforce the phased approach as well as re-emergence of Chinese producers outside the SMSL that are adding significant capacity with next-generation technology.

China-based merchant solar cell producer Guangdong Aiko Solar Energy Technology Co., Ltd (Aiko Solar) for example announced plans at SNEC to become a major supplier of high-efficiency p-type mono PERC and bifacial cells to PV module manufacturers around the world with an 8GW solar cell capacity expansion commitment.

A new greenfield production plant broke ground ahead of the SNEC show and equipment orders were signed with a number of western suppliers on the morning of the first day of the show. The first phase expansion is up to 800MW and completed in the fourth quarter of 2017.

The target is for a three-phase expansion, which is expected to be complete by 2022.

The merchant cell producer is also planning to convert its current 1.6GW of nameplate cell capacity in Foshan City, Guangdong province, to P-type mono PERC in 2017.

SunPower also updated its manufacturing plans with Dongfang Electric Company (DEC) and Tianjin Zhonghuan Semiconductor (TZS) under its JV for P Series mono-PERC technology cells that includes a manufacturing capacity expansion from

1.1GW to 5GW. TZS is also planning a 15GW mono/ingot wafer expansion.

In May, module assembly expansion plans dropped to 1.6GW, compared to 2.8GW in the previous month. However, checks are ongoing as a number of Chinese companies at SNEC announced plans that had little actual detail.

Away from SNEC, China-based integrated PV module manufacturer Shanghai Aerospace Automobile Electromechanical Co (HT-SAAE) announced that it had established a 300MW solar cell and 600MW module assembly plant in Turkey to meet local demand as well as supply Europe and the US at the end of May.

Reports also appeared that Egypt Silica Sand would establish a module assembly pilot line in Egypt with plans to build a 1GW plant sometime in the future.

Unique to May was updated information from CdTe thin-film leader First Solar over its plans to migrate from its small area Series 4 modules to its large-area Series 6 platform. This entails a complete decommissioning over time of all of its 3GW of Series 4 module production capacity in the US and Malaysia as well as adding new capacity at its mothballed facility in Vietnam and extra capacity in the US.

Rather than simply upgrades, First Solar is effectively planning completely new production and therefore warrants being included as new capacity. Based on First Solar's updated plans, over 2GW of effective new capacity is expected to come on stream in 2018 through 2019. Total new capacity is expected to be above 5GW of Series 6 modules once all production lines are decommissioned and refitted and ramped.

June review

The activity in June was half the level seen in the previous month. However, total announcements still stood at over 8GW, driven again by high-efficiency solar cell capacity plans of over 12GW.

Of significance was a major capacity expansion planned by China-based Tongwei Solar (Hefei) Co, which said it was adding 2.3GW of p-type mono PERC production over a 3-5 year timeframe to reach 5GW of total nameplate cell capacity. The company also said that it planned to reach 10GW of cell capacity at an unspecified timeframe.

Once again, module assembly announcements slumped to only 210MW, compared to 1.6GW in May, 2017.

SMSL update

With the majority of SMSL members having already guided on capacity expansions for the year and been reviewed in the last quarterly report, there was still some activity worth mentioning.

In March, Hanwha Q CELLS surprised with plans to build and operate (ingot/wafer/cell/module) plants in Turkey, creating a JV with Turkish firm, Kalyon Holding Energy Group. Initial solar cell and module assembly capacity was expected to be 500MW with plans to start production by the end of 2018. The JV would expand further to 1GW in incremental steps.

Canadian Solar would seem to be continuing to tweak its upstream manufacturing capacity expansion plans as a part of tight capital expenditure controls. The company noted that its in-house solar cell manufacturing capacity was 4.49GW at the end of the second quarter of 2017, while annual capacity at its Funing cell factory had reached 1,440MW, with an additional 850MW cell capacity at its Southeast Asia facility.

Debottlenecking cell production later this year would enable Canadian Solar to reach a nameplate capacity of 4.70GW by year-end. The company expects total worldwide module manufacturing capacity would exceed 7.19GW by year-end, up from initial plans for the year to reach 6.97GW.

LONGi Green Energy Technology noted in its first half year financial report that it was fast-tracking various ingot and

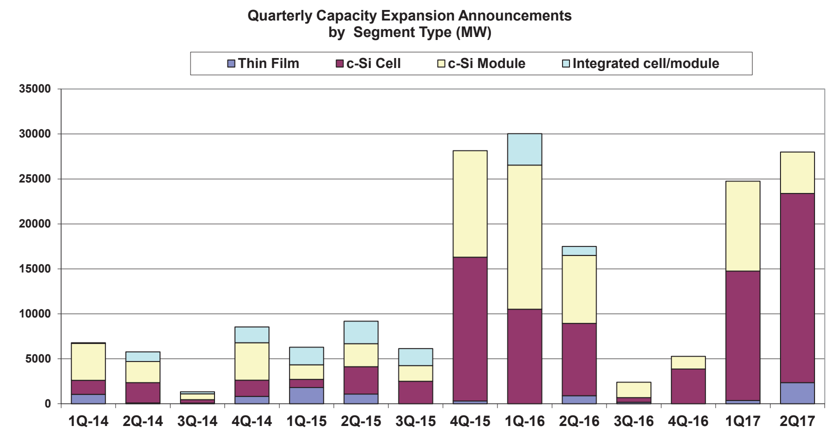


Figure 3. Quarterly capacity expansion announcements by segment type (MW).

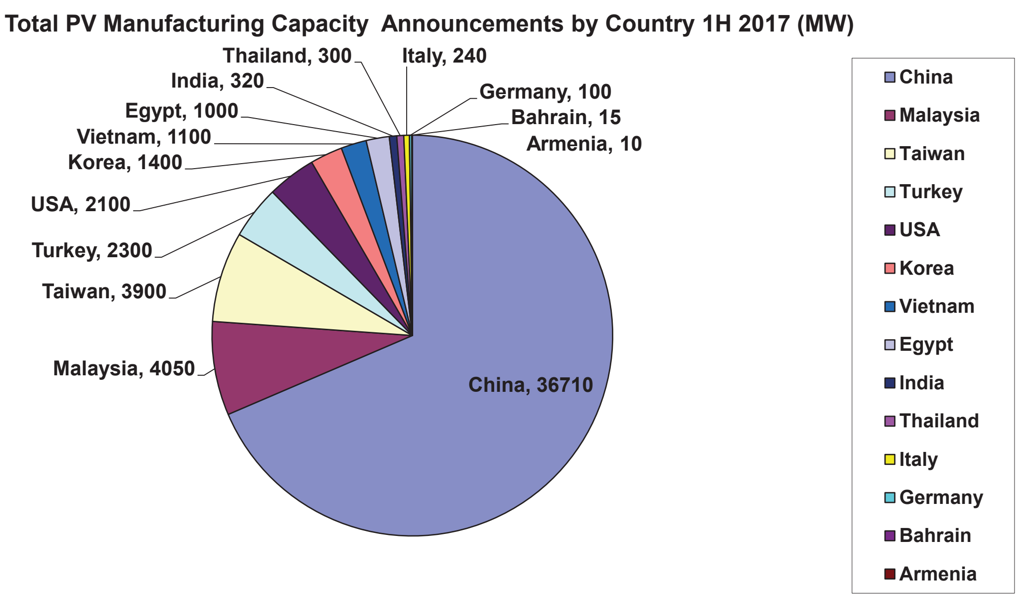


Figure 4. Total PV manufacturing capacity announcements by country H1 2017 (MW).

wafer expansion plans currently under construction and pulling in projects nearing completion where possible, while saying that a 500MW solar cell expansion phase and a 500MW module assembly expansion would also enter production in the fourth quarter of 2017, earlier than expected, due to demand for p-type mono PERC products.

Another strong quarter

Preliminary total global PV manufacturing capacity expansion announcements in the second quarter of 2017 were over 28GW. This included over 2.3GW of thin-film expansions, over 21GW of solar cell and just 4.6GW of dedicated module assembly announcements.

High-efficiency, next-generation solar cell technologies dominated new capacity expansions in both the first and second quarters of 2017. In the second quarter, HJ expansions accounted for 700MW of the total, while P-type mono PERC announcements were notable for reaching nearly 18GW, compared to around 6.3GW in Q1 2017.

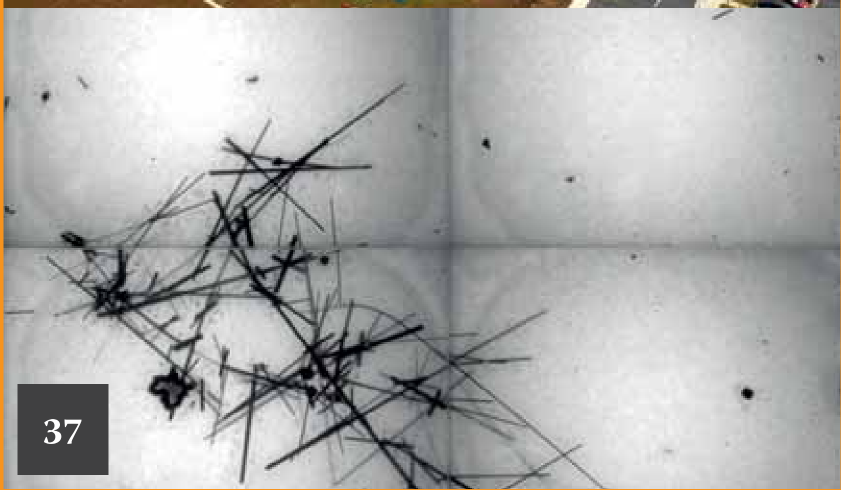
On a geographical basis, China expansions again dominated new announcements in the second quarter. In the first half of 2017, China accounted for almost 70% of planned expansions, while Malaysia and Taiwan remained popular with an 8% and 7% share.

A new emerging country was Turkey, which had a total of 2.3GW of planned new production plants, enjoying a 4% share of planned expansions in the first half of 2017.

Conclusion

The first half of 2017 has produced the second (Q2) and fourth (Q1) largest amount of capacity expansion announcements in the history of the solar industry, driven by global end market demand increases that are set see in excess of 90GW of installations and 100GW of shipments this year. Also fuelling the announcements is the significant migration underway to p-type mono PERC solar cells, although much of what was announced is based on multi-phase multi-year plans, inline with announcements made in the first quarter of 2017.

Materials



News

Meyer Burger supplying REC Group with diamond wire cutting technology

REC Group has around 1,500MW of module capacity in Singapore.

Credit: REC

Leading PV manufacturing equipment supplier Meyer Burger has secured a CHF12 million (US$12.4 million) contract to supply integrated PV module manufacturer, REC Group with its DW 288 Series 3 diamond wire cutting platform.

Meyer Burger said that REC Group, which has its ingot/wafer and cell and module assembly plants located at a dedicated complex in Singapore was planning to completely migrate multicrystalline wafer production to diamond wire cutting technology, with delivery of equipment starting in the third quarter of 2017.

Hans Brändle, CEO of Meyer Burger Technology, said: "This important order confirms our excellent long-term relationship with REC and once more demonstrates that Meyer Burger's DW 288 Series 3 diamond wire cutting technology remains the industry-leading solution for the cost-effective production of solar wafers. The product is highly attractive to customers in both the monocrystalline as well as the multicrystalline wafer markets."

The contract also includes installation and commissioning as well as service support and on-site training.

The move to diamond wire cutting of all its multicrystalline wafers will require REC Group to select wafer texturing technology to complement the wire cutting, often referred to as 'Black Silicon' technology. REC Group is also transitioning all production to PERC and half-cut cell technology. The company has around 1,500MW of module capacity in Singapore.

Steve O'Neil, CEO of REC Group added: "As an industry leader for high-power multi-crystalline solar panels for many years, our success is also based on cutting-edge and cost effective manufacturing technology. Choosing Meyer Burger and their outstanding diamond wire cutting technology enables us to continue to provide high-quality solar panels with a strong reliability at a competitive price."

Polysilicon

Daqo's key financials down on polysilicon price declines in Q2

China-based polysilicon producer Daqo New Energy reported lower than expected revenue, gross profit and margins as polysilicon supply and demand dynamics proved volatile in the second quarter of 2017.

Daqo reported second quarter revenue of US$76.0 million, compared to US$83.8 million in the previous quarter. Gross profit was US$24.2 million, compared to US$35.9 million in the first quarter of 2017. Gross margin declined to 31.9%, compared to 42.8% in the previous quarter.

The company reported that the average selling price (ASP) of polysilicon was US$13.58/kg in the quarter, compared to US$16.66/kg in the previous quarter.

"Due to downstream customer inventory management at the end of the first quarter, ASP fell in April, but ASP started to recover in May," said Dr. Gongda Yao, CEO of Daqo New Energy. "Demand and pricing improved throughout the second quarter, with the ASP in June approximately 15% higher than that in April. So far in the third quarter, customer demand has remained robust with pricing continuing to improve."

Increased polysilicon shipments did not compensate for ASP declines. Daqo reported another record-high polysilicon production volume of 4,993MT, compared to 4,927MT in the first quarter of 2017.

External polysilicon sales volume also set a new record of 4,497MT in the reporting quarter, up from 4,223MT in the previous quarter.

GCL-Poly in 1H 2017 revenue and profit slump on wafer price erosion

Leading polysilicon and solar wafer producer GCL-Poly Energy Holdings reported lower revenue and profits than expected in the first half of 2017, primarily due to wafer price erosion, only partially offset by higher wafer production volumes and stable polysilicon prices.

Although new solar PV installations in China exceeded 24GW in the first half of 2017, GCL-Poly could not financially benefit from the boom directly.

Photovoltaics International sister website, PV Tech, previously highlighted that GCL-Poly's wafer division, GCL-Poly (Suzhou) New Energy, which is the main revenue generator had reported first quarter revenue of approximately US$634.4 million, down over 20% from the prior year period but the polysilicon purchase price on a year-on-year basis had increased more than 20%, while wafer selling prices in the same period had decreased more than 20%.

The result was a collapse in net profit to around US$12.8 million in the first quarter of 2017, compared to around US$169.3 million in net profit in the first quarter of 2016.

Profitability would have come under even higher pressure if it was not for wafer production volumes in the first quarter of 2017 increasing by approximately 19.2%, compared to the prior year period.

The majority of polysilicon production is consumed in-house for the production of multicrystalline wafers, despite its average polysilicon prices remaining stable at US$15.1/kg in the reporting period, external polysilicon shipments were 4,888MT, down from 6,380MT in the first half of 2016, limiting revenue generation from this business unit.

Wafers

Yicheng New Energy closing wire saw operations as solar industry moves to diamond wire

China-based crystalline silicon cutting materials specialist Henan Yicheng New Energy Co (HYNE) said it was

Credit: Meyer Burger

Diamond wire technology is making it harder for slurry-based wire systems to compete.

closing down its slurry-based wire saw manufacturing operations, due to the shift to diamond wire technology by its customer base. The company is shifting to solar cell production instead.

The company noted that the rapid transition to diamond wire technology, which replaces the need for expensive slurries and recycling had resulted in a significant reduction in demand for its conventional wire products and pricing, forcing the company to permanently close its manufacturing operations.

HYNE made the announcement in providing preliminary first half year financial results. The company reported that it expected to make a loss of around RMB222 million to RMB227 million (US$32.8-33.6 million), compared to a profit of around US$27 million in the prior year period.

PV Crystalox shipments increase in 1H 2017 but lower polysilicon sales lead to loss

UK-headquartered multicrystalline solar wafer producer PV Crystalox Solar continues to be impacted by global overcapacity in the wafering sector as first half 2017 financial results reflect.

PV Crystalox reported wafer shipments of 69MW in the first half of 2017, up from 59MW in the prior year period but inline with operating nameplate capacity.

The company noted it had migrated to the 'M2' larger area wafer size (156.75mm x 156.75mm) in the period to meet customer demand for the migration. However, the change to the standard size of wafers negatively impacted the recoverable value of finished product inventory at the 156mm^2 size.

Wafer sales were being driven by the low carbon footprint requirements for PV modules in the French government tendering for utility-scale PV power plants, as its wafering operations are in Germany.

Revenue in the reporting period was €12.6 million, down 64% from the prior year period. The decline was primarily due to reduced polysilicon sales as inventory reduced.

PV Crystalox reported a gross loss of €0.3 million, compared to a gross profit of €6.2 million in the prior year period. This loss was principally due to a wafer inventory write down of €1.4 million. The company had a net cash position of €27.9 million at the end of first half of 2017.

The company had recently announced the planned closure of its multicrystalline ingot/brick production facilities in Oxford, UK.

Solargiga seeing strong demand for mono n-type wafers as sales rebound in 1H 2017

China-based integrated monocrystalline PV manufacturer Solargiga Energy Holdings' sales have rebounded in the first half of 2017, fuelled by demand in China for high-efficiency wafers including n-type wafers for 'Top Runner' PV power plant projects.

Solargiga highlighted that market demand for monocrystalline silicon wafers, high-efficient modules and solar cell's increased significantly, with production capacity utilization rates at high levels with demand outstripping supply, creating shortages in the supply chain.

Demand for n-type monocrystalline bifacial cells and modules are expected to gain attention from the Chinese market in the near future as China initiates its 'Super Runner' programme, according to the company.

The Super Runner programme established through China's National Energy Bureau has launched an upgraded version of the national Top Runner Program, which is intended to promote the application of advance technology in PV power plants.

Solargiga noted that its core upstream monocrystalline ingot and wafer manufacturing operations had been significantly upgraded in 2016, which impacted capacity utilization rates and knock-on effects of weaker economies of scale as well as long-term polysilicon supply contracts with minimum volume purchase conditions.

However, the company said that since the beginning of 2017, ingot and wafer manufacturing operations resumed normal operations with improved efficiencies, also benefiting from the end to long-term polysilicon contracts that carried high purchase prices. The boost in production meant its ability to negotiate new polysilicon supply and better pricing positively impacted its financial performance in the first half of the year.

As a result of resumed operations Solargiga reported external shipments of monocrystalline silicon ingots was 184.5MW in the first half of 2017, an increase of 152% compared to 73.2MW in the prior year period.

External shipments of monocrystalline silicon wafers were 331.7MW, an increase of 47% compared to 225.5MW in the first half of 2016.

The majority of Solargiga's solar cell capacity is used internally for its module production.

Hereaus

Heraeus fails to win IP case on tellurium containing glass frit with Giga Solar

Major metallization paste producer Heraeus Photovoltaics said it had lost a patent case against Taiwan-based Giga Solar Materials Co in the Taiwanese Intellectual Property Court but noted it was reviewing the findings before deciding on an appeal.

In 2015, Heraeus sued rival paste manufacturer Giga Solar for patent infringements of its tellurium contained glass frit used in its advanced PV metallization pastes for solar cell production.

Andreas Liebheit, the president of Heraeus Photovoltaics said: "We are surprised and disappointed by the court's ruling because in the course of two years of litigation we saw our strong patent decision confirmed several times. While we consider our options to appeal, it is important to note that rulings like these send a chilling message to companies throughout our industry who invest significant capital on R&D efforts. Without appropriate protection for legitimate patents and intellectual property, the collective result is less incentive to make necessary investments across the PV industry."

Heraeus said its lost IP case against Giga Solar sent a 'chilling message' to companies that invested in proprietary R&D.

Credit: Heraeus

In recent years, Heraeus Photovoltaics has secured a number of major new customer wins, notably in China and had launched its first new product outside the traditional solar cell paste market.

"As a company, we remain undeterred. To deliver the top quality and efficiency gains our customers need, we will continue to invest, we will continue to rapidly innovate, and we will rigorously protect and defend our intellectual property," added Liebheit.

Heraeus and Tongwei team on next-gen solar cell material development

Heraeus Photovoltaics has extended its supplier status with major China-based integrated PV module manufacturer, Tongwei Solar to collaborate on next-generation high-efficiency wafer and solar technologies.

A key part of the collaboration revolves around joint R&D of front side silver paste, with the goal of setting the industry standard for high-efficiency products.

Tongwei Solar also has aggressive plans to expand capacity. Current solar cell capacity in Hefei, China stands at around 2.6GW with Phase 2 plans reaching around 5GW in the next 3 to 5 years. Overall solar cell capacity at Tongwei is expected to reach around 10GW by 2020.

Andreas Liebheit, president of Heraeus Photovoltaics added: "Heraeus and Tongwei Solar have cooperated for years. By working even closer and in a more focused manner, we believe we can set a new benchmark for the PV industry."

Heraeus Photovoltaics signs new strategic technology partnership with Solar Space

Heraeus Photovoltaics has entered into a new strategic technology partnership with China-based multicrystalline solar cell producer, Solar Space, also known as Zhonghui Photovoltaics (Jiangsu Solar Space Photovoltaic Technology Co.), which was established 2010.

Heraeus said that the new partnership related to high-performance silver metalization pastes for fine-line double printing as well as other new technologies and solutions to optimize metallization paste performance and applications, as well as production process improvements.

Liu Guyan, general manager of Solar Space said: "Based on the remarkable advantages of Heraeus Photovoltaics' SOL9641BX in single process, we will be able to improve our competitiveness with more powerful support from Heraeus in our dual printing and the other processes that are planned for the future. Together with Heraeus expertise, we also expect further breakthroughs in performance through optimization of the SOL9642BX product and production processes."

Solar Space currently has a nameplate solar cell capacity of 1.3GW but has plans to complete four phases of expansions to 3GW by the end of 2017, followed by five phases of expansion to achieve a nameplate capacity of 5GW by the end of 2018.

Optimization potential of the wire sawing process for multicrystalline silicon

Thomas Kaden, **Elena Ershova**, **Marcel Fuchs**, Fraunhofer THM, Freiberg, Germany & **Rajko B. Buchwald**, Meyer Burger (Switzerland) AG, Thun, Switzerland

ABSTRACT

As the diamond wire sawing process becomes increasingly important also for the wafering of multicrystalline silicon, a basic understanding of the material properties that influence the sawing performance becomes necessary. The position of the bricks in the multicrystalline ingot and the role of inclusions in the micrometer range as well as the orientation of the bricks in the wire web were investigated in detail. It is shown that an adaption of the brick sorting prior to wafering can be used to optimize the diamond wire sawing process in terms of increased throughput or lower wire consumption.

Introduction

Today, silicon solar cells are still produced in almost equal shares from mono- and multicrystalline silicon wafers. For monocrystalline silicon the Czochralski-growth (Cz-Si) is the standard technique. In the case of multicrystalline silicon the so-called high performance multicrystalline silicon (HPM-Si) has become the standard base material. While diamond wire sawing (DWS) of monocrystalline silicon is currently being established as the industrial standard with a perspective of core wire diameters even below 70µm, DWS of multicrystalline silicon (mc-Si) is proving to be more challenging. This is due to the material properties of mc-Si, which are determined by a higher concentration of impurities and the presence of inclusions in comparison to Cz-Si. Furthermore, the standard acidic texturing of mc-Si wafers produced by DWS turns out not to be appropriate, since the onset of the etching process is too slow on the shinier DWS wafer surface.

High performance multicrystalline silicon (HPM-Si)

The material quality of multicrystalline silicon was significantly improved by developing a directional solidification process with seeded growth, which drastically reduces the density of dislocations [1]. This so-called high performance multicrystalline silicon (HPM-Si) is now the standard multicrystalline base material for the solar cell production. Using n-type base doping, conversion efficiencies up to 21.9% have been demonstrated recently [2]. Although HPM-Si shows a high electrical quality, there are still impurities present in the material similar to standard mc-Si, which influence the wire sawing process.

Wire sawing technologies

In general, two techniques for multi-wire sawing of crystalline materials exist. In loose abrasive sawing (LAS) a brass-coated steel wire is used in combination with a cutting fluid (the so-called slurry) consisting of a carrier fluid (typically PEG-200) and SiC as loose abrasive particles with a defined grain size (F600 or F800). The wire can be straight or structured, whereby the structured wire allows for higher feed rates. The main abrasion process is the brittle fracture of silicon due to a three-body interaction process with the SiC particles and the wire [3-5].

The second technique is the fixed abrasive diamond wire sawing (DWS), where the crystalline material is cut by diamond particles that are embedded in a nickel or resin coating on a steel core wire. A scheme of the DWS

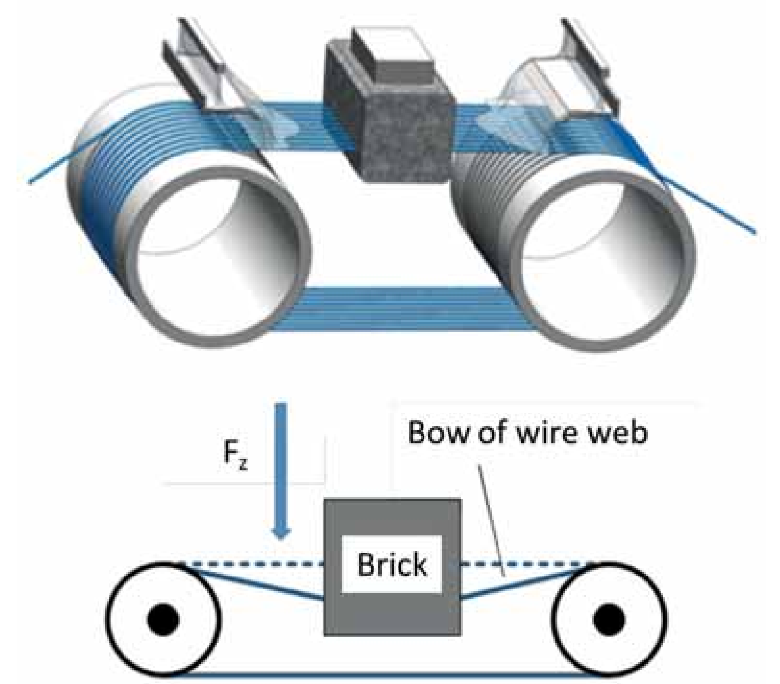


Figure 1. Scheme of diamond wire sawing and bow of wire web.

principle is depicted in Fig. 1. The wire web is moved in oscillation mode (forward/backward); in each forward step a certain amount of new diamond wire is added to compensate for the wire wear. The nozzles above the wire web are used to deliver the water-based cooling medium. The brick is moved through the wire web with defined feed rate in z-direction. Since feed rate and material removal rate are not equal, a bow of the wire web develops during the process which is represented by the force in feed direction F_z (see Fig. 1).

The material removal in this technique is dominated by the ductile abrasion process, which yields shinier wafer surfaces compared to wafers prepared by the FAS technique [6, 7]. DWS allows for highly efficient processes, because higher feed rates are possible, cheap water-based coolants are used as cooling liquid and the kerf loss can be further reduced by the use of thinner wires. Today, 70µm core wire diameters are used in industrial production. An SEM image of such a wire is shown in Fig. 2. Furthermore, DWS offers the potential of kerf recycling, which is currently a widespread topic of research.

Our previous findings in slurry sawing processes revealed differences in the cutting efficiency of bricks from different positions in a multicrystalline silicon ingot. Surprisingly, cutting of bricks from the centre of the ingot turned out to be less efficient than cutting of bricks from the ingot edges and corners, respectively. This is demonstrated by the higher normal force F_z developing during the sawing process as shown in Fig. 3 for sawing processes of each two bricks from the relevant positions of a mc-Si ingot. Typically, there are more impurities present in the edges and corners of the ingot due to diffusion from the crucible. However, the concentration of specific impurities that are less present in the edge and corner bricks might be the main influence on the sawing performance. In the following, bricks from different ingot positions were investigated in DWS processes in order to find out the optimization potential for the industrial wafer production and to determine the main influences on the wire sawing performance.

Diamond wire sawing of HPM-Si from dedicated ingot positions

HPM-Si ingots from one dedicated manufacturer were considered for the investigations. Bricks from different positions in a G5 mc-Si ingot, i.e. from

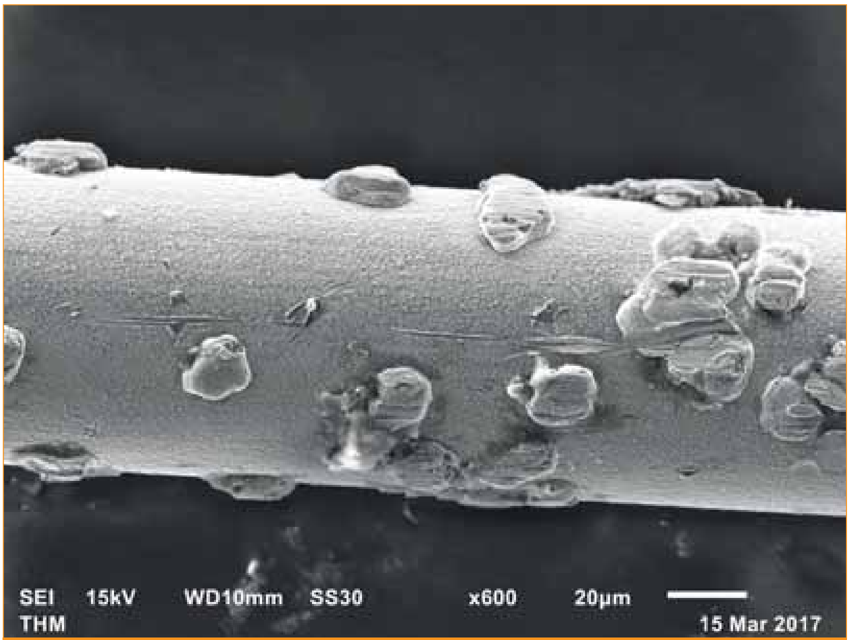


Figure 2. SEM image of a diamond wire with 70µm core diameter and a grit size of 8-12µm.

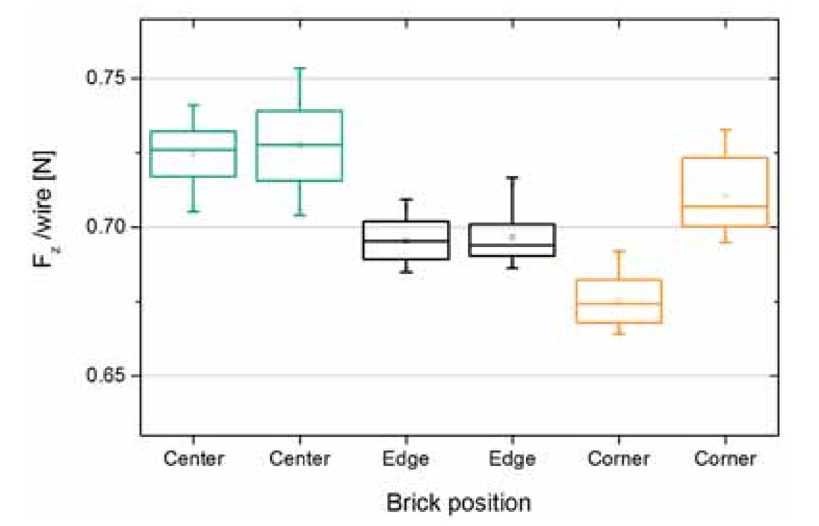


Figure 3. Normal force F_z during slurry sawing processes of multicrystalline bricks from different ingot positions.

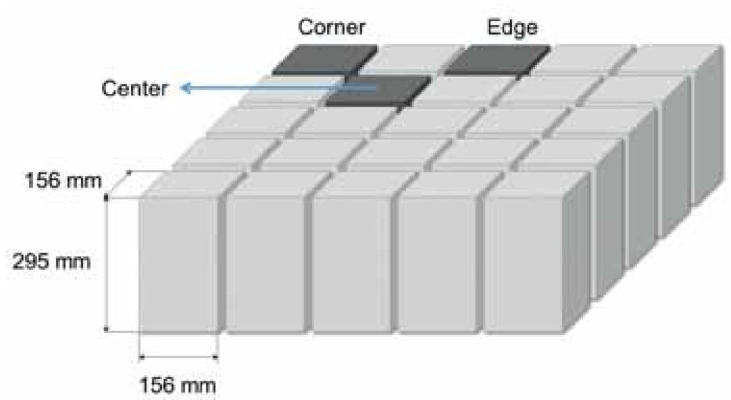


Figure 4. Scheme of the investigated bricks from different positions in a G5 mc-Si ingot.

the corner, edge and centre (see Fig. 4) were investigated in lab scale sawing experiments on a Meyer Burger DS 264 wire saw in diamond wire set-up. A monocrystalline Cz-Si ingot was used as reference. The experiments were done with a silicon load length of 295mm, a 120µm core wire and a diamond grit of 8-16µm at a wire speed of 18 m/s, a wire tension of 28N and a feed rate of 0.55mm/min. Throughout the whole cutting process the forces in three dimensions were monitored using a 3D piezo dynamometer. The normal force F_z, i.e. the force in feed direction, was used to assess the sawing processes for the different bricks. The magnitude of F_z is a measure of the bowing of the wire web under the brick and thus reflects the cutting efficiency.

Pre-characterization of the bricks

Prior to the wafering processes, the bricks were inspected by IR transmission with the standard resolution of 200µm. As it can be seen in Fig. 5, no inclusions are visible at this resolution; these bricks would thus pass the inspection control in the industrial wafering chain. The resistivity of all HPM bricks was in the range of 3-10Ωcm. The ingot position of the bricks was unambiguously determined by carrier lifetime mappings of slabs from the bottom and top of the bricks and can be seen by the extension of the so-called red-zone of low carrier lifetime (see Fig. 6).

Characterization of wafering process and resulting wafer quality

Bricks of the same silicon load length of 295mm were cut with equal process parameters. Thus, the normal force F_z is a measure for the cutting efficiency of the material. As it can be seen in Fig. 7, F_z is the highest in case of the centre brick, for the corner and edge brick a significantly lower force develops in the course of the sawing process. The maximum F_z is about higher 55% for the centre brick compared to the corner brick. For all HPM-Si bricks F_z is higher in comparison to the reference Cz-ingot. These results confirm our findings on ingots of the same manufacturer using slurry sawing processes. However, the differences between the centre brick and bricks from the ingot edge or corner are even more pronounced in DWS. This is likely due to the higher feed rate used in the DWS process and probably also because of the different wear mechanism of the diamonds compared to the SiC particles in the slurry.

The resulting wafer thickness for each brick is depicted in Fig. 8. The thickness correlates with F_z, the higher the force the lower is the wafer thickness. With a higher wire wear (at higher F_z) the effective wire diameter, which is the core diameter plus the double mean grit size, becomes smaller. Thus the created sawing channel is also smaller, resulting in thicker wafers. Consequently, the reference Cz-ingot yields the thinnest wafers.

An important measure for the quality of the wafers is the total thickness variation (TTV). A higher force in the sawing process results in an increased TTV (see Fig. 9). The correlation is given for the HPM-Si bricks, the reference Cz-brick shows a slightly increased TTV. We explain this by minor wire distortion effects during the cutting-in of the pseudo-square Cz-bricks, for which the sawing process was not optimized. Furthermore, the mechanical stability of the wafers was tested by the four-line bending test. No differences within the measurement accuracy where found between the different HPM-Si bricks, neither in the as-sawn state nor in the damage-

Figure 5. IR transmission images of the mc-Si bricks with standard resolution of 200µm.

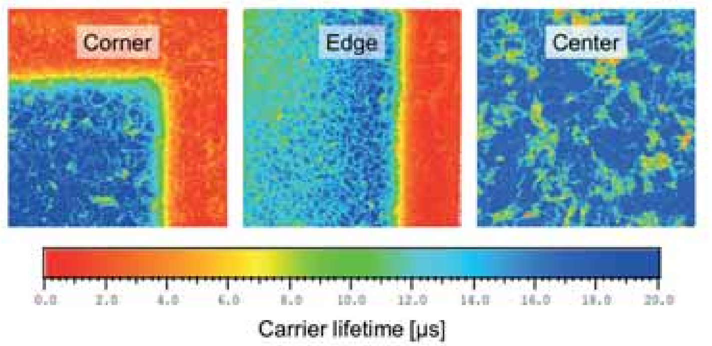


Figure 6. Carrier lifetime mappings of the bottom slabs prove the ingot position of the bricks.

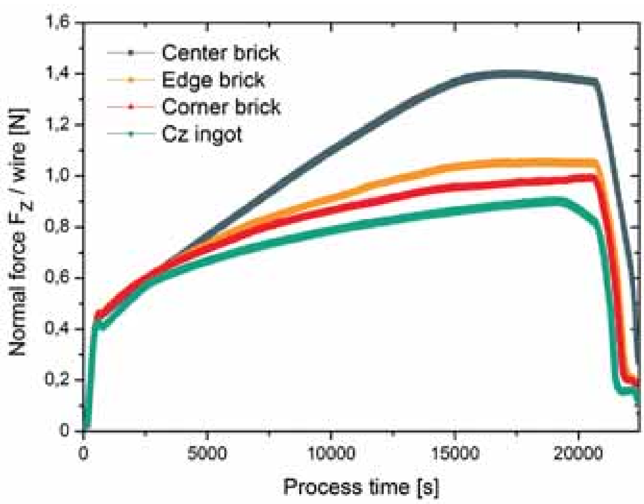


Figure 7. Normal force F_z over the whole process time.

etched state. However, the reference Cz-wafers turned out to be more stable as it is expected.

Influence of different material properties

After finding these significant differences in the cutting efficiency of HPM-Si bricks from different ingot positions, which material property has the dominant effect on the sawing process should be clarified. No correlation was found between F_z and the concentration of interstitial oxygen and substitutional carbon as determined by FTIR spectroscopy. The average grain size as well as the number of relevant grain boundaries was determined as a function of the brick height by X-ray diffraction ("Laue scanner"). The differences of these crystal structure properties between the investigated bricks do not reveal a correlation to F_z, too.

We attribute the differences in the cutting efficiency to the presence of silicon nitride (Si_3N_4) and silicon carbide (SiC) precipitates, which were found by IR microcopy in the bottom and top slabs of the bricks. An example of Si_3N_4 needles in the corner brick are shown in Fig. 10. The majority of precipitates found have been Si_3N_4 needles that are likely originating from the crystallization crucible. SiC precipitates were only rarely found.

By automated determination of the precipitate area and counting the number of inclusions in the bottom and top slabs of the different HPM-Si bricks, the median precipitate area was calculated, yielding significant differences. The mean precipitate area in the centre brick is almost twice the median area in the edge and corner bricks. This correlates with the maximum normal force F_z occurring in the wire sawing process (see Fig 11).

Industrial scale wire sawing of HPM-Si with 70µm core diameter

A larger amount of HPM-Si bricks of the same manufacturer as in the experiments presented above was investigated using a state of the art Meyer Burger DS288 diamond wire saw. The full load length of the machine was used by mounting two ingots in series. The experiments were done with a 70µm core wire, a diamond grit size of 6-12µm and an overall process time of 150 minutes with a wire speed of 30m/s and a wire consumption of about 1.8-2.0m/wafer.

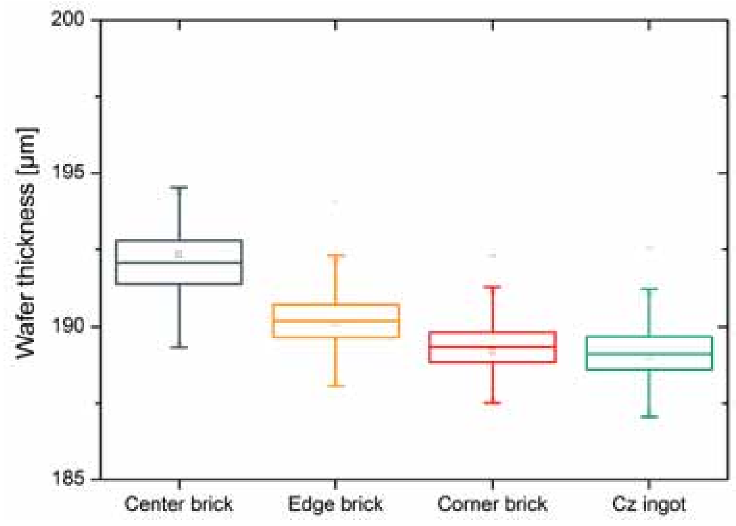


Figure 8. Thickness of the resulting wafers, each box comprises about 830 wafers.

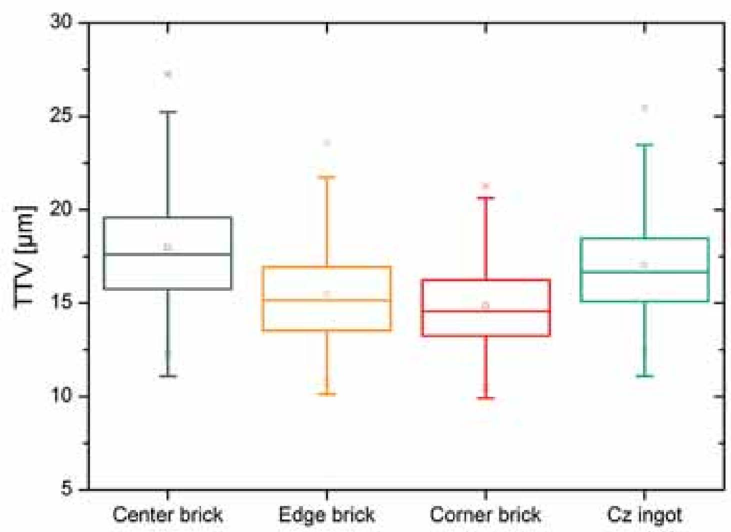


Figure 9. Total thickness variation (TTV) of the resulting wafers, each box comprises about 830 wafers.

Configuration FB to MB	Maximum cut area [cm²/m]	Mean TTV [µm]	Saw mark depth [µm]
Bottom → Top / Top → Bottom	156	6.4	12.6
Top → Bottom / Bottom → Top	185	9.5	15.8
Top → Bottom / Bottom → Top	185	11.2	19.0
Bottom → Top / Bottom → Top	185	6.9	13.9

Table 1: Configuration of the HPM-Si bricks in full load cuts and resulting wafer TTV and saw mark values.

Pre-characterization of the bricks

The bricks were investigated with a high resolution IR transmission system with a spatial resolution of 18µm. Exemplarily shown are point- and needle-like inclusions in a HPM-Si brick in Fig. 12. Different bands of these inclusions are displayed by red to blue color in the images.

After unambiguously determining the bottom and top of the bricks, different configurations of brick arrangements were tested in full load cuts in industrial DWS processes. All bricks contained a section of inclusions near the top of the brick and a second band near the bottom of the brick. The configurations of the bricks from the fixed bearing of the machine (FB) to the movable bearing (MB) are shown Table 1. The FB side is the new wire entry side of the wire web.

In the first configuration a maximum cut area of 156cm²/m wire length was used yielding a mean TTV of 6.4µm. For the following three configurations, a higher maximum cut area of 185cm²/m wire length was used in order to yield a more pronounced effect of the inclusions on the wafer quality. It turns out that configuration starting with the bottom of the first brick from the FB side and arranging the bottom of the second brick also towards the FB side is the most favourable regarding the mean TTV of the wafers. The number of saw marks correlates with the TTV values.

For the second configuration, the influence of the precipitate bands within the bricks on the wafer quality is shown in detail in Fig. 13. The first precipitate band (top of brick #1) looking from the new wire entry side does not have an effect on TTV or saw marks. The precipitate band in the bottom regions of brick #1 and #2 drastically influence the wafer quality as it can be seen by higher thickness values (red color) and more pronounced saw marks. The precipitate band in the top region of brick #2 (MB side) does again not influence the wafer quality, as shown by standard wafer thicknesses (green color) and unremarkable saw mark depths. Generally, the bottom regions of the ingot appear to be harder and have the highest impact on the wafer quality in this configuration.

Conclusion

The inspection and characterization of multicrystalline silicon bricks plays an important role for the optimization of the diamond wire sawing process. It turned out that the standard IR

Materials

transmission with 200μm spatial resolution is not sufficient to detect all impurities, which have a relevant influence on the cutting efficiency of the material.

Comparing bricks from different ingot positions in laboratory-scale DWS experiments, the cutting efficiency shows significant differences as demonstrated by monitoring the force in feed direction over the entire process time. For a specific crystal manufacturer within this work, the bricks from the edges and corners of an HPM-Si ingot can be more easily cut compared to bricks from the ingot centre. This was mainly attributed to the presence of silicon nitride precipitates of different size within these ingots as characterized by IR transmission microscopy. In the case of other crystal producers the situation might be different. If the precipitates in the edge regions of the ingot would be larger, depending on the melt convection during the crystallization process, the cutting efficiency of edge and corner bricks will be lower compared to centre bricks.

The findings offer the potential for process optimization with a cost reduction potential. Thus, a presorting of bricks prior to the wafering could be established, which distinguishes centre and edge/corner bricks, given that the precipitate distribution is known. After presorting, adapted processes regarding feed rate or wire consumption can be applied for the two groups of bricks.

The relevant precipitate distribution can be monitored with a high resolution IR transmission measurement of the bricks, offering a spatial resolution of 18μm. Such a system was used to identify bands of point- and needle-like precipitates within HPM-Si bricks. The position of the precipitate band correlates with the appearance of higher wafer TTV values and saw marks on the wafer surface.

The configuration of bricks regarding the position of brick bottom and top also plays a role when using the full load length on state-of-the-art diamond wire saws with 70μm wire core diameter in industrial processes. A serial arrangement in the order brick bottom to top looking from the fixed bearing to the movable bearing of the machine turned out to be favourable for the crystals of the manufacturer that were investigated here. In general, a further reduction of the size of precipitates, especially of silicon nitride needles and SiC clusters, is desired in order to further improve the cutting efficiency of multicrystalline silicon bricks in diamond wire sawing.

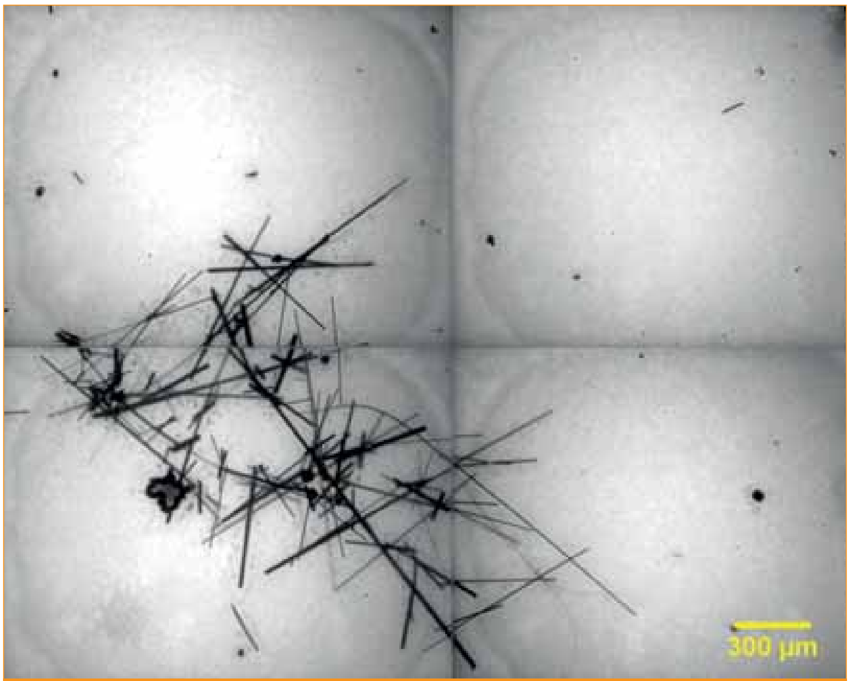


Figure 10: IR transmission microscopy of the corner brick bottom slab showing an aggregation of Si_3N_4 needles.

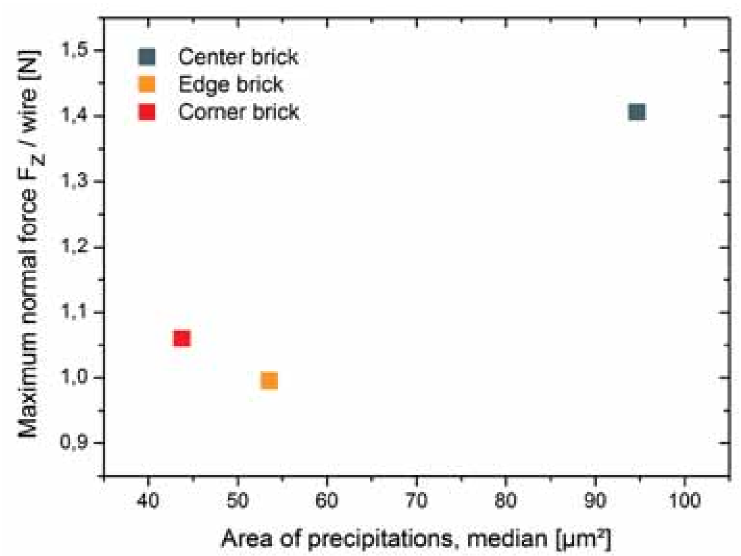


Figure 11. Correlation of F_z and the median precipitate area in the bottom and top slabs from the different HPM-Si bricks.

Acknowledgement

Parts of the research were funded by the Federal Ministry for Economic Affairs and Energy with in the project "DIANA" (Contract No. 0324087B), which is gratefully acknowledged.

References

[1] Riepe, S. 2015, "Development of multicrystalline silicon for 20% efficient n-type solar cells", Proc. of 31st EU-PVSEC, pp. 295-299.

[2] Beneck, J. 2017, "High-Efficiency n-Type HP mc Silicon Solar Cells", IEEE Journal of Photovoltaics, Vol. 7, No. 5, pp. 1171-1175.

[3] Möller, H.J. 2004, "Basic Mechanism

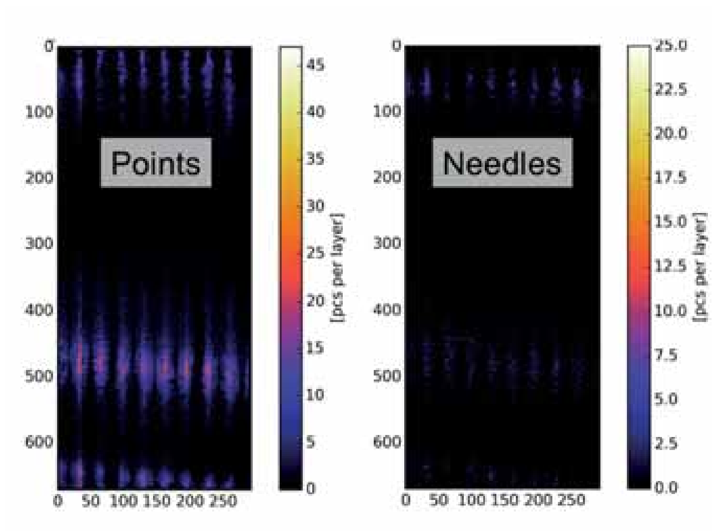


Figure 12. Bands of point- and needle-like defects detected by high-resolution IR transmission.

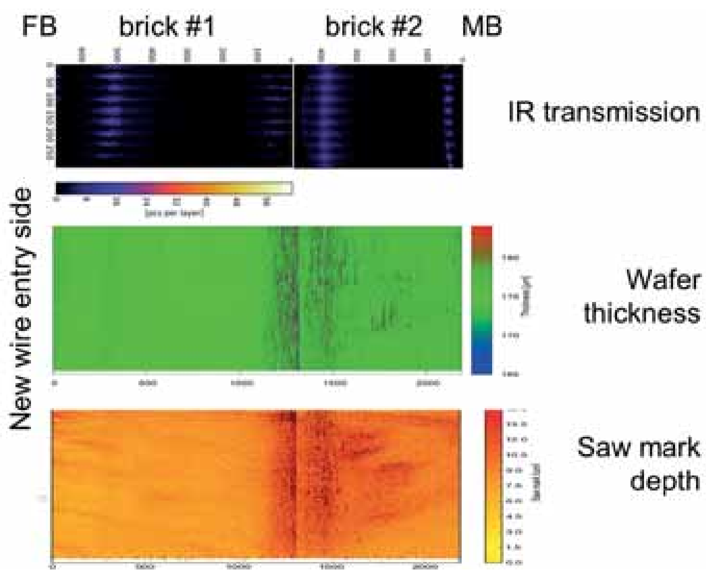


Figure 13. Correlation of precipitate bands with wafer thickness and saw mark depth in the second configuration.

and Models of Multi-Wire Sawing", Advanced Engineering Materials, Vol. 6, No. 7, pp. 501-513.

[4] Behm, T. 2011, "Challenges of the wire saw wafering process", Photovoltaics International, No. 11, pp. 36-47.

[5] Schumann, M. 2009, "The solar cell wafering process", Photovoltaics International, No. 5, pp. 53-59.

[6] Buchwald, R. 2013, "Analysis of the sub-surface damage of mc- and Cz-Si wafers sawn with diamond-plated wire", Energy Procedia, Vol. 38, pp. 901-909.

[7] Würzner, S. 2017, "Characterization of the Diamond Wire Sawing Process for Monocrystalline Silicon by Raman Spectroscopy and SIREX Polarimetry", Energies, Vol. 10, 414.

About the Authors

Thomas Kaden studied applied natural science at TU Bergakademie Freiberg and received his Ph.D. in physics in the photovoltaics group of Prof. H.J. Möller. After working on silicon material topics in the R&D department at Q-Cells S.E. in Bitterfeld, he joined Fraunhofer THM in 2012. Starting with solar module activities, he later joined the wafering group. Since 2016 he is Head of the Group THM Wafering.

Elena Ershova holds a diploma in information technology and systems from TU Wolodga (Russia) and performed the majority of experiments presented here during her bachelor thesis at Fraunhofer THM. In July 2017 she obtained a bachelor of science in environmental engineering from TU Bergakademie Freiberg.

Marcel Fuchs worked as an operator in wafer and solar cell production and was production supervisor of a wafering company before he joined Fraunhofer THM as senior technician in wafering in 2012. He operates the wire sawing machines and gives valuable input in developing and improving sawing processes for different kind of hard-brittle materials.

Rajko B. Buchwald studied applied natural science at the TU Bergakademie Freiberg. He received his Ph.D. in 2010. In 2010 he joined Fraunhofer THM in Freiberg. Under the lead of Prof. Möller he helped making the centre operational to investigate and improve diamond wire slicing processes on industrial scale. After two years as Head of Group Wafering he moved to Meyer Burger (Switzerland) AG in 2016.

Enquiries

Dr. Thomas Kaden
Fraunhofer Technology Centre for Semiconductor Materials THM
Am St.-Niclas-Schacht 13

09599 Freiberg, Germany
Tel.: +49-3731-2033 166

Email: thomas.kaden@thm.fraunhofer.de
Web: www.thm.fraunhofer.de

Epitaxial Si lift-off technology: Current status and challenges

Hariharsudan Sivaramakrishnan Radhakrishnan[1], **Valérie Depauw**[1], **Kris Van Nieuwenhuysen**[1], **Ivan Gordon**[1] & **Jef Poortmans**[1,2,3]

[1]imec, Leuven; [2]KU Leuven; [3]University of Hasselt, Belgium

ABSTRACT

The cost of silicon (Si) continues to be a significant component of the final PV module cost, and thus a major driver towards better Si utilization (g/Wp) in the PV industry. The continuation of this scenario, despite constant reductions in module prices, ensures an ongoing interest in the development of kerfless technologies in general, among which *epitaxial Si lift-off* is one of the more advanced technologies for high-quality monocrystalline silicon (c-Si) wafer production. Since its invention in the late 90s, this technology has been developed by different groups around the world. A number of start-up companies have recently taken on the challenge of commercializing this technology, providing the much-needed fuel for its leap from lab to fab. This paper gives an overview of epitaxial Si lift-off, providing insight into every step of the lift-off cycle and a flavour of the current status of this technology and the challenges it faces.

Kerfless technologies as an enabler of ultra-thin Si

The drive towards better Si utilization (g/Wp) has been an obsession in the Si PV industry over the last few decades as one of the key aspects in making photovoltaic energy production competitive. With the cost of Si still making up a third of the final Si solar module cost, there is continued interest in reducing the cost of Si by producing thinner wafers and reducing kerf losses [1]. However, conventional wafering technologies are hitting a brick wall, as it is increasingly challenging to produce thinner wafers with high yield and low total thickness variation [2]. Moreover, thicker wafers can better withstand automated handling systems in cell and module production lines and are therefore preferred, since yield is a highly sensitive cost factor in PV production [3]. As a result, the average Si thickness has stabilized to around 180µm. In fact, the latest ITRPV roadmap gives a more tempered prediction in terms of wafer thickness reduction in the coming years, compared with previous editions [1].

Numerous alternative technologies to conventional wafer production have been explored in order to eliminate kerf losses and/or to produce ultrathin silicon in a thickness range that is beyond the reach of conventional wafering. Such technologies that allow wafer production with negligible kerf losses are called *kerfless* or *kerf-free* wafering technologies. In many of the kerfless wafering techniques, the Si wafer is detached or released from the surface of a substrate or ingot, in a process called *lift-off*.

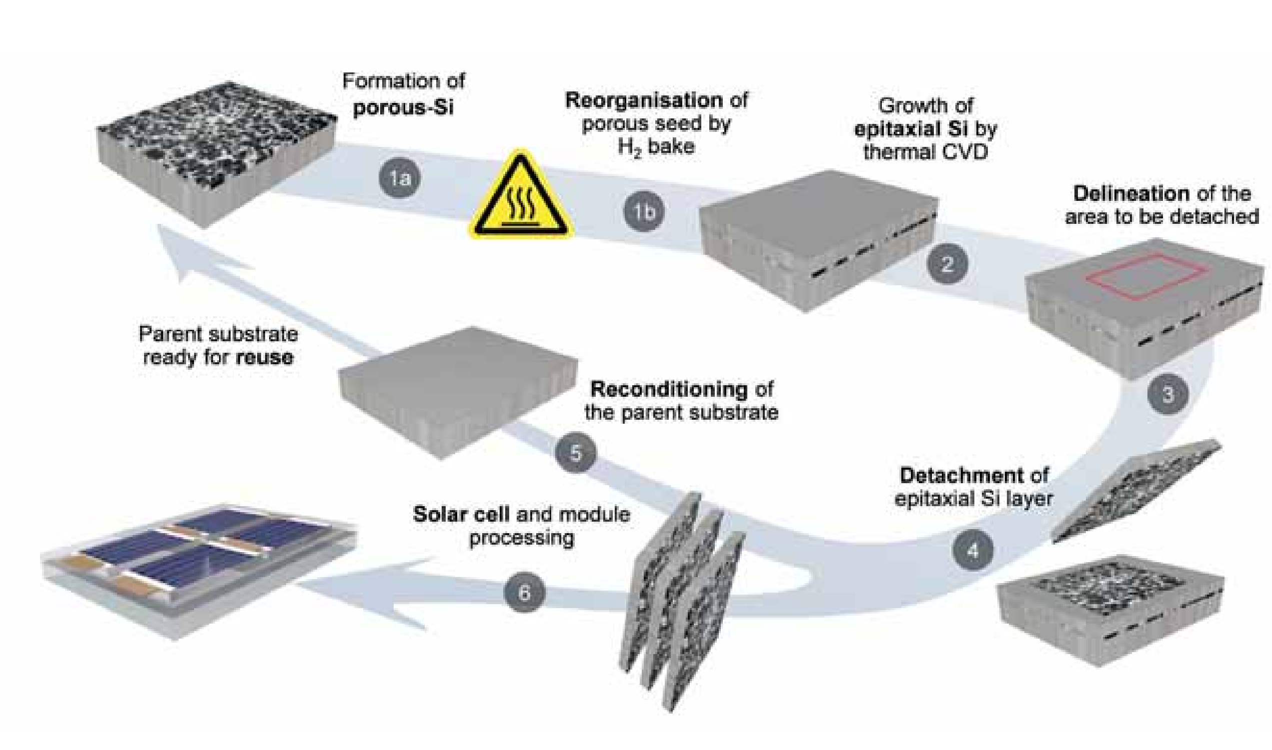


Figure 1. Fabrication of epitaxial Si solar cells and modules from porous-silicon-based epitaxial Si lift-off.

Overviews of various kerfless wafering methods or lift-off processes have been given by Henley [4], Brendel [5], McCann et al. [6], Weber et al. [7] and Bergmann et al. [8]. Currently, an extensive review [9] and a book chapter [10], providing an exhaustive update, are in preparation. Of several dozens of lift-off and kerfless routes investigated, currently one of the most extensively researched and developed routes is the porous-silicon-based lift-off of epitaxial Si. In this paper, an overview of the different technologies underpinning the potentially successful commercial exploitation of epitaxial Si lift-off is presented.

Epitaxial silicon lift-off: the technology, from seed layer to module

The process of porous-silicon-based lift-off of epitaxial Si is shown in Fig. 1. A layer of monocrystalline Si is grown from the vapour phase, using trichlorosilane (TCS) as a precursor, by homoepitaxy. The layer is grown as thin as desired, from a thickness of ~160µm (wafers) down to a few micrometres (foils). The epitaxial growth is performed on a reusable Si substrate, whose surface is porosified and sintered to enable both the growth of epitaxial Si and its subsequent detachment.

"With Si still making up a third of the final module cost, there is continued interest in reducing the cost of Si by producing thinner wafers and reducing kerf losses."

As the solar cell material is directly grown from the gas phase to the required thickness, no wafering is required, and hence no kerf loss is generated. Moreover, as growth is realized using TCS, this lift-off method offers a significant shortcut through the monocrystalline Si PV value chain, by skipping not only wafer sawing but also the expensive and energy-intensive steps of poly-Si rod fabrication (Siemens process) and Czochralski (Cz) ingot pulling. The impact of the parent substrate on the cost is significantly reduced because of its capacity for multiple reuse.

The use of porous silicon to lift off an epitaxial Si layer was pioneered by Yonehara et al. at Canon with the ELTRAN process for SOI wafers [11]; for PV applications, however, the concept was adapted independently and simultaneously by Tayanaka and Matsushita at Sony [12] and Bergmann et al. at IPE [13]. In the following 20 years, the process has seen many different embodiments and is still being pursued by different institutes (e.g. Fraunhofer ISE [14], ISFH [15,16] and imec [17,18]), and companies (Amberwave [19], Crystal Solar [20–22] and NexWafe [23]).

The following subsections explain the various steps in the epitaxial Si lift-off carousel (with reference to Fig. 1): the seed layer formation by porosification and sintering (1) before epitaxial growth (2), followed by the delineation (3) and detachment (4) of epitaxial Si. The parent substrate is then reconditioned (5) for reuse in the next lift-off cycle, while the epitaxial Si wafer/foil is processed into a solar cell (6).

Step 1: Porous silicon as the detachment layer and epitaxial template

Porous silicon (PSi) etching and sintering are at the heart of the lift-off process (Fig. 2). The surface of a monocrystalline Si substrate – the parent – is porosified up to a few micrometres in depth in stacks of different porosities, the simplest case being a double layer with a thick low-porosity layer (~20%) on top of a thin high-porosity layer (~50–60%). When this porosified substrate is loaded into an epitaxial reactor, at a high temperature (>1,000°C) and in a reducing atmosphere (e.g. H_2), its porous microstructure reorganizes. A smooth closed surface with embedded spherical voids forms in the low-porosity layer, while a cavity intermittently interrupted by pillars forms as the detachment plane in the high-porosity layer. In this way, PSi enables the homoepitaxial growth of a high-quality Si layer and its subsequent detachment from the parent substrate. Besides this, the PSi seed layer, with its high internal surface area, is a very efficient gettering centre which captures potential metallic contaminants that could enter the epitaxial Si from the parent substrate or the tool ambient atmosphere [24].

Considering its twofold key role in epitaxial Si lift-off, the porosification step is paramount to the success of the lift-off process and therefore requires tight process control. Porosification is realized by electrochemical etching in an HF-based electrolyte [25]. The Si substrate to be porosified is used as the anode of the electrochemical cell, and a current is applied to create pores at the surface. A surfactant, such as alcohol, is used to achieve

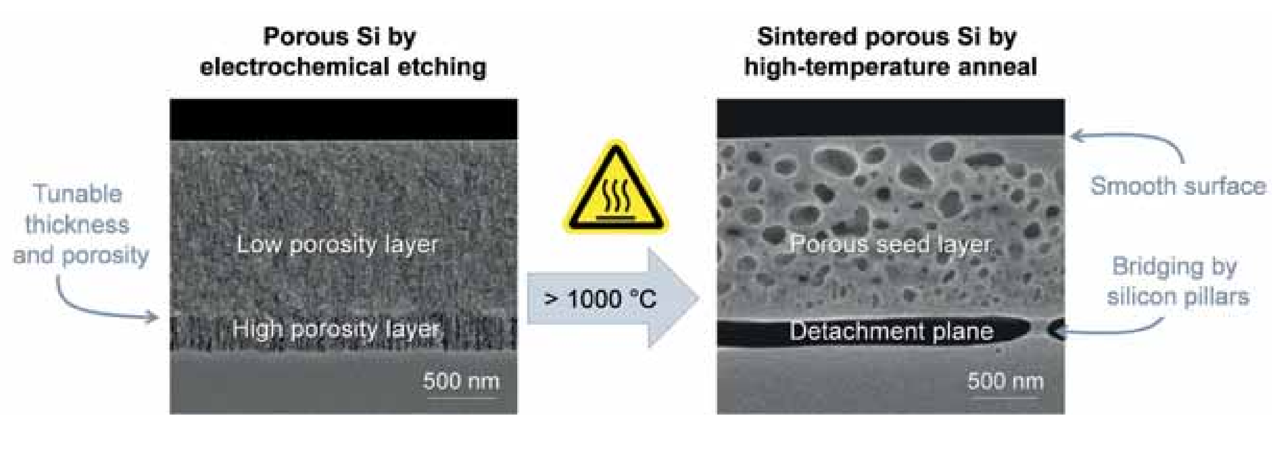


Figure 2. Scanning electron microscopy (SEM) cross sections of a double layer of porous silicon: (a) as-etched, and (b) after reorganization in an epitaxial reactor, offering a smooth epitaxial growth template at the surface and a cavity underneath for the release.

efficient evacuation of the H_2 bubbles produced during the process. The advantage of using electrochemical etching is that the porosity can simply be controlled by the applied current density, while the layer thickness can be controlled by the etch time. However, other parameters influence the pore morphology (dimension, shape, etc.), in particular the substrate doping type and concentration, and the electrolyte composition. In practice, p^{++} substrates are used, as they can be easily contacted electrically and do not require illumination as n-type substrates do. The combination of high current (e.g. 80mA/cm²), flammable compounds (H_2, alcohol) and toxic chemicals (HF) used in PSi fabrication calls for ingenious tool design in order to meet safety and layer quality requirements.

"Porous silicon etching and sintering are at the heart of the lift-off process."

In common porosification tools, the parent substrate is clamped along the edge using an O-ring, which creates an unporosified rim along the substrate edge. This means that the epitaxial Si on this rim cannot be detached, and will become thicker and thicker with every reuse cycle (see 'Reuse of the parent substrate' section below). In tools that enable etching of the complete substrate area, epitaxial Si over the entire area can be released; however, this requires the removal of the epitaxial overgrowth on the edges to release the layer (see 'Delineation of the epitaxial Si foil' section below).

PSi sintering is as critical as porosification to the lift-off process. Upon sintering, the extremely high surface area causes the pores to transform and merge in order to minimize the total surface energy. Theories based on vacancy diffusion [26,27] and stress minimization [28] have been used to explain this microstructure transformation. Pores smaller than a critical radius (which depends on the vacancy supersaturation and residual stress) shrink, feeding larger ones, and, like connecting vessels, pores and voids in the porous stacks mutually interact, until an equilibrium stack is formed. The dependence of the microstructure transformation on the porosity and thickness of the different layers has been investigated in detail [27,29,30]. In addition, the evolution of the residual stress in porous silicon, before and after sintering, in single and double layer stacks has been studied [31,32]. Understanding, and thus predicting, the evolution of the porous stack during sintering is key to optimizing PSi as an epitaxial seed and detachment layer.

Step 2: Epitaxial silicon growth on porous silicon

The growth of the epitaxial Si layer is performed *in situ* on the sintered PSi, by deposition from the vapour phase. The most commonly employed technique is atmospheric pressure chemical vapour deposition (CVD) with trichlorosilane (TCS) as a precursor. Taking place at 1,000–1,200°C, this method ensures the growth of a high-quality monocrystal on the crystalline porous seed surface, at a high growth rate of up to 10µm per minute. The epitaxial Si layer can be grown as thick as desired (20–160µm reported), by tuning the deposition time, and with n- and/or p-type doping with the desired concentration and depth profile by controlling the dopant gas. What can be produced is therefore not just a bare photoactive layer, but also a partially processed solar cell 'precursor' with integrated emitter, back-surface field and front-surface field all in a single process, and tailored to one's needs (Fig. 3). Other noteworthy assets of epitaxial growth are its potential for a narrower spread in crystalline quality and resistivity than in the case of a Cz ingot, and the natural low concentration of O interstitials, compared with Cz Si [20]. These two characteristics respectively result in a tighter solar cell bin for module assembly, and the absence of light-induced degradation.

The recently reported minority-

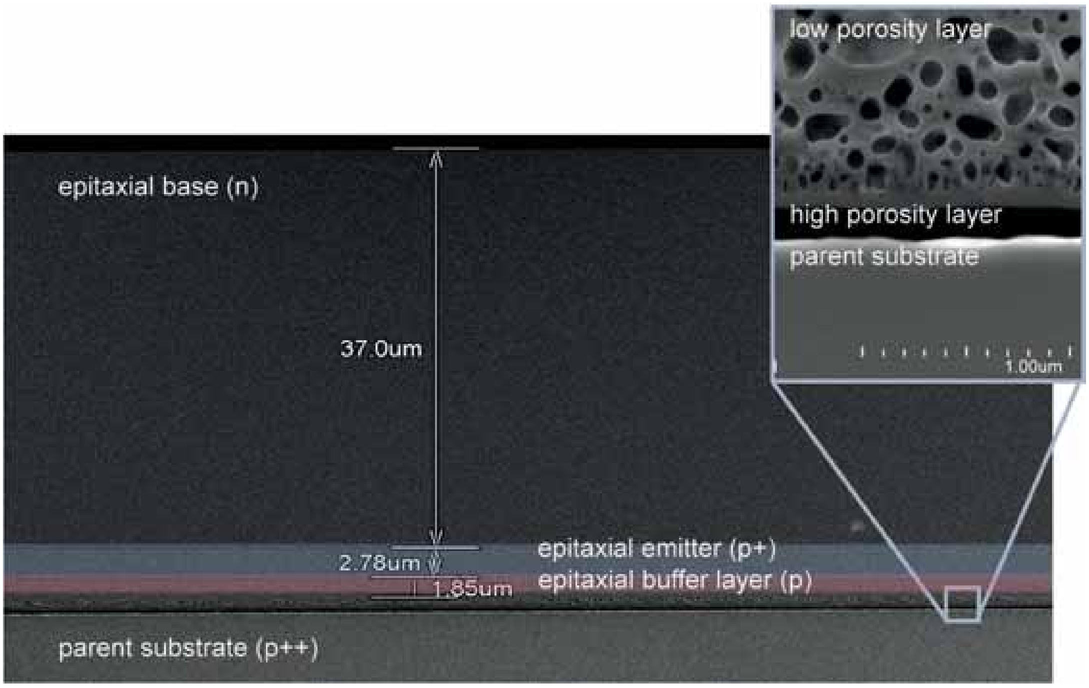


Figure 3. Cross-sectional SEM image of a 40µm-thick epitaxial Si foil with integrated emitter on top of the porous seed layer (inset).

Materials

carrier lifetimes in epitaxial Si are spread over a wide range: 30–700µs for epitaxial foils, referred to as *epifoils* (<70µm) [29,33], and 1–4ms for epitaxial wafers, referred to as *epiwafers* (>100µm) [16,21,22]. The wide range illustrates that many factors influence the material quality. While the nature of the incorporated crystalline defects that influence the quality of Cz and float zone (FZ) silicon is well understood, the array of defects that determine the properties of epitaxial Si is still under investigation.

One of the main factors influencing epitaxial Si quality is the condition of the porous silicon seed layer. The presence of pits and bumps or pronounced roughness at the surface will result in the formation of extended crystalline defects, such as nested stacking faults [14], which have been shown to significantly reduce the minority-carrier lifetime. Additionally, the stress state of the porous seed *below* the surface could also affect the epitaxial Si quality. A higher residual stress, in combination with a rougher surface, has been proven to result in a higher defect density and lower minority-carrier lifetime [29].

A second important factor to be controlled is the material purity. All the process steps up to and including epitaxy require very stringent contamination standards. It has, for instance, been reported that Pt, which is a common cathode material for porosification, has been found in the epitaxial Si, resulting in a reduction in minority-carrier lifetime [34]. More and more attention is now also turning towards intrinsic point defects, which seem to be related to the cooling rate in the epitaxial reactor. A fast cooling rate is also suspected to introduce stress, which could affect the material properties. Slower cooling rates and gettering steps are currently being investigated in order to understand their importance in achieving higher minority-carrier lifetime.

Step 3: Delineation of the epitaxial Si foil

Before the epitaxial Si layer can be detached from the parent substrate, the area to be lifted off needs to be delineated in order to release the edges of the soon-to-become kerfless wafer/foil. Delineation is a crucial step because it defines the wafer edge microstructure, which influences the mechanical strength of the resulting epitaxial Si wafers or foils. A delineation method that leads to a high density of edge defects significantly increases the breakage rate during subsequent handling, manipulation and cell processing [35,36]; this cannot be tolerated in the cost-sensitive PV industry, where yield is of utmost importance [3].

> "Delineation is a crucial step because it defines the wafer edge microstructure, which influences the mechanical strength of the resulting epitaxial Si wafers or foils."

In the conventional Cz wafer production route, the sawn edges of the ingot are polished to ensure defect-free, high-quality edges, which in turn ensures high mechanical strength. For epiwafers or epifoils, the delineation method must be chosen in such a way that high-quality edges are produced, if possible ab initio, while maintaining a high throughput and a low capital cost.

The most common method for delineation is laser ablation (LA) [20,37,38]. During LA, the laser energy is absorbed by the Si and converted mainly into heat, resulting in the localized melting and expulsion of material from the heated spot, which leads to a V-shaped groove, as shown in Fig. 4(a) and (b). The depth can be well controlled so that the laser groove reaches the bottom of the epitaxial Si without damaging the parent substrate. The side wall of the laser groove (which eventually forms the epitaxial Si wafer edge), however, is severely damaged; this defective region is known as the *heat-affected zone (HAZ)*. The extent of the HAZ is strongly dependent on the laser parameters, in particular the duration of the laser pulse, which can be of the order of nanoseconds (ns-LA), picoseconds (ps-LA) or femtoseconds (fs-LA). Shorter pulsed laser sources cause less thermal damage, and could therefore result in higher mechanical strength; however, very short pulsed laser sources, such as fs-lasers, are much more expensive than ns-lasers.

A novel variant of laser ablation is multi-beam laser ablation (mb-LA), developed by ALSI [39]. In this technology, a nanosecond laser source is split using a diffractive optical element (DOE) into an array of smaller beams, each with a lower fluence.

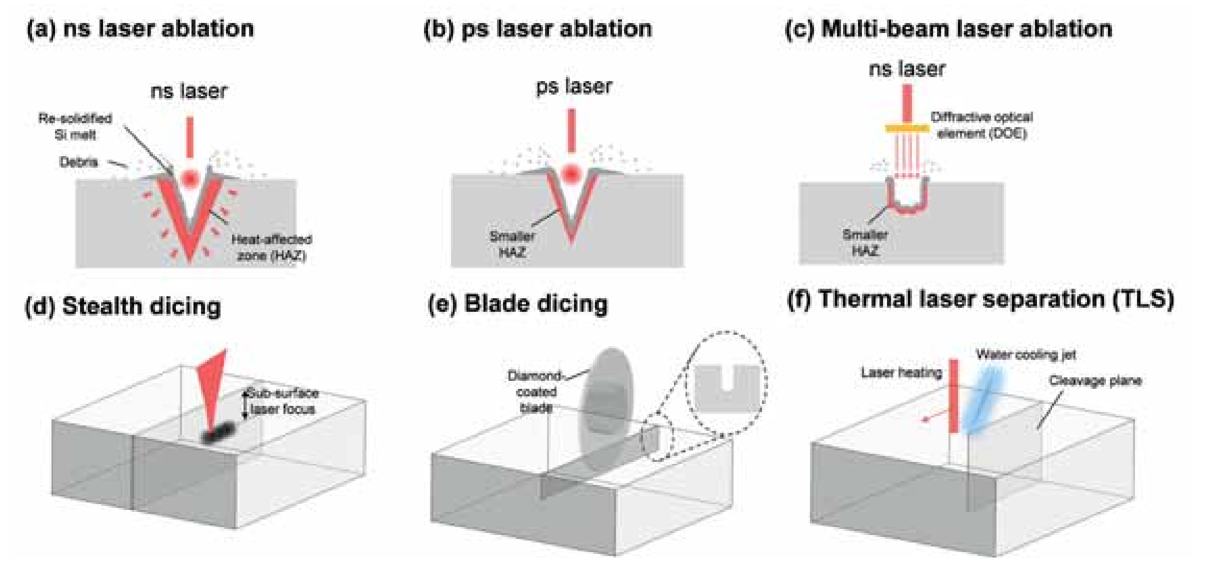


Figure 4. Different delineation methods for defining the area of the epitaxial silicon to be lifted off: (a) nanosecond laser ablation (LA), (b) picosecond LA, (c) multi-beam LA, (d) stealth dicing, (e) blade dicing, and (f) thermal laser separation (TLS).

Since each child beam delivers lower power, the resulting thermal damage is considerably less than in the case of conventional ns-LA (Fig. 4(c)). Moreover, since an array of multiple spatially separated beams are used, the dicing process can be accomplished in a single pass at high speed. Additionally, ALSI has also developed a novel process called *VDOE*, in which the defective HAZ at the top of the laser groove is removed [40]; as a result, the use of this process can result in wafers with higher mechanical strength.

Blade dicing is the workhorse for die separation in the microelectronics industry (Fig. 4(e)), and can be readily applied to the delineation of epitaxial Si. In this process, a circular rotating blade with embedded diamond abrasive particles slices through silicon in a water-cooled environment. The resulting cut shows striations on the side walls and chips at the surface, but is in general much less detrimental to the foil strength than laser-ablated side walls.

Stealth dicing, a novel technique developed by DISCO and Hamamatsu, also for use in the microelectronics industry, utilizes a pulsed infrared laser source that is focused at a depth well below the surface of the Si. When the power density at the focal depth exceeds a critical value, a subsurface-damaged (SD) layer is created. When an external force is applied, cracks propagate from this SD layer towards the surfaces (Fig. 4(d)). The main advantage of stealth dicing is that the defective region can be localized in the middle of the wafer/foil edge, close to the neutral axis, away from the surfaces, where the highest mechanical stresses are experienced while handling or processing.

Finally, another novel technique that has gained attention recently is thermal laser separation (TLS), developed by 3D-Micromac; here, a continuous wave laser source is used to heat Si locally, accompanied by a cooling water jet (Fig. 4(f)). This causes significant localized thermomechanical stresses, which are used to guide a crack from a predefined location along the path of the moving laser and water jet [41]. Since the mechanism is stress-induced cleaving of Si, the wafer edges are defect free. The use of this technique for epitaxial Si lift-off can be quite challenging if the cleavage of only the epitaxial silicon above the detachment plane is desired. However, in the rimless PSi approach (see 'Porous silicon as the detachment layer and epitaxial template' section above) this technique could be readily

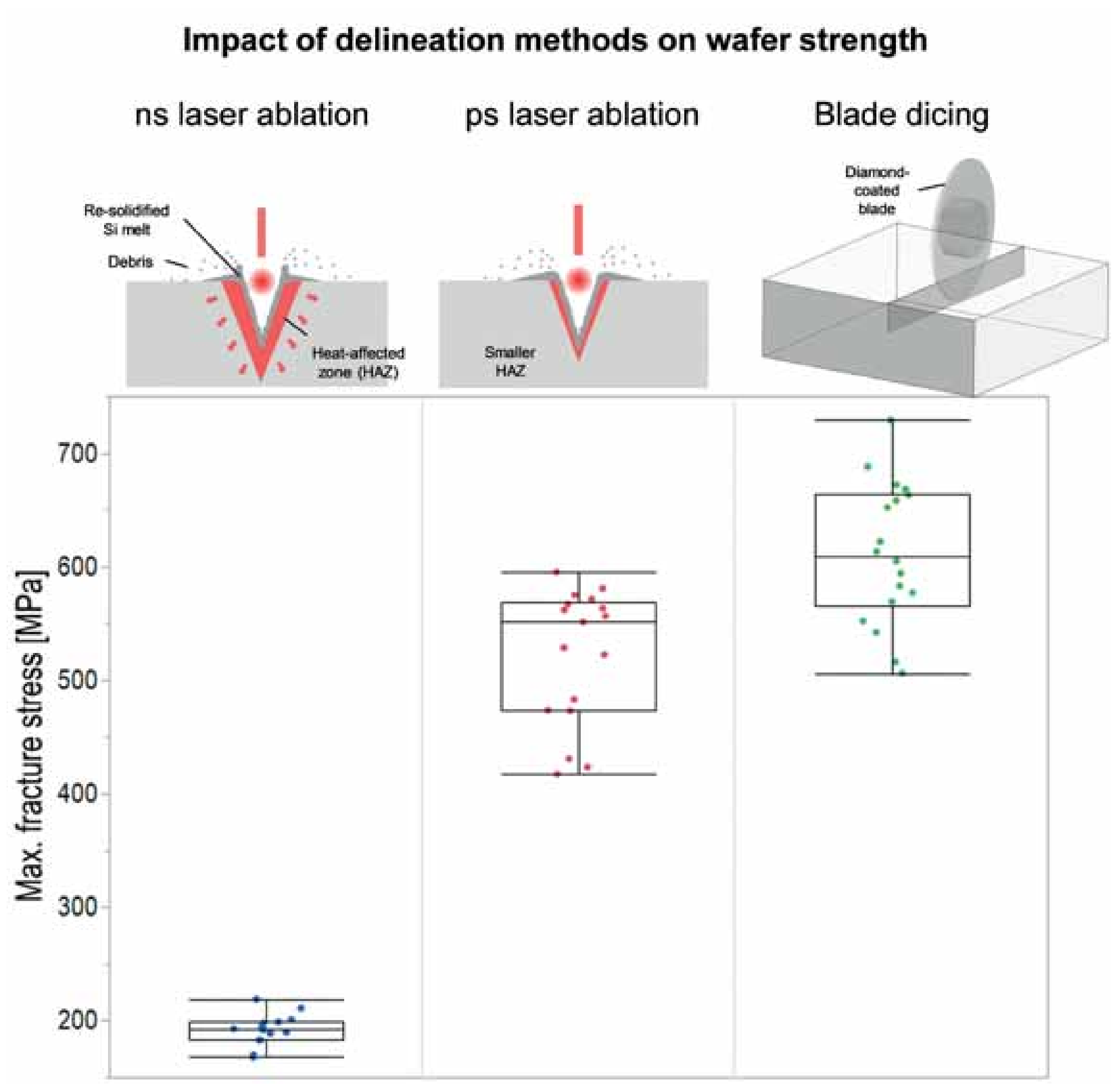


Figure 5. Comparison of the maximum fracture stress of Si diced using three different dicing methods, namely ns-LA, ps-LA and blade dicing (Si thickness: 136µm; size: 6cm × 0.5cm).

employed to simply cut through the epitaxial layer overgrowth at the edges, thus releasing the edges of the epitaxial Si before detachment.

To assess the quality of the edges produced by the different dicing methods, four-line bending tests were performed on 136µm-thick silicon wafer pieces (6cm × 0.5cm), diced using different techniques. A comparison of the mechanical strength of Si resulting from ns-LA (reference process), ps-LA and blade dicing is shown in Fig. 5. As expected, the thermal damage during LA significantly affects the mechanical strength compared with blade dicing. Moreover, the best ps-LA process significantly outperforms the best ns-LA process, owing to the lower HAZ on the side walls [36].

The impact of the dicing methods on the detachment yield and processing yield of thin Si epifoils is currently under evaluation. This should provide information on a set of dicing methods suitable for the Si delineation step, which is not only limited to epitaxial Si lift-off but also more generally applicable for other kerfless methods, as well as for other applications such as the dicing of cells into half cells [41].

Step 4: Detachment from the parent substrate

As described earlier, the detachment layer is a lateral cavity between the parent substrate and the epitaxial silicon layer, interspersed with pillars that connect and hold the epitaxial silicon and the parent substrate together. During the detachment process, these pillars must be broken or dissolved in order to release the epitaxial Si layer from the parent substrate.

While chemical dissolution of the Si pillars may be envisaged, the most common and practical way to rupture the pillars is to simply pull the epitaxial Si and parent substrate apart. Most institutes utilize distributed vacuum chucks to grip and pull them apart in a perpendicular direction to the detachment plane. Since the cross-sectional area of the pillars is only 2–3% of the total area of the wafer surface where the pulling pressure is applied, the stress on them is magnified manyfold, ensuring that the fracture stress of Si is preferentially exceeded at the pillars in the detachment plane, leading to the release of the epitaxial layer [30,38].

A proprietary curved vacuum chuck has been developed at ISFH to implement a peeling force on the pillars, whereby the epitaxial layer is peeled off the parent substrate starting from one corner of the delineated area [38]. This further reduces the external force needed for detachment, since the force is sequentially applied to a small number of pillars at the border of the detachment front, rather than to the entire area of epitaxial silicon. At imec, a similar idea is used, where the detachment front is propagated from one edge or corner of the delineated area, by manually exerting small bending forces. The propagation of the detachment front can be detected using photoluminescence imaging, as shown in Fig. 6.

> "A high detachment success rate close to 100% is crucial for the economic viability of the concept."

Detachment problems occur when defects in the detachment plane prevent the release of the epitaxial Si, often leading to no/partial detachment or breakage. A high detachment success rate close to 100% is crucial for the economic viability of the concept; this is because a failure to detach means not only a reduction in yield in epiwafer production but also a possible yield loss associated with the parent substrate if it cannot be reliably reused. Thus, studying and tackling detachment defects is very important.

The ease of detachment depends on both the density and the size of the pillars [30]. The surfaces of different parent substrates after detachment are shown in Fig. 7. When pillar density is low and the pillars are small (Fig. 7(a)), detachment is easy. However, when either pillar density is high (Fig. 7(b)) or pillars are large (Fig. 7(c)), or both of these are true, detachment is difficult, sometimes leading to partial or no detachment. If the pillar or detachment defect is sufficiently large, the plane of cracking can be deflected into the epitaxial Si, resulting in cracks or holes in the epitaxial layer.

It is possible to differentiate two types of detachment defect: systematic and sporadic. *Systematic defects* can be remedied by control and optimization

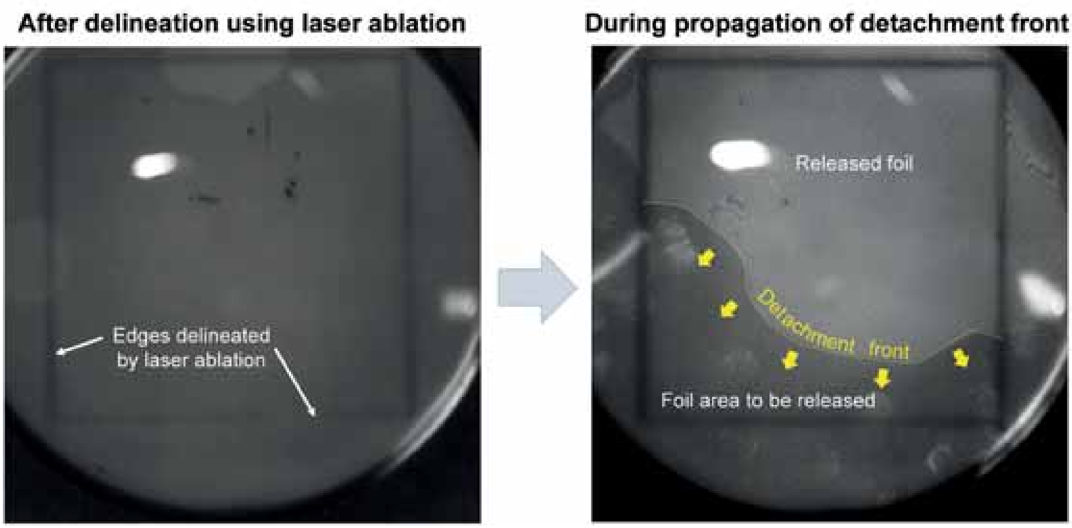


Figure 6. Photoluminescence (PL) images showing the propagation of the detachment front from one edge of the delineated epitaxial Si area to the other edge (the white stains are reflection artefacts).

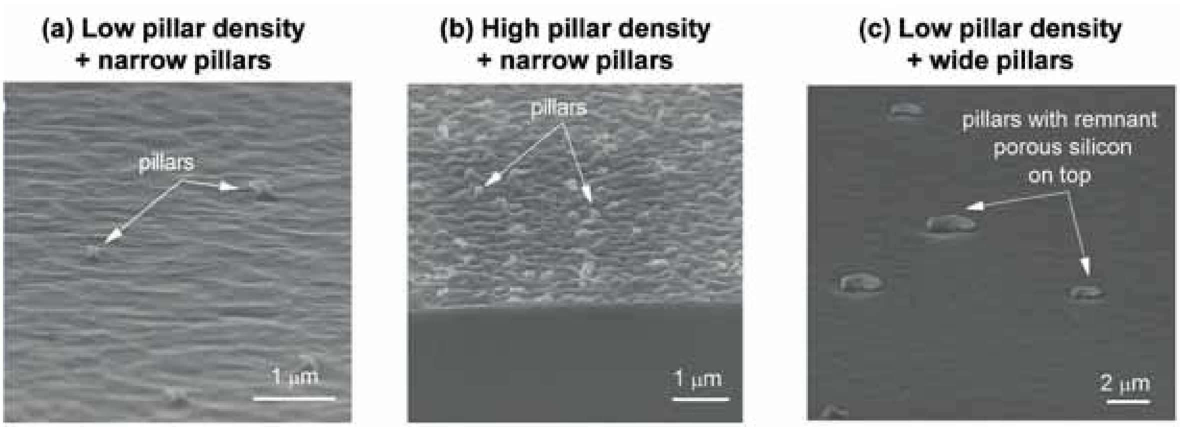


Figure 7. SEM images (tilted view) of the parent substrate surface after detachment [from 30], showing broken pillars, with: (a) low pillar density and small size; (b) high pillar density and small size; and (c) low pillar density and large size.

of the porosification and sintering conditions; for example, high pillar density in the detachment plane can be reduced by increasing the thickness of the low-porosity layer, which acts as a vacancy supply layer for the high-porosity layer during sintering [30]. Another way to deal with these defects is to infiltrate the detachment plane with a liquid, such as water, and use ultrasonication to produce cavitation-induced damage to the pillars, thus weakening them and making detachment easier [30]. High pillar density can also be tackled by using a different detachment method; for example, an extreme case of detachment at a non-reorganized porous silicon layer has been demonstrated in the ELTRAN process, using a high-pressure water jet [42].

Sporadic defects, on the other hand, are a statistical occurrence and can be much more detrimental to detachment. For example, the presence of a large particle on the parent substrate surface prior to porosification could prevent the formation of PSi underneath this particle, leading to a large zone where the detachment plane is absent. Such defects may be dealt with by stringent statistical process control of surface defect density prior to porosification. Other novel methods to address these defects are currently under consideration.

Step 5: Reuse of the parent substrate

After detachment of the epitaxial Si, the parent substrate enters the next cycle of epitaxial Si wafer/foil production. This repeated use of the parent substrate is the cornerstone of the cost savings that the epitaxial Si lift-off concept promises. Rough estimations show that the number of cycles that a parent substrate undergoes is a key parameter in the cost advantage of epitaxial Si wafers over Cz Si wafers [43].

Successful reuse means delivering epitaxial Si with a stable lifetime and detachment yield, cycle after cycle. The parent substrate properties, however, become altered along the process sequence: its surface doping is modified by the high-temperature anneal in H_2 [44], and the detachment process leaves various defects, such as pits and bumps, or possible delineation traces. Moreover, epitaxial Si remnants, such as 'flaps' (detachable epitaxial Si outside the delineated area) connected to the undetachable rim, are left behind after delineation. The parent substrate must therefore be recovered by a reconditioning step, which removes these imperfections to a large extent, with minimal material losses and risk of breakage.

The first report of reuse appeared in the literature in 2001 [45]; since then, there have been reports of more than 50 reuses with stable material quality, indicating that the challenge of multiple reuses can be overcome [20,46,47]. However, little has been communicated on the reconditioning methods. In the documented works, acidic and alkaline wet chemical etching and cleaning have been proposed [44,46,48], to remove a few micrometres of the defective surface and restore sufficient surface smoothness. Some works, however, have reported a degradation of epitaxial Si quality over time, corresponding to increases in surface roughness and defect density, and consequently to decreased minority-carrier lifetime [48,49].

The main concerns for parent substrate reuse are threefold. First, the pits and bumps that result from inevitable defects in the detachment layer may be too large to be smoothened out, at least without extensive parent substrate dissolution during polishing. If this is the case, the next generation of epitaxial Si will be affected by the same defect, and the parent substrate will eventually become unusable (Fig. 8). The solution here is to avoid formation of wide defects in the first place, by achieving a nearly perfect detachment plane, as discussed in the section on detachment from the parent substrate.

Second, the non-porosified wafer rim (see 'Porous silicon as the detachment layer and epitaxial template' section above) leaves, cycle after cycle, a thicker and thicker step, since epitaxial Si that is grown on the rim cannot be detached. Such a large step may prevent processing in certain tools or lead to non-uniformities during porosification or epitaxial deposition. On the other hand, this rim offers a strong support while the substrate is becoming thinner and thinner, further extending the number of reuse cycles. If the step at the edge is to be avoided, then a rimless porosification system is necessary.

Third, and finally, it is important to note that the parent substrate is being cycled through many processes – involving several chemical, thermal and stress cycles – until the detachment of the foil. Any extra step adds to the wafer history: thermal stress upon annealing, mechanical stress upon fixture, potential contaminant in-diffusion, and risk of breakage while handling or processing. The simpler and fewer these steps, the longer the lifetime of the parent substrate could be.

Step 6: Processing of thin Si

As mentioned earlier, recent technological developments have

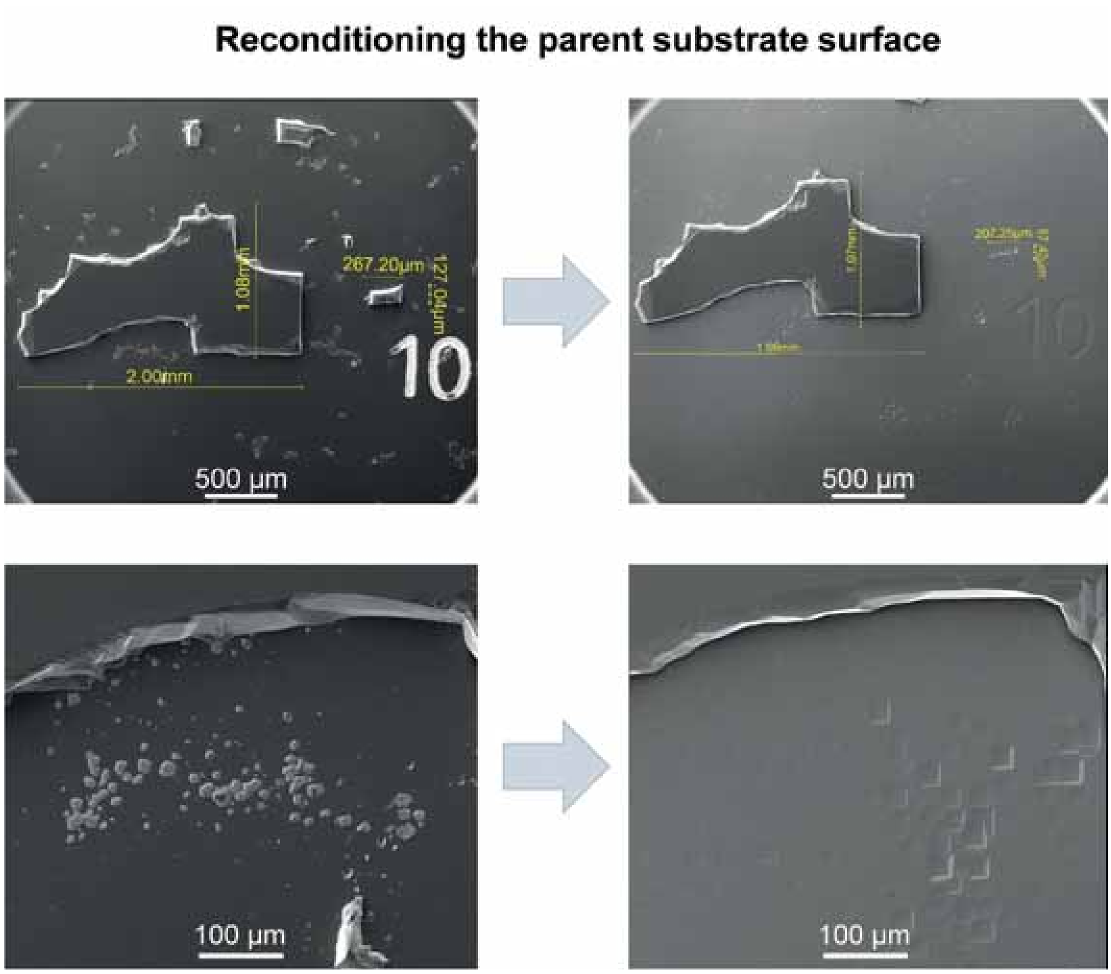


Figure 8. Upon reconditioning by wet chemical etching (here 5µm was removed by TMAH), micrometre-scale defects (such as pillars) are easily dissolved and the surface smoothened out, while larger detachment defects (leading to undetachable epitaxial silicon remnants) remain. Specific markers, such as '10', were used to locate the same region before and after reconditioning.

enabled extremely high epitaxial Si deposition rates of 5–10µm per minute [20,50,51]. This opens the door for growing epitaxial Si wafers of up to ~160–180µm, giving considerable flexibility in the choice of epitaxial Si thickness. Above 100µm, the epitaxial silicon is reasonably rigid and is referred to as an *epiwafer*; below 70µm, the increased flexibility suggests the use of the term *epifoil*.

Epiwafers, by virtue of their rigidity, can be directly used as drop-in wafers in a cell production line, as a replacement for Cz wafers, and sequentially processed into cells, assembled, interconnected and laminated into modules. However, processing thin Si epifoils is a challenging endeavour, owing to their fragility, light weight and high degree of flexibility, and the general consensus is that the mechanical yield loss during handling and processing of Si wafers increases exponentially with decreasing wafer thickness [52–54].

Handling has been reported to be the major cause of mechanical yield loss for thin Si [52]. Automated handling systems in the PV industry are designed and optimized to handle rigid wafers. Foils, however, are highly flexible and bend easily during handling operations, leading to errors and slowdowns in automated handling systems; these issues will impact throughput in an industrial production line. Thus, novel solutions that take into account the unique properties of thin foils must be investigated.

Similarly, different cell process steps entail their own set of challenges when applied to thin foils. For example, during wet processing in cassettes, the electrostatic charges on foil surfaces result in an attractive force between neighbouring foils, causing them to bow and stick together; as a result, the spacing between neighbouring foils must be increased, which translates into lower throughput. Another example is that the asymmetric deposition of dielectrics or metals can cause foils to bow or warp, which is an issue for further processing of these foils.

The challenges of processing freestanding thin Si foils can be completely circumvented by layer transfer of thin Si foils onto a foreign carrier. This type of transfer process has been demonstrated on a variety of rigid foreign carriers, such as ceramic substrates [55–57], metal substrates/metal foils [58,59], highly-doped low-cost conductive Si substrates [60] and superstrates such as glass [18,61–63] or plastics [12]. A detailed overview of the various efforts will be given in forthcoming publications [9,10].

A survey of the various studies conducted by different groups in

Institute [Reference]	Thickness [µm]	η [%]	Cell area [cm^2]	Si sample area [cm^2]	Configuration during processing
Epifoils					
Amberwave/UNSW [58]	18	16.8	4	NR	On parent + steel substrate
ZAE Bayern [67]	25	15.4	3.9	78.5 / 4	On parent + freestanding
IPE [68]	41.6	16.9	2	NR	On parent + glass superstrate
ISFH [15]	42.9	19.1	3.98	6.25	Freestanding
Solexel [47]	43	20.6	243	243	Bonded
imec [64]	47	17.0	16	156.3	Freestanding
imec [63]	47	16.0	4	156.3	Bonded to glass
Epiwafers					
ISE/NexWafe [14]	150	20.0	4	78.5	Freestanding
Crystal Solar/Choshu [22]	150	23.0	243.4	243.4	Freestanding
Crystal Solar/imec [21]	180	22.5	238.45	240	Freestanding

Table 1. Examples of solar cells on epifoils (<70µm) and epiwafers (>100µm), achieved by handling using various configurations. (NR = not reported.)

Strengths: kerfless high-quality silicon at lower costs	Weaknesses: the chasm between lab demos and industrial production
1. Kerfless production of wafers/foils. 2. Shortcut in the PV value chain: no Siemens process, Cz pulling and wafer sawing. 3. Independent from poly-Si supply and cost. 4. Use of lower temperatures than with Cz pulling. 5. Value-added wafers: grown-in junctions, deep junctions. 6. Excellent dopant control allows low wafer-to-wafer variations and unique dopant profiles. 7. Thickness can be tuned as desired. 8. Tuneable wafer area/shape.	1. Development of epitaxial reactors and porous silicon etchers with ever-increasing throughput targets is challenging. 2. TCS-to-epitaxial Si conversion rate (i.e. TCS utilization rate) is not 100%. 3. Purification and recycling of exit gas mixture are crucial. 4. Logistically challenging, since epitaxial reactor must be in close proximity to the TCS manufacturer. 5. Multiple reuse of the parent substrate is critical for cost savings. 6. Porosification in large quatities raises safety concerns.
Opportunities: paradigm shift towards thin wafer adoption in industry	**Threats: the comfort zone**
1. Higher Si utilization (thinner wafers, minimal kerf loss) keeps driving the PV industry. 2. Light-induced degradation is a major issue for Cz wafer modules. 3. Development of novel thin wafer handling technologies and systems opens doors for thin Si. 4. Development of advanced optical confinement methodologies enables use of thin Si. 5. Requirements of flexible or curved modules in building-integrated PV (BIPV) systems raises need for thin Si. 6. Epitaxial lift-off is one of the more advanced kerfless technologies in terms of Si quality and technological maturity.	1. Cost advantage of epiwafers over Cz wafers is decreasing. 2. PV manufacturing is highly sensitive to yield loss, and higher breakage rate of thinner wafers is a discouraging factor. 3. There may be resistance to adopting novel handling technologies for thin wafers/foils if cost advantage is not sufficiently high. 4. Successful technological advancement and investments in other kerfless technologies compete with epitaxial Si lift-off as the next-generation kerfless technology of choice.

Table 2. SWOT matrix.

processing epitaxial Si foils and wafers into solar cells is summarized in Table 1. A variety of different solar cell technologies have been employed: heterojunction solar cells [64], PERC/PERL solar cells [15,65] and interdigitated back-contact (IBC) solar cells [66], in both freestanding and bonded configurations. In all these efforts, the maximum area of thin Si foil processed in a freestanding configuration is limited to 156.25cm^2, in order to reduce mechanical yield losses. Thick epitaxial silicon wafers, on the other hand, do not have such a size limitation. With supported processing, size is not a constraint and large-area Si foils can be readily processed into cells, keeping in mind the constraints of processing a complex bonded stack.

SWOT analysis of epitaxial Si lift-off technology

Epitaxial Si as a replacement for Cz wafers implies a wealth of changes to PV module manufacturing. This section discusses, in the form of a SWOT (strengths, weaknesses, opportunities and threats) analysis, the unique selling points as well as the Achilles' heels of this technology, in relation to the present and future technologies that will continue to shape the PV industry. Table 2 presents the SWOT matrix, according to the authors' best knowledge.

> "The struggle is now to establish the industrial viability of the epitaxial Si concept."

Conclusion and outlook: at a watershed

Epitaxial Si lift-off technology is currently a top candidate for the production of kerfless and low-cost monocrystalline Si wafers in the PV

industry. It offers wafers as thin as desired, with inbuilt doping profiles, at substantial cost and energy savings compared with Cz wafers.

Beginning with efficiencies of 12.5% in 1998, to today's record cells yielding 20.6% on foils [47] and 23.0% on wafers [22], several institutes and companies have demonstrated the high quality of their epitaxial Si. The struggle is now to establish the industrial viability of the epitaxial Si concept. The contest is, however, very difficult, with critically low margins for PV manufacturers, and the decreasing Cz wafer cost further narrowing the economic advantage. With one company having left the game (Solexel) and three companies still pursuing this concept (Amberwave, Crystal Solar and NexWafe), epitaxial Si lift-off technology is at a watershed. Whether the remaining participants will now find their place in the PV sun or fade away is strongly dependent on whether PV manufacturers and investors will be able, and willing, to take the risk of leaving the comfort zone of Cz wafer processing and integrating in the near future a longer-term solution.

Acknowledgments:
We thank Filip Duerinckx and Miha Filipič for proof-reading the manuscript, the epifoils team at imec for the scientific work and discussions and our external collaborators (ALSI, DISCO and University Anhalt). We are also grateful for the financial support from IIAP partners and the European commission via the funded projects, CABRISS, Cheetah and NextBase.

References

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

[2] Walters, J. et al. 2016, "Challenges associated with diamond wire sawing when generating reduced thickness mono-crystalline silicon wafers", *Proc. 43rd IEEE PVSC*, Portland, Oregon, USA, pp. 0724–0728.

[3] Powell, D.M. et al. 2012, "Crystalline silicon photovoltaics: A cost analysis framework for determining technology pathways to reach baseload electricity costs", *Energy Environ. Sci.*, Vol. 5, No. 3, p. 5874.

[4] Henley, F.J. 2010, "Kerf-free wafering: Technology overview and challenges for thin PV manufacturing", *Proc. 36th IEEE PVSC*, Valencia, Spain, pp. 1184–1192, 2010.

[5] Brendel, R. 2001, "Review of layer transfer processes for crystalline thin-film silicon solar cells", *Jpn. J. Appl. Phys.*, Vol. 40, No. 7, pp. 4431–4439.

[6] McCann, M.J. et al. 2001, "A review of thin-film crystalline silicon for solar cell applications. Part 1: Native substrates", *Sol. Energy Mater. Sol. Cells*, Vol. 68, No. 2, pp. 135–171.

[7] Weber, K. et al. 2002, "Transfer of monocrystalline Si films for thin film solar cells", Review paper (ANU) [https://openresearch-repository.anu.edu.au/bitstream/1885/40834/3/Liftoff_Review_paper.pdf].

[8] Bergmann, R.B. 1999, "Crystalline Si thin-film solar cells: A review", *Appl. Phys. A*, Vol. 69, No. 2, pp. 187–194.

[9] Sivaramakrishnan Radhakrishnan, H. et al. [in preparation], "Thin crystalline silicon: Overview of lift-off technologies and module fabrication approaches".

[10] Sivaramakrishnan Radhakrishnan H. & Depauw, V. [in preparation], "Lift-off approaches for thin crystalline silicon", in *Thin Film Solar Cells: Fabrication, Characterization and Applications*, Poortmans, J., Ed. Chichester, UK: John Wiley & Sons, Ltd.

[11] Yonehara, T., Sakaguchi, K. & Sato, N. 1994, "Epitaxial layer transfer by bond and etch back of porous Si", *Appl. Phys. Lett.*, Vol. 64, No. 16, p. 2108.

[12] Tayanaka, H., Yamauchi, K. & Matsushita, T. 1998, "Thin-film crystalline silicon solar cells obtained by separation of a porous silicon sacrificial layer", *Proc. 2nd WCPEC*, Vienna, Austria, pp. 1272–1277.

[13] Bergmann, R.B. et al. 1999, "Thin film solar cells on glass by transfer of monocrystalline Si films", *Int. J. Photoenergy*, Vol. 1, No. 2, pp. 89–93.

[14] Milenkovic, N. et al. 2016, "Epitaxial n-type silicon solar cells with 20% efficiency", *Proc. 43rd IEEE PVSC*, Portland, Oregon, USA, pp. 58–61.

[15] Petermann, J.H. et al. 2012, "19%-efficient and 43 μm-thick crystalline Si solar cell from layer transfer using porous silicon", *Prog. Photovolt: Res. Appl.*, Vol. 20, No. 1, pp. 1–5.

[16] Gemmel, C. et al. 2017, "4.5 ms effective carrier lifetime in kerfless epitaxial silicon wafers from the porous silicon process", *IEEE J. Photovolt.*, Vol. 7, No. 2, pp. 430–436.

[17] Van Nieuwenhuysen, K. et al. 2012, "High quality epitaxial foils, obtained by a porous silicon based layer transfer process, for integration in back contacted solar cells", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 2471–2474.

[18] Govaerts, J. et al. 2015, "Solar cells from epitaxial foils: An epifoil epiphany", *Energy Procedia*, Vol. 77.

[19] Lochtefeld, A. et al. 2013, "15%, 20 micron thin, silicon solar cells on steel", *Proc. 39th IEEE PVSC*, Tampa, Florida, USA.

[20] Hao, R. et al. 2014, "High efficiency solar cells on direct kerfless 156 mm mono crystalline Si wafers by high throughput epitaxial growth", *Proc. 40th IEEE PVSC*, Denver, Colorado, USA, pp. 2978–2982.

[21] Kuzma-Filipek, I. et al. 2016, "22.5% n-PERT solar cells on epitaxially grown silicon wafers", *Proc. 32nd EU PVSEC*, Munich, Germany, pp. 560–564.

[22] Kobayashi, E. et al. 2016,"Heterojunction solar cells with 23% efficiency on n-type epitaxial kerfless silicon wafers," *Progress in Photovoltaics: Research and Applications*, vol. 24, no. 10, pp. 1295–1303.

[23] Janz, S. et al. 2015, "N-type and p-type silicon foils fabricated in a quasi-inline epi reactor with bulk lifetimes exceeding 500 μs", *Proc. 31st EU PVSEC*, Hamburg, Germany.

[24] Sivaramakrishnan Radhakrishnan, H. et al. 2012, "Gettering of transition metals by porous silicon in epitaxial silicon solar cells", *physica status solidi (a)*, Vol. 209, No. 10.

[25] Föll, H. et al. 2002, "Formation and application of porous silicon", *Mater. Sci. Eng. R Rep.*, Vol. 39, No. 4, pp. 93–141.

[26] Labunov, V., Bondarenko, V. & Glinenko, I. 1986, "Heat treatment effect on porous silicon", *Thin Solid Films*, Vol. 137, pp. 123–134.

[27] Ott, N. et al. 2004, "Evolution of the microstructure during annealing of porous silicon multilayers", *J. Appl. Phys.*, Vol. 95, No. 2, pp. 497–503.

[28] Ghannam, M.Y. et al. 2010, "Interpretation of macropore shape transformation in crystalline silicon upon high temperature processing", *J. Appl. Phys.*, Vol. 108, No. 7, p. 74902.

[29] Sivaramakrishnan Radhakrishnan, H. et al. 2014, "Improving the quality of epitaxial foils produced using a porous silicon-based layer transfer process for high-efficiency thin-film crystalline silicon solar cells", *IEEE J. Photovolt.*, Vol. 4, No. 1, pp. 70–77.

[30] Sivaramakrishnan Radhakrishnan, H. et al. 2015, "Kerfless layer-transfer of thin epitaxial silicon foils using novel multiple layer porous silicon stacks with near 100% detachment yield and large minority carrier diffusion lengths", *Sol. Energy Mater. Sol. Cells*, Vol. 135, pp. 113–123.

[31] Karim, M. et al. 2014, "Tuning of strain and surface roughness of porous silicon layers for higher-quality seeds for epitaxial growth", *Nanoscale Res. Lett.*, Vol. 9, No. 1.

[32] Milenkovic, N. et al. 2015, "Porous silicon reorganization: Influence on

Materials

the structure, surface roughness and strain", *J. Cryst. Growth,* Vol. 432, pp. 139–145.

[33] Sivaramakrishnan Radhakrishnan, H. et al. 2014, "Addressing the key challenges in the successful implementation of high efficiency porous silicon-based layer-transferred epitaxial solar modules", *Proc. 6th WCPEC*, Kyoto, Japan, pp. 193–194.

[34] Powell, D.M. et al. 2016, "Exceptional gettering response of epitaxially grown kerfless silicon", *J. Appl. Phys., Vol.* 119, No. 6.

[35] Käsewieter, J. et al. 2013, "Failure stress of epitaxial silicon thin films", *Energy Procedia*, Vol. 38, pp. 926–932.

[36] Sivaramakrishnan Radhakrishnan, H. et al. 2017, "Overview of novel dicing methods for the delineation and exfoliation of thin kerfless Si epitaxial foils with high mechanical strength", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.

[37] Matte, E. et al. 2013, "Layer transfer process assisted by laser scribing for thin film solar cells based on epitaxial foils", *physica status solidi (a),* Vol. 210, No. 4, pp. 682–686.

[38] Kajari-Schröder, S. et al. 2013, "Lift-off of free-standing layers in the kerfless porous silicon process", *Energy Procedia,* Vol. 38, pp. 919–925.

[39] Hendriks, R., van Borkulo, J. & Mueller, M. 2009, "Paradigm shift in compound semiconductor production since the introduction of laser dicing", *Proc. CS ManTech.*, Tampa, Florida.

[40] Van Borkulo, J. et al. 2017, "Multi beam full cut dicing of thin Si IC wafers", *Proc. CSTIC 2017*, Shanghai, China.

[41] Eiternick, S. et al. 2015, "High quality half-cell processing using thermal laser separation", *Energy Procedia,* Vol. 77, pp. 340–345.

[42] Yonehara, T. & Sakaguchi, K. 2001, "Eltran®: Novel SOI wafer technology", *JSAP Int.,* No. 4, pp. 10–16.

[43] Bearda, T. et al. 2016, "Thin epitaxial silicon foils using porous-silicon-based lift-off for photovoltaic application", *MRS Adv.,* Vol. 1, No. 48, pp. 3235–3246.

[44] Hajijafarassar, A. et al. 2016, "Multiple reuse of the silicon substrate in a porous silicon based layer transfer process", *Proc. 32nd EU PVSEC*, Munich, Germany, pp. 313–316.

[45] Bergmann, R.B. et al. 2001, "Monocrystalline Si films from transfer processes for thin film devices", *MRS Proc.*, Vol. 685, p. D2.1.1.

[46] Steckenreiter, V. et al. 2012, "Reconditioning of silicon substrates for manifold re-use in the layer transfer process with porous silicon", *Proc. 22nd Intl. PVSEC*, Hangzhou, China, pp. 1–4.

[47] Kapur, P. et al. 2013, "A manufacturable, non-plated, non-Ag metallisation based 20.44% efficient, 243 cm^2 area, back contacted solar cell on 40 µm thick mono-crystalline silicon", Presentation, 28th EU PVSEC, Paris, France.

[48] Horbelt, R. et al. 2005, "Manifold use of growth substrate in the porous silicon-layer transfer-process", *Proc. 31st IEEE PVSC*, Lake Buena Vista, Florida, USA, pp. 1193–1196.

[49] Steckenreiter, V. et al. 2016, "Reuse of substrate wafers for the porous silicon layer transfer", *IEEE J. Photovolt.,* Vol. 6, No. 3, pp. 783–790.

[50] Reber, S. et al. 2003, "The RTCVD160 – A new lab-type silicon CVD processor for silicon deposition on large area substrates", *Proc. 3rd WCPEC*, Osaka, Japan, pp. 1368–1371.

[51] Reber, S. et al. 2012, "Advances in equipment and process development for high-throughput continuous silicon epitaxy", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 2466–2470.

[52] Kray, D. et al. 2004, "Comprehensive experimental study on the performance of very thin laser-fired high-efficiency solar cells", *Proc. 19th EU PVSEC*, Paris, France, pp. 608–611.

[53] Münzer, K.A. et al. 1999, "Thin monocrystalline silicon solar cells", *IEEE Trans. Electron Dev.,* Vol. 46, No. 10, pp. 2055–2061.

[54] Wang, S. et al. 2013, "Large-area free-standing ultrathin single-crystal silicon as processable materials", *Nano Lett.*, Vol. 13, No. 9, pp. 4393–4398.

[55] Solanki, C.S. et al. 2002, "Transfer of a thin silicon film on to a ceramic substrate", *Thin Solid Films,* Vol. 403–404, pp. 34–38.

[56] Gazuz, V., Scheffler, M. & Auer, R. 2006, "Thin 60 µm-thick crystalline silicon solar cell on ceramic substrate by Al-bonding", *Proc. 4th WCPEC*, Waikoloa, Hawaii, USA, pp. 976–979.

[57] Kumar, A. & Ravi, K.V. 2011, "Thin single crystal silicon solar cells on ceramic substrates: November 2009 – November 2010", Subcontract Report NREL/SR-5200-51935 < http://www.osti.gov/scitech/servlets/purl/1018880>.

[58] Wang, L. et al. 2014, "Development of a 16.8% efficient 18 µm silicon solar cell on steel", *IEEE J. Photovolt.,* Vol. 4, No. 6, pp. 1397–1404.

[59] Saha, S. et al. 2013, "Single heterojunction solar cells on exfoliated flexible ~25 µm thick mono-crystalline silicon substrates", *Appl. Phys. Lett.*, Vol. 102, No. 16, pp. 1–6.

[60] Sivaramakrishnan Radhakrishnan, H. et al. 2016, "Solar cells and mini-modules based on 40 µm-thick epitaxial Si foils: Towards conductive bonding onto low-cost Si powder sintered supporting substrates", *Proc. 32nd EU PVSEC*, Munich, Germany, pp. 1268–1271.

[61] Bergmann, R.B. et al. 2002, "Advances in monocrystalline Si thin film solar cells by layer transfer", *Sol. Energy Mater. Sol. Cells*, Vol. 74, No. 1–4, pp. 213–218.

[62] Chen, C. et al. 2013, "High efficiency screen-printed 156cm^2 solar cells on thin epitaxially grown silicon material", *Proc. 39th IEEE PVSC*, Tampa, Florida, USA, pp. 2179–2182.

[63] Sivaramakrishnan Radhakrishnan, H. et al. 2017, "Heterojunction IBC solar cells on thin (< 50 µm) epitaxial Si foils produced from kerfless layer transfer process", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.

[64] Bearda, T. et al. 2017, "Fabrication of silicon heterojunction cells on 50µm epitaxial substrates", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.

[65] Wang, A. et al. 1996, "21.5% efficient thin silicon solar cell", *Prog. Photovolt: Res. Appl.,* Vol. 4, No. October 1995, pp. 55–58.

[66] Haase, F., Kajari-Schröder, S. & Brendel, R. 2013, "High efficiency back-contact back-junction thin-film monocrystalline silicon solar cells from the porous silicon process", *J. Appl. Phys.*, Vol. 114, No. 19.

[67] Brendel, R. et al. 2002, "Crystalline thin-film Si cells from layer transfer using porous Si (PSI-process)", *Proc. 29th IEEE PVSC*, New Orleans, Louisiana, USA, pp. 86–89.

[68] Reuter, M. et al. 2009, "50 µm thin solar cells with 17.0% efficiency", *Sol. Energy Mater. Sol. Cells*, Vol. 93, No. 6–7, pp. 704–706.

About the Authors

Hariharsudan Sivaramakrishnan Radhakrishnan (Hari) pursued his Ph.D research at KU Leuven and imec, Belgium, on porous silicon-based gettering and epitaxial Si lift-off and solar cells. He received the EMRS Young Scientist Award in 2012 and IMEC scientific excellence award in 2014. Since graduating in 2014 he has been working as a researcher at imec, Belgium, with a keen interest in the topics of epitaxial Si lift-off, heterojunction IBC solar cells and i^2-module concept for thin silicon, and is involved in EU projects, CABRISS and NextBase.

Valérie Depauw is a research engineer at imec, involved in several EU projects. She started playing with lift-off techniques at the end of 2004, at the start of her Ph.D, and has not stopped since then. She has built expertise around making "holes" inside silicon, by tailoring porous silicon for kerfless wafering and exploring advanced nanostructures for light trapping in (ultra-) thin crystalline-silicon solar cells. She received the EMRS Young Scientist Award in 2009.

Kris Van Nieuwenhuysen obtained her degree in engineering in 2000. She then joined the Si solar cell group of imec, where she has been the main expert in Si epitaxial CVD processes for solar cell fabrication. She was the main responsible for the realization of the >16% efficient full epitaxial solar cell at imec. She developed several epi processes both in low-pressure and atmospheric pressure CVD systems and was involved in several European projects.

Ivan Gordon obtained his Ph.D from the University of Leuven, Belgium in February 2002. He started to work at imec in June 2003, where he is currently leading the Silicon Photovoltaics group, working on c-Si wafer-based solar cells, thin-film silicon solar cells, and advanced module concepts for ultra-thin c-Si wafer-based cells. Since 2008, he has been editor of the journal Solar Energy Materials and Solar Cells. Since 2011, he has also been associate editor for the IEEE Journal on Photovoltaics. He has authored and co-authored more than 200 journal and conference papers. Since January 2016, he has been coordinator of the joint programme on photovoltaics of the European Energy Research Alliance (EERA).

Prof. Jozef Poortmans received his Ph.D from the KU Leuven, Belgium, in June 1993. Afterwards he joined the photovoltaics group and, in 2003, became the PV Department Director. Since 2013, he has been Scientific Director of the PV and Energy activities of imec. He has been a board member of Eurec Agency and is presently a member of the steering committee of the EU PV Technology Platform. Prof. Poortmans has authored or co-authored more than 500 papers that have been published in conference proceedings and technical journals. Since 2008 he has been part-time Professor at the KU Leuven. In 2013 he became also part-time Professor at University Hasselt. Since 2016, he has been the coordinator of R&D-strategy of EnergyVille, an institutional partnership between imec, VITO, KU Leuven and University Hasselt focused on the themes of smart cities and smart grids.

Enquiries

Hariharsudan Sivaramakrishnan Radhakrishnan
Silicon Photovoltaics
Imec
3001 Leuven
Belgium
Kapeldreef 75
Tel: +32 16 28 11 73
Email: sivarama@imec.be
Web: www.imec.be

Cell Processing

NREL and CSEM set multi-junction III–V/Si solar cell efficiency record

Credit: CSEM

A joint research programme has yielded promising results for multi-junction cell efficiencies.

The US Department of Energy's National Renewable Energy Laboratory (NREL), the Swiss Center for Electronics and Microtechnology (CSEM) and the École Polytechnique Fédérale de Lausanne (EPFL) have achieved dual- and triple-junction cell efficiency gains.

In testing silicon-based multi-junction solar cells, researchers found that the highest dual-junction efficiency (32.8%) came from a tandem cell that stacked a layer of gallium arsenide (GaAs) developed by NREL atop a film of crystalline silicon developed by CSEM.

An efficiency of 32.5% was achieved using a gallium indium phosphide (GaInP) top cell, while a third cell, consisting of a GaInP/GaAs tandem cell stacked on a silicon bottom cell, reached a triple-junction efficiency of 35.9% – just 2% below the overall triple-junction record.

The perennial problem for GaAs (III–V) based solar cells has been the production costs and the dominance of crystalline silicon as the solar substrate of choice.

However, the researchers believe that production costs of tandem cells on silicon can become commercially viable in the future.

The researchers assumed a 30% cell efficiency of a GaInP-based cell would cost US$4.85 per watt today and a GaAs-based cell would cost US$7.15 per watt. But as manufacturing ramps up and the efficiencies of these types of cells increased to around the 35% mark, the researchers estimated that the cost per watt could fall to 66 US cents for a GaInP-based cell and to 85 cents for the GaAs-based cell.

Cell efficiencies

GCL-SI hits 20.6% efficiency for its multicrystalline PERC solar cells

China-based PV manufacturer GCL System Integration Technology (GCL-SI) has broken its own solar cell average efficiency for its self-developed PERC cells in mass production by utilizing Reactive Ion Etching (RIE) technology – reaching 20.6% from 20.1% in February.

"We have now effectively resolved the issue of multicrystalline PERC cell degradation and power loss," said Zhang Chun, head of GCL-SI's R&D cell team. "Through proper regeneration annealing processing, an additional absolute efficiency gain up to 0.15% can be reached. Furthermore, the LID results show properly treated cells have significant improvement in degradation behaviour with less than 1% relative efficiency loss.

"GCL-SI will further advance towards the goal of realising an average efficiency of 20.5% and a maximum efficiency of somewhere between 20.8% and 21% in 2017."

The company recently showcased its 'black silicon' multicrystalline modules, its latest mono PERC offerings and dual-glass products as well as energy storage systems at Intersolar Europe. Black silicon is well known for its extremely low reflectance and low absorption of some kinds of photovoltaic applications. GCL-SI has taken the lead in the integration of all three existing methods – additive direct texturing, metal assisted chemical etching (MACE), and RIE – thus making massive manufacturing a reality in terms of cost reduction and efficiency gain.

1366 Technologies and Hanwha Q CELLS edge cell record up to 20.3%

US-based wafer producer 1366 Technologies and Hanwha Q CELLS have announced a new cell record of 20.3% using 1366's 'direct wafer' technology.

The pair also confirmed average cell efficiencies are now 20.1% on their pilot line that uses 1366 wafers and Hanwha Q CELLS' Q.ANTUM cell architecture. The records have been confirmed by Fraunhofer ISE CalLab. The companies are currently increasing cell efficiencies at a rate of 0.8% per year.

1366 Technologies' production method draws individual wafers from the cooled surface of molten silicon rather than sawing wafers from ingots. This reduces the energy required and lowers material waste from sawing.

The first commercial use of the 1366 technology is a 500kW plant in Japan.

Credit: 1366 Technologies

Hanwha Q CELLS and 1366 Technologies have jointly achieved a new cell record using 'direct wafer' technology.

Production

Hanwha Q CELLS reaches a billion 'Q.ANTUM' solar cell production milestone

'Silicon Module Super League' (SMSL) member Hanwha Q CELLS has reached a new production milestone of one billion high-efficiency 'Q.ANTUM' solar cells, equivalent to around 5GW.

The Q.ANTUM cells are based on PERC technology the company developed at its R&D facilities in Germany, put into production in 2012 and now fabricates in Malaysia, China and South Korea.

Seong-woo Nam, CEO of Hanwha Q CELLS, commented: "Having achieved one billion of commercially mass produced Q.ANTUM solar cells is an outstanding milestone for our company and a powerful demonstration of Hanwha Q CELLS' leadership in the solar industry. As our core technology platform, we will continue to develop and push Q.ANTUM technology to achieve even higher yields and lower LCOE for our customers."

Hanwha Q CELLS was the largest producer of solar cells in 2016 and was ranked fourth largest module manufacturer (by shipments) in 2016.

Renewsys launches five-busbar cell production in India's Telangana

India-based solar equipment manufacturer Renewsys India, part of international conglomerate Enpee Group, has launched production of five-busbar solar PV cells at a Hyderabad facility in the Indian state of Telangana.

The firm claims it is the first Indian company to produce five-busbar cells domestically. The products are part of Renewsys' RESERV range of multicrystalline cells, which are manufactured using European PV cell equipment.

Commercial production of modules containing these cells will start from July onwards. Increasing the number of busbars in a cell lowers the series resistance and thus increases the current, allowing for greater module performance.

Having started cell production in India back in 2016, Renewsys also recently completed ramping cell lines from 30MW to 130MW, reaching full capacity at the end of April.

Avinash Hiranandani, managing director, Renewsys India, said: "Renewsys recognizes that quality raw materials, commitment to R&D and competitively priced products are crucial to the solar industry, affecting the performance and success of PV solar power systems. The launch of five-busbar cells and modules will significantly improve the performance of solar PV systems."

German consultancy Solsol helped on the cell production line work.

PV Nano Cell and Merck to push deployment of conductive inks

Conductive inks specialist PV Nano Cell is joining forces with major materials firm Merck to develop and deploy its single-crystal, nanometric inks such as copper and silver to expand its applications.

PV Nano Cell's 'Sicrys' inks are designed to enable non-contact digital inkjet printing rather than traditional screen (or stencil) printing of c-Si solar cells, although the applications and target markets are varied for the technology.

"PV Nano Cell will provide the expertise and specific formulations of Sicrys to support Merck's focus on measuring the inks' performance in different applications for various markets," said Marc Feiglin, head technology scouting and partnerships at Merck in Israel.

Credit: Hanwha Q CELLS

Hanwha Q CELLS has produced one billion of its 'Q.ANTUM' PV cells.

News

Orders

Aurora wins new bifacial solar cell sales deal with equipment supplier

Inline solar cell measurement equipment specialist Aurora Solar Technologies (AST) has secured a new deal with an unidentified solar cell equipment supplier for its 'Decima' Gemini measurement system, and 'Veritas' process visualization system for high-efficiency bifacial solar cells.

"We have been working with this recognized industry leader for over two years and are excited to work together to deploy our unique bifacial cell solutions and jointly document the benefits," said Michael Heaven, Aurora's president and CEO. "This order is a result of our unique capabilities in the measurement and process characterization of bifacial cells and we look forward to communicating these benefits to the industry through this project."

The new deal for inline measurement tools is to support faster ramp-up times of new production lines and assist in solar cell R&D and production equipment development for bifacial cells.

Meyer Burger wins US$23 million in PERC solar cell tool orders

Leading PV manufacturing equipment supplier Meyer Burger has secured orders worth around CHF22million (US$23.2 million) from an existing customer in Asia for its PERC (Passivated Emitter Rear Cell) tool technology.

Meyer Burger said that the order was for its 'SiNA' front side cell coating systems and its 'MAiA 2.1' systems for rear side passivation coating for PERC cell architecture.

The new orders are to support the Asia-based customer's plans to upgrade and further expand its production volume of high efficiency PERC cells. Revenue recognition on the order was said to be expected in 2018.

Credit: Meyer Burger

Meyer Burger has scooped fresh orders for its PERC production tools.

The vast majority of orders placed in 2017 for its PERC technology have included delivery and the start of revenue recognition in 2017. PERC technology can boost absolute cell efficiencies by at least 1%. In May 2017, Meyer Burger said it would temporarily increase production capacity for MAiA 2.1 equipment to meet strong demand.

Intevac expects order for 12 'ENERGi solar ion implant tools' to ship in 2017

Specialist semiconductor and PV equipment supplier Intevac expects to start shipping its largest ever single tool order in the second half of 2017. The order with with a customer in China planning to ramp n-type mono IBC (Interdigitated Back Contact) solar cells and modules, including bifacial modules.

The order booked in March 2017 was for 12 'ENERGi' solar ion implant tools to support 1GW of new high-efficiency n-type mono IBC cell production, providing the opportunity to also produce bifacial solar cells. The order was the largest placed with the company outside its core hard disk drive (HDD) manufacturing market.

Intevac's plans to start shipping tools in the second half of 2017, supports the view that a major technology buy-cycle to migrate to high-efficiency products is less likely to be impacted by any new US trade actions relating to the US ITC 'Section 201' case. High-efficiency cells and modules are currently in high demand and a global shortage has developed.

Company news

Motech reduces Q2 losses as solar cell shipments increase

Taiwan-based PV cell and module manufacturer Motech Industries continued a fourth consecutive quarterly loss, yet losses declined on increased solar cell shipments in the second quarter of 2017.

Motech reported second quarter revenue of NT$5,598 million (US$184.6 million), compared to NT$5,069 million (US$167.1 million) in the previous quarter, around a 10% increase.

Sales in July dipped slightly from the previous month. Motech had sales of NT$1,987 million, compared to NT$2,032 million in June.

Gross profit in the quarter was negative NT$267 million (US$8.8 million), compared to a negative gross profit of NT$593 million (US$19.5 million) in the first quarter of 2017. Gross margin was negative 4.8%, down from negative 11.8% in the previous quarter. The company reported a negative net profit margin of 12.4%, down from a negative net profit margin of 20.1% in the first quarter of 2017.

Solar cell shipments in the quarter were 837MW, up from 727MW in the first quarter of 2017, a 15% quarter-on-quarter increase.

Motech reported first half 2017 revenue of NT$10,667 million, compared to NT$18,464 million in the prior year period, a 42% decline.

The company reported first half year 2017 solar cell shipments were 1,564MW, compared to 2,414MW in the prior-year period, over a 34% decline, year-on-year.

3SUN seeking €14.1 million funding for heterojunction solar cell tool purchases

Enel Green Power's a-Si thin-film module manufacturing subsidiary, 3SUN, is hoping to obtain a €14.1 million grant from Italy's national agency for attracting investment and enterprise development, Invitalia, to support the purchase of heterojunction (HJ) solar cell tools to switch production to the higher efficiency silicon technology.

3SUN had also hosted the launch meeting of AMPERE (Automated Photovoltaic cell and Module industrial Production), which is funded by the Horizon 2020 European research and innovation programme (LCE-09-2016-2017), aimed at increasing the EU PV industry's competitiveness.

The AMPERE meeting included major European research centres and commercial companies and was coordinated by 3SUN. Funding for the AMPERE consortium amounted to €14 million, which included €8.3 million for 3SUN and €0.5 million for Enel Green Power.

The AMPERE funding is primarily being used for the purchase and installation of the automated HJ manufacturing equipment at the 3SUN facility in Catania, Sicily.

The potential €14.1 million grant from Invitalia has already been appropriated by the Ministry for Economic Development and the Region of Sicily.

Enel Green Power had previously announced that the 3SUN production switch to HJ cell/module production would cost around €80 million and the R&D facility, dubbed Innovation Lab, would require an investment of around €20 million.

Metallization techniques and interconnection schemes for high-efficiency silicon heterojunction PV

Jonas Geissbühler, **Antonin Faes**, **Agata Lachowicz**, **Christophe Ballif** & **Matthieu Despeisse**, CSEM PV-center, Neuchâtel, Switzerland

ABSTRACT

The major cell and module producers are focusing on silicon heterojunction technology as potentially the next generation of crystalline PV for mass production, since it has already demonstrated high energy conversion efficiency, easy integration in a bifacial module, low temperature coefficient and simplicity of manufacture. Because of the different cell architecture and materials involved in these solar cells, specific metallization and interconnection processes must be used. This paper discusses these processes, and in particular investigates the evolution of low-temperature-cured silver paste that has occurred in the market, as well as the impressive reduction in the specific bulk resistivity achieved in this area. The interconnection scheme used during module manufacturing strongly influences the requirement imposed on the solar cell metallization. In this respect, it is shown how significant silver saving can be achieved by using a combination of multiwire interconnection and fine-line screen-printing. For more specific interconnections requiring metallization with longer fingers, copper plating can be applied, resulting in a highly conductive metallization grid. Finally, the discussion will turn to how the metallization and interconnection techniques can be adapted to back-contacted silicon heterojunction solar cells.

Introduction

Since the first demonstration by Sanyo in the 90s of crystalline silicon heterojunction (SHJ) solar cells with already promising energy conversion efficiencies above 18% [1], this device architecture has experienced an extraordinary history of development, embodying outstanding scientific findings and efficiency records [2,3]. In particular, a significant breakthrough occurred in 2014, when Panasonic achieved a 25.6% cell efficiency with an interdigitated back-contact silicon heterojunction (IBC-SHJ) cell, which became the highest efficiency ever recorded for any crystalline silicon solar cell [4]. Even more recently, this quest for ultra-high efficiency has further intensified and led to efficiencies of 25.1% for a two-side-contacted SHJ [5] and 26.7% for an IBC architecture, which is the current world record for a crystalline silicon solar cell [6,7]. Industrially, there have also been impressive achievements, with the commercialization of high-efficiency SHJ-based solar modules [8], and the availability of production tools capable of manufacturing high-efficiency SHJ at an industrial throughput [9]. Of note is the AMPERE European

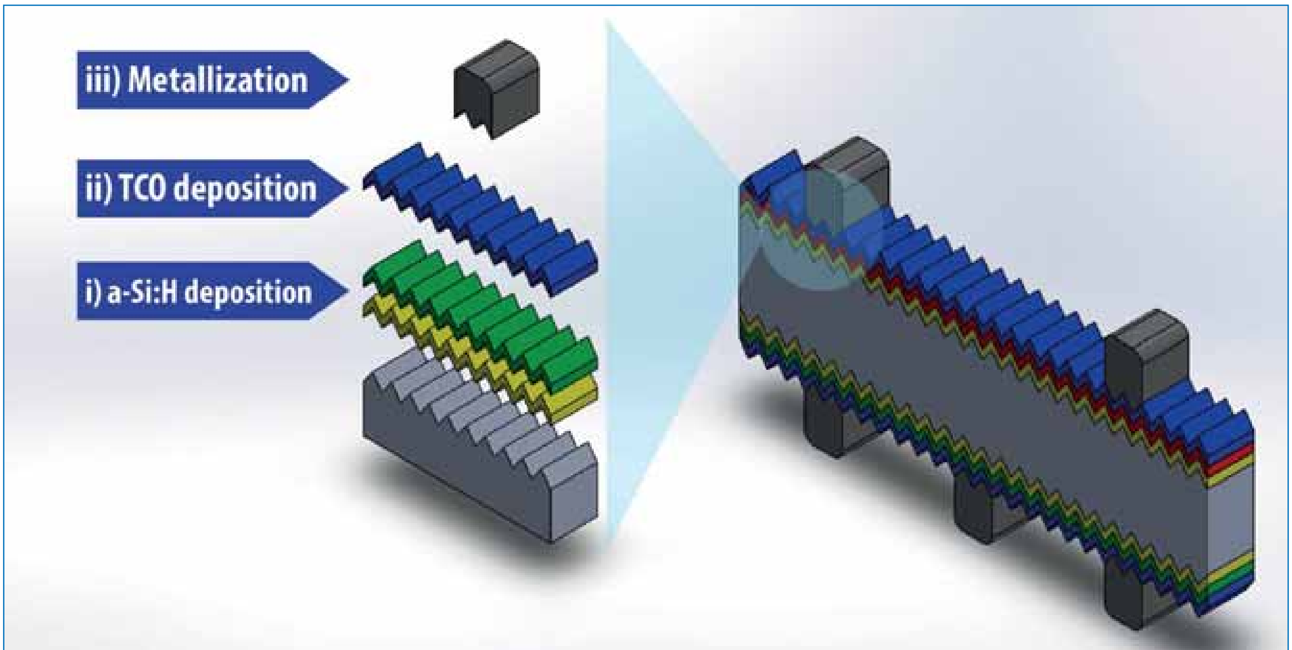


Figure 1. Manufacturing steps and schematic cross section of a finished bifacial silicon heterojunction solar cell.

initiative for setting up an innovative full-scale automated production line for SHJ cells and modules [10].

A key element in explaining the popularity of SHJ devices is their astonishingly simple architecture, and therefore the low number of process steps involved in their manufacture. Fig. 1 highlights this simplicity, whereby the textured silicon wafer is first coated with intrinsic and doped amorphous silicon to ensure excellent surface passivation (which is perfectly suited to the use of thin wafers), as well as to promote an efficient charge-carrier separation. This is followed by the deposition of transparent conductive oxide (TCO) layers, acting as both an antireflection coating and a conductive electrode to extract and laterally conduct the electrical current. In a final step, these electrodes are further reinforced by means of a metallization process, such as the screen printing of a silver paste [2]. In addition to the straightforwardness of their manufacture, SHJ cells also offer important advantages when deployed in PV installations: not only are they intrinsically made with a bifacial architecture, but they also feature a temperature coefficient in the range -0.23 to -0.3%/°C [11,12]. Furthermore, SHJ cells can be used in high-efficiency devices, such as tandems [13].

"Specific low-temperature-cured silver pastes must be used for SHJ solar cells."

A consequence of the significantly different cell architecture, and of the use of hydrogenated amorphous silicon, is a limitation of the maximum temperature acceptable for metallization, typically around 200°C. This clearly prohibits the use of silver metallization pastes used for homojunction devices, which are typically sintered around 800°C [2]. Therefore, specific low-temperature-cured silver pastes must be used for SHJ solar cells, with the inherent drawback of being around two to three times more resistive than their high-temperature counterparts; this has a considerable impact on the entire metallization and interconnection techniques used for cell and module manufacturing [14]. This paper will discuss how that limitation is circumvented with the recent developments made in SHJ metallization and module integration; it will also show how the appropriate metallization design and the cell interconnection scheme can be chosen.

Link between metallization techniques, grid design and interconnection scheme

The choice of the metallization technique is closely linked to the interconnection scheme used during module manufacturing, and vice versa; this consequently affects the design of the metallization grid. A key parameter of the grid design is the finger length, defined here as the maximum distance that the electricity has to flow along the finger (i.e. half the busbar-to-busbar distance in a standard H-pattern).

Fig. 2 shows an estimation of the power loss induced by a metallization grid for different line resistivities and different finger lengths (this includes the electrical power losses occurring in the TCO and the fingers and the shadowing of the fingers; busbars are not taken into account here). For each condition, an optimization of the number of fingers is carried out on the assumption of a constant TCO sheet resistance of 100Ω/sq. and a finger width of 50µm. The finger length is expressed in relation to different grid designs, ranging from an H-pattern with two busbars (finger length of 3.9cm) to the ultimate multiwire approach, in which the finger length is reduced to values below 10mm [15,16]. The different line resistivities are

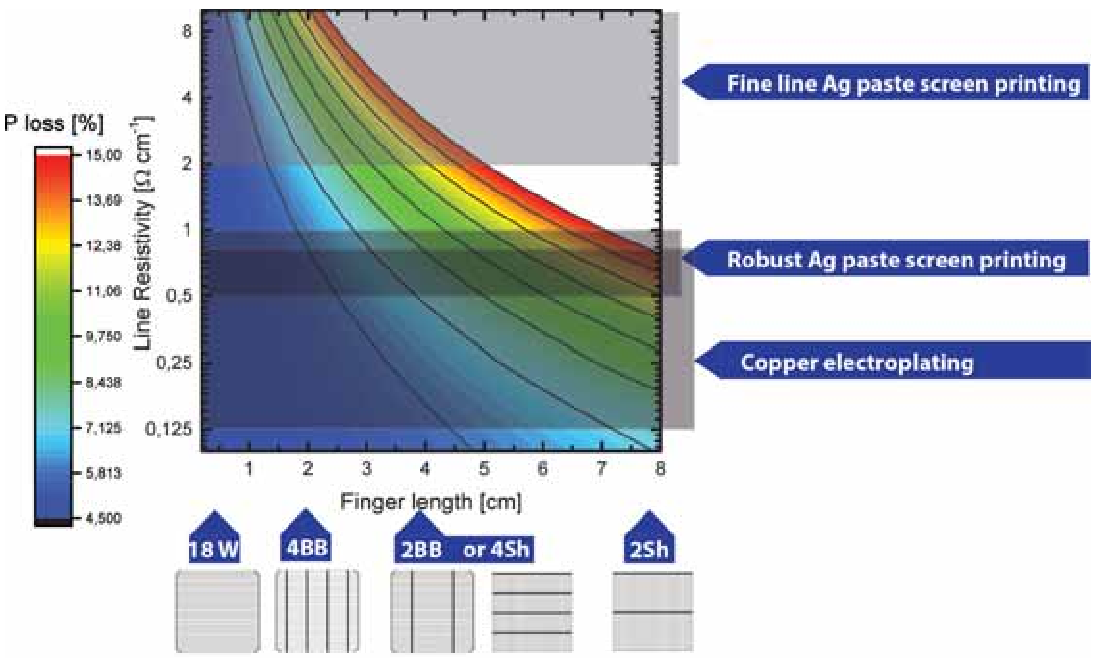


Figure 2. Estimation of optical and electrical power losses induced by a metallization grid, as a function of line resistivity and finger length. Examples of interconnection schemes are given for 18 wires (18W), two or four busbars (2BB or 4BB), and shingled-cell connection with two or four subcells (2Sh or 4Sh).

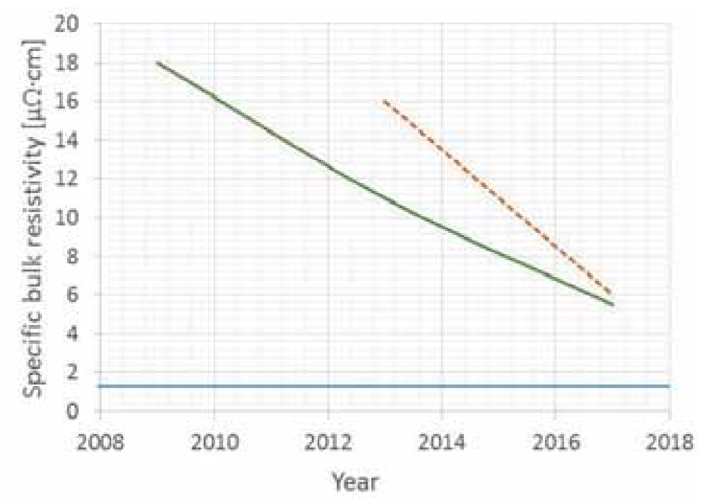


Figure 3. Evolution of the specific bulk resistivity of low-curing-temperature silver paste compared with pure silver (horizontal line). The continuous line represents the paste after 30min curing at 200°C, while the dashed line indicates the paste after curing for 30min at 180°C (data courtesy of Namics Corporation).

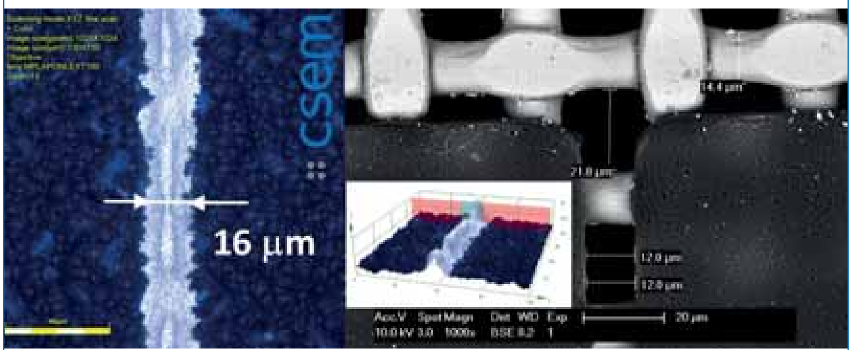
illustrated here by three metallization techniques: 1) fine-line silver paste screen printing; 2) 'robust' silver paste screen printing; and 3) copper electroplating.

From Fig. 2, the L^2 dependency of the power loss occurring in the finger can be identified, which shows clearly how the line resistivity constraint can be relaxed when switching from the busbar approach to the multiwire approach. In contrast, when fingers must be kept long, a different approach is necessary in order to achieve very low values of line resistivity. A good example is the shingled-cell approach, where cells are cut and directly interconnected to each other by overlapping them [17]. In this case, the number of subcells has to be ideally kept as low as possible in order to minimize the losses caused by the laser cutting, to avoid the handling of a large number of subcells and to reduce the lost area induced by the overlapping. As an example, if a four-subcell cut is considered, the finger length is equivalent to a two-busbar approach, which therefore implies that the line resistivity is to be kept at least below 1Ω/cm. In the following sections, different metallization techniques will be investigated, as well as adapted interconnections schemes.

Low curing-temperature silver paste and screen-printing technique

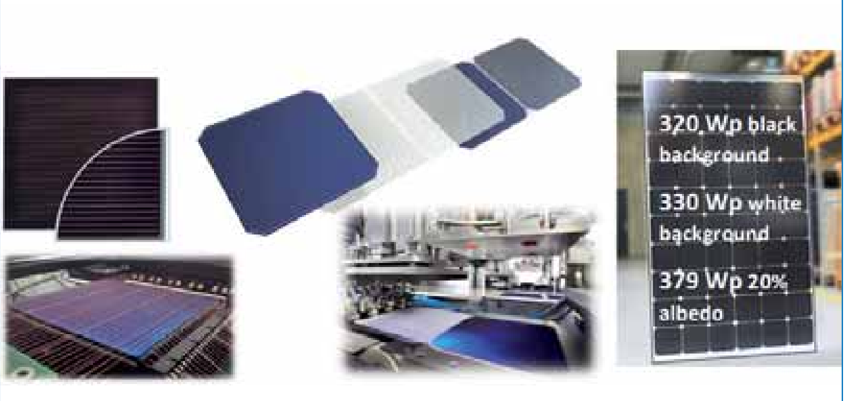
Within the last couple of years, the choice of low-curing-temperature silver paste dedicated to SHJ solar cells has changed drastically. Prior to that, high-performance low-temperature silver pastes were highly sensitive to their storage conditions, and their processing necessarily implied long curing times and temperatures above 200°C. In this respect, the curing had a significant impact on the cell precursor, resulting in a trade-off between the precursor performance and paste resistivity. Thanks to the developments made with these products during the last decade, the pastes can today be stored at ambient temperature or in a standard fridge, which greatly simplifies their storage and their shipment, allowing important reductions in cost. Regarding the curing, this step can now be done much faster and with an infrared furnace, which reduces both the thermal budget of the cell and the furnace footprint in the production environment. Certain pastes now obtain their optimal bulk resistivity after just a few minutes at only 150°C. The paste cost per weight is aligned to the silver price and is now in the same range compared to high temperature silver pastes. However due to their higher specific bulk resistivity, this implies using more low temperature silver paste. Thanks to improvements in the silver filler, composed of a multimodal distribution of flakes and particles [18], the best bulk resistivity has dropped from 18µΩ·cm back in 2009 to 5.5µΩ·cm today, as shown in Fig. 3. Some prototype pastes have even obtained values below 5µΩ·cm, which is only about three times the bulk resistivity of pure silver (1.58µΩ·cm). The printability of these products has improved significantly, leading to less paste spreading on the finger sides; this has meant a reduction in optical shadowing and an improvement in line conductivity, as smoother fingers can be obtained with the same amount of silver. As a consequence of these printability improvements, screen openings as small as 30µm and 20µm can be used in pilot production and in R&D respectively [19–21].

A record print of a line width of just 16µm on a textured wafer coated with ITO has been demonstrated by using a special mesh with zero-angle orientation and a screen opening of only 12µm, as shown in Fig. 4 [22]. High paste reflectivity and a triangular finger shape are preferred in order to reduce the effective finger shadowing on the module by 50 or 60% [23]. Finally, the range of products has increased, with specific pastes dedicated to ribbon interconnection, multiwire interconnection and busbar printing [24,25].



Source: CSEM

Figure 4. Optical image (left) and 3D image (inset) of a screen-printed line on a textured wafer coated with ITO, and SEM image (right) of the screen mesh and opening.



Credit: Meyer Burger

Figure 5. Busbarless cells and GridTouch measurement, the SWCT concept and the bifacial record module. The metallization and interconnection costs are reduced to a minimum level, while maintaining maximum product reliability. Courtesy of Meyer Burger.

Ribbon interconnection

Initially, SHJ solar cells used the same interconnection scheme as standard diffused cells, and were metallized using a busbar design and interconnected by soldered ribbons. However, for reliable soldering on low-temperature-cured silver paste, a minimum thickness of about 20µm at the busbar is necessary in order to avoid silver leaching. For 6" cells with a three-busbar design, this can lead to a total silver paste lay-down for bifacial cells of 1g (of which 40% is used for the busbars), or 0.5g for monofacial cells using sputtered silver at the rear. These values are divided by two when using a five-busbar design, and with the use of the most recent paste with higher conductivity the amount is likely to drop to below 200mg per side. However, with such standard soldering, SHJ metallization is clearly a limiting cost factor [26].

Today, the ribbon interconnection can be glued using electrically conductive adhesives or conductive films with a production tool, while maintaining the same reliability as for soldering [27–31]. The glueing techniques have two main advantages. The first is that the screen printing of busbars can be omitted, leading to what is referred to a *busbarless cell design*, in which the ribbons directly contact the screen-printed fingers through an adhesive [24,25]. The total silver consumption for a bifacial cell can therefore be reduced to 0.3g or 0.2g in the four- or five-ribbon case respectively. In the five-ribbon case, the silver cost is reduced to $0.1/wafer and $0.018/Wp (assuming a silver price of $500/kg and a cell efficiency of 22%). The second advantage of a gluing approach is that because no soldering is involved, textured ribbons can be used, which allows the recycling of the light falling on the ribbon, increasing the module power by up to 2%$_{rel}$. [32,33].

Multiwire interconnection

Wire-based interconnection technology is now becoming a very popular alternative to ribbons, as it can decrease the power losses in the metallization grid, reduce interconnection shadowing, improve module reliability against cell cracking, and increase module power output by 3 to 4%$_{rel}$. [15,34].

> "SWCT is perfectly suited to SHJ solar cell interconnection, since the soldering is performed during the lamination step."

The SmartWire Connection Technology (SWCT) from Meyer Burger (see Fig. 5) consists of a low-melting-point alloy coated on copper wires which are supported by a polymer foil; the technology was initially developed by Day4 Energy [35]. SWCT is perfectly suited to SHJ solar cell interconnection, since the soldering is performed during the lamination step [16,36]. The distance between wires is only 8mm, which allows the finger line resistivity to be as high as 10Ω/cm; in pilot production, the line width can be decreased to under 50µm and the total silver paste lay-down for bifacial cells can be reduced to less than 60mg [36,37]. With only 60mg of silver in total per bifacial cell using SWCT, the metallization and interconnection costs are significantly lowered, and SHJ technology becomes cost competitive compared with standard diffused cells [26]. Recently, Zhao et al. demonstrated a conversion efficiency of more than 23% for a cell batch in pilot production, measured with GridTouch, and recorded 320Wp for a bifacial module with a black background, 330Wp with a white backsheet, and 379Wp with a 20% back-side albedo [19] (see Fig. 5).

Notably in the last few years, extensive work has enabled in particular a significant reduction in the cost of the wire, defining a new generation SWCT, enabling all IEC accelerated ageing tests performed at TÜV Rheinland to be passed multiple times, bringing a multiwire solution highly performing, highly reliable and cost effective [38]. This type of multiwire approach is hence likely to be the best, in terms of readiness and lowest cost, for wide-scale metallization of SHJ, while preserving the advantage of lean cell processing.

SWCT further opens up the possibility of implementing new metallization technologies in the solar industry, as the requirement regarding line resistivity is reduced. In this respect, copper paste screen printing [39], silver nanoparticle inkjet printing [40] and flexographic printing [41] have been implemented in PV modules at the R&D level. SWCT can even contact directly the TCO at the SHJ cell surface; this could allow the metallization step to be completely eliminated from the cell production line. An efficiency of up to 20% for an active module and a reliability over 200 thermal cycles have been demonstrated with such an approach [42].

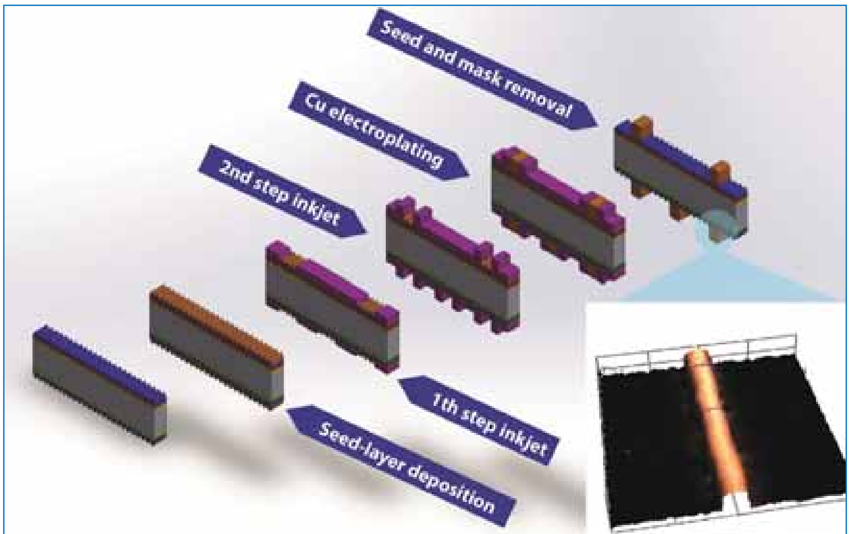
Copper electroplating

A different approach to further improving the performance of SHJ metallization is to replace the silver paste screen printing by the electrodeposition of copper. Although this technique is already well reported in the literature for homojunction solar cells, its application to SHJ solar cells is more recent and involves a total redevelopment of the processes because of the very different device architecture [43,44]. Indeed, a major difference between SHJ solar cells and their diffused-junction counterparts is the presence of the conductive TCO film at the solar cell surfaces, which cannot act as a plating mask, unlike the dielectric anti-reflection coating layer in the diffused-junction case. Moreover, if direct electrodeposition on the TCO is considered, the adhesion of copper may be problematic and will require either specific pre-treatment [45,46] or a thin electroplated nickel layer [44]. However, even with the addition of a nickel-plated adhesion layer, evidence of micro-voids has been found, which might lead to reduced finger adhesion [44].

Another approach is based on depositing a conductive seed layer by physical vapour deposition (PVD) [47]. In addition to providing an adhesion layer with the underlying TCO, this film exhibits a high lateral conductance (a few Ω/sq., compared with possibly several hundred Ω/sq. for a TCO layer). Therefore, the electrical current for the electroplating can easily be homogeneously distributed over the solar cell surface, and the electrical contact can be directly made on the seed layer. This allows plating on either the n-side or the p-side, without the requirement of using light-induced plating, as well as simplifying the simultaneous plating of both sides in the case of a bifacial solar cell.

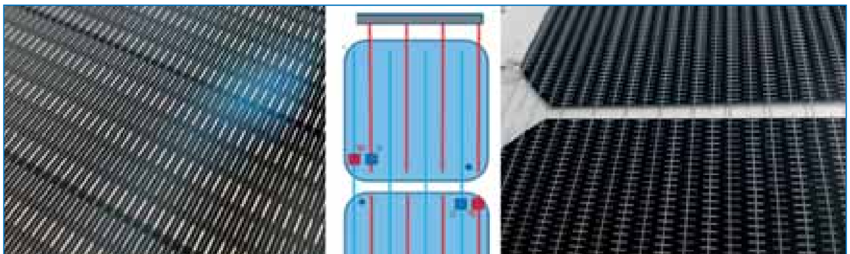
As a consequence of the conductive nature of the TCO films, a patterning technique forming an insulating layer everywhere except where the fingers need to be grown is required. Although traditional photolithography has often been used for this purpose in research, achieving ultra-narrow geometries down to 15µm, its potential application in an industrial context remains uncertain because of the high cost of chemicals and its overall complex process flow [44]. With this in mind, several alternatives have been proposed, such as:

- Low-cost photolithography using dry photosensitive film [47].
- Screen printing of an insulating mask [48].
- Dielectric mask and laser transfer [49].
- Inkjet printing of a functional ink (which prevents the cross linking of an underlying resist layer) [45].
- Inkjet printing of hot-melt mask [50].



Source: CSEM

Figure 6. Process flow for the copper electroplating of a bifacial SHJ solar cell.



Credit: Meyer Burger

Figure 7. Multiwire interconnection of back-contacted silicon heterojunction solar cells developed with the support of the Swiss-CTI. Courtesy of Meyer Burger.

With the use of the hot-melt film technique, Hermans et al. reported a finger width of less than 20µm. As mentioned in that study, a critical aspect in lowering the processing cost is to ensure a low consumption of hot-melt masking ink; this was accomplished by using a two-step approach, where a thin layer of masking ink is used and only thickened in the finger vicinity in order to properly define the edges, allowing the amount of masking ink to be reduced by more than 70% [50]. An illustration of this process is shown in Fig. 6, where an SHJ precursor is coated on both sides with a metallic seed layer. During the first step of inkjet printing, a thin layer of hot melt is deposited, followed by a second inkjet printing step, in which the finger geometry is accurately defined. The fingers are then grown by electroplating. It is noted that in the bifacial case, both sides of the solar cell can be processed simultaneously. Finally, the hot-melt plating mask and the excess seed layer are chemically removed.

> "Remarkable efficiencies have recently been achieved by using copper electroplating for the metallization of SHJ devices."

The copper electroplating metallization technique offers several benefits. First, the paste spreading issue encountered during screen printing is completely absent; this means that, in combination with the use of an appropriate patterning technique, the finger width, as well as the shadowing induced by the metallization grid, can be significantly reduced. Second, as the resistivity of electrodeposited copper is close to the electrical resistivity of pure copper, highly conductive lines can be produced. As a result, remarkable efficiencies have recently been achieved by using copper electroplating for the metallization of SHJ devices – for instance, 25.1% by Kaneka, and 23.1% for Silevo, a company acquired by SolarCity (now Tesla) in 2014 [5,51]. At the module level too, copper plating gives rise to impressive efficiencies, as demonstrated by Sunpreme with a record efficiency of 402Wp for a bifacial module incorporating 72 SHJ cells [52].

As shown in Fig. 2, a line resistivity below 0.5Ω/cm can be achieved using this technique, which allows the design of a metallization grid with a finger length longer than that for other metallization techniques and enables the use of an interconnection with two or three busbars. Even more importantly, in the case of a shingled-cell interconnection, copper electroplating allows the cell to be cut into a minimum number of subcells, thus reducing the losses induced by the cutting process.

SHJ interdigitated back-contact

IBC-SHJ architecture has recently attracted a lot of interest with, in particular, the achievement of energy conversion efficiencies of 26.7% and 25.6% at the cell level by Kaneka and Panasonic respectively [4,6,7]. Kaneka has also reported a world-record module conversion efficiency of 24.37% [53]. Regarding the metallization of such devices, different strategies exist. One option is to use two interdigitated metallization combs with busbars on each side. Although the metallization lines can be larger than in the metallization grid discussed earlier, their length of ~15cm in the case of 6" solar cells entails the use of a substantial amount of metal in order to prevent significant electrical losses in the fingers. This can be realized by electroplated highly conductive lines. Copper layers with ultralow tensile stress are necessary, enabling finger heights of a few tens of microns on 6’’wafers, without introducing wafer bending as obtained e.g. from electrolytes developed at CSEM [54].

The most elegant solution to avoid important metallization at the back side of the IBC cell is, however, to use two levels of multiwire interconnection instead. For this, only two or three screen-printing steps are necessary for producing silver fine line, conductive pads and isolation pads (see Fig. 7). Each odd and even wire will contact the p and n polarities respectively, and the order is reversed on the neighbouring cells. A second notable advantage of this interconnection approach is the possibility of having bifacial back-contacted solar cells. Within the Next-Base project, the European Union firmly supports the development and implementation of such advanced metallization and interconnection concepts for IBC-SHJ solar cells [55].

Conclusions

Different materials and techniques brought to industrial maturity can be used for the metallization of SHJ solar cells. In particular, low-temperature-cured silver pastes have undergone extensive development in recent years, with lower minimum bulk resistivities of just three times the resistivity of pure silver having been achieved. Importantly, the interconnection scheme used during module manufacturing alters in a significant way the requirements regarding line resistivity. In this respect, the multiwire approach decreases the limitations related to finger resistivity, allowing the use of fine-line screen printing; this technique enables considerable reductions to be made in silver paste consumption and optical shadowing, ultimately yielding higher module performance. For the implementation of a wider variety of interconnection technologies and approaches, an alternative metallization technique, such as copper plating, should be considered. Copper plating is well suited, for instance, to the use of existing interconnection equipment with a small number of busbars or for shingled modules: narrow, but still highly conductive, fingers are achievable, thus minimizing the shadowing due to the metallization.

> "The production costs associated with SHJ technology are shrinking, making it one of the most cost-competitive PV technologies for energy production."

To conclude, SHJ technology has already demonstrated a reduced levelized cost of electricity (LCOE) thanks to the native bifacial architecture and the low thermal coefficient. Now, with the recent findings and developments in the field of metallization and interconnection, the production costs associated with SHJ technology are shrinking, making it one of the most cost-competitive PV technologies for energy production.

References

[1] Tanaka, M. et al. 1992, "Development of new a-Si/c-Si heterojunction solar cell: ACJ-HIT (artificially constructed junction-heterojunction with intrinsic thin-layer)", Jpn. *J. Appl. Phys.*, Vol. 31, No 11, pp. 3518–3522.

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

[3] Battaglia, C., Cuevas, A. & De Wolf, S. 2016, "High-efficiency crystalline silicon solar cells: Status and perspectives", *Energy Environ. Sci.*, Vol. 9, pp. 1552–1576.

[4] Masuko, K. et al. 2014, "Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cells", *IEEE J. Photovolt.*, Vol. 4, No. 6, pp. 1433–1435.

[5] Adachi, D., Hernández, J.L. & Yamamoto, K. 2015, "Impact of carrier recombination on fill factor for large area heterojunction crystalline silicon solar cell with 25.1% efficiency", *Appl. Phys. Lett.*, Vol. 107, p. 233506.

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

[7] Green, M.A. et al. 2017, "Solar cell efficiency tables (version 50)", *Prog. Photovolt: Res. Appl.*, Vol. 25, pp. 668–676.

[8] Panasonic [https://eu-solar.panasonic.net/en/solar-panel-vbhn240sj25-vbhn245sj25.htm#product-description-Downloads].

[9] Meyer Burger, HELIA fact sheet [https://www.meyerburger.com/ch/en/meyer-burger/products-and-systems/product-detail/product/helia/].

[10] AMPERE European project [http://www.ampere-h2020.eu/].

[11] Mishima, T. et al. 2011, "Development status of high-efficiency HIT solar cells", *Sol. Energy Mater. Sol. Cells*, Vol. 95, No. 1, pp. 18–21.

[12] Haschke, J. et al. 2017, "The impact of silicon solar cell architecture and cell interconnection on energy yield in hot & sunny climates", *Energy Environ. Sci.*, Vol. 10, pp. 1196–1206.

[13] Essig, S. et al. 2017, "Raising the one-sun conversion efficiency of III–V/Si solar cells to 32.8% for two junctions and 35.9% for three junctions", *Nature Energy*, Vol. 6, 17144.

[14] Despeisse, M. et al. 2015, "Metallization and interconnection for silicon heterojunction solar cells and modules", *Photovoltaics International*, 30th edn, pp. 61–67.

[15] Braun, S., Micard, G. & Hahn, G. 2012, "Solar cell improvement by using a multi busbar design as front electrode", *Energy Procedia*, Vol. 27, pp. 227–233.

[16] Papet, P. et al. 2016, "New cell metallization patterns for heterojunction solar cells interconnected by the Smart Wire Connection Technology", *Energy Procedia*, Vol. 67, pp. 203–209.

[17] Beaucarne, G. et al. 2016, "Materials challenge for shingled cells interconnection", *Proc. 6th Metalliz. Worksh.*, Konstanz, Germany.

[18] Körner, S. & Eberstein, M. 2016, "High-performance screen-printable pastes for HJT cells", *Photovoltaics International*, 34th edn, pp. 64–71 [https://www.pv-tech.org/technical-papers/high-performance-screen-printable-pastes-for-hjt-cells].

[19] Zhao, J. et al. 2017, ">23% Silicon heterojunction solar cells in Meyer Burger's demo line: Results of pilot production on mass production tools", *Proc. 44th IEEE PVSC*, Washington DC, USA.

[20] Bettinelli, A. et al. 2016, "Advanced PV research using the screen-printing technology", Asada Mesh Adv. Scr. Print. Worksh.

[21] Papet, P. et al. 2014, "Silver usage reduction for monofacial and bifacial heterojunction solar cells", *Proc. 4th Metalliz. Worksh.*, Konstanz, Germany.

[22] Faes, A. et al. 2015, "Screen-printing for high efficiency solar cells", Asada Mesh Adv. Scr. Print. Worksh.

[23] Chen, Y. et al. 2016, "Shape and homogeneity of front metal fingers – Impact on cell efficiency and its distribution in production lines", *Proc. 6th Metalliz. Worksh.*, Konstanz, Germany.

[24] Yoshidaa, M. et al. 2012, "Novel low-temperature-sintering type Cu-alloy pastes for silicon solar cells", Energy Procedia, Vol. 21, pp. 66–74.

[25] Beaucarne, G. et al. 2015 "Innovative cell interconnection based on ribbon bonding of busbarless cells using silicone-based electrically conductive adhesives", *Energy Procedia*, Vol. 67, pp. 185–193.

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

[27] Teamtechnik [http://www.teamtechnik.com/en/solar/stringer-tt/stringer-tt1400-eca/].

[28] Schneider, A. et al. 2013, "Progress in interconnection of busbar-less solar cells by means of conductive gluing", *Energy Procedia*, Vol. 38, pp. 387–394.

[29] Geipel, T., Huq, Z. & Eitner, U. 2014, "Reliable interconnection of the front side grid fingers using silver-reduced conductive adhesives", *Energy Procedia*, Vol. 55, pp. 336–341.

[30] Nagase [http://nagaseamerica.com/product/conductive-ribbonstringer-attach-adhesives/].

[31] Henkel Adhesives [http://www.henkel-adhesives.com/com/content_data/181901_enewsletter_AP_Conductive_Adhesives_for_PV_0210_final.pdf].

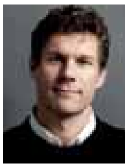
[32] Muehleisen, W. et al. 2016, "Comparison of output power for solar cells with standard and structured ribbons", *EPJ*

Cell Processing

Photovolt., Vol. 7, pp. 70701.
[33] Holst, H. et al. 2016, "Increased light harvesting by structured cell interconnection ribbons: An optical ray tracing study using a realistic daylight model", *Energy Procedia*, Vol. 92, pp. 505–514.
[34] Söderström, T., Yao, Y. & Grischke, R. 2015, "Low cost high energy yield solar module lines and its applications", *Proc. 42nd IEEE PVSC*, New Orleans, Louisiana, USA.
[35] Schneider, A., Rubin, L. & Rubin, G. 2006, "Solar cell improvement by new metallization techniques – The DAY4TM electrode concept", *Proc. 4th WCPEC*, Waikoloa, Hawaii, USA, pp. 1095.
[36] Faes, A. et al. 2014, "SmartWire solar cell interconnection technology", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands.
[37] Strahm, B. et al. 2015, "The Swiss Inno-HJT project: Fully integrated R&D to boost Si-HJT module performance", *Proc. 31st EU PVSEC*, Hamburg, Germany.
[38] Ballif, C. et al. 2017, "Novel designs and materials for durable PV modules: Applications on the ground, in cities and in the air", *Proc. 44th IEEE PVSC*, Washington DC, USA.
[39] Faes, A. et al. 2015, "Diverse metallization schemes enabled by SmartWire connection technology", *Proc. 31st EU PVSEC*, Hamburg, Germany.
[40] Hermans, J. 2015, "Inkjet printing of Ag nanoparticle inks for heterojunction solar cell metallization", *Proc. 9th SNEC Int. PV Power Gen. Conf.*, Shanghai, China.
[41] Lorenz, A. et al. 2016 "Flexo-printed busbarless solar cells for multi-wire interconnection", *Energy Procedia*, Vol. 98, pp. 46–60.
[42] Despeisse, M. et al. 2016, "Metallization and interconnection technologies for silicon heterojunction solar cells", *Proc. 26th Internat. PVSEC*, Singapore.
[43] Lennon, A., Yao, Y. & Wenham, S. 2013, "Evolution of metal plating for silicon solar cell metallization", *Prog. Photovolt: Res. Appl.*, Vol. 21, No. 7, pp. 1454–1468.
[44] Geissbuhler, J. et al. 2014, "Silicon heterojunction solar cells with copper-plated grid electrodes: Status and comparison with silver thick-film techniques", *IEEE J. Photovolt.*, Vol. 4, No. 4, pages 1055–1062.
[45] Li, Z. et al. 2015, "Patterning for plated heterojunction cells", *Energy Procedia*, Vol. 67, pp. 76–83.
[46] Tous, L. 2014, "Nickel/copper plated contacts as an alternative to silver screen printing for the front side metallization of industrial high efficiency silicon solar cells", Ph.D. dissertation, KU Leuven – Faculty of Engineering, Belgium.
[47] Ishimura, F. et al. 2016, "Metal wrap through heterojunction solar cell with plated electrode", *Proc. 32nd EU PVSEC*, Munich, Germany.
[48] Khanna, A. et al. 2015, "Screen-printed masking of transparent conductive oxide layers for copper plating of silicon heterojunction cells", *Appl. Surf. Sci.*, Vol. 349, pp. 880–886.
[49] Glatthaar, M. et al. 2017, "Novel positive-masked plating process for silicon heterojunction solar cell metallization", Presentation, 44th IEEE PVSC, Washington DC, USA.
[50] Hermans, J. et al. 2014 "Advanced metallization concepts by inkjet printing", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands.
[51] Heng, J.B. et al. 2014, ">23.1% high efficiency tunnel oxide junction bifacial solar cell with electroplated Cu gridlines", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands.
[52] Li, B. 2016, "Industrial bifacial silicon heterojunction technology that improves system LCOE", Hercules Worksh., Berlin.
[53] Yamamoto, K. et al. 2017, "Record-breaking efficiency back-contact heterojunction crystalline Si solar cell and module", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.
[54] Lachowicz, A. et al. 2017, "Copper plating chemistry for solar cells", *Proc. 33rd EU PVSEC*, Amsterdam, The Netherlands.
[55] NextBase European project [http://nextbase-project.eu/].

About the Authors

Jonas Geissbühler received his Ph.D. in 2015 from EPFL, Switzerland, with a thesis topic of high-efficiency silicon heterojunction solar cells. He joined the CSEM PV-center in 2016, where his research interests include the metallization of silicon heterojunction solar cells, inkjet printing and high-efficiency silicon heterojunction solar cells.



Antonin Faes received his Ph.D. in 2006 for his work on solid oxide fuel cells at the Interdisciplinary Center for Electron Microscopy (CIME) and the Industrial Energy System Laboratory (LENI) at EPFL. In 2012 he joined the CSEM PV-center in Neuchâtel, where he is responsible for c-Si solar cell metallization and interconnection activities, with a particular focus on silicon heterojunction solar cells.

Agata Lachowicz studied chemistry at Heinrich Heine University Düsseldorf and worked initially on processes for printed circuit boards, followed by development of etching and plating processes for solar cells at Schott Solar and optimization of PERC cells at Meyer Burger Germany. She joined CSEM PV-center in 2014 for development of plating processes for silicon heterojunction cells.

Christophe Ballif received his Ph.D. from EPFL, Switzerland, in 1998. In 2004 he became a full professor with the Institute of Microengineering at the University of Neuchâtel, where he directs the Photovoltaics and Thin-Film Electronics Laboratory, which is now part of EPFL. Since 2013 he has also been the director of the CSEM PV-center. His research interests include materials for PV, high-efficiency c-Si solar cells, module technology, BIPV and energy systems.

Matthieu Despeisse received his Ph.D. in 2006 for his work on advanced detectors at CERN in Geneva, Switzerland. He then joined EPFL in 2009 as head of the thin-film silicon photovoltaics research team. Since 2013 he has led research activities at CSEM concerning crystalline silicon photovoltaics and metallization, with a special focus on silicon heterojunction technology, passivating contacts, metallization and interconnection.

Enquiries

Jonas Geissbühler
Jacquet-Droz 1
CH-2002 Neuchâtel
Switzerland

Email: jgr@csem.ch

Towards a high-throughput metallization for silicon solar cells using rotary-printing methods

Andreas Lorenz, **Anna Münzer**, **Martin Lehner**, **Armin Senne**, **Roland Greutmann**, **Heinz Brocker**, **Thomas Ott**, **Friedhelm Hage** & **Florian Clement**, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

ABSTRACT

Today, flatbed screen printing is the state-of-the-art technology for solar cell metallization; however, the throughput of a single flatbed screen-printed metallization line is currently limited to approximately 2,000 wafers/h. A highly promising route to significantly increasing throughput is the use of rotary-printing methods, with an expected throughput of at least 6,000 wafers/h. This paper presents two innovative rotary-printing technologies: flexographic printing and rotary screen printing. *Flexographic printing* is a high-speed method that is capable of realizing narrow contact fingers for front-side metallization. *Rotary screen printing* is particularly suited to rear-side metallization, as it combines the advantages of thick-film metallization with a very high printing speed. The actual achievements and challenges of these highly promising approaches will be discussed, and the path of future research activities will be outlined.

Introduction

Modern single metallization lines using flatbed screen printing (FSP) can realize a maximum output of approximately 2,000 wafers/h [1]. For several reasons, achieving a significant further increase in throughput of the FSP process is technically challenging. First, the usage of high-viscous silver and aluminium pastes requires a separate, and hence time-consuming, flooding and printing step. Second, the speed of the FSP process is limited by the rheological properties of the pastes, and is therefore highly dependent on the development and availability of suitable pastes.

Elevating the solar cell metallization process to a new level of productivity thus requires new concepts in the future. One such, highly promising, concept is the use of high-speed rotational printing methods for the front- and rear-side metallization of silicon (Si) solar cells. The vision for a future high-throughput back-end metallization line combines different rotary-printing methods (Fig. 1), among which rotary screen printing (RSP) and flexographic (or flexo) printing (FXP) are particularly promising techniques. RSP is closely related to FXP and primarily suited to the rear-side metallization of aluminium back-surface field (Al BSF) or passivated emitter and rear contact (PERC) solar cells. Other possible fields of application are the structured rear-side metallization for bifacial solar cells [2], or the separate imprinting of busbars within a dual-

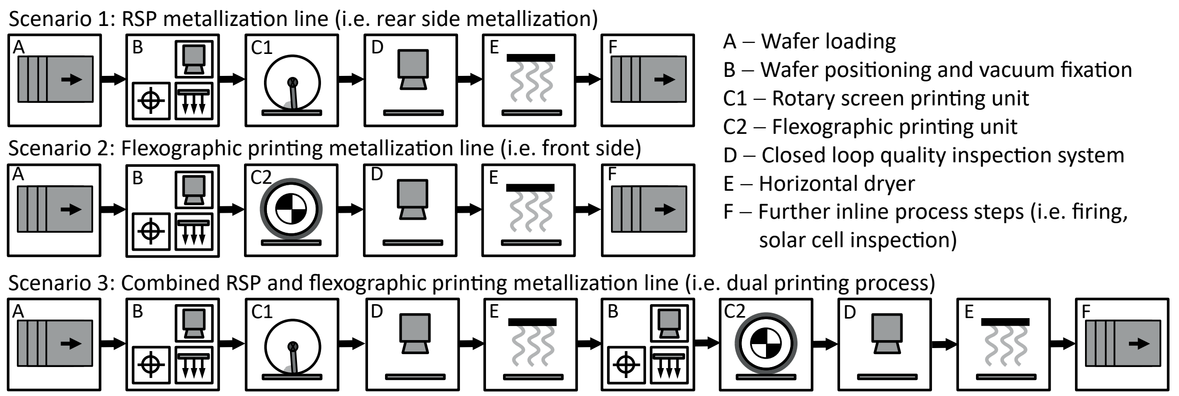


Figure 1. Illustrative presentation of different configurations for a back-end metallization line using rotary-printing methods. Scenarios 1 and 2 represent concepts for a rear-side metallization line using RSP and a front-side metallization line using FXP respectively. Scenario 3 combines both technologies in one metallization line (i.e. for a dual-printing process of busbars and contact fingers).

printing process. FXP technology [3] is a high-speed letterpress printing method using flexible photopolymer or rubber printing plates. With this technology it is possible to apply very narrow contact fingers, and it is thus primarily suited to front-side metallization using either a seed-and-plate approach [4–6] or a direct metallization process for solar cells with wire interconnection [7].

"One of the main goals is the development of a prototype demonstrator using RSP and FXP units to realize the front- and rear-side metallization of Si solar cells with a throughput of 6,000–8,000 wafer/h."

In 2015 a project consortium of several industry partners led by ASYS Group and Fraunhofer ISE initiated the ambitious Rock-Star project (contract number 13N13512 [8]) with the aim of evaluating the potential of RSP and FXP technologies [7,9] for the metallization of Si solar cells. The joint project is partly supported by the German Federal Ministry of Education and Research (BMBF) within the Photonics Research Germany funding programme. One of the main goals of the project is the development of a prototype demonstrator using RSP and FXP units to realize the front- and rear-side metallization of Si solar cells with a throughput of 6,000–8,000 wafer/h. To cope with this ambitious challenge, a close cooperation in the field of automation and wafer handling (ASYS Group), printing technology and machine manufacturing (Gallus Ferd. Ruesch AG), and material/process optimization (ContiTech Elastomer Coatings, Fraunhofer ISE, TU Darmstadt IDD) is essential. This paper presents the current state of the art and discusses the existing challenges with regard to solar cell front- and rear-side metallization using both technologies.

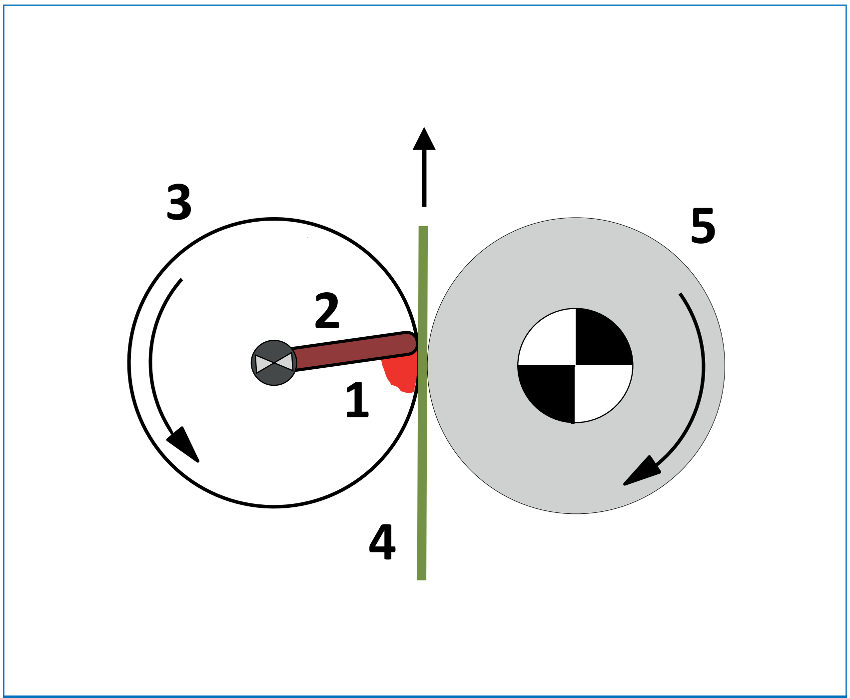


Figure 2. Schematic of an RSP unit for web-based materials. The paste (1) is pressed by a fixed squeegee (2) through the openings of the rotating cylinder screen (3). The web-based substrate (4) is guided by an impression cylinder (5) opposite the cylinder screen.

Figure 3. The RSP unit of the Gallus EM 280 label printing machine, which was used for the experiments. This printing machine allows a printing speed of up to *v* = 100m/min. (1.7m/s).

Rotary screen printing

While FSP is widely known as a state-of-the-art technology for thick-film metallization, RSP is a fairly unknown printing technology. However, RSP is a well-established and highly developed high-speed printing technology commonly used for specific applications such as textile or label printing [10]. Similar to FSP, RSP can print thick films on various substrates. To date, RSP has almost exclusively been used for web-based materials, such as foil, paper, textile fabrics and cardboard; such web-fed machines with RSP units can realize a printing speed of up to 160m/min. (2.7m/s) [11]. The high metallization quality of screen-printed thick-film metallization in combination with the rotary-printing principle of RSP could therefore be a highly promising

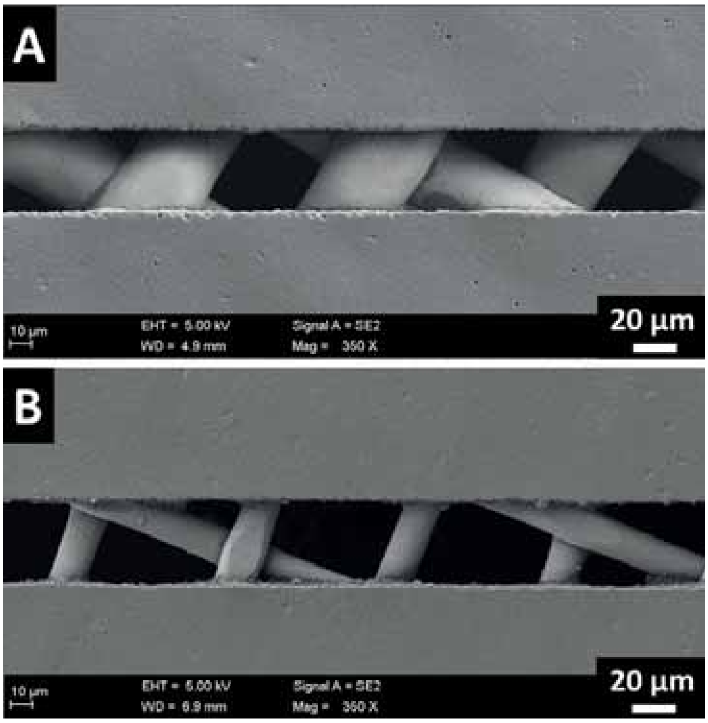


Figure 4. SEM images of a fine-line opening in an RSP cylinder screen (A) and in an FSP flatbed screen (B). The significantly greater wire thickness of the RSP screen mesh is clearly visible.

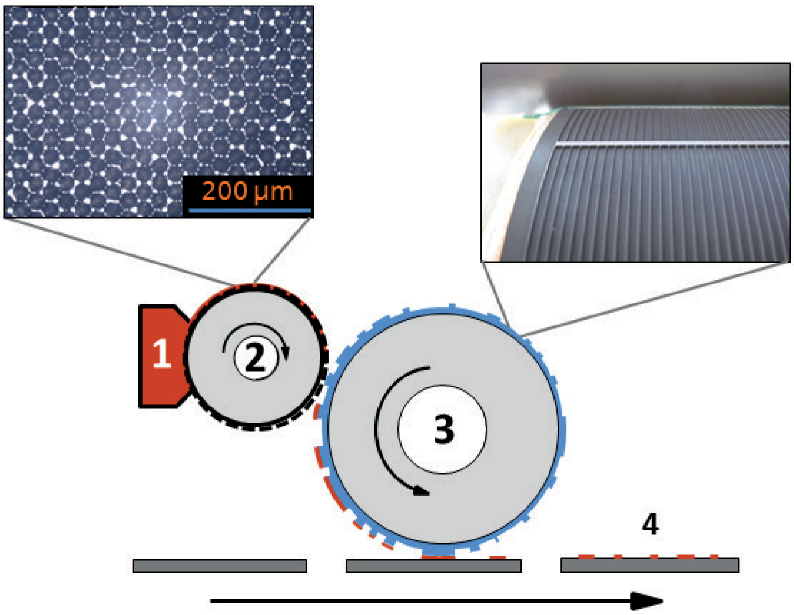


Figure 5. Schematic of a (theoretical) FXP unit for the metallization of silicon solar cells: from the ink reservoir (1), a defined amount of ink is transferred by the anilox roll (2) onto fine finger elements on the printing plate (3), and subsequently onto the silicon wafer (4).

path for a future high-throughput metallization line. The first attempts to use this technology for solar cell metallization date back as far as 1999; however, there are no known published results from these activities [12].

If one compares FSP and RSP technology, one fundamental difference becomes apparent: FSP requires two printing steps for the metallization of one solar cell. In the *flooding step*, the open areas of the flatbed screen are filled with paste using a metal flood bar. In the second stage – the *printing step* – the paste is pressed through the openings of the flat screen by a flexible squeegee. RSP, on the other hand, is a continuous process, meaning that the paste is constantly pressed through the openings of the rotating cylinder screen by a fixed squeegee (Figs. 2 and 3). The time-consuming two-step printing process associated with FSP can thus be avoided.

While the continuous printing process of RSP is a clear advantage with respect to throughput, RSP also experiences some drawbacks compared with FSP. First, the RSP cylinder screens require a considerably higher stability of the mesh than in the case of FSP flatbed screens. To ensure this stability, the meshes in rotary screens have significantly thicker wires ($d_{wire} \approx 30$–$50\mu m$) than in flatbed screens ($d_{wire} \approx 14$–$25\mu m$), as illustrated in Fig. 4.

Thicker wires obviously reduce the open area of the mesh, and hence the paste transfer capacity per unit area; they could also increase the impact of so-called *mesh marks* on the printed finger geometry. A second characteristic of RSP is the necessity of a lower paste viscosity compared with FSP pastes, which can be explained by the continuous printing process and the absent pre-filling of the screen. Reducing the paste viscosity usually has an impact on effects such as paste spreading on the wafer surface, and could thus negatively affect the resulting finger geometry. A lower paste viscosity could also affect other important rheology parameters of the paste, such as yield stress and wall slipping [13]. The rheological requirements of RSP metallization have not yet been sufficiently examined to categorically assess these effects on finger geometry.

Flexographic printing

FXP technology is a well-known and widely used printing technology, usually for graphic arts printing on substrates such as cardboard, paper and foil. Roll-to-roll FXP machines can realize a printing speed of up to 800m/min. on web-based materials. While this throughput is obviously unrealistic for the non-continuous metallization of Si solar cells, FXP technology nevertheless offers the potential to increase throughput considerably in cell metallization. Fig. 5 illustrates the working principle of a (theoretical) FXP unit for solar cell metallization.

> "FXP technology offers the potential to increase throughput considerably in cell metallization."

FXP uses a flexible relief printing plate or sleeve [14] as the image carrier. Compressible foam tape is applied below the printing plate in order to compensate for unevenness and to assure a homogeneous ink transfer. The ink is transferred from the ink chamber onto the so-called *anilox roll*, a steel cylinder with a finely textured chromium or ceramic surface. Inks with a low to medium viscosity can be used, depending on the properties of the anilox roll and on the requirements of the printing subject. Excessive ink is removed from the surface of the anilox roll by a doctor blade. The anilox roll continuously wets the elevated areas of the printing plate with a uniform layer thickness. The printing layout (elevated areas on the printing plate) is continuously printed on the substrate by the rotating cylinder.

The relatively low printing pressure and the flexibility of the plate enable fine structures to be printed, even on very rough substrates such as textured silicon wafers. The critical parameters in the FXP process are the printing pressure, anilox roller properties, ink properties and material tolerances. The applicable layer thickness with FXP is usually limited to $d_{layer} \leq 10\mu m$, which represents a challenge for high-aspect-ratio (height-to-width ratio) contact fingers. FXP has proved its ability to print ultrafine conductive structures in many printed electronics applications, such as micro-scale conductive networks [15,16], roll-to-roll polymer solar cell modules [17], cathode layers for batteries [18], and conductive lines [19].

In respect of the front-side metallization of Si solar cells, two different approaches are of interest. The idea behind the seed-and-plate approach is to print a fine-line seed-layer grid on Si wafers; this layer can subsequently be enhanced by light-induced plating (LIP) using silver (Ag) or a stack of nickel (Ni) as a diffusion barrier, copper (Cu) as a conducting layer, and Ag or tin (Sn) as an anti-oxidation capping layer. The second approach is the direct front-side metallization of Si solar cells without subsequent plating; the most critical aspect of this approach is the realization of the grid with a sufficiently low lateral finger resistance R_L.

Rotary screen-printed rear-side metallization

The metallization of the rear side of Al BSF or PERC solar cells requires the transfer of a homogeneous Al layer with a thickness of approximately 20–30µm. Prior to the feasibility study, it was unclear whether RSP technology would be able to meet this challenge with satisfying results. Consequently, an experiment with respect to the rear-side metallization of Al BSF solar cells was conducted using industrially pre-processed p-type Czochralski-grown silicon (Cz-Si) precursors with well-known properties ($R_{sh} \approx$ 85–90Ω/sq.).

A major challenge for the experiment was the availability of an adequate test assembly for the metallization of the Si wafer. The test assembly was realized by fixing the wafers manually on the foil web of a Gallus EM 280 label printing machine with an RSP unit [20] (Fig. 6). This improvised assembly allowed a safe transport of single wafers through the printing unit, with an alignment tolerance of approximately 1–1.5cm between the printing image and the wafer. In order to realize a full solar cell layout on the precursors despite this alignment tolerance, it was decided to print a smaller cell layout (125mm × 125mm) on 6" precursors (156mm edge length).

For the RSP rear-side metallization, three different cylinder screens with varying screen-mesh properties (mesh count and theoretical paste transfer volume V_{th}) were used. A commercially available Al paste for Al BSF solar cells was iteratively diluted to an adequate viscosity. Subsequently, all cells were cut out along the position of the printed image by laser cutting. In a second step, the front-side grid

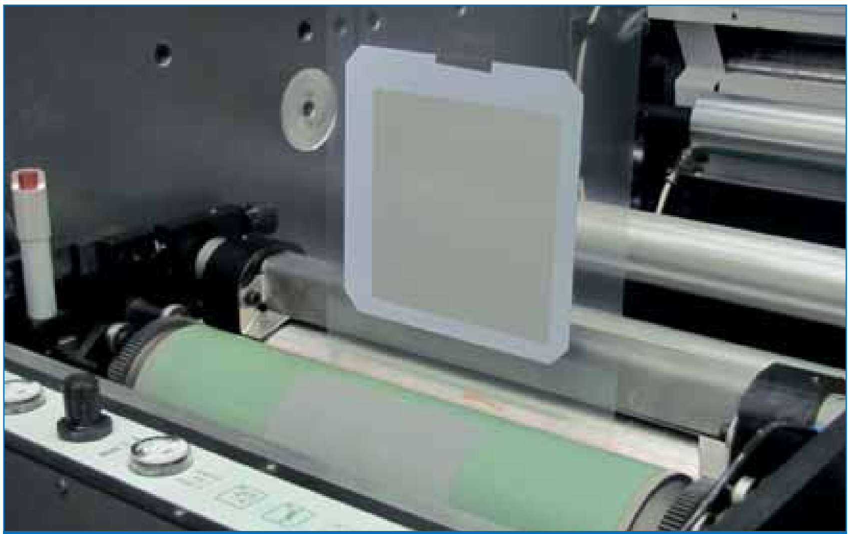


Figure 6. Transport of a Si wafer through the RSP printing unit by fixing it on a foil web.

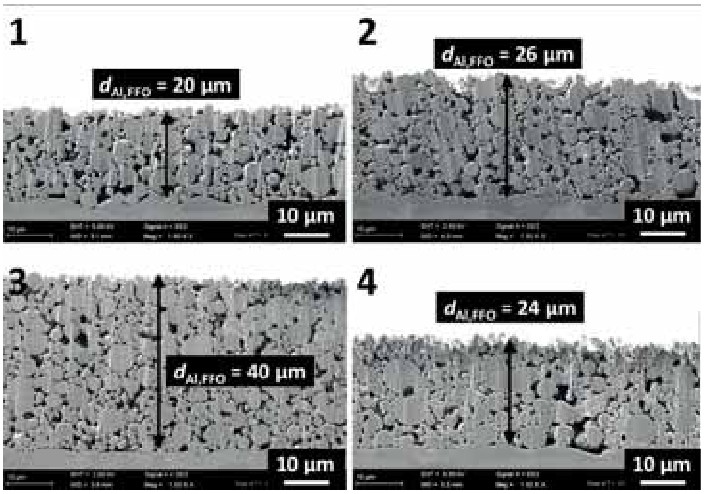


Figure 7. SEM cross-sectional images of the Al rear-side metallization after contact firing. Images 1 to 3 represent samples with RSP rear-side metallization and different cylinder screens. Image 4 is the reference sample with FSP rear-side metallization.

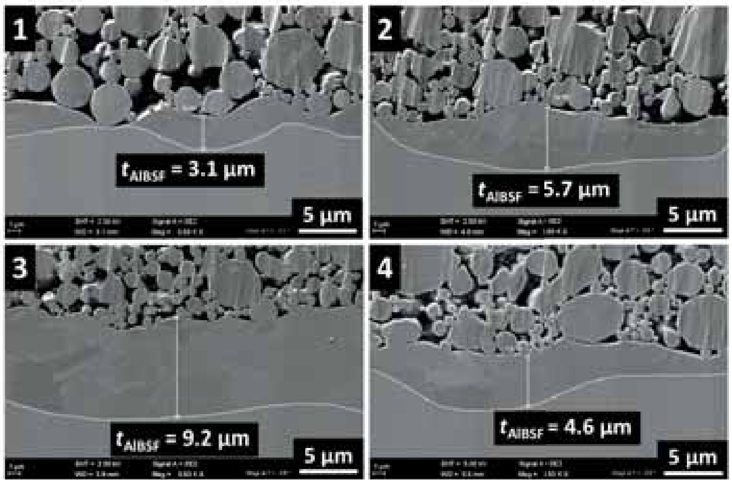


Figure 8. SEM cross-sectional images and local measurement of the resulting Al BSF depth after contact firing. Images 1 to 3 represent samples with RSP rear-side metallization and different cylinder screens. Image 4 is the reference sample with FSP rear-side metallization.

Rear-side metallization	Mesh [wires/inch]	Theoretical paste volume V_{th} [cm³/m²]	Ø Layer thickness [µm]	Ø Depth of Al BSF [µm]	Ø V_{oc} [mV]	Ø j_{sc} [mA/cm²]	Ø FF [%]	Ø η [%]
RSP	200	22	20	2.5	639.0 ± 3.0	37.5 ± 0.2	80.4 ± 0.1	19.2 ± 0.2
RSP	145	32	26	3.6	641.7 ± 0.7	37.5 ± 0.1	80.6 ± 0.2	19.4 ± 0.1
RSP	88	67	40	7.8	642.7 ± 0.4	37.5 ± 0.1	80.2 ± 0.3	19.4 ± 0.1
FSP	280	27	24	4.0	642.2 ± 0.5	37.6 ± 0.1	80.0 ± 0.2	19.3 ± 0.1

Table 1. Properties of rotary and flatbed screens, layer thickness after contact firing, depth of Al BSF, open-circuit voltage V_{oc}, short-circuit current density j_{sc}, fill factor FF, and energy conversion efficiency η for various solar cell groups.

(85 contact fingers, three busbars with w_b = 1.0mm) was printed using FSP with a standard screen (400 wires/inch, nominal finger width w_n = 45µm). Finally, a contact firing step, *I–V* measurements and an SEM analysis of the rear-side metallization were carried out. In parallel, a reference group with FSP front and rear-side metallization was fabricated on identical cut-down precursors, using the same pastes and layouts.

The experiment revealed several important aspects. A significant finding was the fact that commercially available Al pastes can be used for RSP after slight modification (dilution) in order to adjust the viscosity. The layer thickness of the rear-side metallization could be easily controlled by choosing a cylinder screen with an adequate paste transfer capacity (Fig. 7 and Table 1). Optimal results were achieved using a cylinder screen with a mesh count of 145 wires/inch. The resulting mean layer thickness of d_{Al} = 26µm after contact firing was close to the layer thickness of the reference cells with FSP rear-side metallization (d_{Al} = 24µm). The use of a cylinder screen with 88 wires/inch led to a significantly thicker Al layer of d_{Al} = 40µm, which induced a strong bowing of the solar cells due to thermal expansion in the contact firing process. This bowing needs to be minimized, as it negatively affects, or even prevents, the automation of wafer handling in subsequent process steps.

> "With RSP it is possible to realize a high-quality rear-side metallization for Al BSF solar cells using a slightly diluted Al paste and an optimal cylinder screen mesh."

An analysis of the BSF using SEM further revealed a clear dependence of the BSF depth t_{ALBSF} on the initial Al layer on the rear side (Fig. 8). This dependency has also been found in previous studies [21–23] and can be explained by a varying concentration gradient between Al and Si during the formation of the Al–Si eutectic in the contact firing process [24]. An inspection of the *I–V* results revealed a visible effect of t_{ALBSF} on open-circuit voltage V_{oc} of the solar cells (Table 1). The optimum balance with regard to the *I–V* results and the minimal bow could be achieved with a cylinder screen having 145 wires/inch. For this screen configuration, the conversion efficiency (η = 19.4%) was similar to that for the FSP reference group (η = 19.3%). To summarize the results, it was found that with RSP it is possible to realize a high-quality rear-side metallization for Al BSF solar cells using a slightly diluted Al paste and an optimal cylinder screen mesh. Transferring the rear-side metallization process from FSP to RSP technology should therefore be a relatively easy task.

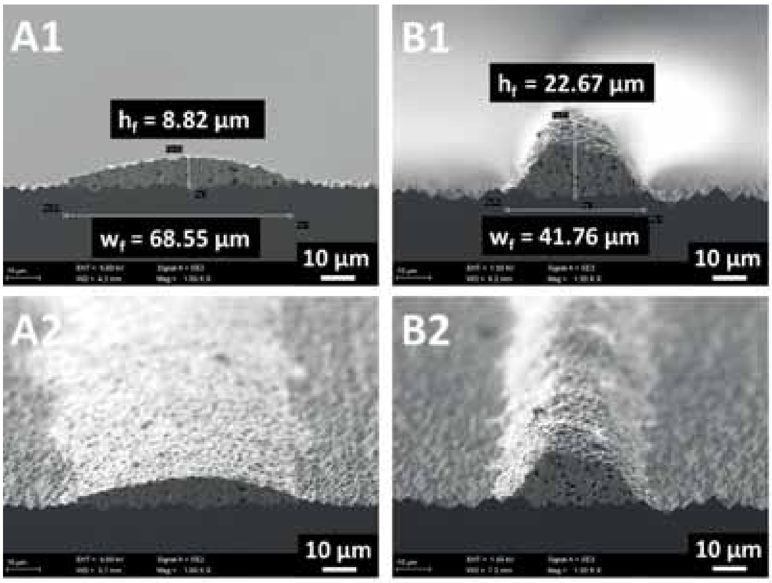


Figure 9. SEM images of a contact finger printed with RSP (A1 and A2) and with FSP (B1 and B2). The much higher aspect ratio of the FSP contact finger is clearly visible.

Rotary screen-printed front-side metallization

The metallization of the front side of Si solar cells is a considerably greater challenge with regard to the printing process. The front-side grid needs to be printed with narrow, uninterrupted contact fingers, and preferably with a small tolerance in finger width and height. Moreover, to minimize the shading losses of the grid and the series resistance losses due to the lateral finger resistance R_L at the same time, the fingers should be printed with a high aspect ratio. To achieve these challenging goals, paste suppliers

have put much effort into gradually improving FSP metallization pastes. With the use of RSP for the front-side metallization, one can expect considerable challenges regarding finger geometry, as the thicker wires of the mesh limit the paste transfer capability, and the necessity to adapt the viscosity probably affects the resulting finger geometry.

To evaluate the general feasibility of RSP front-side metallization, an experiment similar to that for rear-side metallization was set up. In this case, the front side was printed using an RSP fine-line cylinder screen with a mesh count of 400 wires/inch and a 4" layout (A = 125mm × 125mm, three busbars with w_b = 1.0mm, 85 fingers with w_n = 35µm) on p-type Cz-Si precursors with an edge length of 156mm. A commercially available Ag paste was used after being slightly diluted with a sufficient thinner. A reference group with FSP front-side metallization was fabricated in parallel. All cells were equipped with a standard FSP rear-side metallization for Al BSF solar cells.

A statistical analysis of the finger geometry using confocal microscopy and SEM analysis revealed significant differences between RSP and FSP (Fig. 9). RSP contact fingers showed, as expected, a significantly broader finger width and a lower finger height compared with FSP contact fingers. This demonstrates that further optimization of paste rheology and cylinder screens is needed in order to enable RSP technology to realize a fine-line front-side metallization of PERC or Al BSF solar cells. Nevertheless, RSP is probably capable of printing less challenging patterns, such as a rear-side grid for bifacial solar cells [2], or busbars in a dual-printing process.

Flexographic-printed front-side metallization

The promising results of feasibility studies using flexography for a seed-and-plate-approach on small-sized solar cell samples [4,5,25] form the basis of the FXP activities at Fraunhofer ISE. A major challenge was the availability of an adequate machine platform to print fine-line grids on non-bendable Si wafers, as FXP machines are usually roll-to-roll based. It was possible to overcome this hurdle by using a laboratory machine of the type Nissha Angstromer S15 with a vacuum table to fix the wafers (Fig. 10).

Initial research activities at Fraunhofer ISE between 2012 and 2015 focused on the seed-and-

Figure 10. Nissha Angstromer S15 flexographic printing machine with a ContiTech Laserline fine-line printing plate and a Cz-Si precursor fixed on the vacuum table.

Figure 11. ContiTech Laserline laser-engraved flexographic EPDM printing plate with a fine-line H-pattern layout for seed-layer metallization.

plate approach using p-type Cz-Si-precursors with a 156mm edge length. Ag inks for the seed-layer metallization, based on an existing ink formulation, were developed in-house [6]. High-precision laser-engraved ethylene-propylene-diene rubber (EPDM) plates of the type ContiTech Laserline CSC, with a nominal finger width down to w_n = 5µm, were used to apply the seed-layer front-side grid (Fig. 11).

Extensive trials and significant efforts to optimize materials and machine settings finally led to promising printing and solar cell results. A mean finger width of w_f = 53µm could be obtained after reinforcing the seed-layer grid with Ni-Cu-Ag LIP [26]. The best group of solar cells achieved a mean conversion efficiency of η =19.1%, which was close to the results obtained for reference solar cells with a state-of-the-art FSP front-side metallization (η = 19.3%) [26]. However, total Ag consumption for the front-side metallization of the FXG solar cells ($m_{Ag} \approx$ 15mg/cell) was considerably reduced compared with the FSP reference cells ($m_{Ag} \approx$ 96mg/cell). This approach is therefore particularly attractive in the event of sharply rising silver prices.

From 2014 onwards, research activities in the framework of the Rock-Star joint project focused on a direct metallization of Si solar cells using FXP. Extensive printing tests identified the anilox roller and the ink rheology as key parameters in controlling finger geometry and achieving fingers with a higher aspect ratio [9]. The use of an anilox roller with a large ink transfer capacity and a high-viscous Ag ink led to contact fingers with a mean width w_f below 30µm [27] and a finger height up to $h_f \approx$ 12µm. However, realizing such narrow contact fingers with a sufficiently low lateral finger resistance using FXP technology is still challenging.

FXP, with a mean lateral finger resistance of R_L = 6.1Ω/cm (FSP metallization: $R_L \approx$ 0.4–0.6Ω/cm), is currently well suited to the front-side metallization of busbarless solar cells with multiwire interconnection (e.g. Meyer Burger's SmartWire concept [28]). In the test runs, busbarless solar cells with FXP front-side metallization achieved a mean conversion efficiency η of up to 19.4% on p-type Cz-Si precursors, and have been successfully interconnected in a working demonstration module [7]. Future R&D activities within the Rock-Star project will focus on further decreasing lateral finger resistance of the FXP direct metallization to make this highly promising concept attractive for H-pattern solar cells with five or more printed busbars.

Summary

Rotary-printing techniques represent a highly promising approach for raising the Si solar cell metallization process to a new level of productivity. A project consortium consisting of several project partners in the fields of automation, machine engineering, material development and research has set itself the ambitious goal, within the framework of the funded Rock-Star joint project, of realizing a demonstrator device with a desired throughput of 6,000–8,000 wafers/h. Development activities within the project focus on two printing technologies: RSP and FXP. The current results show that RSP is capable of realizing the rear-side metallization for Al BSF solar cells with the same quality as that with FSP. Similar results for PERC solar cells have not yet been demonstrated, but can be expected. Using RSP for the front-side metallization of Al BSF or PERC solar cells still represents a challenge and requires further optimization of paste rheology and cylinder screens.

> "Future R&D will focus on optimizing the FXP and RSP processes for the front-side metallization of Al BSF and PERC solar cells with five or more busbars."

As regards FXP, the proof of concept has been successfully shown in a multitude of experiments since 2012. With FXP it is possible to realize either a fine-line seed-layer metallization for subsequent reinforcement by LIP, or a direct metallization without LIP. The first approach is highly applicable to the front-side metallization of H-pattern solar cells, and has the benefit of reducing silver consumption per cell by up to 85% compared with FSP. The second approach, direct metallization, is currently limited by the achievable lateral finger resistance, but already works well for the front-side metallization of busbarless solar cells with multiwire interconnection. Future R&D within the Rock-Star project will focus on optimizing the FXP and RSP processes for the front-side metallization of Al BSF and PERC solar cells with five or more busbars.

Acknowledgements
This work was partly supported by the German Federal Ministry of Education and Research (BMBF) within the Photonics Research Germany funding programme under Contract No. 13N13512 (Rock-Star). The authors further thank Gallus Ferd. Ruesch AG, Somont GmbH, Meyer Burger AG, ContiTech Elastomer-Beschichtungen GmbH and DFTA-TZ Stuttgart for the support of this work.

References
[1] ASYS Group 2016, "Metallization lines" [http://www.asys.de/agweb/en/products-solutions/01_metallization/].
[2] Safir, Y. 1990, "Bifacial solar cell", US Patent US5665175A.
[3] Kipphan, H. (Ed.) 2001, *Handbook of Print Media*. Berlin: Springer.
[4] Frey, M. et al. 2011, "Front-side metalization by means of flexographic printing", *Energy Procedia*, Vol. 8, pp. 581–586.
[5] Thibert, S. et al. 2013, "Flexographic process for front side metallization of silicon solar cells", *Proc. 28th EU PVSEC*, Paris, France, pp. 1013–1016.
[6] Lorenz, A. et al. 2014, "Developing a high throughput printing technology for silicon solar cell front side metallisation using flexography", *J. Print Media Technol. Res.*, Vol. 4, pp. 227–240 (doi:10.14622/JPMTR-1408).
[7] Lorenz, A. et al. 2016, "Flexographic printing – Towards an advanced front side metallization approach with high throughput and low silver consumption", *Sol. Energy Mater. Sol. Cells*, Vol. 157, pp. 550–557 (doi:10.1016/j.solmat.2016.07.025).
[8] ASYS Group 2015, "Rock-Star joint project", Press release [http://www.asys.de/agweb/images/aktuelles/Pressemitteilung/2015/12_Rockstar/2015_10_02_press_release_RockStar.pdf].
[9] Lorenz, A. et al. 2016, "Flexo-printed busbarless solar cells for multi-wire interconnection", *Energy Procedia*, Vol. 98, pp. 46–60 (doi:10.1016/j.egypro.2016.10.080).
[10] Kipphan, H. (Ed.) 2000, *Handbuch der Printmedien: Technologien und Produktionsverfahren*. Heidelberg: Springer.
[11] Gallus Ferd. Rüesch AG 2016,

Cell Processing

"Technical specification Gallus RCS 430" [http://www.gallus-group.com/en/labelprinting/products/gallus-rcs-330-430].

[12] Hahne, P. 2000, "Innovative Druck- und Metallisierungsverfahren für die Solarzellentechnologie", Dissertation, FernUniversität, Hagen, Germany.

[13] Pospischil, M. 2016, "A parallel dispensing system for an improved front surface metallization of silicon solar cells", Dissertation, Albert-Ludwigs-Universität, Freiburg, Germany.

[14] Flexographic Technical Association 2013, *Flexography: Principles and Practices 6.0*, 6th edn.

[15] Deganello, D. et al. 2010, "Patterning of micro-scale conductive networks using reel-to-reel flexographic printing", *Thin Solid Films*, Vol. 518, pp. 6113–6116 (doi:10.1016/j.tsf.2010.05.125).

[16] Deganello, D. et al. 2012, "Impact of metered ink volume on reel-to-reel flexographic printed conductive networks for enhanced thin film conductivity", *Thin Solid Films*, Vol. 520, pp. 2233–2237 (doi:10.1016/j.tsf.2011.08.050).

[17] Krebs, F.C., Fyenbo, J. & Jørgensen, M. 2010, "Product integration of compact roll-to-roll processed polymer solar cell modules: Methods and manufacture using flexographic printing, slot-die coating and rotary screen printing", *J. Mater. Chem.*, Vol. 20, pp. 8994–9001 (doi:10.1039/c0jm01178a).

[18] Wang, Z. et al. 2014, "Development of MnO_2 cathode inks for flexographically printed rechargeable zinc-based battery", *J. Power Sources*, Vol. 268, pp. 246–254 (doi:10.1016/j.jpowsour.2014.06.032).

[19] Kwak, M.K. et al. 2010, "Fabrication of conductive metal lines by plate-to-roll pattern transfer utilizing edge dewetting and flexographic printing", *J. Colloid Interface Sci.*, Vol. 343, pp. 301–305 (doi:10.1016/j.jcis.2009.11.003).

[20] Gallus Ferd. Rüesch AG 2015, Technische Daten Maschinensystem Gallus EM 280.

[21] del Alamo, J., Eguren, J. & Luque, A. 1981, "Operating limits of Al-alloyed high-low junctions for BSF solar cells", *Solid-State Electron.*, Vol. 24, pp. 415–420 (doi:10.1016/0038-1101(81)90038-1).

[22] Aijuan, G. et al. 2009, "Effect of the back surface topography on the efficiency in silicon solar cells", *J. Semicond.*, Vol. 30, p. 74003 (doi:10.1088/1674-4926/30/7/074003).

[23] Kaminski, A. et al. 2002, "Aluminium BSF in silicon solar cells", *Sol. Energy Mater. Sol. Cells*, Vol. 72, pp. 373–379 (doi:10.1016/S0927-0248(01)00185-4).

[24] Seith, W. 1955, *Diffusion in Metallen: Platzwechselreaktionen*. Berlin, Heidelberg: Springer.

[25] Thibert, S. et al. 2012, "Silver ink experiments for silicon solar cell metallization by flexographic process", *Proc. 38th IEEE PVSC*, Austin, Texas, USA, pp. 2266–2270.

[26] Lorenz, A. et al. 2015, "Comprehensive comparison of different fine line printing technologies addressing the seed and plate approach with Ni-Cu-plating", *Proc. 30th EU PVSEC*, Kyoto, Japan, pp. 732–736.

[27] Lorenz, A. et al. 2016, "Progress with rotational printing for the front side metallization of silicon solar cells", *Proc. 32nd EU PVSEC*, Munich, Germany, pp. 413–419.

[28] Meyer Burger AG 2014, "SmartWire Connection Technology" [https://www.meyerburger.com/user_upload/dashboard_news_bundle/376409e022f7d2ae6f6e29318f8055410774c7fd.pdf].

About the Authors

Andreas Lorenz studied printing technology at the University of Printing and Media in Stuttgart, Germany, and received his diploma degree in 2006 for his work at manroland AG on printed electronics applications using flexography. From 2007 to 2012 he worked as a junior product manager at manroland AG before joining Fraunhofer ISE as a Ph.D. student in 2012, where his focus is on the front- and rear-side metallization of Si solar cells using high-throughput rotary-printing techniques.

Anna Münzer studied physics at the Eberhard Karls University of Tübingen, Germany, where she completed her bachelor's in 2015. She then began studies for a master's in renewable energy engineering and management in Freiburg, Germany, and joined Fraunhofer ISE in 2016, initially as an intern and later as a research assistant. Her research activities focus on rotary-printing technologies for Si solar cell metallization.

Thomas Ott received his diploma degree in mechatronics engineering from the University of Applied Sciences Ulm, Germany. From 2009 to 2015 he was with the Ulm University of Applied Sciences, where his work focused on the long-term stability of CIGS thin-film solar cells. Since 2016 he has been with ASYS Automatisierungssysteme GmbH, Dornstadt, Germany, in the department of solar processes and applications.

Florian Clement is head of the MWT solar cells/printing technology group. He studied physics at the Ludwig Maximilian University of Munich and the University of Freiburg, and obtained his diploma degree in 2005. He was subsequently awarded a Ph.D. by the University of Freiburg in 2009. His research focuses 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.

Enquiries

Andreas Lorenz
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstraße 2
79110 Freiburg, Germany

Tel: +49 (0)761 4588 5299
Email: andreas.lorenz@ise.fraunhofer.de

High-efficiency solar cells on n-type HP mc-Si

Jan Benick, **Florian Schindler**, **Stephan Riepe**, **Patricia Krenckel**, **Armin Richter**, **Ralph Müller**, **Hubert Hauser**, **Frank Feldmann**, **Bernhard Michl**, **Martin C. Schubert**, **Martin Hermle**, **Andreas Bett** & **Stefan W. Glunz**, Fraunhofer ISE, Freiburg, Germany

ABSTRACT

N-type high-performance multicrystalline silicon (HP mc-Si) has proved to have an excellent material quality. This paper presents details of the growth of HP mc-Si, as well as the properties of this material and its use in the fabrication of high-efficiency solar cells. The electrical material quality (charge-carrier lifetime) of mc-Si can be significantly improved by replacing the standard crystallization process with a seed-assisted growth for the crystallization of HP mc-Si. However, judging by the material quality for the application to high-efficiency solar cells, not only is the charge-carrier lifetime of crucial importance for the efficiency potential, but also other material properties, such as the base resistivity, are significant. Applying the optimal mc material, an analysis based on device simulation reveals an efficiency potential of the order of 22.4%. Finally, the results are shown for n-type HP mc-Si solar cells with a diffused boron front emitter and a full-area passivating rear contact (TOPCon). A certified efficiency of 21.9% is demonstrated, which represents the highest efficiency reported so far for multicrystalline silicon solar cells.

Introduction

Increasing solar cell efficiency is a powerful lever for further cost reductions in photovoltaics. For industrial-type screen-printed p-type solar cells on monocrystalline silicon, efficiencies of up to 22.6% have so far been reported [1], whereas for a comparably processed p-type solar cell on multicrystalline silicon (mc-Si), the highest certified efficiencies reported to date are 21.3% [2] and 21.6% [3]. Even so, p-type mc-Si accounts for ~70% of global solar cell production [4]. Although mc-Si suffers from a higher carrier recombination caused by structural defects and a higher concentration of impurities, the simpler crystallization process used offers a cost advantage potential over monocrystalline silicon.

The highest efficiencies for silicon solar cells so far, however, have been achieved with n-type silicon, with a record efficiency of 26.7% being reported for an interdigitated back-contact (IBC) solar cell [5]. The high material quality of n-type silicon is mainly due to its relative tolerance to common impurities (e.g. Fe), resulting in higher minority-carrier diffusion lengths compared with p-type substrates with a similar impurity concentration [6]. With advances in crystallization techniques, such as seed-assisted growth for the fabrication of high-performance multicrystalline silicon (HP mc-Si) [7], the material quality of mc-Si wafers has significantly increased in recent years, mainly because of a reduced density of recombination-active dislocation clusters.

The HP mc-Si process, combined with the above-mentioned benefits of n-type silicon, might therefore offer opportunities for a low-cost, high-efficiency silicon material which has the potential to reduce the efficiency gap with monocrystalline silicon [8]. This paper describes the fabrication process for a high-efficiency solar cell with a passivating rear-side contact (TOPCon [9]) on high-quality n-type HP mc-Si.

> “The development of HP mc-Si has made it possible to significantly improve the material quality of mc-Si.”

Material development

The crystallization of n-type mc-Si at Fraunhofer ISE started several years ago with the crystallization of standard n-type mc-Si. A comparison of that material with p-type mc-Si from a comparable crystallization process revealed an advantage of n-type doped mc-Si as a result of its lower sensitivity to typical metal impurities [10]. The development of HP mc-Si [7] has made it possible to significantly improve the material quality of mc-Si. With the use of granular silicon as seed material placed on the bottom of the crucible, a homogeneous and small-grained crystal structure was developed for the laboratory ingots of G2 size, equivalent to 75kg of silicon (Fig. 1). This led to a massive reduction in dislocation density and thus to an improvement in minority-carrier lifetime in the wafers.

In 2015 n-type HP mc-Si crystallized

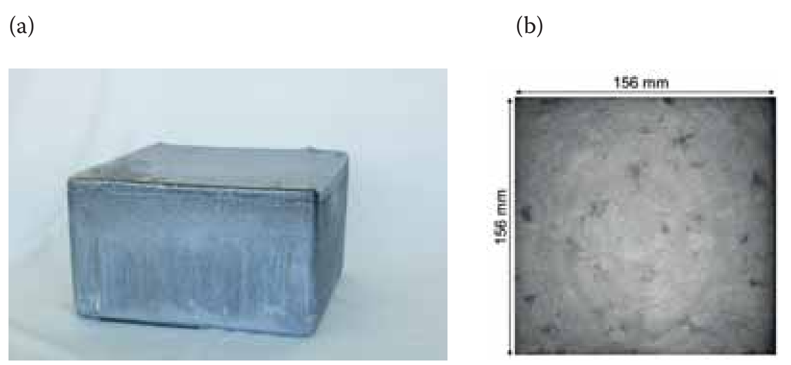


Figure 1. (a) An n-type HP mc-Si ingot of G2 size. (b) Photoluminescence image of a wafer from a centre brick in the upper third of an HP mc-Si ingot.

at Fraunhofer ISE was demonstrated to be a suitable base material for high-efficiency solar cells, with the achievement of an efficiency of 19.6% from an n-type mc-Si solar cell featuring a passivating rear-side contact (TOPCon [9]) and an isotextured front surface [8]. The crystallization process for HP mc-Si was recently further optimized by the use of high-purity crucibles and improved thermal processes, and the base resistivity was adapted in order to be optimally suited to the TOPCon cell concept.

Analysis of material potential

To demonstrate the improvement in the material quality of n-type mc-Si crystallized at Fraunhofer ISE, a thorough efficiency analysis of three materials was performed: 1) standard n-type mc-Si; 2) n-type HP mc-Si; and 3) optimized n-type HP mc-Si. For the investigation of the material quality, lifetime samples were processed by applying the high-temperature steps of the utilized solar cell process sequence, including a boron diffusion at 890°C and an annealing step at 800°C (both for 1h). Thus, it was ensured that the material quality of the lifetime samples corresponded to the material quality of the final solar cells.

To ensure an injection-independent surface passivation, the samples were passivated with SiN_x films.

Images of the bulk minority-charge carrier lifetime were obtained by injection-dependent photoluminescence (PL) imaging, calibrated by modulated PL [11]. A combination of these images with a PC1D [12,13] simulation of the TOPCon cell enables a prediction of the material's efficiency potential by an efficiency-limiting bulk recombination analysis (ELBA) [14], as well as allowing a detailed loss analysis, as suggested in Schindler et al. [15]. Further information about the procedure and the simulation parameters, as well as details about an investigation of the impact of the base resistivity, can be found in Schindler et al. [16].

Fig. 2(a) shows predictions of the spatially resolved efficiency potential of the three materials. The corresponding material-related efficiency losses with regard to the simulated device limit (no Shockley-Read-Hall (SRH) material limitations) of 23.1% are illustrated in Fig. 2(b). The largest losses of ~2.4%$_{abs.}$ occur in the n-type mc-Si created from a standard crystallization process: these losses can be separated into inner grain losses (~1%$_{abs.}$, orange part of the left bar in Fig. 2(b)), and losses due to recombination-active structural crystal defects (~1.4%$_{abs.}$, grey meshed part of the left bar in Fig. 2(b)). Consequently, the efficiency of a TOPCon solar cell based on this material would be limited to approximately 20.7%.

The HP mc-Si crystallization process suppresses the creation of highly recombination-active dislocation clusters, while the use of a high-purity crucible reduces the inner grain losses due to homogeneously distributed impurities. A significant reduction in efficiency losses is therefore observed for the second material: the n-type HP mc-Si features inner grain losses of ~0.3%$_{abs.}$, and losses of ~0.7%$_{abs.}$ due to recombination-active structural crystal defects, which sum up to total efficiency losses of ~1%$_{abs.}$ (see centre column in Fig. 2).

Finally, by optimizing the HP mc-Si crystallization process it is possible to decrease the area fraction of grain boundaries and consequently reduce the losses due to recombination-active structural crystal defects. In combination with an adaptation of the base resistivity, the total losses could be reduced to ~0.7%$_{abs.}$ for the optimized n-type HP mc-Si, which would allow efficiencies of the order of 22.4% (see right column in Fig. 2) with the TOPCon cell concept.

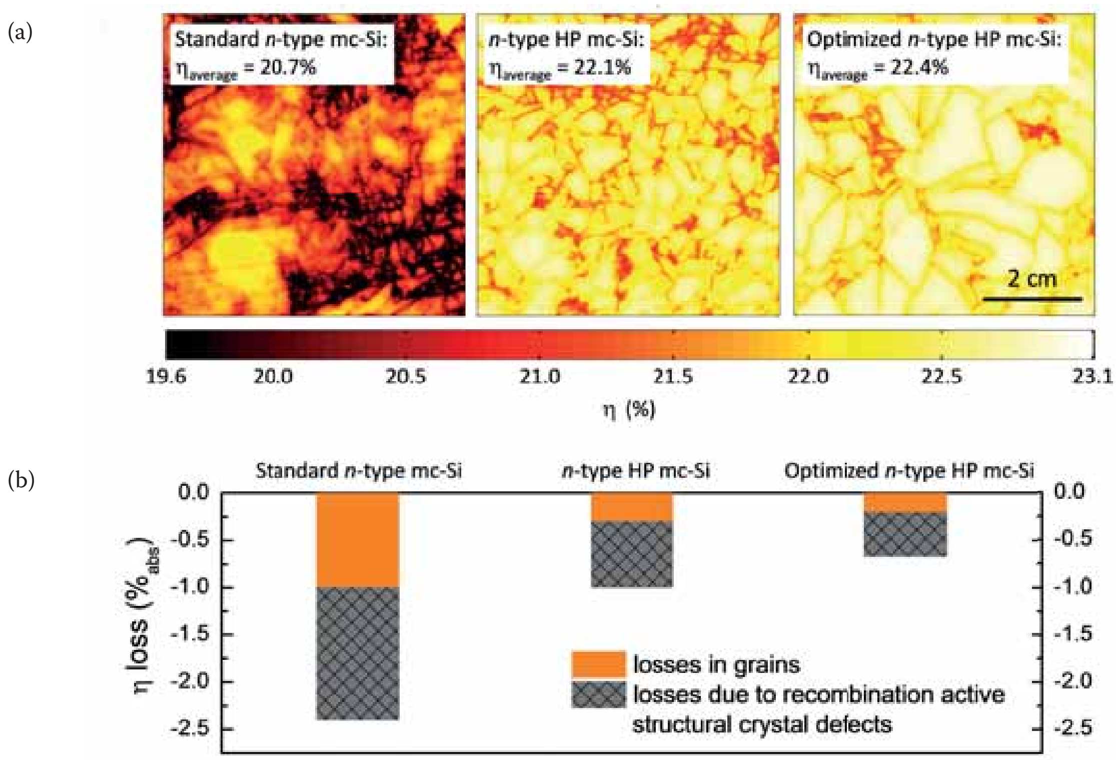


Figure 2. (a) ELBA prediction of the spatially resolved efficiency potential for the three different n-type mc-Si materials – standard, high-performance and optimized high-performance crystallization process; (b) corresponding solar cell efficiency losses.

It should be noted that the gain in efficiency potential for the optimized n-type HP mc-Si material was partly achieved by the correct choice of base resistivity. Fig. 3 shows a simulation of the efficiency as a function of base resistivity for two different materials, for the TOPCon cell concept described above. A defect-free material is limited by Auger recombination at low resistivities, and features an increasing efficiency with increasing base resistivity (orange dashed curve in the lower graph of Fig. 3). In contrast, a material with an injection-independent background lifetime of 1ms is also limited by Auger recombination for very low resistivities, but the efficiency reaches a maximum at a base resistivity of ~0.45Ω·cm, before it decreases again for higher resistivities.

The decrease at high resistivities is attributed to fill factor losses, as illustrated by the black solid line in the upper graph of Fig. 3, which shows the normalized cell parameters for the defect-limited material as a function of resistivity. The fill factor losses towards high resistivities are not a series-resistance effect, but rather a recombination effect which influences V_{mpp} and also leads to losses in the pseudo fill factor. The decrease towards lower resistivities is attributed to J_{sc} limitations caused by Auger recombination (black dotted line in the upper graph of Fig. 3). For n-type HP mc-Si, the correct choice of base resistivity is therefore of the utmost importance for fabricating highly efficient solar cells.

> "For n-type HP mc-Si, the correct choice of base resistivity is of the utmost importance for fabricating highly efficient solar cells."

Surface texture

To suppress surface reflection of incident light, and thus maximize the current of a solar cell, specific structures have to be applied to the solar cell front side. These structures typically consist of a surface texture in combination with an anti-reflection coating. For monocrystalline silicon, the surface texture consists of small pyramids, which can be realized by anisotropic etching in alkaline solutions. When this texturing is used in combination with an anti-reflection coating, the weighted reflectance of such a surface can be as low as 2%.

In the case of mc-Si, however, the application of a pyramidal surface texture is not possible, because of the varying crystal orientations of the different grains; thus acidic solutions are used for the surface texturing of mc-Si solar cells in industrial production. Unfortunately, the quality of this type of surface texture does not match the excellent optical and electrical quality of pyramidal textures. Alternative technologies exist, however, which enable the creation of textures with a performance comparable to that of a pyramidal texture on mc-Si; two examples are the honeycomb texture [17,18] and black silicon [19,20].

The honeycomb texture (based on photolithography) has already been applied to the multicrystalline record solar cell (20.4% efficiency) presented by Schultz et al. in 2004 [17]. The other approach, which was also used for creating the surface texture of the high-efficiency HP mc-Si solar cells in this work, is based on black silicon; the nanostructured black-silicon surface enables an almost perfect suppression of the surface reflection, with values of less than 1% for the weighted reflectance. In the past, the surface passivation of this nanostructured surface with very steep needles ('silicon grass') was an issue, but this could fortunately be resolved by the introduction of deposited Al_2O_3 layers (atomic layer deposition: ALD), which yield a very conformal coating even on black-silicon-textured surfaces [21–24].

For the creation of black-silicon textures, typically reactive ion-etched (RIE) processes are utilized. In this study, however, an inductively coupled plasma (ICP) process with a very low bias voltage (as proposed in Hirsch et al. [25]) was employed in order to keep the surface damage due to the plasma etching as low as possible. With the ICP process, a separate damage etch prior to surface passivation is not necessary. An SEM micrograph of the surface texture realized by the ICP process is shown in Fig. 4: it can be seen that the texture does not feature the very steep needles typical of a classic black-silicon texture. The height of the texture is less than 1µm, and the aspect ratio is around 2.

The corresponding reflectance measurements for assessing the optical quality of this surface texture are shown in Fig. 5. With just the surface texture, i.e. without the anti-reflection coating, the surface reflection is already quite low. When the measured reflectance is weighted with the sun spectrum (AM1.5g, 280–1,000nm), the total reflectance is of the order of 2.5%.

To further reduce the surface reflection, an anti-reflection coating can be added. In the current study a layer stack consisting of Al_2O_3 (ALD) and SiN_x (plasma-enhanced chemical vapour deposition: PECVD) was applied. As can be seen in Fig. 5, the application of this anti-reflection coating further reduces the surface reflection, and values of ~1% for the weighted reflectance can be achieved. The optical performance of the applied plasma texture is therefore comparable to that of a classic black-silicon texture.

In addition to an excellent optical performance, the front-side texture needs to demonstrate a high electrical quality (low surface recombination) as well as being compatible with subsequent processing steps, such as emitter diffusion and surface passivation. The results of the tests of emitter diffusion (90Ω/sq., BBr_3 tube diffusion) and surface passivation by Al_2O_3 (ALD) showed that the performance of the ICP black-silicon texture compared quite well with that of a pyramidal texture as applied to monocrystalline silicon, with values for the recombination pre-factor J_{0e} of the order of 50fA/cm^2.

Solar cells

On the basis of the excellent results obtained in respect of the material quality of n-type HP mc-Si, as well as the facility to implement all necessary process steps, high-efficiency solar cells were fabricated from the multicrystalline n-type silicon. The schematic of the solar cell is shown in Fig. 6: the features of the applied cell design (as discussed above) are an ICP black-silicon surface texture, a BBr_3-diffused front-side emitter (90Ω/sq.) passivated by an Al_2O_3/SiN_x (ALD/PECVD) layer stack, and photolithographically defined and evaporated front contacts. The solar cell rear side incorporates a passivating contact consisting of a wet-chemically grown thin tunnel oxide covered by a PECVD-deposited a-SiC_x:P layer (TOPCon [9]) with a full-area Ag metallization.

A photograph of a final high-efficiency solar cell fabricated on n-type HP mc-Si is shown in Fig. 7. Within the active cell area with the black-silicon texture, the grain structure of the multicrystalline silicon can no longer be seen – the cell area appears perfectly black. In the spaces between the active solar cells, however, the small grains of the HP mc-Si are clearly visible.

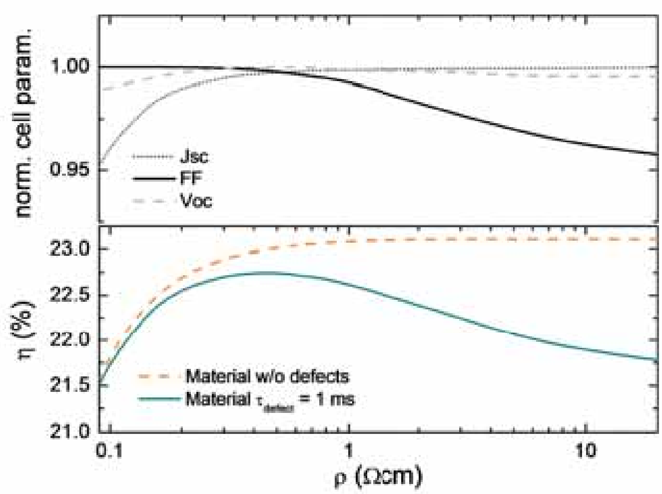


Figure 3. Impact of base resistivity on solar cell performance. The lower graph shows the conversion efficiency for a solar cell with a perfect material quality, as well as for a cell with a limited lifetime (injection-independent background lifetime of 1ms). The upper graph shows the normalized *I–V* parameters of the cell with the limited lifetime.

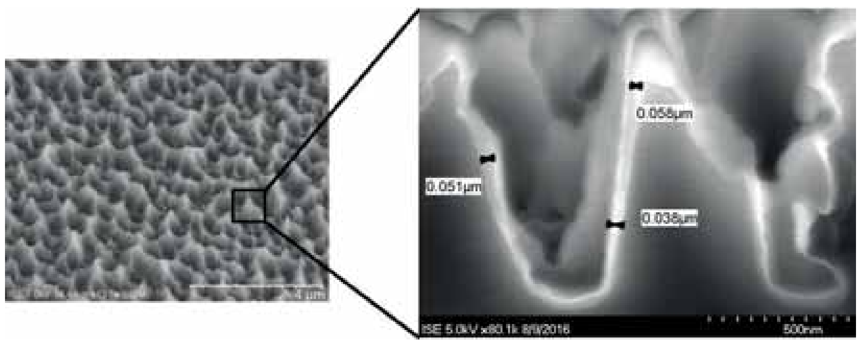


Figure 4. SEM micrograph of the front-side plasma texture (black silicon) on the n-type HP mc-Si. The micrograph on the right shows an enlargement of the surface texture with the Al_2O_3/SiN_x anti-reflection coating.

A summary of the corresponding $I–V$ parameters measured for the best solar cells is shown in Table 1. In addition to the n-type HP mc-Si solar cells with a black-silicon texture, the table also includes the results for cells of the same material with a planar surface, as well as for reference solar cells made of n-type float-zone (FZ) silicon. It can be seen that the FZ reference solar cells delivered a high conversion efficiency of 23.3%, which is close to the maximum achievable using the applied technology (23.6%, based on device simulation [26]). This indicates that almost the full potential of the applied cell structure was exploited.

> "The resulting conversion efficiency of the black-silicon-textured cells was 21.9%, which is the current world-record efficiency for a multicrystalline silicon solar cell."

In the case of the multicrystalline solar cells with the black-silicon texture, a high open-circuit voltage V_{oc} of 672.6mV, a high short-circuit current density J_{sc} of 40.8mA/cm^2, and a fill factor FF of 79.7% were obtained. The resulting conversion efficiency of the black-silicon-textured cells was 21.9%, which is the current world-record efficiency for a multicrystalline silicon solar cell.

A comparison of the multicrystalline solar cells with the black-silicon texture and with the planar front side reveals a small difference in V_{oc} of 3.5mV (676.1mV was measured for the planar solar cells). This difference represents an additional J_{0e} resulting from the surface texture of 20fA/cm^2, which is exactly what would have been expected on the basis of lifetime test samples, and confirms that the passivation of the black-silicon texture by the Al_2O_3/SiN_x layer stack was effective. The comparable FF values for the planar and textured solar cells show that the surface texture did not have any detrimental effect on the front-side metallization. However, as can be seen from the FZ reference, the applied structure allows higher values for FF and pFF. As the pFF does not rely on series-resistance effects, and because the parallel resistance is sufficiently high (>4kΩ·cm^2), the relatively low FF is most likely directly related either to the quality of the base material (e.g. recombination at the maximum power point (mpp)), or to effects connected with the multicrystalline nature of the material.

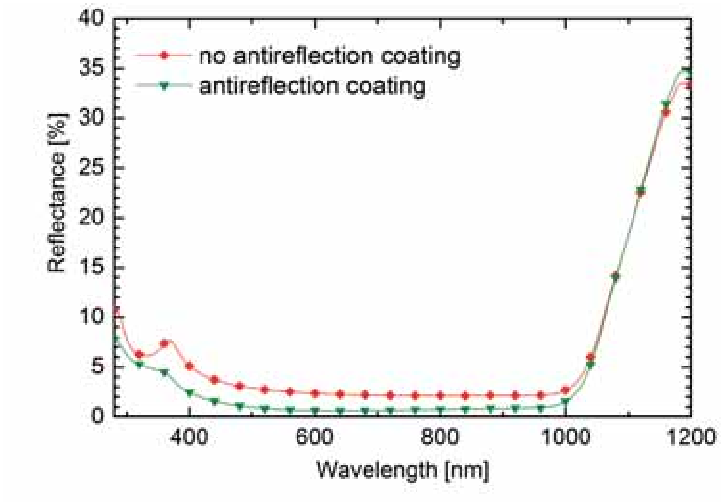


Figure 5. Measured reflectance of the black-silicon-like plasma texture without and with an Al_2O_3/SiN_x anti-reflection coating.

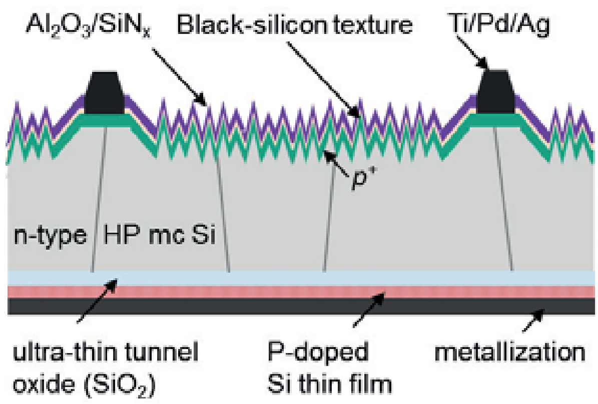


Figure 6. Schematic of the n-type HP mc-Si solar cell on multicrystalline silicon.

The high J_{sc} (40.8mA/cm^2) for the black-silicon texture indicates an effective reduction in the surface reflection. This reduction can be also seen in the reflectance curves shown in Fig. 8: the measured surface reflectance of the black-silicon cells (especially in the short-wavelength range) is even lower than the reflectance of the FZ reference solar cells with a pyramidal surface texture. As can be seen by the reflection in the long wavelength range, similar light trapping can be observed for both front-side structures. Nevertheless, the J_{sc} measured for the multicrystalline solar cells is less than the value for the FZ reference solar cells; this can be attributed to losses in the long wavelength range (see IQE curve in Fig. 8). As both cells feature the same rear-side structure (passivating contacts, TOPCon), this difference is also most likely related to the base material.

Conclusion and outlook

In the study reported in this paper it was demonstrated that n-type HP mc-Si is well suited to the fabrication of high-efficiency solar cells. The transition from standard mc-Si to an improved crystal structure with a low impurity concentration could reduce the material-related efficiency losses to about 0.5%$_{abs.}$ when the ideal base resistivity is utilized. On the assumption of a high-efficiency cell structure with passivating contacts (e.g. TOPCon), an efficiency potential well above 22% for the multicrystalline silicon is possible. When an adapted TOPCon cell fabrication process with a black-silicon front-surface texture and a 90Ω/sq. Al_2O_3-passivated boron emitter

	V_{oc} [mV]	J_{sc} [mA/cm2]	*FF* [%]	*pFF* [%]	η [%]
N-type FZ Si, random pyramids	683.9	41.5	82.2	84.1	23.3
N-type HP mc Si, planar surface	676.1	37.3	79.5	81.7	20.1
N-type HP mc Si, black-silicon texture	672.6	40.8	79.7	81.6	21.9*

*Certified measurement by Fraunhofer ISE CalLab (4cm^2 aperture area).

Table 1. Measured *I–V* parameters (AM1.5g, 100mW/cm^2, 25°C) of the best FZ and HP mc-Si solar cells of each group (FZ – random pyramidal texture; HP mc-Si – planar surface or black-silicon-textured surface).

was employed, a record efficiency of 21.9% was achieved for the n-type HP mc-Si solar cells.

> "The implementation of an optimized technology is expected to bridge a significant portion of the efficiency gap with monocrystalline silicon."

In future work the limitations of the multicrystalline silicon in combination with the processing steps needed for cell fabrication will be investigated in more detail in order to derive optimization strategies. The implementation of an optimized technology is expected to bridge a significant portion of the efficiency gap with monocrystalline silicon, thus raising the cost advantage potential of multicrystalline silicon.

Acknowledgements

The authors would like to thank F. Haas, P. Häuber, A. Leimenstoll, F. Schätzle, S. Seitz, A. Seiler, C. Harmel, R. van der Vossen and E. Schäffer for their support with the cell processing and measurements. The authors also would like to acknowledge Wacker Polysilicon for the silicon materials and fruitful discussions. This project was funded by the German Federal Ministry for Economic Affairs and Energy under Contract No. 0324034 (multiTOP).

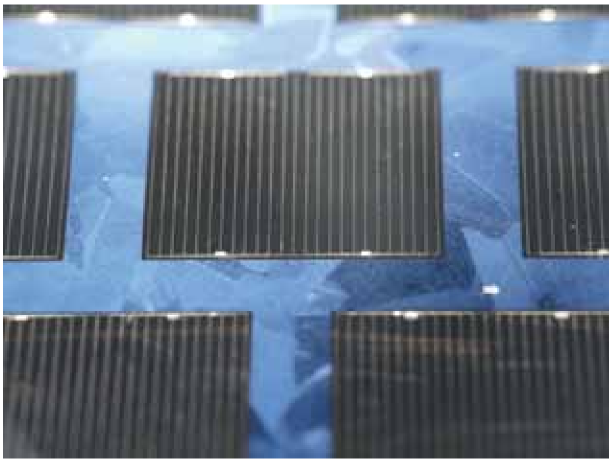


Figure 7. Photograph of the final high-efficiency n-type HP mc-Si solar cell.

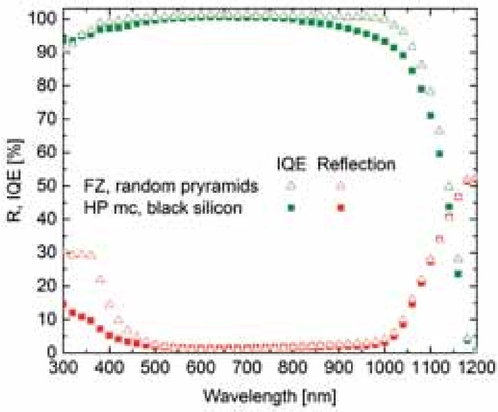


Figure 8. Measured internal quantum efficiency (IQE) and reflection curves for the n-type HP mc-Si solar cell featuring a black-silicon surface texture, and for the n-type FZ reference solar cell with a random pyramidal texture.

References

[1] Trina Solar 2016, "Trina Solar announces new efficiency record of 22.61% for mono-crystalline silicon PERC cell", Press release [http://phx.corporate-ir.net/phoenix.zhtml?c=206405&p=irol-newsArticle&ID=2230468].

[2] Deng, W. et al. 2016, "Development of high-efficiency industrial p-type multi-crystalline PERC solar cells with efficiency greater than 21%", *Energy Procedia*, Vol. 92, pp. 721–729.

[3] Zheng, P. et al. 2017, "21.63% industrial screen-printed multicrystalline Si solar cell", *physica status solidi (RRL)*, Vol. 11, No. 3.

[4] Fraunhofer ISE, "Renewable energy data", Report [https://www.ise.fraunhofer.de/de/daten-zu-erneuerbaren-energien.html].

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

[6] Macdonald, D. & Geerligs, L.J. 2004, "Recombination activity of interstitial iron and other transition metal point defects in p-and n-type crystalline silicon", *Appl. Phys. Lett.*, Vol. 85, No. 18, pp. 4061–4063.

[7] Yang, Y.M. et al. 2015, "Development of high-performance multicrystalline

silicon for photovoltaic industry", *Prog. Photovolt: Res. Appl.*, Vol. 23, No. 3, pp. 340–351.

[8] Schindler, F. et al. 2015, "High-efficiency multicrystalline silicon solar cells: Potential of n-type doping", *IEEE J. Photovolt.*, Vol. 5, No. 6, pp. 1571–1579.

[9] Feldmann, F. et al. 2014, "Passivated rear contacts for high-efficiency n-type Si solar cells providing high interface passivation quality and excellent transport characteristics", *Sol. Energy Mater. Sol. Cells*, Vol. 120, pp. 270–274.

[10] Schindler, F. et al. 2015, "Potential gain in multicrystalline silicon solar cell efficiency by n-type doping", *IEEE J. Photovolt.*, Vol. 5, No. 2, pp. 499–506.

[11] Giesecke, J.A. et al. 2011, "Minority carrier lifetime imaging of silicon wafers calibrated by quasi-steady-state photoluminescence", *Sol. Energy Mater. Sol. Cells*, Vol. 95, No. 3, pp. 1011–1018.

[12] Clugston, D.A. & Basore, P.A. 1997, "PC1D version 5: 32-bit solar cell modeling on personal computers", *Proc. 26th IEEE PVSC*, Anaheim, California, USA, pp. 207–210.

[13] Haug, H. et al. 2015, "PC1Dmod 6.1 – state-of-the-art models in a well-known interface for improved simulation of Si solar cells", *Sol. Energy Mater. Sol. Cells*, Vol. 142, pp. 47–53.

[14] Michl, B. et al. 2012, "Efficiency limiting bulk recombination in multicrystalline silicon solar cells", *Sol. Energy Mater. Sol. Cells*, Vol. 98, pp. 441–447.

[15] Schindler, F. et al. 2014, "Solar cell efficiency losses due to impurities from the crucible in multicrystalline silicon", *IEEE J. Photovolt.*, Vol. 4, No. 1, pp. 122–129.

[16] Schindler, F. et al. 2017, "Optimized multicrystalline silicon for solar cells enabling conversion efficiencies of 22%", *Sol. Energy Mater. Sol. Cells*, Vol. 171, pp. 180–186.

[17] Schultz, O. et al. 2004, "Multicrystalline silicon solar cells exceeding 20% efficiency", *Prog. Photovolt: Res. Appl.*, Vol. 12, No. 7, pp. 553–558.

[18] Hauser, H. et al. 2012, "Honeycomb texturing of silicon via nanoimprint lithography for solar cell applications", *IEEE J. Photovolt.*, Vol. 2, No. 2, pp. 114–122.

[19] Oh, J. et al. 2012, "An 18.2%-efficient black-silicon solar cell achieved through control of carrier recombination in nanostructures", *Nature Nanotech.*, Vol. 7, No. 11, pp. 743–748.

[20] Repo, P. et al. 2013, "N-type black silicon solar cells", *Energy Procedia*, Vol. 38, pp. 866–871.

[21] Algasinger, M. et al. 2013, "Improved black silicon for photovoltaic applications", *Adv. Energy Mater.*, Vol. 3, No. 8, pp. 1068–1074.

[22] Repo, P. et al. 2013, "Effective passivation of black silicon surfaces by atomic layer deposition", *IEEE J. Photovolt.*, Vol. 3, No. 1, pp. 90–94.

[23] Repo, P. et al. 2013, "Passivation of black silicon boron emitters with atomic layer deposited aluminum oxide", *physica status solidi (RRL)*, Vol. 7, No. 11, pp. 950–954.

[24] Otto, M. et al. 2012, "Extremely low surface recombination velocities in black silicon passivated by atomic layer deposition", *Appl. Phys. Lett.*, Vol. 100, No. 19, p. 191603.

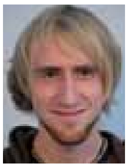
[25] Hirsch, J. et al. 2016, "Optoelectronic properties of black-silicon generated through inductively coupled plasma (ICP) processing for crystalline silicon

solar cells", *Appl. Surface Sci.*, Vol. 374, pp. 252–256.

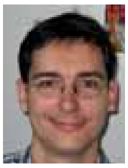
[26] Fell, A. 2013, "A free and fast three-dimensional/two-dimensional solar cell simulator featuring conductive boundary and quasi-neutrality approximations", *IEEE Trans. Electron Dev.*, Vol. 60, No. 2, pp. 733–738.

About the Authors

Jan Benick studied microsystems technology at the University of Freiburg, Germany, and received his Ph.D. from the University of Freiburg/Fraunhofer ISE in 2010. He stayed on as a scientist at Fraunhofer ISE, where he is now head of the group focusing on cleanroom technologies for high-efficiency silicon solar cells.



Florian Schindler received his diploma degree in physics in 2011 from the University of Freiburg, Germany, in collaboration with Fraunhofer ISE. In 2015 he was awarded a Ph.D., again in collaboration with Fraunhofer ISE, by the University of Freiburg. The research for his thesis focused on the electrical material properties and efficiency limits of compensated and multicrystalline silicon. He currently holds a postdoc position in the material and cell analysis group at Fraunhofer ISE.



Stephan Riepe received his Bachelor's from the University of Sydney, Australia, and his diploma degree in physics from the University of Freiburg, Germany, in 1999 and 2001 respectively. He then joined Fraunhofer ISE, working on silicon characterization. Since receiving his Ph.D. from the University of Konstanz, Germany, in 2008 for his work on efficiency-limiting defects in multicrystalline silicon, he has been head of the crystallization and wafering research group at Fraunhofer ISE.

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

Armin Richter received a Ph.D. in physics in 2014 for his work on the development of n-type silicon solar cells and an in-depth characterization of Al2O3-based silicon surface passivation. His research interests include atomic layer deposition for PV applications, a fundamental understanding of surface passivation, and the development of high-efficiency silicon solar cells along the entire process chain.

Ralph Müller received his Masters's in microsystems engineering in 2011 from the University of Freiburg, Germany, in collaboration with Fraunhofer ISE. In 2016 he obtained his Ph.D. from the University of Freiburg, with a thesis topic of ion implantation for high-efficiency silicon solar cells. He is currently a postdoctoral researcher at Fraunhofer ISE.

Hubert Hauser studied microsystems engineering at the University of Freiburg, Germany, and received his Ph.D. from the University of Freiburg in 2013. His thesis concerned the development of nanoimprint lithography processes for PV applications. Since his graduation he has been working as a scientist in the micro- and nanostructured surfaces group at Fraunhofer ISE.

Frank Feldmann holds a Master's and a Ph.D. in electrical engineering from RWTH Aachen and the Albert Ludwig University of Freiburg respectively. In 2016 he was awarded the Junior Einstein Award, sponsored by SolarWorld AG, for the development of the TOPCon technology, which enables efficiencies beyond 25%. He is currently a postdoctoral researcher at Fraunhofer ISE.

Bernhard Michl studied physics at the University of Mainz, Germany, and received his diploma degree in 2008. The research for his diploma thesis on series resistance imaging was carried out at Schott Solar, Alzenau, Germany, in conjunction with Fraunhofer ISE. For his Ph.D., he focused on the characterization of mc-Si material and the efficiency limits in high-efficiency mc-Si solar cells. Up until 2017 he has been working as a postdoc in the material and solar cell characterization group at Fraunhofer ISE.

Martin C. Schubert studied physics at the Universities of Montpellier, France, and Freiburg, Germany, and received his Ph.D. in physics in 2008 from the University of Konstanz, Germany. From 2013 to 2014 he was with JAXA and Meiji University, Japan, as a guest professor. He is currently head of the characterization and simulation department at Fraunhofer ISE.

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

Andreas W. Bett received his diploma degree in physics and diploma degree in mathematics from the Albert Ludwig University of Freiburg, Germany, in 1988 and 1989 respectively. In 1992 he was awarded a Ph.D. in physics by the University of Konstanz, Germany. He joined Fraunhofer ISE in 1987, and was appointed director of the institute in 2017.

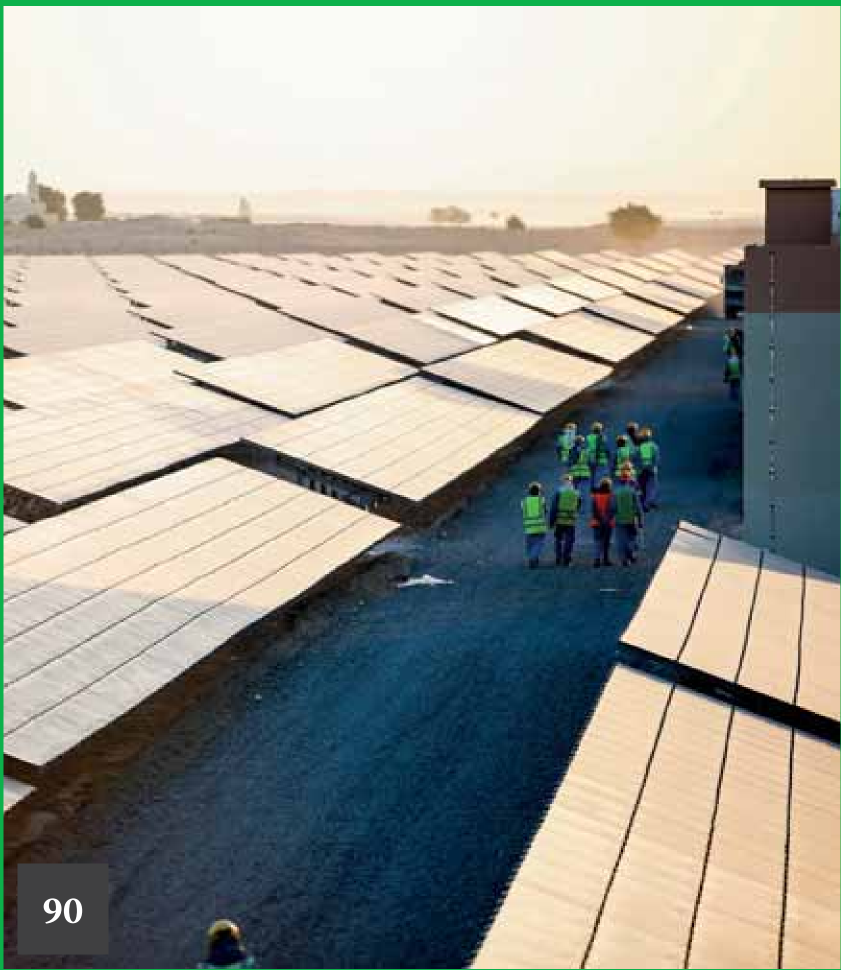
Stefan W. Glunz received his Ph.D. from the University of Freiburg, Germany, in 1995. He is the director of the solar cells development and characterization division at Fraunhofer ISE, and a professor of photovoltaic energy conversion at the Albert Ludwig University of Freiburg. His research interests include the design, fabrication and analysis of high-efficiency solar cells.

Enquiries

Jan Benick
Fraunhofer ISE
Heidenhofstr. 2
Freiburg 79110
Germany

Tel. +00497614588-5020
Email: jan.benick@ise.fraunhofer.de
Website: www.ise.fraunhofer.de

Thin Film



First Solar raises shipments and guidance for 2017


Credit: First Solar

First Solar has raised shipment and revenue guidance for 2017 in anticipation of a strong second half.

Thin-film PV manufacturer First Solar has raised both shipments and revenue expectations for 2017 after reporting net sales of US$623 million in the second quarter of 2017, down from US$892 million in the previous quarter.

In the previous quarter, First Solar had increased sales guidance by US$50 million to a revised range of US$2.85 billion to US$2.95 billion for the full year. In reporting second quarter results, the company increased sales guidance again to a range of US$3.0 billion to US$3.1 billion, setting the company up for a strong second half to the year.

"We executed well in the second quarter with solid non-GAAP earnings of $0.64, record quarterly shipments of nearly 900MW (DC) and bookings of 1.5GW since our last earnings call," said Mark Widmar, CEO of First Solar. "We are encouraged by the continuing strong demand for our Series 4 product and are focused on meeting our customers' current needs. At the same time, our efforts to ensure the manufacturing and market readiness of Series 6 remain our highest priority. With the first Series 6 equipment being installed at our Ohio factory, and an increasing number of mid-to-late stage Series 6 bookings opportunities, we are pleased with our progress thus far."

First Solar also increased full-year module shipments from previous guidance of being in a range of 2.4GW to 2.6GW to a higher range of 2.6GW to 2.7GW. Module shipments in the second quarter were around 900MW. Module shipments in the first quarter of 2017 had been around 400MW.

New technologies

Imec pushes perovskite tandem silicon mini-module to record 23.9% conversion efficiency

Nanoelectronics research centre imec has taken a perovskite/silicon tandem mini-module-on-cell stack to a record 23.9% conversion efficiency, significantly exceeding its 20.2% efficiency figures reported in 2016.

In 2016, imec developed in collaboration with Solliance a semi-transparent perovskite mini-module stacked on top of a high-efficiency interdigitated back-contact (IBC) crystalline silicon solar cell in a four-terminal tandem configuration with an aperture area of 4cm² to produce a 20.2% conversion efficiency.

Several new engineering tricks were used to boost the tandem mini-module to 23.9% conversion efficiencies.

"Two innovations are key to this achievement," said Tom Aernouts, group leader for thin-film photovoltaics at imec and perovskite PV programme manager at Solliance. "First, a different perovskite material (CsFAPbIBr) was used, largely improving the stability and conversion efficiency of the 4cm² semi-transparent perovskite module to 15.3%. Second, the architecture of the stack was optimized for minimal optical losses by adding an anti-reflection texture on top of the module and a refractive index matching liquid between the perovskite module and the Si solar cell."

Imec believes that stacking the perovskite solar cells or modules on top of silicon solar cells is a key route to eventual commercialization of perovskite material options with power conversion efficiencies potentially above 30% with the opportunity to be relatively low cost for tandem cell roadmaps.

Chinese start-up achieves conversion efficiency of 16% for perovskite mini-module

Perovskite materials start-up Hangzhou Microquanta Semiconductor has reported that a perovskite mini-module, certified by testing firm Newport in Montana, US has achieved a new world record of 16% conversion efficiency.

Details of the 16% efficiency of the 16cm² perovskite mini-module were also reported in recent edition of *Progress in Photovoltaics.*

According to Microquanta the perovskite mini-module world record of 16% was achieved only three months after setting a prior record of 15.2%. Progress was made, primarily due to the focus on improving the deposition uniformity for large area thin films.

Dr. Jizhong Yaom CEO of Microquanta said: "Early this year, we improved uniformity for large area thin-film deposition, which is one of the bottlenecks in the field, so we have been able to increase the efficiency of the mini-module from 12.1% to 15.2%. Then, we further improve the result to 16% by optimizing the fabrication processes. This efficiency is approaching the silicon based module in the market."

Progress in Photovoltaics noted Microquanta's certified "initial" efficiencies but highlighted that "the stability of these devices were not investigated but not expected to be good".

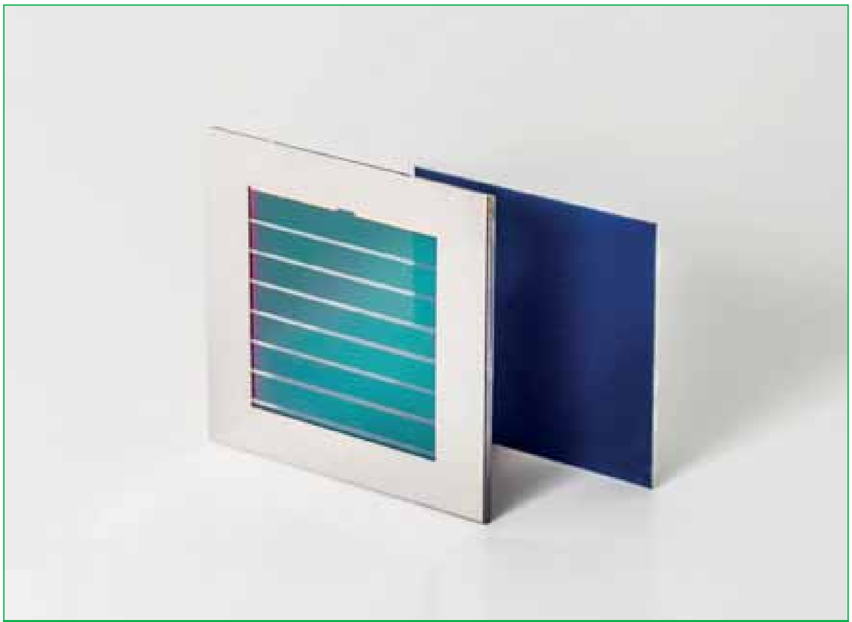
JinkoSolar starts perovskite cell R&D collaboration

JinkoSolar has started a collaboration with Greatcell Solar, formerly Dyesol, and the Nanyang Technology University (NTU) in Singapore focusing on perovskite solar cells.

Greatcell Solar said that the perovskite collaboration was non-exclusive but developmental work would be on a confidential basis.

Late last year, Trina Solar and Wuxi Suntech announced they were collaborating on perovskite solar cells with the Australian Centre for Advanced Photovoltaics (ACAP), based at the University of New South Wales.

Greatcell Solar rival, UK-based Oxford Photovoltaics, has already signed a joint development agreement with an unidentified global manufacturer of solar cells and modules and purchased the former Bosch Solar CIS thin-film



Credit: Imec

Imec has racked up another efficiency milestone with tandem peroviskite/silicon solar technology.

production site in Brandenburg an der Havel, Germany to provide potential customers with batches of tandem cells for evaluation as part of its IP licensing business model.

Under the agreement between JinkoSolar, Greatcell said it would make available developmental perovskite cells for further evaluation.

NanoFlex in consortium developing next-gen thin-film technology with US Army

Next-generation thin-film technology start-up NanoFlex Power is part of a consortium awarded a US$6.5 million contract from the US Army Research Laboratory's Army Research Office to develop high power, flexible and lightweight solar modules for portable power applications.

The consortium consists of NanoFlex, SolAero Technologies, a manufacturer of high-efficiency solar cells, the University of Michigan and the University of Wisconsin.

As part of the programme, NanoFlex and solar cell developer SolAero Technologies will collaborate on incorporating non-destructive epitaxial lift off (ND-ELO) processes and related technologies into SolAero's fabrication process to reduce the production cost of ultra-high efficiency compound semiconductor solar cells. The University of Michigan and the University of Wisconsin are also participating in the four year programme.

Dean Ledger, CEO of NanoFlex said: "Until now, high performance compound semiconductor solar cells have not been available to the Army at reasonable prices. This programme will enable the development and use of TRL-7 flexible solar module prototypes with more than twice current power performance at a competitive price to the Army."

CIGS

Midsummer receives follow-on flexible CIGS equipment order

Sweden-based flexible CIGS thin-film solar cell equipment supplier Midsummer has received a follow-on order from an undisclosed customer.

Midsummer said that it would be supplying a further two of its compact 'DUO' thin-film solar cell manufacturing systems to the customer, due to demand for flexible CIGS modules.

"Our DUO system is now the most widely spread manufacturing tool for flexible CIGS solar cells in the world," said Sven Lindström, CEO, Midsummer AB.

The equipment supplier is expected to ship the systems before the end of 2017.

Centrotherm sharing in tool orders from Manz for China CIGS thin-film lines

PV specialist equipment supplier centrotherm has secured a number of sputtering system tool orders for two turnkey CIGS thin-film facilities being supplied by equipment and automation specialist Manz for JV customers Shanghai Electric Group and Shenhua Group.

Centrotherm said that the tool orders were placed with its subsidiary FHR Anlagenbau and are valued in the lower double-digit euro million range.

Torsten Winkler, general manager of FHR said: "Since our founding in 1991 we have considered ourselves as pioneers in vacuum process technology for the deposition of a wide range of functional thin films. The special electrical, optical or other functional coatings are used today in many different sectors. We can contribute our core competence into the development partnership with Manz. Together we intend to further enhance the efficiency and competitiveness of thin-film solar technology in the photovoltaic market."

The equipment companies aim to form a strategic partnership to further develop thin-film technology.

Chinese CIGS thin-film customer of Singulus cuts initial tool order in half

Specialist PV manufacturing equipment supplier Singulus Technologies has said an unidentified customer in China that ordered CIGS thin-film tools in March 2017 valued at over €20 million has reduced the order to around €10 million.

Recently, Singulus announced that it had received a partial pre-payment from the customer in the single-digit million euro range, with the remaining balance due in the following weeks. The equipment order includes Singulus' VISTARIS vacuum sputtering systems as well as its TENUIS II system for wet chemical buffer layer deposition.

Singulus did not say why the initial order had been reduced by 50%.

Siva Power secures a further US$25 million in funding for CIGS thin-film technology

US-based CIGS thin-film start-up Siva Power has secured a further US$25 million in funding for its planned CIGS thin-film pilot and demonstration production line.

Siva Power first announced a US$5 million investment round to build a pilot line to produce small-scale production to demonstrate its co-evaporation source technology at its facility in Santa Clara, California in May 2016.

The company said that the new funding would also be used to develop its solar module business.

In early February 2017 the company said it had acquired process equipment from thin-film solar manufacturers First Solar and bankrupt Bloo Solar. Additionally, the company's development facility has been expanded to 35,500 square feet.

Private investors in this funding round were hedge fund founder, Jim Simons and Mark Heising, managing director of VC firm, Medley Partners, an existing investor in the company.

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

Progress and trends in CIGS and perovskite/CIGS PV

S. Nishiwaki, T. Feurer, F. Fu, S. Pisoni, S. Buecheler, A. N. Tiwari, Laboratory for Thin Films and Photovolatics, Empa-Swiss Federal Laboratories for Materials Science and Technology, Duebendorf, Switzerland

ABSTRACT

Improvements in the efficiencies of CIGS thin-film solar modules and the industrial production status of a few select companies are briefly reviewed. Industrial sub-module efficiencies of 19.8% on 7 x 5cm^2, 19% on 30 x 30cm^2 and 17% record efficiency on large-area industrial size (0.940m^2) as well as the production volume ramp-up show a strong progressive trend in the industrial manufacturing sector. Roll-to-roll manufacturing of solar modules on metal and polymer foils is gaining industrial maturity as the modules find attraction for numerous applications where lightness and flexibility in form factor offer distinctive advantages. Construction of Net Zero Energy Buildings, reduction of CO_2 footprint and the integration of PV in buildings and vehicles open new application opportunities. However, low cost installation and high efficiency are needed, and future research objectives address those topics of low cost and high performance. While lab-scale solar cell efficiencies of up to 22.6% on glass and 20.4% on flexible polymer are achieved, further research efforts are directed towards finding ways for 25% efficiency with single junction CIGS and 30% with tandem solar cells combining semitransparent perovskite with CIGS solar cells.

Introduction

Thin-film solar cells based on chalcopyrite semiconductor Cu(In,Ga)(S,Se)$_2$ compound (hereafter called CIGS or CIGSeS irrespective of the exact composition) have continuously drawn interest because of their progressively increasing high photovoltaic conversion efficiencies and the merits of long-term performance stability, high energy yield, low cost production potentials and other advantages for industrial manufacturing and application of solar modules [1]. Installation of solar modules on buildings and transport vehicles is gaining momentum in achieving CO_2 footprint reductions and for construction of new Nearly Zero Energy Buildings by 2020, according to the directives of the EU Commission. CIGS solar modules are especially attractive for such applications. Most of the CIGS companies have already demonstrated installations of aesthetically beautiful and energy efficient modules developed on glass as well as flexible foils.

The CIGS Whitepaper (http://cigs-pv.net/cigs-white-paper-initiative/) jointly prepared in 2015 by a large group of experts from academia and industries highlighted the report with caption of "The time to invest is now", giving all the good reasons which include the inherent advantages of large-area, scalable thin-film deposition technologies for production of low-cost solar modules and manufacturing on glass as well as flexible foils. Recent reports indeed show that investments in CIGS manufacturing technologies have started picking up. Amongst several announcements only a few are mentioned in this report. European equipment suppliers such as Singulus, FHR-Centrotherm and Midsummer have reported purchase orders for their deposition equipment in Asia. Singulus is providing a different type of thin-film coating equipment for large volume production plants to be built in China by CNBM Company using the CIGS technology developed by AVANCIS.

The CIGS solar cells can be grown with a variety of deposition methods but high-temperature co-evaporation of elements and sputtering metals or alloys followed by selenization and sulfurization in some cases are the two most commonly used methods for the growth of absorber layers for high-efficiency solar cells. Generally high-efficiency solar cells on glass and stainless steel substrates are developed with high temperature (>550°C) CIGS processing while low temperature (about 450°C) CIGS deposition is used for polymer films. The most commonly used back and front electrodes are Mo and transparent conducting ZnO:Al or ZnO:B, respectively. Chemical bath-deposited CdS is used for junction formation with CIGS absorber but alternatively layers and deposition methods are also used, albeit with somewhat compromised efficiency values.

Industrial production of solar modules can be divided into three categories depending on the choice of substrate: glass for rigid modules or metal or polymer foils for lightweight flexible solar modules with roll-to-roll manufacturing. While production of solar modules on glass has reached an adequate level of industrial maturity for large volume production, the roll-to-roll manufacturing of flexible solar modules is still in the phase of evolution – with most of the plants operating below 10-50MW production capacity. Below is a status summary of a few selected CIGS module production companies.

CIGS solar module production on glass substrates

Manz AG in Germany, provider of a CIGS turnkey production plant, stands on a successful track record of several years of development work at Stuttgart University, ZSW (Center for Solar Energy and Hydrogen Research Baden-Württemberg) and Würth Solar in Germany. At the CIGSfab of Manz, the CIGS absorber layers are grown by co-evaporation of elements and chemical bath deposition is used for CdS buffer layer coating. With module efficiencies of up to 16% from its CIGSfab plant Manz is expanding R&D and production operations in partnerships with Shenhua Group, Shanghai Electric and Beijing Future Science Park Development Group in China. ZSW, a pioneering institute with numerous contributions in the advancement of CIGS, is an exclusive R&D partner of Manz and has been leading the progress of CIGS solar cells on glass substrates with a current world record efficiency of 22.6%. The two are collaborating for further improvement of module efficiencies.

Solar Frontier in Japan is the largest manufacturer of CIGSeS PV modules with a current production capacity of about 1GW per year. Solar Frontier has been consistently improving the conversion efficiency of solar cells, submodules and large area production modules. In a three step process, high temperature selenization of sputtered metal precursor followed by sulfurization, is used for the coating of CIGSeS absorber layer. The conversion efficiencies of 22.3 and 22.0% on CdS-buffered and Cd-free cells were achieved in 2015-2016 [2,3], and by transferring these technologies into the submodule development, 19.2 and 19.8% efficiencies have been achieved on 30 × 30 and 7 × 5cm^2-sized Cd-free sub-modules and mini-modules, respectively [2–5]. The two devices are basically identical except for the alkali metal treatment only applied on the mini-module. Recently, Solar Frontier announced the launch of a new model (SFK series) whose module output is ranged from 180W (14.7%$_{TA}$) to 185W (15.1%$_{TA}$), which has an improvement of 10W from the previous model with the same size [6]. The upgrade of the module output was mainly brought about by transferring technologies developed in the previous sub-module research. Figure 1 shows the past pgoress and future projection for Solar Frontier's technology. Solar Frontier is currently targeting a 25% cell efficiency and 220W module output in 2020. Solar Frontier's research has been performed under Japanese national NEDO project, which is targeting levelized cost of electricity (LCOE) of 14 and 7 yen/kWh in 2020 and 2030, respectively. The former and latter targets are comparable to the business electricity price (grid parity) and conventional thermal power (generation parity) in Japan, respectively.

Solibro is another leading CIGS module manufacturing company, with a 145MW production capacity plant in Thalheim, Germany, using co-evaporation technology for the growth of absorber layers. Solibro has a close partnership with Uppsala University, Sweden, where innovative R&D on CIGS solar cells has resulted in breakthroughs and advancements in the technology. In 2014 Solibro announced a 21.0% aperture area efficiency on 1cm^2 area cell and then

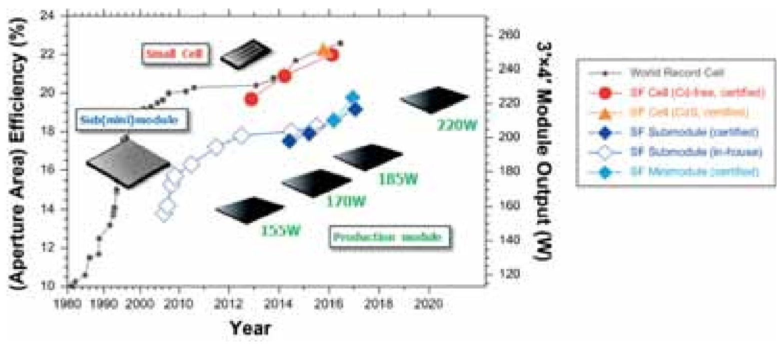


Figure 1: Progress and projection of Solar Frontier's technology in lab and on production scale. Figure supplied by Hiroki Sugimoto and Takuya Katou, Solar Frontier.

Figure 2. Production efficiency evolution at Solibro of champion modules (blue dots) and monthly average (red dots). Figure supplied by Lars Stolt, Solibro.

a 30 x 30cm^2 sub-module with 18.8% aperture area efficiency (internal measurement). The average efficiency of Solibro´s modules have progressed to about 15% (Figure 2).

Solibro has recently announced a new record efficiency of 17% on a 0.940m² module size with 159.6Wp power, independently measured by TÜV Rheinland, Germany; 17.9% is the measured aperture area efficiency of such a module. The module was manufactured at the Solibro production plant in Germany using standard production equipment and processes, which indicates the capability of the company to produce high-efficiency modules comparable to the best commercial polycrystalline silicon wafer modules. Solibro is also developing solar modules with aluminium grids and thinner TCO. The company has successfully applied metal grid on large size modules and reported a gain ≥ + 0.7 % in absolute total area efficiency with this approach.

AVANCIS in Germany develops and manufactures its CIGSeS modules using the AVANCIS 'SEL-RTP' process (stacked elemental layer – rapid thermal processing) in combination with a dry Cd-free PVD buffer process, namely the proprietary thermal evaporation of In_xS_y:Na. The efficiency development of the CIGSeS technology is driven in the Munich-based R&D pilot line based on medium-sized 30 x 30cm^2 CIGSeS modules. Figure 3 depicts the evolution of the externally certified champion efficiencies of AVANCIS' 30 x 30cm^2 modules over the past years. The graph shows the steady increase of the efficiencies without an indication for any saturation upto now.

The efficiency development on 30 x 30cm^2 modules resulted in parallel in a steady increase of the performance of the AVANCIS' PowerMax product family with power classes now reaching 150W or 15.7% aperture area efficiency. The production capacity of AVANCIS is 100MW/year each in Torgau, Germany, and in Ochang, South Korea, and now AVANCIS, a part of the CNBM Group, is expanding production capacity to 1.5GW/year in Bengbu, China, and 1GW/year in Meishan, China.

The CIGSeS modules of AVANCIS foster the company's premise of a thin-film technology to be used as a premium component for the building industry: in the construction of solar active facades for public, commercial and residential buildings. The flexibility in colour, transparency, size and shape which is required for the building industry is per se compatible with CIGSeS thin-film processing on glass substrates. For this purpose, AVANCIS has recently launched a new architects panel for solar facades with variable colours. Its PowerMax Skala is a first-of-a-kind product with frameless design and backrails, and has received the German building code approval (abZ).

The PV module as a solar active building material embedded into the roof or facade imposes new demands for material research for the module itself and for its interaction with the other building materials. For example, aesthetic product attributes like homogeneity, gloss and angle dependency are becoming at least coequal to electrical specifications. In this emerging market, CIGS or CIGSeS modules can substantiate their unique aesthetic properties besides their electrical pros like high shading tolerance, good low light characteristics, low temperature coefficient and broad spectral response.

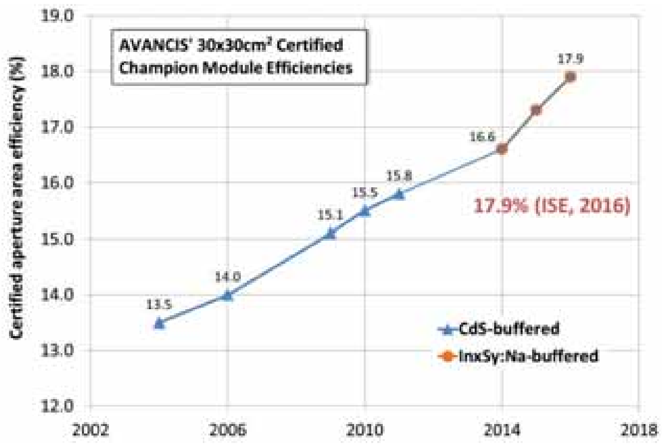


Figure 3. Externally certified champion efficiencies of AVANCIS' 30 x 30cm^2 CIGSSe modules. Blue triangles represent modules with CdS buffer layer, orange dots In_xS_y:Na-buffered modules. Figure supplied by Thomas Dalibor and Jörg Palm, AVANCIS.

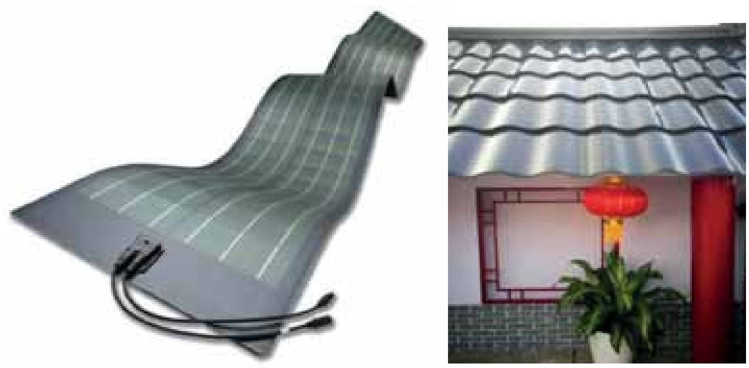


Figure 4. Flexible CIGS solar modules on steel foils (left picture from Urs Schoop, Global Solar Energy) and Miasole-Hanergy's solar tile (right picture from Atiye Bayman, MiaSolé).

Flexible CIGS modules with roll-to-roll manufacturing process

Flexible lightweight CIGS solar modules produced with roll-to-roll manufacturing offer numerous advantages for potentially low cost production of solar modules, and they enable new application possibilities, especially where much heavier rigid modules are not suited or when easy customization in terms of shape/size/power is desired. Such modules are specifically attractive for applications in buildings (BIPV, BAPV and rooftops), vehicles, airships, portable power, etc. Production of flexible solar modules with roll-to-roll processing is challenging because of the lack of appropriate quality equipment and processing knowhow, especially on the topics of CIGS growth, interconnect technology, low cost transparent moisture barrier films, and substrate foils. Realizing the great potential of flexible lightweight solar cells as a differentiated product for hugely untapped market solar cell development work started a few years back and now companies have started production on limited scale. Choice of flexible substrate- metal or polymer, CIGS absorber deposition method and interconnect technology for module making are the key differentiators for companies.

Global Solar Energy, USA, is the first company to commercially produce flexible CIGS solar cells on stainless steel foil with roll-to-roll manufacturing methods and open the market with applications where solar modules with lightweight and flexibility features are desired. CIGS layers are deposited by co-evaporation of elements in a roll-to-roll coating system. Large area solar cell strips are cut from the roll and they are subsequently stringed together with metal grid/wire to make large area modules (Figure 4). Production modules with aperture area efficiencies up to 16.3% are reported and its modules are fully certified to UL and IEC standards.

Global Solar Energy has commissioned two fully automated Integrated Cell Interconnect (ICI) manufacturing lines with combined capacity of 50MW/year in Tucson, Arizona, and the company is expanding capacity in China for volume manufacturing. In 2013 Global Solar Energy was acquired by Hanergy group. The company is currently improving the production technology

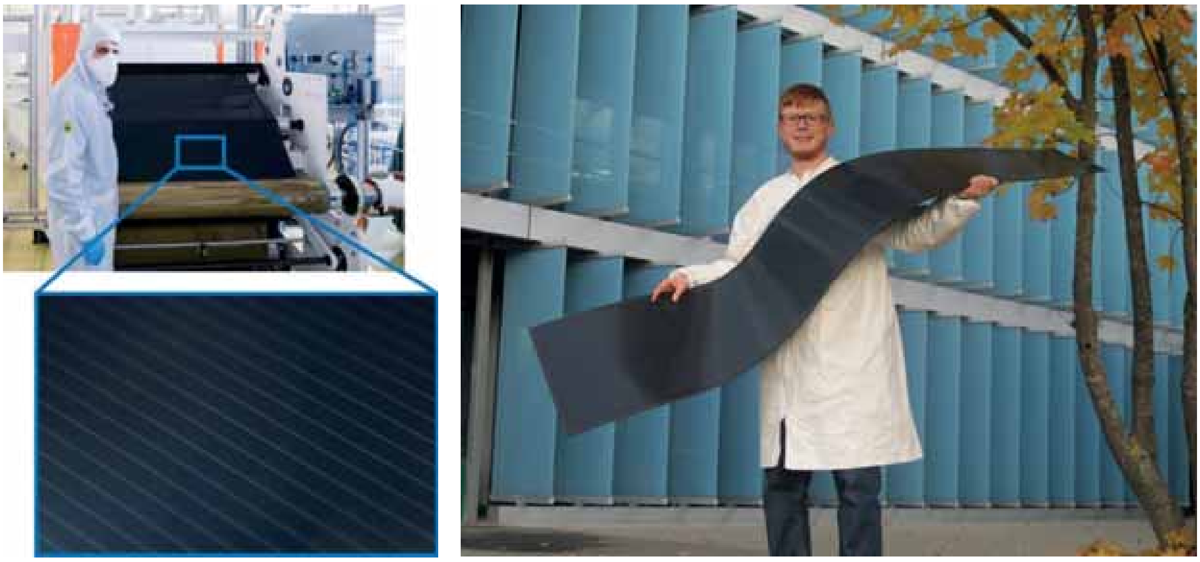


Figure 5. Flisom's laser patterning system for monolotithich interconnect of cells on 1 meter wide rolls (left) a large-area flxible solar module produced on polymer film (right).

for higher performance and lower cost and it aims to reach to the production cost below US$0.50/Wp in future.

MiaSolé, owned by Hanergy company, has a production plant in Sunnyvale, California, and has reported 19% efficiency CIGS cells (1sq cm area cell and measured by NREL) using a sputtering method and a corresponding 17.4% module 0.49sq m) efficiency measured by Fraunhofer ISE. The MiaSolé FLEX series modules are the solar industry's highest efficiency flexible CIGS thin-film modules on the market today with a production conversion efficiency of 16.5%.

All MiaSolé PV products use the flexible cells manufactured with MiaSolé's proprietary deposition equipment called the Roll Coater. Roll Coater is an integrated multi-chamber tool where all the films that comprise the solar device are deposited sequentially on a 50 micron thick stainless steel foil. Solar cells are finished with a low resistance collection grid that is applied by roll lamination. This basic cell technology has been used since 2009 when the first product was introduced to the market. MiaSolé provides both rigid glass and flexible lightweight products in a variety of form factors. In the last three years the company has focused on product development for applications in distributed power generation and off-grid applications.

MiaSolé has demonstrated steady increases of aperture area conversion

Figure 6. Lightweight flexible solar modules of Flisom for BIPV applications in EU-PVSITES project. Source: PVSITES/Flisom.

efficiency in its products since 2009, from 11% to 16.5% today, and is planning to get to 17.5% in 2018. MiaSolé is also a provider of manufacturing equipment for PV factories that use MiaSolé technology and it is seeing strong business growth in China with a >2GW of backlog.

Flisom in Switzerland is a spin-out company of ETH Zurich and has close partnership with Empa-Swiss Federal Laboratories for Materials Science and Technology, which holds the 20.4% efficiency world record for flexible CIGS solar cells processed with a low temperature (~450°C) process. Flisom uses co-evaporation of elements and alkali post-deposition treatment (PDT) for deposition of CIGS absorber layers on polyimide films in roll-to-roll coating system for one meter width rolls. The company has developed its own proprietary roll-to-roll manufacturing equipment and processes for production of monolithically interconnected flexible solar modules on polymer film. Laser patterning not only enables high throughput production but also provides aesthetically nice looking uniform dark appearance (Figure 5).

Polymer films, in contrast to steel foils, do not require barrier coatings against detrimental metal impurities from the substrate and also provide an insulating surface as needed for monolithic interconnections. However a low temperature CIGS deposition process is needed for polyimide films. With low temperature grown absorbers in one meter wide roll-to-roll coating system solar cells of 16.8% efficiency (without anti-reflection coating) have been achieved. Laser patterned monolithic sub-modules and large area modules of 12% to 15%, depending on the module area, have been achieved. Flisom, while further improving the efficiency and ramping up production volume on 15MW plant, has started commercial supply of lightweight flexible solar modules for diverse applications including roofs and facades of buildings. Within the EU-PVSITES project Flisom is developing lightweight flexible solar modules for different types of BIPV applications including curved roofs (Figure 6). PVSITES consortium is working on an "industrial joint approach to provide robust BIPV technology solutions and the ultimate goal is to significantly enhance BIPV market deployment in the short and medium term". The objective of the PVSITES project is driven by the needs for Nearly Zero Energy Buildings according to the directives of the EU commission.

Ascent Solar in the USA and Sunplugged in Austria are the other companies involved in manufacturing of flexible CIGS solar cell on polymer films. Swedish company Midsummer is a supplier of equipment and offers DUO systems with a capacity of 5MW/year. Midsummer does not use a roll-to-roll manufacturing method, rather an all-sputtering process in which cells are developed on 15.6 x 15.6cm^2 stainless pieces resembling silicon wafers that are subsequently stringed together to make solar modules. Midsummer has reported a 16.4% total area efficiency on 6"cells. Besides them there are some other stealth mode or early stage companies developing technologies for industrial production of CIGS modules.

Solar cell efficiency improvements and Sharc25

Recent improvements in the efficiency of CIGS solar cells were triggered by a post deposition treatment (PDT) first invented by Empa where they applied KF PDT to achieve a breakthrough with 20.4% efficiency cells on polymer film with a low temperature process. The alkali PDT method was later adapted and applied by several research groups for efficiency improvements. Solibro and Solar Frontier have reported 21% and 22.3% efficiency cells, respectively, with the application of KF PDT on their absorber layers.

In June 2016 an independently certified cell record efficiency of 22.6% with anti-reflective coating (ARC) was achieved by ZSW with a CIGS absorber, which underwent an in-situ RbF-PDT process and involved a solution-grown CdS buffer in combination with a (Zn,Mg)O high-resistive layer and a ZnO:Al as front contact. It should be noted that CIGS cell efficiencies above 20% with ARC could be achieved with KF-PDT, RbF-PDT, and even CsF-PDT of the CIGS absorber layer, whereas Na was supplied from the glass substrate [8]. In addition, many single cells were fabricated with high reproducibility at ZSW with an efficiency level around 22% (with ARC).

Even such high efficiencies achieved for CIGS thin-film solar cells reveal that there is still a prominent gap between experimental results and the theoretical Shockley-Queisser limit of 33% for single-junction solar cells. This was one of the reasons why the EU funded project "Sharc25" was initialized in 2015 with the goal to challenge the key limiting factors in state-of-the-art CIGS solar cells, namely non-radiative carrier recombination and light absorption losses in emitter layers.

Sharc25 is coordinated by the Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), focusing mainly on high-temperature CIGS deposition and device fabrication. The consortium consists of 11 research partners from eight European countries. The idea behind this EU-funded project is to pool these organizations' multidisciplinary skills in a bid to push the CIGS cell performance towards 25%.

ZSW's partners in this endeavor are scientific coordinator of the project, Empa-Swiss Federal Laboratories for Materials Science and Technology, with special expertise on low-temperature CIGS growth, and IMEC in Belgium, which contributes on the development of passivation layers for the CIGS absorber using skills borrowed its work in silicon PV. They could successfully adapt a standard technique for structuring to the comparably rough front side of the CIGS absorber to realize point contact openings in passivation layers grown by ALD.

In addition, partners with special and often unique expertise in materials and device characterization are on board: the HZB (Helmholtz-Zentrum Berlin für Materialien und Energie, D) with lab- and synchrotron-based x-ray and electron spectroscopies, and the International Iberian Nanotechnology Laboratory INL, with expertise in Kelvin probe force microscopy, both for CIGS surface and CIGS/buffer interface characterization. They could for instance reveal that there is a distinct difference in the first growth stages of CBD CdS and Zn(O,S) buffer layers on CIGS with RbF-PDT in terms of chemical composition at the interface and p-n junction formation. The University of Luxembourg, specialized in photoluminescence and admittance measurements, is also on board to analyze bulk absorber properties, and the University of Rouen, France, to perform highly spatially resolved atom probe tomography analyses on the CIGS absorber, revealing for example the distribution of alkali metals on a nanometer scale; thus, Rb intentionally introduced by RbF-PDT process accumulates at the CIGS grain boundaries and also at dislocations. These in-depth analyses were supported by ab-initio calculations with density functional theory (DFT) carried out by Aalto University from Finland, with a focus on intrinsic and extrinsic defects in CIGS and 2D/3D device simulations performed at the University of Parma, Italy. A main result from DFT is that Li and Na compared to Rb and Cs have distinct effects on the structure of the $CuInSe_2$ absorber whereas K lies in between [9]. The companies Flisom and Manz assess results in terms of exploitation, manufacturability and transferability to production.

Launched in May 2015, the project will run for 3.5 years with funding sourced from the EU research framework programme Horizon 2020 and the Swiss government.

Towards 30% efficiency tandem solar cells:

The power conversion efficiency of single junction solar cells is intrinsically limited by the trade-off between absorption losses where photons with energies lower than the bandgap are not absorbed, and thermalization losses where hot carriers excited by high-energy photons rapidly thermalize to the bandgap energy of the absorber, releasing the extra energy as heat. In 1961, Shockley and Queisser calculated the theoretic limit of power conversion efficiency for a p-n junction solar cell to be around 33% considering only radiative recombination as required by the principle of detailed balance [10].

A viable way to overcome the S-Q limit for a single junction device is stacking solar cells with different bandgaps in a tandem (the number of junction equals two) or multi-junction structure, where the thermalization loss is minimized. In a tandem configuration, a wide-bandgap solar cell is stacked on top of a narrow-bandgap solar cell, so that the wide-bandgap top cell absorbs the high energy photons with minimized thermalization loss and transmits low energy photons into the narrow-bandgap bottom cell. The tandem and multi-junction concept has been successfully realized on expensive single-crystal III-V materials, and attempts to develop cheap tandems based on polycrystalline thin-film solar cells has had limited success mainly due to the lack of suitable wide-bandgap top cells.

This situation has changed recently with the advent of emerging perovskite solar cells. Perovskite solar cells have several distinct advantages, such as wide bandgap, which is tunable over a broad energy range, and high efficiency, which make them an ideal candidate as top cells in tandem configuration with CIGS bottom cells to realize highly efficient and cost-effective thin-film photovoltaics. Tandem solar cells can be connected in a four-terminal configuration (Figure 7) or two-terminal configuration, each with their own advantages and disadvantages. In the four-terminal configuration tandem, the top and bottom cells are individually processed and mechanically stacked together, which means the top cell and bottom cell are electrically independent and optically coupled. This type of tandem is easy to make and has less restriction in design as no tunnel junction or recombination layer is needed, and no current matching is required. However, more electrical components, including maximum power point trackers and converters,

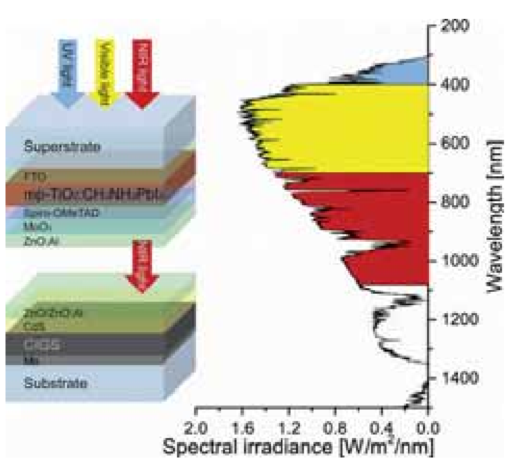


Figure 7. Schematic illustration of four-terminal perovskite-CIGS tandem solar cells. Reproduced with permission from [11].

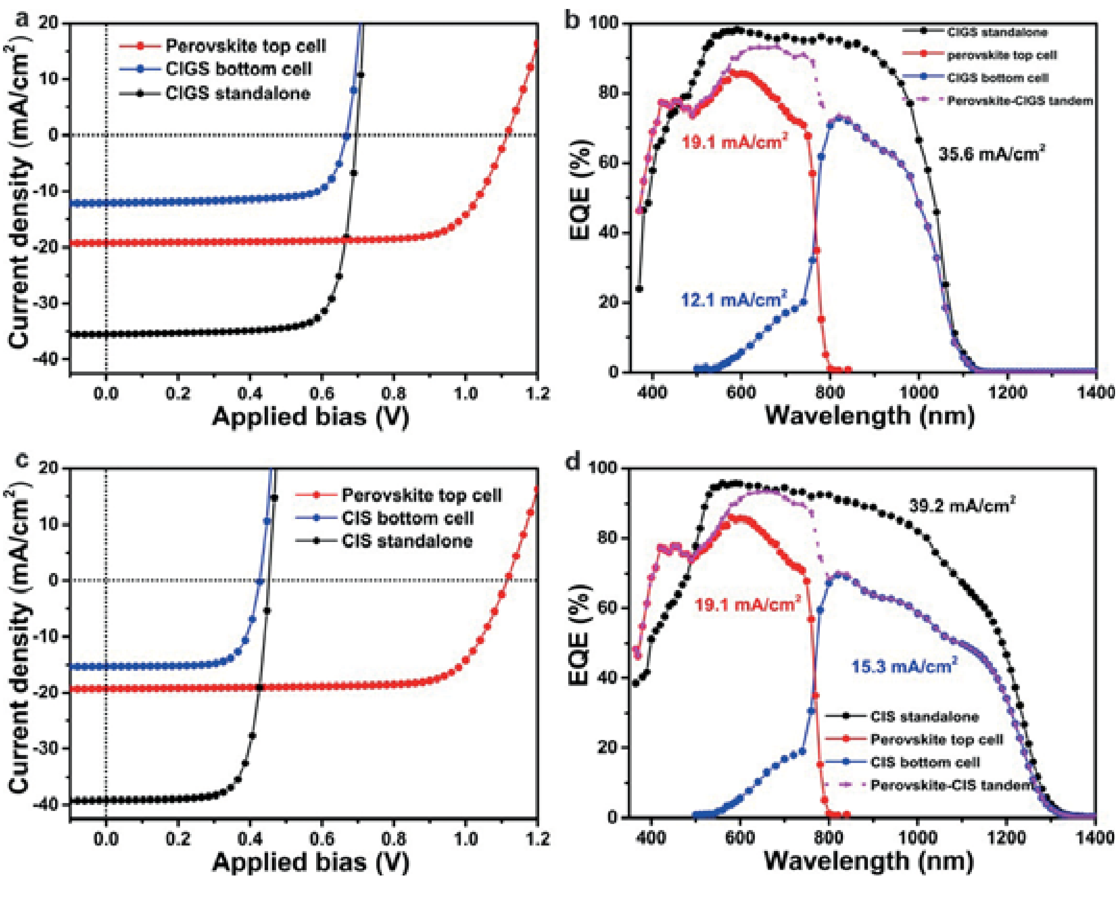


Figure 8. Current density-voltage curves (a) and EQE spectra (b) of the perovskite-CIGS in four-terminal tandem configuration; current density-voltage curves (c) and EQE spectra (d) of the perovskite-CIS in four-terminal tandem configuration. Reproduced with permission from [12].

Solar cell	V_{OC} (V)	J_{SC} (EQE) (mA/cm^2)	*FF* (%)	*Eff* (%)	MPP (%)	Cell area (cm^2)
Perovskite top cell	1.116	19.1	75.4	16.1	16.1	0.286
CIGS (standalone)	0.696	35.6	77.3	19.2	19.2	0.213
CIGS bottom cell	0.669	12.1	73.6	6.0	6.0	0.213
Perovskite-CIGS four-terminal tandem					22.1	
CIS (standalone)	0.453	39.2	73.1	13.0	13.0	0.213
CIS bottom cell	0.428	15.3	73.1	4.8	4.8	0.213
Perovskite-CIS four-terminal tandem					20.9	

Table 1. Photovoltaic parameters of perovskite-CI(G)S four-terminal tandem solar cells.

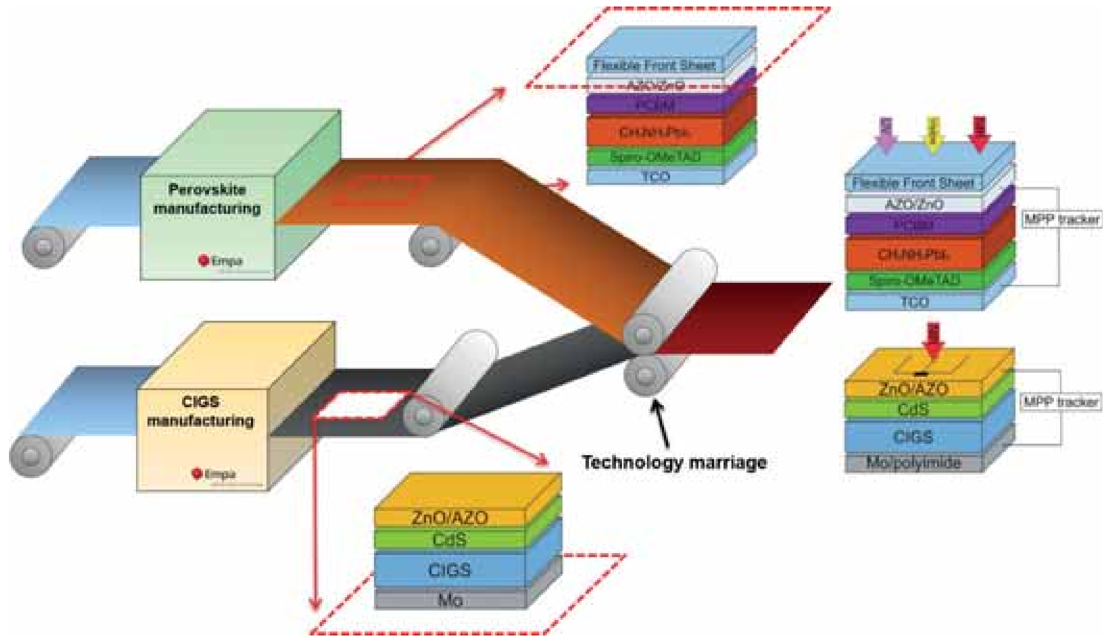


Figure 9. Schematic illustration of future roll-to-roll manufacturing of flexible Perovskite-CIGS polycrystalline thin-film tandem solar cells. The perovskite top cell and CIGS bottom cell could be fabricated individually on flexible substrates and then laminated together to make tandem device.

are needed, which will add additional cost. Moreover, the use of three TCOs (transparent conducting oxides) in four-terminal tandems will also introduce strong parasitic absorption. In the two-terminal configuration (monolithic tandem), the top and bottom cells are deposited sequentially on top of each other. There is only one electric circuit in the tandem device and only one TCO is needed, therefore reducing the cost and optical loss. This architecture requires a tunnel junction or recombination layer deposited between each junction to allow the current flow, and the current is dictated by the sub-cell that yields the lowest current as required by current-matching conditions. As the functional layers are sequentially deposited on top of each other, this imposes severe constraints on processing conditions and affects the yield.

The tandem solar cells work best when the solar spectrum is optimally utilized by both top and bottom absorbers. Under the standard AM1.5G one-sun illumination, the theoretical maximum efficiency in both two- and four-terminal configurations is around 45%, which is higher than 33% predicted in the SQ limit for single junction device. Besides the coherent merits of thin-film technology, another advantage of CIGS over c-Si is that the bandgap of CIGS can be easily tuned by varying the [Ga]/([Ga]+[In]) ratio in the absorber to realize current matching.

Here, we demonstrate the feasibility of adjusting the current of the bottom cell by comparing two different absorbers – namely, the state-of-the-art CIGS composition and Ga-free $CuInSe_2$ (CIS), with bandgaps of 1.15 eV and 1 eV, respectively. The J–V curves and EQE spectra of the perovskite top cell and CIGS bottom cell are shown in Figure 8 and the corresponding photovoltaic parameters are summarized in Table 1. The efficiencies of the CIGS and CIS used are 19.2% and 13%, respectively. Combined with the 16.1% perovskite top cell, efficiencies of 22.1% and 20.9% are measured in four-terminal tandem configuration. Absolute efficiency gains of 2.9% (CIGS bottom cell) and 4.8% (CIS bottom cell) are achieved compared to the highest-efficiency sub-cell. Further improved collection in the near-infrared region of the CIS cells will enable current-matching monolithic tandem devices to be built without sacrificing the high-energy photons in the top cell. Due to the low-temperature processing of the substrate configuration inverted perovskite solar cells, direct monolithic growth on the CI(G)S bottom cells is feasible. In the future, thin-film perovskite-CIGS tandem solar cells can be processed by high throughput roll-to-roll manufacturing processes to further reduce the production cost as shown in Figure 9.

Conclusion

The progress in efficiency and production of CIGS solar cells and modules show excellent trends for further successful deployment of the technology as companies ramp-up production volumes with new and enhanced production capacities. Already achieved results indicate the possibility of industrial production of modules with higher efficiencies -17%-19% with new production plants in future. Lightweight and flexible solar modules will find more and more market opportunities for their application in buildings, transport, space and portable power generation, and the huge market potential will drive the enhanced efforts in roll-to-roll manufacturing on a larger scale. Innovative research in labs is expected to develop device concepts and processing methods for greater efficiencies – 25% for single junction and 30% for all thin-film tandem devices in future. These targets may seem ambitious but a retrospective look to historical developments suggests the viability of success with innovation.

Acknowledgements

The authors thank the contributions from Wolfram Witte, ZSW; Lars Stolt, Solibro; Hiroki Sugimoto and Takuya Katou, Solar Frontier; Thomas Dalibor and Jörg Palm, AVANCIS; Urs Schoop and Jeff Britt, Global Solar Energy; Atiye Bayman, MiaSolé; Stephan Stutterheim, Flisom. Some of the mentioned results are from projects: EU-Sharc25, EU-PVSITES, Swiss National Science Foundation (SNF)-NRP70, PV2050, SNF-NanoTera and Swiss Federal Office of Energy (SYNERGY and CIGS projects).

References

[1] T. Feurer et al. Progress in thin film CIGS photovoltaics – Research and development, manufacturing, and applications, Progress in Photovoltiacs: Research and Applications (2016), DOI: 10.1002/pip.2811.

[2] T. Kato, "Cu(In,Ga)(Se,S)2 solar cell research in Solar Frontier: Progress and current status", *Jpn. J. Appl. Phys.* 56, 04CA02 (2017).

[3] M. A. Green et al., "Solar cell efficiency tables (version 49)", Prog. Photovolt: Res. Appl. 25, 3 (2017).

[4] Solar Frontier press release (Feb. 27, 2017). "Solar Frontier's CIS thin-film submodule achieves highest efficiency world record of 19.2%." Available: http://www.solar-frontier.com/eng/news/2017/0227_press.html

[5] T. Kato et al., "Enhanced efficiency of Cd-free Cu(In,Ga)(Se,S)2 minimodule via (Zn,Mg)O second buffer layer and alkali metal post treatment", 44th IEEE Photovolt. Spec. Conf., June 25-30, 2017, Washington D.C., USA.

[6] Solar Frontier press release (Jun. 21, 2017). Available: http://www.solar-frontier.com/jpn/news/2017/0621_press.html [in Japanese].

[7] A. Chirilă et al., "Potassium-induced surface modification of Cu(In,Ga)Se_2 thin films for high-efficiency solar cells." *Nature Materials*, 2013. 12: p. 1107 - 1111.

[8] P. Jackson et al., "Effects of heavy alkali elements in Cu(In,Ga)Se_2 solar cells with efficiencies up to 22.6%", *Phys. Stat. Sol.* (RRL) 10 (2016) 583.

[9] M. Malitckaya et al., "Effect of Alkali Metal Atom Doping on the $CuInSe_2$-Based Solar Cell Absorber", *J. Phys. Chem.* C 121 (2017) 15516.

[10] W. Shockley and H. J. Queisser. "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", J. Appl. Phys. 32, 510 (1961).

[11] L. Kranz et al., "High-Efficiency Polycrystalline Thin Film Tandem Solar Cells", J. Phys. Chem. Lett. 6, 2676 (2015).

[12] F. Fu et al., "High-efficiency inverted semi-transparent planar perovskite solar cells in substrate configuration", Nature Energy 2, 16190 (2016).

About the Authors

Dr. Shiro Nishiwaki received his Ph.D degree in engineering in 1996 from the Hokkaido University, Sapporo, Japan. Prior to joining the Laboratory for Thin Films and Photovoltaics at Empa in 2008 he worked at Matsushita Electric Co. Ltd., Advanced Technology Research Laboratories, Kyoto, Japan (1997 - 2000), Optoelectronics Division of Electrotechnical Laboratory (present name: National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan (2000), Hahn-Meitner-Institute, Abt SE2, Berlin, Germany (2000 - 2004), Institute of Energy Conversion, Newark, USA (2004 – Dec. 31, 2007). His research and development work is focused on processing of high-efficiency CIGS solar cells on different substrates.

Thomas Feurer received his master degree in physics from the Swiss Federal Institute of Technology (ETH) Zurich in 2014. He started his Ph.D at the Laboratory for Thin Films and Photovoltaics at Empa subsequently. His current research is focused on low bandgap CIGS solar cells and tandem devices with perovskite top cells.

Fan Fu received his master degree in materials science from Wuhan University of Technology (China) in 2013. He started his Ph.D at the Laboratory for Thin Films and Photovoltaics at Empa in 2014. His current research is focused on the design, synthesis and characterization of organic-inorganic hybrid perovskite solar cells and exploring their potential in thin-film tandem applications with CIGS solar cells.

Stefano Pisoni received his master degree in 2015 from the Polytechnic of Milan with master thesis project at University of Oxford. He is working at the Laboratory for Thin Films and Photovoltaics for his doctoral thesis. His current research activities are perovskite solar cells on different substrates including flexible foils, mini-module development and tandem solar cells.

Dr. Stephan Buecheler studied physics at ETH Zurich and received his diploma in 2007. After receiving his Ph.D. from ETH Zurich in 2010 he took the position of group leader in the Laboratory for Thin Films and Photovoltaics at Empa, where his research group is currently working on highly efficient CIGS, CdTe and perovskite solar cells, advanced concepts for tandem solar cells, topics of industrial interests to improve efficiencies and the use of material and device characterization techniques. His other research activity includes thin film solid state batteries.

Prof. Dr. Ayodhya N. Tiwari received his M.Sc. from the University of Roorkee, India in 1981, and his Ph.D. from the Indian Institute of Technology (IIT) Delhi in 1986. He joined ETH (Swiss Federal Institute of Technology) Zürich in 1989 and established a research group on compound semiconductor thin-film solar cells. In 2008, he joined Empa-Swiss Federal Laboratories for Materials Science and Technology as the head of the Laboratory for Thin Films and Photovoltaics. His lab at Empa is working on different types of thin-film solar cells covering fundamental and applied research topics for improving efficiencies, simplifying processing of devices, advance device structures, as well as on applied topics of industrial interests. His lab holds efficiency world records for flexible solar cells. He is an adjunct professor at ETH Zürich. He is a founder and chairman of Flisom AG, a Swiss company involved in the production of monolithically interconnected flexible and lightweight CIGS solar modules.

PV Modules

'Rebooted' SolarWorld Industries starts production

Credit: SolarWorld

The new SolarWorld parent company has wasted no time re-starting production.

Newly formed German PV module manufacturer SolarWorld Industries GmbH has officially started production, according to the insolvency administrator for SolarWorld AG.

SolarWorld Industries GmbH has taken ownership of SolarWorld AG's production plants in Saxony and Thuringia as part of the deal struck with the insolvency administrator, Horst Piepenburg.

SolarWorld Industries GmbH is majority owned by former founder and chairman of SolarWorld AG, Frank Asbeck, and another key investor in the bankrupt firm, Qatar Solar Technologies (QST), which has taken a 40% shareholding in the recently formed SolarWorld Industries.

SolarWorld Industries' manufacturing facility in Arnstadt, Thuringia undertakes monocrystalline ingot and solar cell production, while the facilities in Freiburg, Saxony focus on wafer and module assembly.

SolarWorld Industries has approximately 600MW of mono ingot/wafer capacity and 1,000MW of nameplate cell and module capacity in Germany.

The new company is following SolarWorld AG's previous plan to stop multicrystalline ingot/wafer, cell and module production and switch to higher efficiency P-type monocrystalline PERC technology, including bifacial cells and modules.

Results

JA Solar's module shipments smash guidance in Q2

Having turned, and then continued to remain cautious about its business outlook for the second-half of 2017, JA Solar reported second quarter results that simply defied previous guidance, driven by greater than expected demand in China and the start of a rush to stockpile in the US.

JA Solar reported second quarter total shipments of 2,389.2MW. External PV module shipments were 2,147.5MW and solar cell shipments were 167.2MW, compared to previous guidance of 1,550MW to 1,650MW for the second quarter of 2017.

External shipments were therefore up 88.3% year-on-year and up 68.3% from the previous quarter. Due to the strong customer demand that is expected to continue through the third quarter of 2017, JA Solar reduced its module shipments to its own downstream PV project business and cut expected project completions for the year from a high of 250MW to a new ceiling of 150MW.

Product shipments within China accounted for 59.2% of total shipments in the quarter, up from 39.7% in the first quarter of 2017.

PV module shipments to North America remained unchanged on a percentage basis at 8.1% from the previous quarter but total volume was around 174MW, compared to around 107MW in the first quarter of 2017.

Hanwha Q CELLS changing sales strategy due to near-term industry uncertainties

'Silicon Module Super League' (SMSL) member Hanwha Q CELLS has said its key strategic focus is to diversify its regional and market segment sales in 2017, while reiterating full-year PV module shipment guidance to be in the range of 5.5GW to 5.7GW in 2017.

In reporting first quarter 2017 financial results, management said in its earnings call that it was attempting to broaden its sales and product mix to mitigate market risks of being overly dependent of sales generated from the US and China.

"I would like to note that our industry is faced with uncertainties of near-term global demand outlook. Particularly into all largest cell demand markets namely China and the United States in the second half of 2017," noted Jay Seo, CFO of Hanwha Q CELLS in the earnings call.

"Any module changes in demand trend from these two largest markets can create cascading effects to global solar demand dynamics and pricing trends across [the] solar value chain. For this reason, our key strategic focus here will be the diversification of our revenue profile by region and by market segment and to strengthen our sales backlog to maximize our operational visibility throughout 2017 and into 2018. From our product side, 2017 will be a transitional year for our portfolio," added Seo.

From the lab

ISC Konstanz to spearhead new PV research centre in Chile

German PV research institute ISC Konstanz is leading the development of a new solar development laboratory in Chile.

With the backing of the Chilean government, ISC Konstanz, Fraunhofer Chile, SERC and the French CEA INES will pursue the lowest LCOE possible through a range of activities including optimising desert performance, tracking and bifacial modules. The work will cover soiling, system design and the best module configurations for the harsh climatic conditions.

"It will not be testing only but developing [products] too," said Radovan Kopecek, CTO at ISC Konstanz. "We will set up a module pilot line where we will test and develop new components, new stringing, new design and so on," he added.

The Atacama Module and System Technology Center (AtaMoS-TeC) will spend the first 18-24 months with the member institutes continuing development of their desert modules. During this period of ongoing work, the

Credit: ISC Konstanz

ISC Konstanz' AtaMo technology in the field at the PDSA testing site in the Atacama desert.

News

centre's building will be constructed and equipment assembled for the pilot line.

At that point, a staff of 25-30 researchers will begin working at the facility.

Kopecek told PV Tech that the partnership with CORFO, Chile's economic promotion body, will look to stimulate use of the new facility's research in mainstream production. A policy of technology transfer will also ensure that other countries with desert conditions can benefit from its work.

Industry partners, including Enel, Colbún, Mondragón and Cintac have contributed US$5 million with CORFO providing US$12 million of funding for the project.

JinkoSolar pushes bar on anti-PID testing

Leading 'Silicon Module Super League' member JinkoSolar has raised its potential-induced degradation (PID) resistance test metrics for its standard 1,000V and its 1,500V solar modules, using an extended IEC62804 standard.

The IEC62804 test includes a 96-hour PID resistance test under the conditions of 85% degrees and 85% relative humidity ("double 85") at +/-1,000V, with a degradation of less than 5%.

JinkoSolar said that its standard 1,000V 'mass produced' modules had their guaranteed performance time improved to 192 hours under the IEC62804 double anti-PID standard. The company had said in November, 2016 that it had met the 96-hour PID conditions.

JinkoSolar also said that its 1,500V modules had also met the 96-hour PID resistance test.

"JinkoSolar's products deliver a stable performance over their entire service life. We have taken the extra step that exceeds industry standards to guarantee the performance. We are the first module manufacturer to guarantee that all our Standard Mass Produced PV Modules meet the IEC double anti-PID resistance standards. I am confident this will create a better and more secure investment environment for our customers," said Kangping Chen, CEO of JinkoSolar.

India

Indian glass capacity enough for domestic solar manufacturers says anti-dumping petitioner

India has enough tempered solar glass capacity to cater for its own PV manufacturers despite the introduction of anti-dumping duties against certain tempered glass imports from China, according to the Indian firm that originally petitioned for the trade measures.

India's largest solar glass firm Borosil Glass Works was the sole anti-dumping petitioner in a recent investigation, despite there being a number of other tempered glass suppliers in India. This is because Borosil is the only Indian supplier that produces its own annealed (raw) glass rather than importing.

Borosil vice chairman Pradeep Kheruka told PV Tech that other Indian firms over the last 15 years have tended to import annealed glass from China before having it tempered and supplying it locally to the solar industry.

This month the Ministry of Finance went ahead with tariffs on tempered glass from China where at least one side is more than 1,500mm, with a minimum 90.5% transmission and a thickness of less than or equal to 4.2mm. The anti-dumping duties will be in the range of US$52.85/MT to US$136.21/MT.

Piyush Goyal warning on Indian solar quality – 'We are watching your performance'

Stricter quality standards are due to be brought in for Indian solar tenders, including inspections for modules, cells and wafers, according to energy and mines minister Piyush Goyal.

Issuing a warning to both developers and manufacturers at the Indo-German Energy Forum in June, Goyal said: "Bear in mind we are watching, we are watching your performance."

The Ministry of New and Renewable Energy (MNRE) had already released a draft technical regulation for testing and standardisation of solar equipment last August. This came after months of industry commentators expressing fears over the quality of equipment being brought into India, particularly with the plummeting of solar project tariffs.

Since then, manufacturers from Taiwan, China and India have all told PV Tech that tier-one manufacturers tend to have to give their lowest priced bill of materials to the Indian market, given the focus on cost reductions. This has led to fears about whether other less reliable equipment is entering the country.

Goyal has now said: "Quality standards are going to be tightened for all future bidding. There will be inspection of facilities before we approve people for their ability to participate in tenders, so even developers will have to procure from approved companies [only]."

Bifacial

News

Jolywood partners with TUV NORD and CPVT on preliminary testing standard for bifacial solar modules

Dedicated n-type monocrystalline module manufacturer Jolywood (Taizhou) Solar Technology Co. Ltd (Jolywood) has collaborated with TUV NORD and the National Center of Supervision and Inspection on Solar Photovoltaic Product Quality (CPVT) to establish a preliminary testing standard for bifacial solar modules.

The company said that it had recently held a seminar with the testing organizations related to the best testing methods for bifacial modules based on long-term outdoor testing, laboratory research validation and collection of data.

Jolywood noted that the 'I-V test method was preliminarily confirmed after discussions on bifacial solar cell modules, including test conditions, test methods and processes, nominal requirements for module nameplates, test reports and other relevant elements. At the same time, the corresponding recommended values of the standard have also been proposed in accordance with different installation sites.'

Liu Yong, CEO of Jolywood Solar Technology said: "This a significant step forward for Jolywood. We expect it to bring commercial success. Jolywood is committed to promoting further cost-cutting in the breakthrough technology and its large-scale application in order to inject new momentum into the industry."

Enel, National Research Council found renewable energy lab to develop bifacial modules

Enel Green Power (EGP) has partnered with the Italian Institute for Microelectronics and Microsystems (IMM) of the National Research Council (NRC) to create a dedicated laboratory to explore renewable energy technologies, and in particular, develop bifacial PV modules.

The new institution will be located within the Enel Innovation Lab at Passo Martino, near Catania in Sicily. The installation of the new lab, with a core of researchers specialized in the science and technology of materials and devices, is intended to develop the site as an Innovation Campus and promote the growth of start-ups in the renewable energy sector.

Credit: Florian Solar Products

Enel and IMM are creating a new laboratory at Passo Martino, near Catania in Sicily, to explore new technologies, including bifacial.

As well as the development technologies for bifacial modules, the lab's activities will mainly focus on the development of solar cells and high-efficiency PV systems, with a special focus on reliability and cost, EGP has said.

Advanced structures for silicon solar cells will also be studied and developed in order to increase the efficiency of power generation, as well as high-efficiency and low-cost generation technologies to be used to mimic a process similar to photosynthesis with artificial structures.

Bifacial will be mainstream in two years says LONGi

Bifacial modules will be the standard utility-scale PV product for LONGi Solar, according the company's president.

Speaking to PV Tech, Zhenguo Lee said that the company had a lead on the rest of the industry but expected them to follow shortly after.

"Our plan in two years, is that [p-type mono PERC] bifacial modules will be our mainstream product and we expect that in three to five years this industry will be using bifacial. Except for certain residential applications, where there is not enough distance behind the panel," he said.

"Customers only need to pay a little extra to get a big return from the back side. That's the beauty of bifacial products," he added, warning that it was important for manufacturers to create some consistency around the panels and how specifications are presented to customers.

"As of today we don't have product industry-wide standards for bifacial modules. We choose to list the front and rear power output so that customers can use these for their system design and assess what boost they can get from the rear," said Lee.

According to LONGi, even grassland surfaces under a bifacial array can offer a 10% boost to generation, which it believes will ensure take-up of the technology in all markets, not just those where typical project sites have a high albedo such as on water or pale desert.

JinkoSolar collaborates with TUV Rheinland on bifacial module testing standards

Leading Silicon Module Super League (SMSL) member JinkoSolar said it had been collaborating with TUV Rheinland to develop standardized testing methods for bifacial PV module technology.

JinkoSolar noted that it had already been working in this area, having convened the IEC/TC82 solar cell working group and efforts by Dr. Jin Hao, VP of JinkoSolar and had been inviting domestic and foreign experts to discuss draft testing procedures for IEC60904-1-2 bifacial standards and gy.

The company also said that it had joined a working group organized by Dr. Christos from TUV Rheinland to develop standardized testing methods with a draft of the testing method having recently been released for review.

Dr. Jin Hao said: "As an industry leader, JinkoSolar has deployed considerable resources towards further developing its bifacial technology and standardizing testing methods. We will continue to work with authoritative independent technical service providers such as TUV Rheinland to further study and standardize testing methods for bifacial modules used in outdoor power generation systems."

Complex problems require simple solutions: How to measure bifacial devices correctly?

Radovan Kopecek & **Joris Libal**, ISC Konstanz, Germany

ABSTRACT

Bifaciality is making significant inroads into the PV market. However, besides further technological developments in cost-effective cells, modules and systems, there are still many other issues that need to be addressed. One of the most important of these is the standardization of bifacial measurements for solar cell and modules. This paper summarizes the actions and status in the area of standardization.

Introduction

LONGi, Jolywood and many other large PV manufacturers claim that bifacial mono c-Si technology is the future [1,2]. Since 2015, bifacial PV installations have been entering multi-MW installation levels [3], and are expected to enter multi-GW levels in 2018. Even now, many companies in India – such as Adani, Vikram Solar and Tata Power Solar – are taking (or planning to take) this route [4]. In addition, several large electrical energy suppliers – such as EDF, Enel and Imelsa – are heading in this direction, and EDF is in the process of installing a 90WMp bifacial system in Mexico [5].

Why are these companies doing this? The answer is simply because the bifacial gain in many cases justifies the additional costs associated with bifacial modules [3,6]. One good example is the 'La Hormiga' PV plant ('BiSoN Farm'), close to St. Felipe in Chile (Fig. 1), with a nominal power of 2.5MWp.

Before conditioning the ground, the bifacial gain at the La Hormiga plant was about 15%; after partial coverage of the ground with white quartz, the gain increased to 27%, but this is estimated to be 30% or more with full coverage. If these rough measurements are superimposed on the graph in Fig. 1(b) of reported bifacial gains for many PV systems (as indicated by the red dots), they lie very close to the expected average gain. At the moment, data are being collected and evaluated to include the real data points in this graph.

> "Commercially available PV system simulation programs available on the market cannot model the real bifacial gain correctly."

It is very difficult to promote and sell bifacial modules and systems even though real data already exist (as is the case for the 1.25MWp bifacial system built with modules from PVGS in 2013, which has generated an average bifacial gain of nearly 20% during three years' operation [7]). The bankability of bifaciality is still low, one reason being that commercially available PV system simulation programs available on the market (such as PVsyst) cannot model the real bifacial gain correctly. The beneficial impact of the distance of the modules from the ground on the rear-side contribution to the energy yield is generally underestimated. Whereas PVsyst yields a constant bifacial gain from heights exceeding 0.25m, the real values in systems (and using, for example, view factor modelling) are still significantly increasing for heights up to 1.5m, depending on the ground albedo [8].

Another important challenge is the lack of qualification standards for *I–V* measuring and other aspects. One of the reasons is that, because there are a large number of applications and even greater variations in values for ground albedo, it is difficult to define fair standard measuring conditions (STC). In addition, bifacial electrical gain is affected differently in various geographic locations: it very much depends on the availability of diffuse

(a) (b)

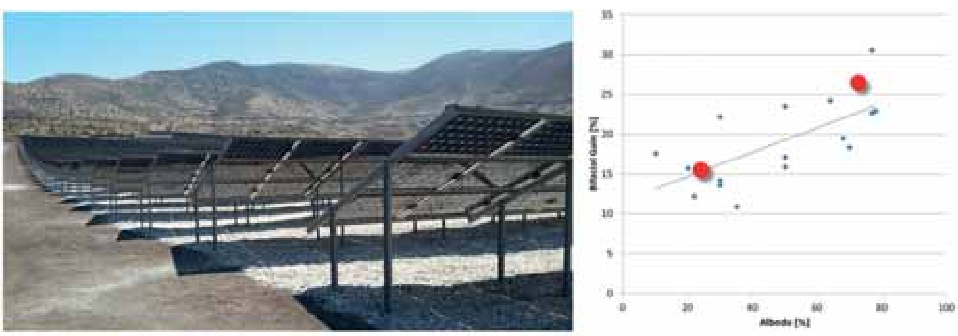


Figure 1. (a) La Hormiga PV plant, where up to 30% bifacial gain has been observed. (b) Reported bifacial gain as a function of albedo for many installed PV systems; the red dots indicate the La Hormiga rough measurements.

sunlight compared with direct sunlight. Total electrical production for bifacial modules is therefore more difficult to predict than for monofacial ones; however, because this issue is important for the bifacial roadmap of many large companies, there are currently various actions in progress for standardization. In Asia many (but also uncoordinated) actions in respect of standardization have been reported [4]:

> Earlier this month, the Chinese solar major, Jinko Solar, teamed up with TÜV Rhineland, the German testing, inspection and certifying agency, and a respected name in the solar industry, to evolve testing standards for bifacial modules. Jinko is, however, not the first. Yingli, the supplier to the world's biggest bifacial solar plant of 50MW in China, is evolving standards in-house, while Jolywood (Taizhou) Solar, has tied-up with TÜV Nord for bringing out testing standards.

The European bifacial consortium, led by Pasan, submitted standard measuring conditions to the IEC in October 2016. The IEC committee is scheduled to comment on this by August 2017, after which the procedure can be fine-tuned. The focus of this paper will be on that proposal; before that, however, the different applications on the market of bifacial modules in large systems will be briefly described in the next section.

Bifacial PV systems: different applications

Whereas monofacial modules are limited in terms of their field of application, bifacial modules can be used in many different modes, making standardization much more complicated. Not only does the energy yield of two sides of a module need to be considered, but also the installation of the module in different arrangements leads to different and very interesting applications. Fig. 2 depicts the three most important installation geometries: (a) the classical slanted, sun-oriented set-up; (b) a horizontal mounting; and (c) a vertical installation. All of these installations have different expected bifacial electrical gains; however, they all make sense for different purposes. With a combination of different bifacial installation geometries, the electricity generation peak can be adjusted to match the electrical demand, which means less storage is necessary.

> "With a combination of different bifacial installation geometries, the electricity generation peak can be adjusted to match the electrical demand, which means less storage is necessary."

Standard slanted sun-oriented installation

This arrangement is used for maximum electrical harvesting and results in the highest power density; it can be employed in large field installations and flat rooftop systems. The bifacial gains as a function of ground albedo for these optimal installations were shown earlier in Fig. 1(b). However, low module installation heights may be necessary because of wind loads (e.g. in rooftop systems), in which case the bifacial electrical gain will be reduced. Depending on the ground albedo, this can lead to a very large decrease in bifacial gain [6]. If an albedo of 60% (for example) is assumed, a reduction from 25% to 15% in bifacial gain can be expected when the module height is reduced from 1m to 0.15m.

Horizontal installation

Horizontal installations are used, for example, for carport applications or for building integration on flat roofs. This arrangement is a special case of the previous installation, with an inclination angle of 0°.

Vertical installation

Vertical installations (90° inclination angle) are very attractive options when using bifacial modules. The most interesting case is when the sides of the module are oriented towards the east and the west: in this case a high bifacial coefficient is required, because in the morning, one side faces the sun, while in the late afternoon, the other side assumes this role. Applications for this geometry are manyfold: field installations, flat-rooftop systems, facade applications and even sound-blocking PV systems. As the electrical generation peak is different from that in the south-oriented case, there are many business cases relating to how to make use of this special shape of the electrical generation curve. More electricity can be generated in the morning and late afternoon, and less during the noontime period; therefore less storage is needed.

Bifacial solar cell measurement

The *I–V* measurement of a monofacial solar cell is quite simple: various chucks and various contacting methods can

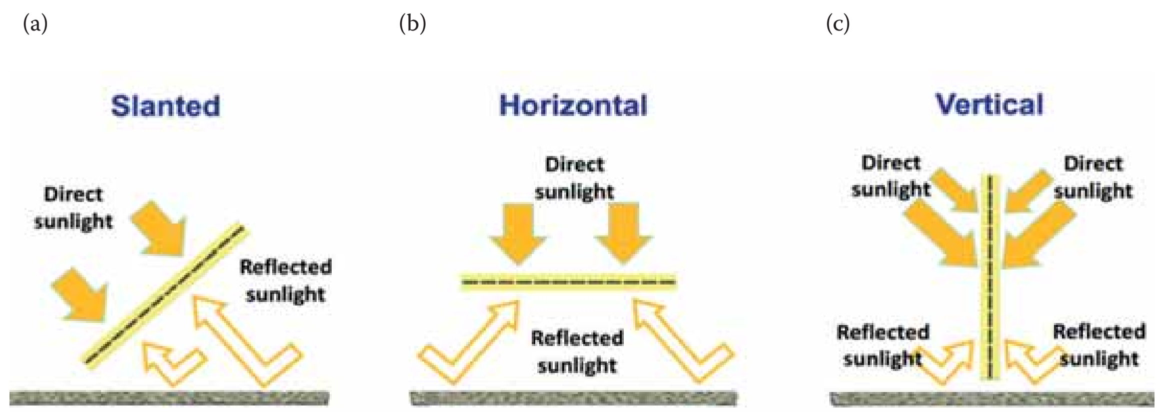


Figure 2. Possible installation geometries for bifacial modules: (a) slanted, (b) horizontal, (c) vertical.

be used, and the same electrical results will be obtained. Even so, round robins at different institutes lead to slightly different electrical parameters I_{sc}, V_{oc} and FF and resulting efficiencies. For the most part, the values for FF differ as a result of the various contacting methods – if a conducting chuck is employed at the rear side, or if a scissor system (two-sided contact bars with spring-loaded pins) is used.

The measurement of bifacial cells becomes more complicated, since the rear side is open and contributes to the electrical gain. As the rear side of a bifacial cell is more advanced than in the case of standard Al-BSF technology, the efficiencies are currently well in excess of 20%, and even approach 22% for some PERC+ and PERT cells. This goes hand in hand with an increase in the V_{oc} of such cells, and therefore in the electrical capacity of the solar cell. As a consequence, longer light pulses are required for the I–V measurement of bifacial cells than those used with Al-BSF solar cells: the standard pulse lengths of 5ms are not sufficiently long to correctly measure the efficiency. For voltages of 660–670mV (screen-printed PERC, PERT), pulse lengths of about 50ms are necessary, whereas for 720mV (passivated contacts, HJT), as much as 200ms is required.

"The measurement of bifacial cells becomes more complicated, since the rear side is open and contributes to the electrical gain."

Fig. 3 shows the different possibilities for the measurement of bifacial solar cells. The differences in all cases are the front- and rear-side contacting, and whether only the front side, or subsequently the rear side, is illuminated. It will be seen later, in the measurement standard paragraph, that bifacial cells too can be measured and the bifacial gain determined using just one illumination source.

In the case of Fig. 3(a), the light source can only illuminate one side, and the rear contact is facilitated via a reflective and conductive measuring chuck. If bifacial modules are used, this case then provides currents that are too high, as the chuck creates additional reflection of the light penetrating through the solar cell. In addition, the fill factor is also too high, as the chuck results in additional lateral conductivity. The solution is to use a black non-conductive chuck, as shown in Fig. 3(b).

The differences in the electrical parameters when using these different chucks are shown in Fig. 4. These measurements, performed on one PERT solar cell at the CalLab at FhG ISE, were presented at the first bifacial PV workshop – bifiPV – in 2012 in Konstanz [9]. The difference in absolute efficiency is about 0.2%$_{abs.}$, mostly resulting from the higher current and fill factor.

Another attractive solution is to use scissor contacts: not only are the results the same as for the black non-conductive chuck, but with this method it is possible to illuminate the solar cell from the rear side as well. One option is to use an additional light source from the rear, as shown in Fig. 3(c), or alternatively an arrangement of mirrors can be employed, as shown in Fig. 3(d). In the latter case, the rear-side illumination, which corresponds to the albedo, can be simulated by using a filter. In the standardization paragraph it will be explained how the arrangements in Fig. 3(b) (one-sided illumination on a black chuck) and in Fig. 3(c) (two-sided illumination with scissor contacts) can both be used at STC for bifacial devices.

Bifacial module measurement

As illustrated in Fig. 5, bifacial modules can be measured in a very similar way to that described above for bifacial solar cells. Fig. 5(a) shows the measurement of a bifacial module at STC with one-sided illumination from the front side and undesired reflection from the rear side. Fig. 5(b), on the other hand, shows the set-up with no illumination from the rear side, used for a monofacial-like set-up for the determination of the front-side P_{max} at STC. Fig. 5(c) and (d) show two different possibilities for implementing two-sided illumination of a bifacial module with defined rear-side irradiance levels, by using either rear-side reflectors or an additional light source for illuminating the rear side of the module.

Bifacial measurement standards

This section will cover the most important points from the proposal for a bifacial I–V measurement standard submitted to the IEC committee in October 2016 [8], which will be commented on by the IEC committee in August 2017. The text uses in part the exact formulation from Fakhfouri [10].

The bifacial I–V characterization procedure, under consideration for the potential future IEC standard, defines two cases:

1. Measurements by PV laboratories
2. Measurements in PV production environments

The possibilities and the needs of these are different, but the measurement results provided are complementary. The combination of laboratory and production measurements allows good information to be gleaned, at a reasonable cost and complexity, about bifaciality and the expected bifacial power gain.

Measurements with two-sided illumination

A solar simulator with the possibility of simultaneously illuminating the bifacial device on both sides can be used (see Fig. 6(a)). Such simulators are able to provide irradiance at variable levels on the two sides, by using either two light sources or one light source in combination with mirrors and grey filters. At the irradiance levels used for the characterization of bifacial devices, the non-uniformity of irradiance must be below 5% on both sides. The proposal for the new IEC standard stipulates:

- At least three different irradiance levels (G_{Ri}) on the rear side are required, each with simultaneous illumination of the front side with 1,000W/m^2.

- At least two specific P_{max} values, $P_{max_{BiFi10}}$ and $P_{max_{BiFi20}}$ for G_{R1} = 100W/m^2 and G_{R2} = 200W/m^2 respectively, must be reported.

- If the irradiance levels on the rear side do not correspond to G_{R1} and G_{R2}, $P_{max_{BiFi10}}$ and $P_{max_{BiFi20}}$ must be obtained by linear interpolation of the data series P_{max} versus G_{Ri}.

Measurements with one-sided illumination

Determination of bifacial coefficient

To determine the bifaciality

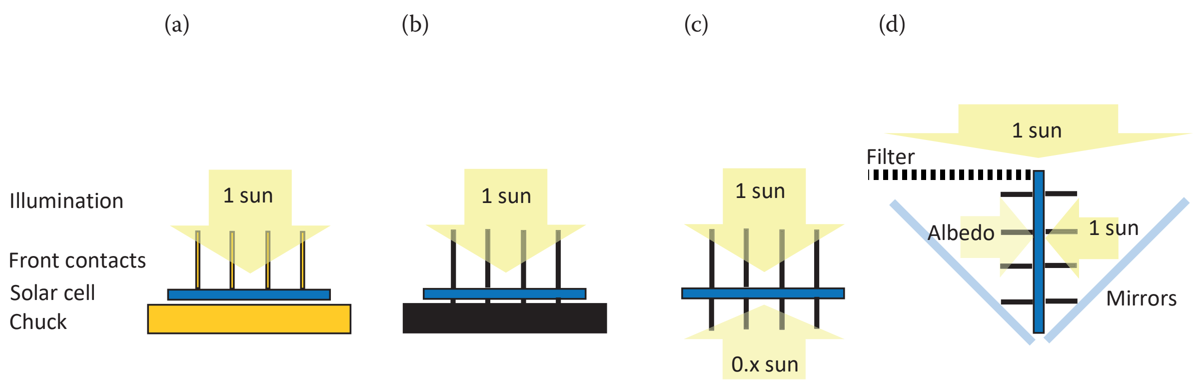
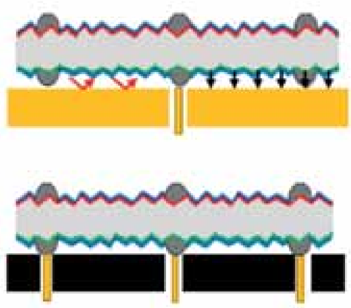


Figure 3. Possible measurement arrangements for bifacial solar cells.



Chuck	Jsc [mA]	Voc [mV]	FF [%]	eta [%]
Golden*	39.12	647.5	79.47	20.13
Black*	38.69	647.1	79.35	19.86
Combined	39.12	647.5	79.35	20.10
Δ	1.1%	<0.1%	0.2%	1.3%

(*ISE CalLab measurements)

Figure 4. Differences in electrical parameters when using different chucks [7].

coefficients of the test specimen, the main I–V characteristics of the front and rear sides must be measured at STC (G = 1,000W/m^2), as shown in Fig. 6(b1) and (b2). A non-reflecting background must be used in order to avoid the illumination of the non-exposed side. The non-exposed side is considered to be non-irradiated if the irradiance is measured to be below 3W/m^2 on at least two points of the non-exposed side of the device, while also fulfilling the requirement of a non-uniformity of irradiance of less than 5% for the front and rear sides.

Short-circuit current bifaciality coefficient φ_{Isc}, usually expressed as a percentage, is the ratio between the short-circuit current generated exclusively by the rear side of the bifacial device and that generated exclusively by the front side:

$$\varphi_{Isc} = \frac{Isc_r}{Isc_f} \qquad (1)$$

where Isc_x is the short-circuit current at STC under one-sided illumination, with index x = 'f' for front side and 'r' for rear side. Both currents are measured at STC (1,000W/m^2; 25°C; IEC 60904-3 reference solar spectral irradiance distribution).

The spectral mismatch correction shall be applied to the measurement of Isc_f and Isc_r in accordance with IEC 60904-7, unless it is known that the front and the back of the bifacial device have identical spectral responsivities.

Other bifaciality coefficients shall be reported and are calculated from:

$$\varphi_{Voc} = \frac{Voc_r}{Voc_f} \qquad (2)$$

$$\varphi_{Pmax} = \frac{Pmax_r}{Pmax_f} \qquad (3)$$

where ϕ_{Voc} is the open-circuit voltage bifaciality coefficient, ϕ_{Pmax} is the maximum power bifaciality coefficient, Voc_x is the open-circuit voltage, and $Pmax_x$ is the maximum power. Both of the last two are obtained with one-sided illumination at STC, where the index x again indicates front-side (f) or rear-side (r) illumination. Spectral mismatch corrections shall be applied in accordance with IEC 60904-7 in the above-mentioned calculations.

Measurement at equivalent irradiance levels

To carry out indoor measurement of the power generation gain, a standard solar simulator with adjustable irradiance levels for one-sided illumination can be used. At least three different irradiance levels on the rear side are required. Two specific Pmax values, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ for G_{R1} = 100W/m^2 and G_{R2} = 200W/m^2 respectively, must be reported. Again, if the irradiance levels on the rear side do not correspond to G_{R1} and G_{R2}, $Pmax_{BiFi10}$ and $Pmax_{BiFi20}$ must be obtained by linear interpolation of the data series Pmax versus G_R.

The quantities $Pmax_{Bifi10}$ and $Pmax_{Bifi20}$ for the device must be measured by illumination of just the front side with equivalent irradiance levels G_{Ei}; these levels depend on the bifaciality coefficient, corresponding to 1,000W/m^2 on the front side, plus different rear-side irradiance levels G_{Ri} (see Fig. 6(b3)). The equivalent irradiance levels are thus:

$$G_{Ei} = 1{,}000 + \varphi \cdot G_{Ri} \qquad (4)$$

where ϕ is equal to the smaller of ϕ_{Pmax} and ϕ_{Isc}. For example, a device with a maximum power bifaciality of ϕ_{Pmax} = 80% must be irradiated on the front side at the level G_{E2} = 1,160W/m^2 in order to provide the equivalence of G_{R2} = 200W/m^2. The Pmax measured under this illumination level G_{E2} corresponds to the quantity $P\text{max}_{\text{BiFi20}}$.

I–V characterization of bifacial devices in practice

Two cases are to be considered for the *I–V* characterization of bifacial devices. The first case is where the bifaciality coefficients of the test specimen are not known, which is common for newly developed or modified devices, and when the measurements are performed by PV laboratories or accredited agents. The second case is where the bifaciality coefficients of the test devices are known, which is typical in PV manufacturing environments, when reference devices of the same technology as the devices to be tested are available.

In PV laboratories the procedure is as follows. First, *I–V* measurements under STC are performed separately for both sides of the test device. From these *I–V* curves, the bifaciality coefficients of the test device are determined. When the test device is to be used as a reference device, the key data is reported for both sides under STC with monofacial irradiance. To report the bifacial power gain, it is necessary to determine $P\text{max}_{\text{BiFi10}}$ and $P\text{max}_{\text{BiFi20}}$, either directly from measurements or from linear interpolation of measurements at other equivalent irradiance levels.

To determine the bifacial power gain in PV production facilities, where reference devices are available, the PV panels are measured under STC at an irradiance level of 1,000W/m^2 only on the front, yielding monofacial-like values. To report the bifacial power gain, the values of $P\text{max}_{\text{BiFi10}}$ and $P\text{max}_{\text{BiFi20}}$ are calculated, at the appropriate equivalent irradiance levels, by applying the bifaciality coefficients of the reference device. The main differences are summarized in Table 1.

In addition to the indoor measurement procedures described here, the proposal for the new *I–V* measurement standard for bifacial modules describes also the possibility of obtaining $P\text{max}_{\text{BiFi10}}$ and $P\text{max}_{\text{BiFi20}}$ from outdoor measurements and appropriate extrapolations.

It is important to standardize not only the parameters from the *I–V* characteristics, but also the qualification procedures followed by quality-assurance institutions, such as TÜV. In the latter, it is even more difficult to agree on standardization procedures, since the bifacial cell and module manufacturers (as already mentioned) work with different institutions [4].

Some of the most crucial procedures to be agreed upon (which differ from those for the classic double-glass module) include testing bypass diodes at maximum current (which has to be defined), and measuring potential-induced degradation (PID), which can now affect both sides. Depending on the specific application, even hail-

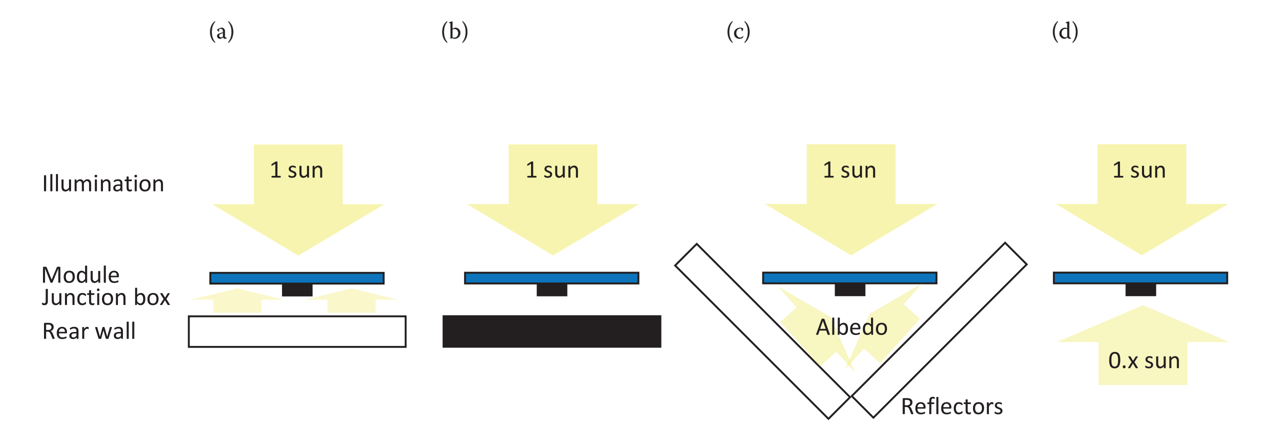


Figure 5. Possible measuring arrangements for bifacial modules.

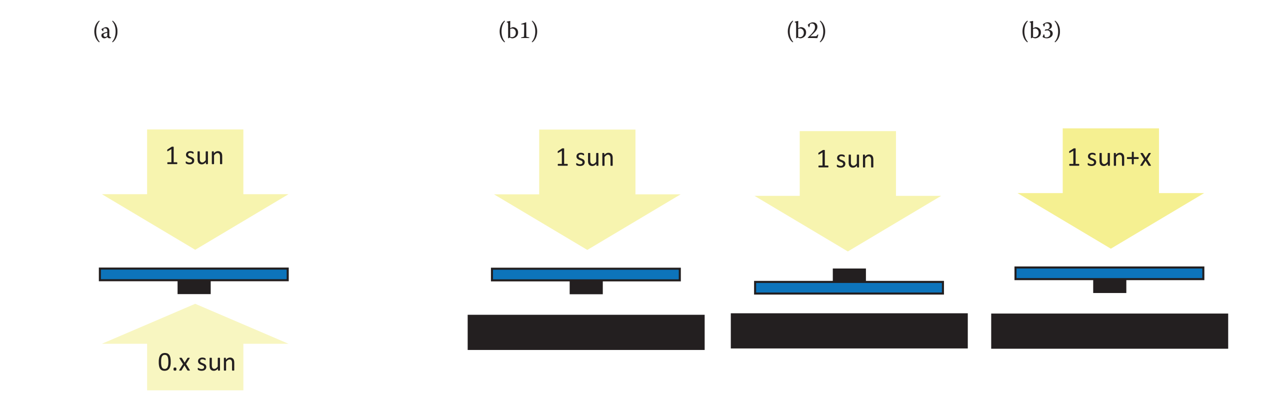


Figure 6. Possible standardized measurement methods for bifacial modules.

PV laboratories	PV production	
I–V measurements	STC front STC rear Possibly front @ G_E	STC front
Bifaciality coefficients	Calculate φ	Use φ (reference device)
Bifacial gain	Measurement or calculation: $P_{max} = f(G_R \text{ or } G_E)$	Calculation: $P_{max_{BiFi10}}$ and $P_{max_{BiFi20}}$
Reporting	Key data at STC $P_{max} = f(G_R \text{ or } G_E)$	$P_{max_{STC}}$ $P_{max_{BiFi10}}$ and $P_{max_{BiFi20}}$

Table 1. Differences in bifacial *I–V* characterization in practice.

impact tests will have to be performed on the rear side (such as in the case of vertical installations). It is therefore expected to take a long time to define qualification standards.

> "It is important to standardize not only the parameters from the *I–V* characteristics, but also the qualification procedures followed by quality-assurance institutions."

How to sell bifaciality?

It is still extremely difficult today to sell bifacial solar cells and modules, as installers are not used to this product. Large PV systems are installed by electricity providers (EDF, Enel, Imelsa, Yingli, etc.) who have gained experience with bifacial installations on a small scale and have themselves proved the bifacial gains.

The difficulty is also due to the absence of reliable commercially available bifacial simulation programs on the market, as well as the lack of standards for bifacial measurements. So far, no bifacial module manufacturer has used the proposed measurement standard described earlier. There is a great deal of reported in-house data on bifacial gains, which is extremely confusing to customers. The question has arisen during bifacial workshops as to whether a certain bifacial gain must be guaranteed in order to be able to sell bifaciality. From these discussions, a bifacial gain guarantee of 10–15% is considered to be realistic, as this represents the lowest value when some basic installation rules are fulfilled.

Summary and outlook

The bifacial technology share of the market is rapidly growing; indeed, the ITRPV predicts that in 2024 about 20% of the market will use bifacial products [11]. As discussed in this paper, however, the bifacial community still has to work on many issues, such as standards and qualifications, simulations and bankability. All these topics are scheduled for discussion at the 2017 bifiPV workshop in October 2017 in Konstanz [12], where everyone is invited to participate and cultivate the future of bifaciality. .

References

[1] PV-Tech 2017, "Intersolar Europe 2017: Bifacial will be mainstream in two years says LONGi", News report [https://www.pv-tech.org/news/intersolar-europe-2017-bifacial-will-be-mainstream-in-two-years-says-longi].

[2] PV-Tech 2017, "SNEC 2017: The next big solar module trend on display", Editor's blog [https://www.pv-tech.org/editors-blog/snec-2017-the-next-big-solar-module-trend-on-display].

[3] Kopecek, R. & Libal, J. 2017, "Quo vadis bifacial PV?", *Photovoltaics International*, 35th edn, pp. 86–91.

[4] The Hindu Business Line 2017, "Solar modules that provide energy from both the sun and reflected light are set to alter the game" [http://m.thehindubusinessline.com/specials/clean-tech/bifacials-solar-solar-energy-india-solar-panels/article9775926.ece].

[5] pv magazine 2016, "EDF wins 90 MW solar project in Mexico's second auction" [https://www.pv-magazine.com/2016/10/04/edf-wins-90-mw-solar-project-in-mexicos-second-auction_100026345/].

[6] Kopecek, R., Shoukry, I. & Libal, J. 2016, "Cost/kWh thinking and bifaciality: Two allies for low-cost PV of the future", *Photovoltaics International*, 30th edn, pp. 88–97.

[7] Nishiyama Sakata Denki Co. Ltd 2017 [http://www.nishiyama-s-denki.co.jp/].

[8] NREL internal communications on ISC's comparative simulations/comparison with experimental results.

[9] Lossen, J. 2012, Presentation, 1st bifiPV Workshop, Konstanz, Germany.

[10] Fakhfouri, V. (IEC project team) 2016, "IEC 60904-1-2: Measurement of current-voltage characteristics of bifacial photovoltaic devices", 3rd bifiPV Workshop, Miyazaki, Japan.

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

[12] bifiPV Workshop [www.bifiPV-workshop.com].

About the Authors

Dr. Radovan Kopecek is one of the founders of ISC Konstanz. He has been working at the institute as a full-time manager and researcher since January 2007 and is currently the leader of the advanced solar cells department. Dr. Kopecek received his M.S. from Portland State University, USA, in 1995, followed by his diploma in physics from the University of Stuttgart in 1998. The dissertation topic for his Ph.D., which he completed in 2002 in Konstanz, was thin-film silicon solar cells.

Dr. Joris Libal works at ISC Konstanz as a project manager, focusing on business development and technology transfer in the areas of high-efficiency n-type solar cells and innovative module technology. He received a diploma in physics from the University of Tübingen and a Ph.D. in the field of n-type crystalline silicon solar cells from the University of Konstanz. Dr. Libal has been involved in R&D along the entire value chain of crystalline silicon PV for more than 10 years.

Enquiries

ISC Konstanz
Rudolf-Diesel-Straße 15
78467 Konstanz
Germany

Tel: +49 7531-36 18 3-22
Email: radovan.kopecek@isc-konstanz.de

Detailed power loss/gain characterization of PV modules with multi-busbar, half-cut cells and light-trapping ribbon

Jai Prakash Singh[1], Yong Sheng Khoo[1], Cai Yutian[1], Srinath Nalluri[1], Sven Kramer[2], Axel Riethmüller[2] & Yan Wang[1]

[1]Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS), Singapore;
[2]teamtechnik Maschinen und Anlagen GmbH, Germany

ABSTRACT

Compared with three-busbar (3-BB) full-cell designs, the use of multi-busbar and half-cut cell technologies can significantly reduce resistive losses and thus allow higher cell and module efficiencies. At the same time, there is a net reduction in silver paste consumption for the electrodes of the solar cells. In addition to these approaches, light-trapping ribbon (LTR) has also shown potential for improving PV module performance. This paper presents a detailed simulation- and experiment-based study of the power gain arising from the implementation of multi-busbar, half-cut and LTR approaches. Both cell and module performance were modelled using a 2D finite-element grid modelling software package (Griddler) developed by SERIS. Several single-cell and large-size modules were fabricated, and the performances of various module designs were compared. On the basis of the results from the experiments and simulations, the optimum design (number of busbars, busbar width, number of fingers, etc.) of the cell/module was determined. The results show that, compared with a widely used 3-BB full-size cell module, an optimized multi-busbar halved-cell module with LTR can enhance the module performance by more than 5%. Finally, an economic analysis considering the change in the design is presented.

Introduction

To guarantee the long-term competitiveness of the PV industry, the cost of PV power generation ($/kWh) must be continuously reduced. Such reduction can be achieved in two ways: 1) by improving PV module performance (efficiency, annual energy yield, reliability); 2) by reducing manufacturing costs ($/Wp).

To improve the module efficiency/power, various advanced technologies can be incorporated, such as multi-busbar [1,2], halved-cell [3,4] and light-trapping ribbon [5,6]. These technologies have yielded promising results in terms of improving module performance. Multi-busbar technology has a twofold effect on module performance and cost: 1) higher cell efficiency as a result of the reduction in the effective finger length and lower silver consumption (narrower fingers); 2) greater module power as a result of the reduction in the effective series resistance of the interconnecting ribbons [7,8]. In addition, halved-cell modules also show promising potential for improving module performance with minimal cost increase. The increase in performance of halved-cell modules is the result of improved fill factor (*FF*) because of the reduced resistive power loss in the ribbons, and improved current because of the 'static concentration' effect of light scattered from the backsheet [4,9].

This paper investigates the electrical and optical effects on module performance of using multi-busbar, halved-cell and light-trapping ribbon approaches. Detailed simulation and experimental studies have been performed to quantify the gain in module power using the above-mentioned approaches compared with the widely used three-busbar (3-BB) full-cell PV module design.

> "A multi-busbar approach is an effective way to improve module performance."

Theoretical background

Multi-busbar module

It is well known that solar cell metallization significantly affects the optical and electrical performance of the cell and module. Optical performance is influenced mainly by optical shading due to metal coverage, which directly impacts the short-circuit current (I_{sc}) in the solar cell and module. At the same time, the cell metallization affects the electrical performance because of the series resistance introduced by the metal finger grid, metal-semiconductor contact resistance and emitter resistance. In the case of a PV module, the electrical performance is mainly influenced by the effective ribbon series resistance [3]. To enhance the cell/module power, the front metallization should therefore be optimized for minimum shading and resistive losses. A multi-busbar approach is an effective way to improve module performance, since it can offer the following advantages:

1. The metal grid finger length is shortened, which results in a reduction in effective finger resistance; thus, narrower fingers can be used (Fig. 1, bottom).

2. As the number of busbars increases, less current flows in each busbar and ribbon; this reduces the resistive losses in the ribbon, and a narrower busbar (and ribbons) can then be used to reduce the ribbon shading.

3. The use of less material (silver paste and copper ribbons) can offer a significant saving.

Accordingly, the solar cell and the stringed solar cell should be optimized for finger width/height, number of fingers, number of busbars, busbar width and ribbon width, while considering the optimum performance at the module level. These parameters are optimized using simulation software and presented in the next section.

Halved-cell module

Another approach to improving the module performance is using halved-cell modules. Cutting cells in half is an effective way of decreasing the resistive power loss in PV modules, since this can reduce the amount of current flowing in each ribbon by half. Halved-cell modules have been reported by several researchers and PV module manufacturers: the method has already been applied by some major PV module manufacturers (Mitsubishi, REC, BP Solar) in their commercially available PV modules [10,11].

> "Halved-cell PV modules yield not only improved electrical performance but also better optical performance."

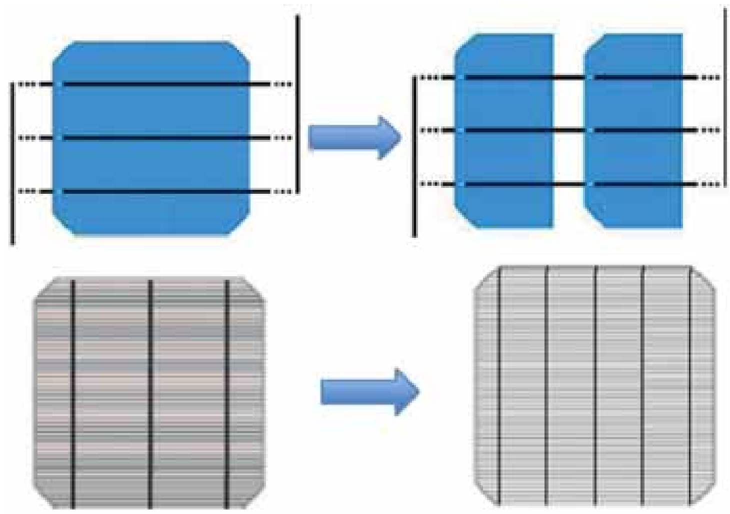


Figure 1. Schematics of half-cut and multi-busbar cell approaches.

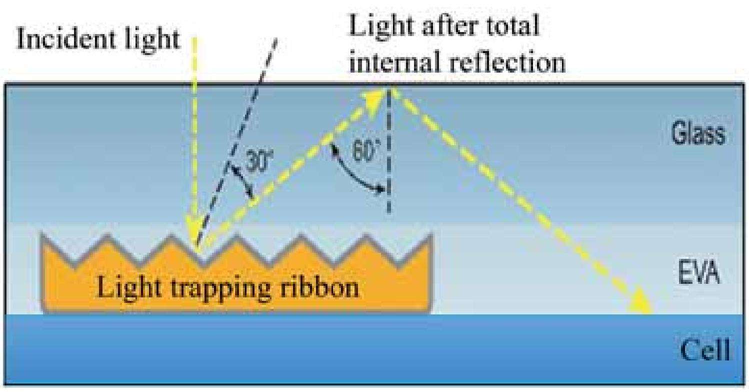


Figure 2. Light trapping in a PV module using LTR.

Fig. 1 (top) shows the schematics of two stringed half-cut solar cells. Halved-cell PV modules yield not only improved electrical performance but also better optical performance, resulting in higher currents compared with full-size cell modules. The higher module current is mainly due to the static concentration effect of light incident on the cell-gap region of the module, as described in Guo et al. [4] and Singh [9]; this effect, however, is not included in the current study.

Light-trapping ribbon

In a wafer-based PV module, most of the light incident on the conventional flat interconnecting ribbon is reflected back and escapes through the front glass. On the assumption of a ribbon reflectance of 100%, there is an optical loss of about 2.88% due to light reflection from the flat ribbon for a standard PV module with a 3-BB configuration and a ribbon width of 1.5mm. If the soldering ribbon is designed with a textured surface (such as a V groove), the light reflected by the ribbon will be at an angle to the module plane. If the groove height and spacing are optimized, it is possible that the light can be reflected at an angle greater than the total internal reflection angle for the glass–air interface. In this case, the light reflected at the ribbon will be totally internally reflected at the front glass–air interface and redirected onto the solar cells, thus increasing the module current generation potential. Such a ribbon can be termed a *light-trapping ribbon (LTR)* or a *light-harvesting string (LHS)* [5,12]. Fig. 2 shows the light path in a module with a textured ribbon (V groove).

Measurements and simulation results

Griddler, a 2D finite-element grid modelling software package developed at SERIS [13], was used to optimize the front-side metal grid for different numbers of busbars. The software simulates the *I–V* curves of the cell and the stringed cell (with ribbon) by calculating the voltage distribution throughout the cell; it considers all the electrical parameters of a solar cell (e.g. recombination properties and resistive components) as input to the model. For each number of busbars, the various metallization parameters – such as busbar width, number of fingers and finger width – that yield the highest module power are optimized. The power gains in all the different cases are calculated by comparing the performance with a standard 3-BB reference module with 1.5mm busbar widths. The finger width was kept constant at 45µm for all the different metallizations. The simulated cell parameters V_{oc}, I_{sc}, *FF* and efficiency for the 3-BB reference cell are respectively 632.9mV, 8.99A, 79.53% and 18.61%. Table 1 shows the simulation parameters used in the Griddler software to optimize the cell and module design.

Power gain and electrical performance of multi-busbar and halved-cell modules

Fig. 3 shows the simulation results for module efficiency/power gain for different numbers of busbars compared with a 3-BB full-cell module: it is seen that for a full-size cell module, a power gain of ~1.3% is achievable for a six-busbar (6-BB) configuration. This gain becomes greater if the multi-busbar approach is combined with the halved-cell approach: in total, a power gain of more than 4% is possible using a combination of the two approaches, as shown in Fig. 3 and Table 2.

In addition, Table 2 shows the optimized ribbon (and busbar) width for different module/cell configurations. The optimized values of busbar and ribbon also depend upon the ribbon availability and cost. Slight changes in the optimum width, however, will change the module power only marginally. For example, in a five-busbar (5-BB) full-cell module design, if a ribbon width of 0.9mm (busbar width 0.8mm) is used instead of an optimum ribbon width of 0.8mm, the module power from the simulation will be 267.2W (as compared with the 267.4W shown in the table). Thus, a ribbon width can be chosen on the basis of availability of the nearest possible width.

It should be noted here that the power gains presented in Fig. 3 do not include the gain due to the backsheet concentration effect resulting from the change in module design from full cell to halved cell. The power gains in the multi-busbar and halved-cell approaches mainly arise from improvements in the *FF* and I_{sc} of the module, as explained in the theoretical background section. The gain contribution due to an improvement in open-circuit voltage (V_{oc}) is minimal; this is mainly because of the reduction in semiconductor/metal recombination for less metal coverage. It should be noted here that the power gains from half-cut cell approaches for five and six busbars correspond to ribbon widths of 0.4mm and 0.3mm. In practice, however, the realization of such narrow ribbons will depend on the capability of the multi-busbar stringer, and this might reduce the achievable power gain. With the current teamtechnik stringer, a minimum ribbon width of 0.5mm can be used. Considering this limitation, the optimum half-cut design has 5-BB cells (0.5mm ribbon width) and a simulated module power of 274.9W.

Performance of PV modules using multi-busbar, half-cut cell and LTR technologies

If LTR is incorporated into the multi-busbar and half-cut cell approaches discussed earlier, the cell and module will have to be re-optimized accordingly. To find the optimum performance resulting from the use of LTR, the optical performance of this type of ribbon is first measured and quantified. This data is then used in Griddler to simulate the optimum parameters for the solar cells and modules. To measure and quantify the performance of LTR, external quantum efficiency (EQE) measurements are taken for single-cell mini-modules fabricated using LTR and standard ribbons. The EQE measurements are carried out on a number of points on the module area other than the ribbon, as shown in Fig. 4.

> "LTR can recapture more than 75% of incident light, whereas with normal ribbon this value is only ~4%."

Fig. 5 shows the EQE measurements on different ribbon (standard ribbon and LTR) areas and on the module active area. The EQE measurements on the ribbons are normalized using the J_{sc} (calculated using EQE) of the mini-module. The results show that LTR can recapture more than 75% of incident light, whereas with normal ribbon this value is only ~4%. This corresponds to a net current gain of ~2% for a standard 3-BB module with a ribbon width of 1.5mm.

With the use of Griddler and the measured optical properties of LTR, the cell was modelled and optimized for a given busbar width for different numbers of busbars (four, five and six) and for full-cell and halved-cell designs. For the simulation, the cells were assumed to be fabricated from the same wafer (differing only in metallization); hence, the cell/module parameters used were the same as those for the baseline 3-BB cell and module described in the previous section. Fig. 6 shows the simulated module power and performance gain for various module designs.

The corresponding LTR widths and cell busbar widths are given in Table 3. From the simulation results obtained, it can be seen that if a 6-BB full-cell is used in combination with LTR, a performance gain of ~3.6% can be achieved. If the halved-cell approach is also used in this combination, a total performance gain of more than 5% can be achieved.

Experimental results and discussion

To experimentally determine the power gain for a large-size PV module with the different approaches discussed earlier, four different types of PV module were fabricated. The solar cells used in this study were metallized as per optimized simulated screen design. For all of the metallization designs, pre-metallized cells from the same batch were used. A state-of-the-art teamtechnik stringer in the PV module lab at SERIS was then used to produce strings for the

Parameter	Value
Emitter sheet resistance	80Ω/sq.
Finger/busbar sheet resistance	3Ω/sq.
Contact resistance	$2.0m\Omega \cdot cm^2$
Finger width	45µm
J_{01} (passivated area)	$460fA/cm^2$
J_{01} (metal contact)	$960fA/cm^2$
J_{02} (passivated area)	$20nA/cm^2$
J_{02} (metal contact)	$50nA/cm^2$
Busbar width	variable (0.2mm–1.5mm)
Ribbon width	variable (0.3mm–1.7mm)
Ribbon thickness	0.2mm
Ribbon resistivity	$1.728\times10^{-8}\Omega \cdot m$

Table 1. Parameters used for front-grid optimization using Griddler simulations.

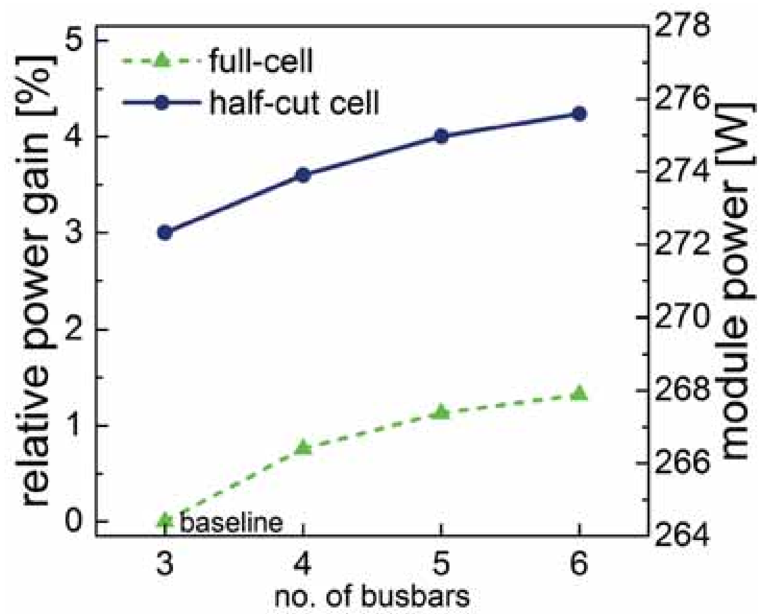


Figure 3. Simulation results for multi-busbar modules with full and halved cells. (A 3-BB full-cell module was chosen as the reference.)

Module type	Cell busbar width [mm]	Ribbon width [mm]	Simulated 60-cell module power [W]	Performance gain [%]
Baseline (3-BB full-cell)	1.5	1.5	264.4	–
4-BB full-cell	0.9	1.0	266.4	0.77
5-BB full-cell	0.7	0.8	267.4	1.13
6-BB full-cell	0.6	0.7	267.9	1.32
4-BB halved-cell	0.5	0.6	273.9	3.60
5-BB halved-cell	0.3	0.4	275.0	4.00
6-BB halved-cell	0.2	0.3	275.6	4.24

Table 2. Simulated module power and performance gain for multi-busbar and halved-cell approaches.

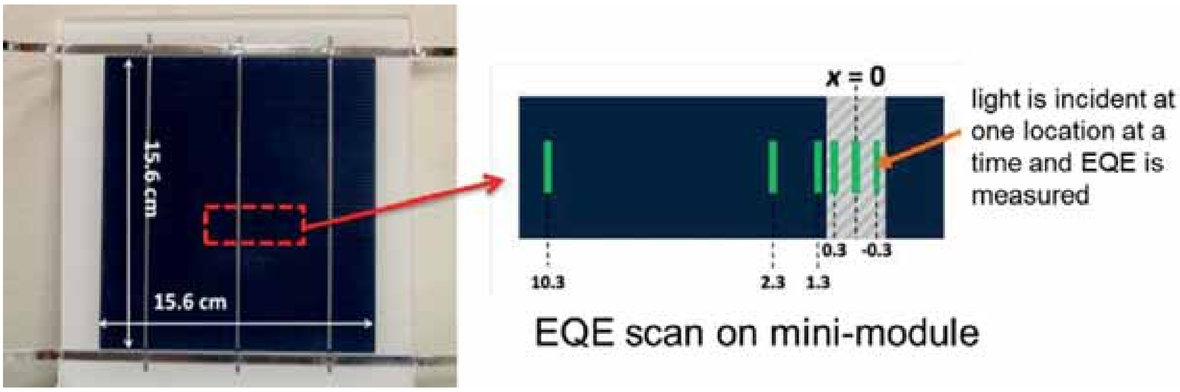


Figure 4. Measurements schemes for LTR and standard flat ribbon in a mini-module using a spot-area illumination spectral-response measurement system.

different cell designs, i.e. three, five and six busbars, with full and half-cut solar cells, as given in Table 4. This stringer can produce strings using 0.5mm-wide ribbon with a high accuracy of ribbon alignment to the solar cell busbar.

To fabricate halved-cell modules, the solar cells were cut in half using a nanosecond laser at SERIS's solar cell lab; the same material and processes were used to fabricate all these modules. The *I–V* characteristics of all the PV modules were then measured using a h.a.l.m. sun simulator (class $A^+A^+A^+$) at SERIS's PV module lab. The cell gaps and string gaps for full-cell modules were kept at 3mm and 5mm respectively. The halved-cell modules were produced with a cell gap of 2mm and a string gap of 5mm. LTRs from Schlenk [12] were used in this study; these were also characterized using EQE measurements on single-cell mini-module samples as described in the previous section. Photographs of sample modules are shown in Fig. 7.

> "The simulation and experimental results show that for the 6-BB with LTR design, the module performance can be improved by ~3.6%."

Table 4 lists the measured *I–V* parameters of the four modules, and Fig. 8 shows the performance gain of these modules relative to a 3-BB full-cell reference module. In the figure the performance gains obtained from the measurements of the experimental module samples are aligned with the corresponding simulation results

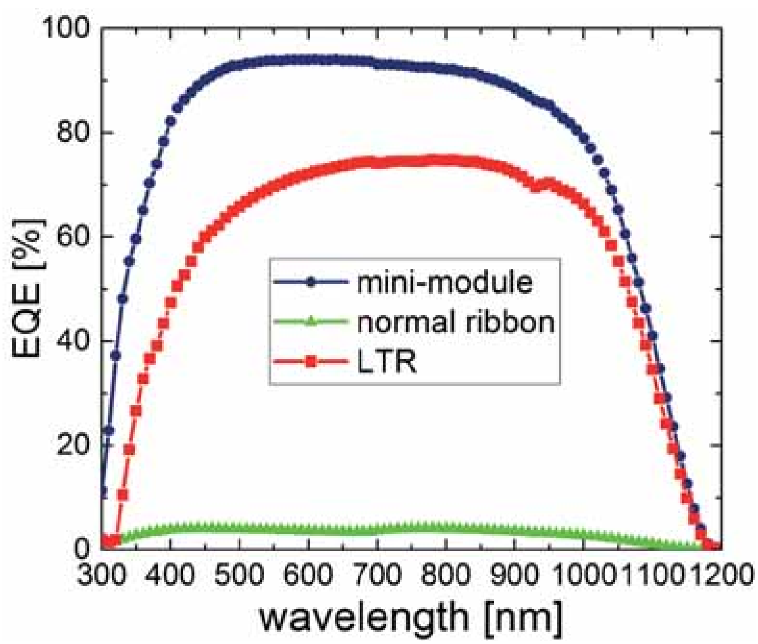


Figure 5. Measured EQE for the illumination points on LTR and normal soldering ribbon, and on the module active area (without ribbons).

presented in the previous section. The additional differences between full-cell and half-cell modules in comparison to the simulated results are mainly due to the optical gain from the backsheet static concentration effect, which was not considered in the simulation study.

The simulation and experimental results show that for the 6-BB with LTR design, the module performance can be improved by ~3.6%. The half-cut cell concept can be combined with the multi-busbar and LTR concepts in order to achieve a performance gain of more than 5%. This, however, will require additional cost associated with cell cutting, and potentially more stringers will be needed to produce the same MW of module power. Thus, the viability of half-cut concepts requires further study by considering the additional CapEx and cost.

Another interesting conclusion can be drawn when the power gains are compared with the results in the literature for multi-wire technology. A multi-wire module can enhance performance by ~1.76% compared with a standard 3-BB module [7]; however, the multi-wire module requires a completely new stringer, and the wire material will impose additional cost on the module. It is therefore more favourable to use a 6-BB stringer together with LTR, since this combination can provide the required enhancement to module performance without much investment and major modifications to the module manufacturing facilities.

Cost-benefit analysis

In an earlier section, the benefit of multi-busbar and LTR from a performance point of view was explored. Ultimately, module manufacturers care about the cost of the module; thus, a cost analysis is necessary in order to evaluate the technologies with regard to their economic feasibility. This section presents a cost analysis, taking into consideration both the silver saving because of different metallization techniques and the cost of LTR. The objective of the analysis is to achieve a minimum $/Wp cost of the PV module.

For the cost analysis, the relative costs of module components for a standard large-size PV module are required. With information from a market survey conducted by SERIS and the available information from module material manufacturers, the relative cost contributions of the module components for standard 60-cell PV modules were estimated and are given in Table 5. In addition to the information in Table 5, the silver cost is assumed to be 4.4% of the total solar cell cost in these cost calculations.

Now, by estimating the metal fraction for different cell designs and calculating the amount of ribbon required for the large-size module, it is possible to access the relative change in the module cost with respect to the baseline module (3-BB). Fig. 9 shows the relative change in the cost for different module designs with multi-busbar and LTR enhancements compared with a standard 3-BB module. It is interesting to note that, despite the higher power gain resulting from the LTR approach (discussed earlier), the cost reduction potential is limited for these module types compared with the multi-busbar approach; this is mainly because of the additional cost of LTR, whereas the increase in silver consumption with the use of wider busbars is only marginal. From the cost analysis in Fig. 9 it can be observed that the cost of the module with LTR does not change significantly when moving from six busbars to four: a 4-BB module with LTR can provide a potential

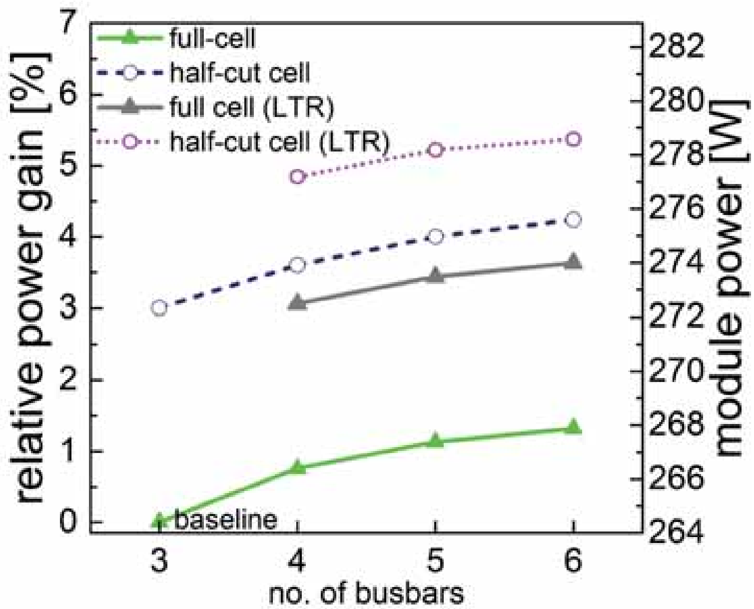


Figure 6. Simulated power gain and module power for multi-busbar, full-cell and LTR designs. (A 3-BB full-cell module was chosen as the reference.)

Module type	Cell busbar width [mm]	LTR width [mm]	Simulated module power [W]	Performance gain [%]
4-BB full-cell	1.4	1.5	272.5	3.06
5-BB full-cell	1.2	1.3	273.5	3.44
6-BB full-cell	1.0	1.1	274.0	3.63
4-BB halved-cell	0.7	0.8	277.2	4.84
5-BB halved-cell	0.6	0.7	278.2	5.22
6-BB halved-cell	0.4	0.5	278.6	5.37

Table 3. Simulated module power and performance gain using LTR for different cell/module types.

Module type	Front-side BB width [mm]	Ribbon width [mm]	I_{sc} [A]	V_{oc} [mV]	*FF* [%]	Power [W]	Relative power gain [%]
3-BB full-cell	1.5	1.5	8.922	37.82	76.72	258.9	–
5-BB halved-cell	0.4	0.5	9.184	37.97	78.13	272.5	5.25
5-BB full-cell with LTR	1.1	1.2	9.152	37.89	77.35	268.2	3.6
6-BB full-cell	0.5	0.6	9.013	37.95	76.91	263.1	1.6

Table 4. Measured electrical parameters of four large-size PV modules.

Figure 7. Photographs of fabricated sample PV modules (5-BB LTR, 6-BB, 5-BB halved-cell, 3-BB).

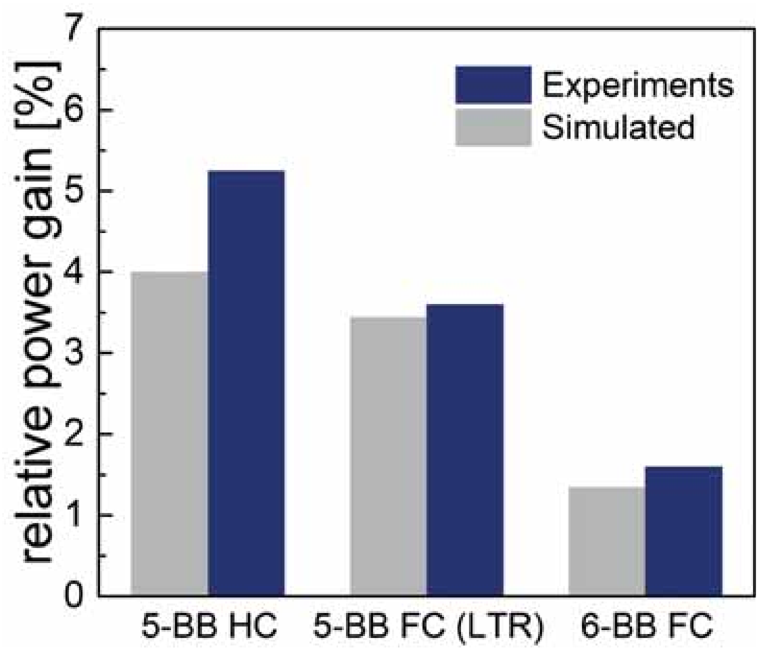


Figure 8. Simulation and experimental power gains for different PV modules fabricated at SERIS. (A 3-BB full-cell module was chosen as the reference.)

cost reduction of ~2.2%, which is only slightly lower than that for a 6-BB module. Notwithstanding the additional cost of LTR, this technology is very effective for high-power premium modules, where the main focus is to achieve maximum power.

Conclusion

With the use of the multi-busbar approach together with LTR and half-cut cell technologies, a significant improvement in module performance is possible. Stringers such as the one from teamtechnik are currently available on the market and can fabricate the strings using half-cut and LTR technologies with four, five or six busbars. The simulation and experimental results obtained show that an improvement of ~3.6% in module performance is possible with a 6-BB and LTR approach; with the additional use of the half-cut concept, this gain is further increased to 5.3%.

"With LTR and a 4-BB module, a cost reduction of ~2.2% is possible."

An economic analysis was performed for the multi-BB and LTR approaches. The cost-benefit analysis shows that the multi-busbar technique has the potential to reduce the module cost by ~2.5%. Because of the higher cost of LTR, however, the power gain in this case does not always translate to a reduction in module cost. Nevertheless, with LTR and a 4-BB module, a cost reduction of ~2.2% is possible. With all the approaches combined, a high-power premium module can be realized, although at additional cost.

References

[1] Braun, S. et al. 2014, "High efficiency multi-busbar solar cells and modules", *IEEE J. Photovolt.*, Vol. 4, No. 1, pp. 148–153.

[2] Chen, N. et al. 2013, "Assessing the impact of multi-busbars on metallization cost and efficiency of solar cells with digital inkjet-printed gridlines", *Proc. 10th HONET-CNS*, Magosa, Cyprus, pp. 60–65.

[3] Guo, S. et al. 2013, "A Quantitative Analysis of Photovoltaic Modules Using Halved Cells", *Int. J. Photoenergy*, Vol. 2013, p. 8.

[4] Guo, S. et al. 2015, "Investigation of the short-circuit current increase for PV modules using halved silicon wafer solar cells", *Sol. Energy Mater. Sol. Cells*, Vol. 133, pp. 240–247.

[5] Schneider, J. et al. 2014, "Combined effect of light harvesting strings, anti-reflective coating, thin glass, and high ultraviolet transmission encapsulant to reduce optical losses in solar modules", *Prog. Photovolt: Res. Appl.*, Vol. 22, No. 7, pp. 830–837.

[6] Sachs, E.M. et al. 2009, "Light-capturing interconnect wire for 2% module power gain", *Proc. 24th EU PVSEC*, Hamburg,

	Solar cells	Glass	EVA	Backsheet	Ribbon	Busing ribbon	Frame	Other
Cost contribution [%]	70.8	5.1	3.3	7.8	1.5	0.4	6.8	4.3

Table 5. Distribution of the component costs for a 60-cell silicon PV module.

Germany, pp. 3222–3225.
[7] Braun, S. et al. 2013, "Multi-busbar solar cells and modules: High efficiencies and low silver consumption", *Energy Procedia*, Vol. 38, pp. 334–339.
[8] Braun, S. et al. 2013, "The multi-busbar design: An overview", *Energy Procedia*, Vol. 43, pp. 86–92.
[9] Singh, J.P. 2015, "Comparison of glass/glass and glass/backsheet PV modules using bifacial silicon solar cells", *IEEE J. Photovolt.*, Vol. 5, No. 3, pp. 783–791.
[10] REC 2017, "REC TwinPeak", Product sheet [http://www.recgroup.com/en/products/rec-twinpeak-family-home].
[11] Mitsubishi Electric 2012, "PV modules: Monocrystalline", Product sheet [http://www.mitsubishielectric.com/bu/solar/pv_modules/monocrystalline/technologies.html].
[12] Schlenk 2017, "Metal foils", Product sheet [http://www.schlenk.com/index.php?id=351&L=1].
[13] Wong, J. 2013, "Griddler: Intelligent computer aided design of complex solar cell metallization patterns", *Proc. 39th IEEE PVSEC*, Tampa, Florida, USA, pp. 933–938.

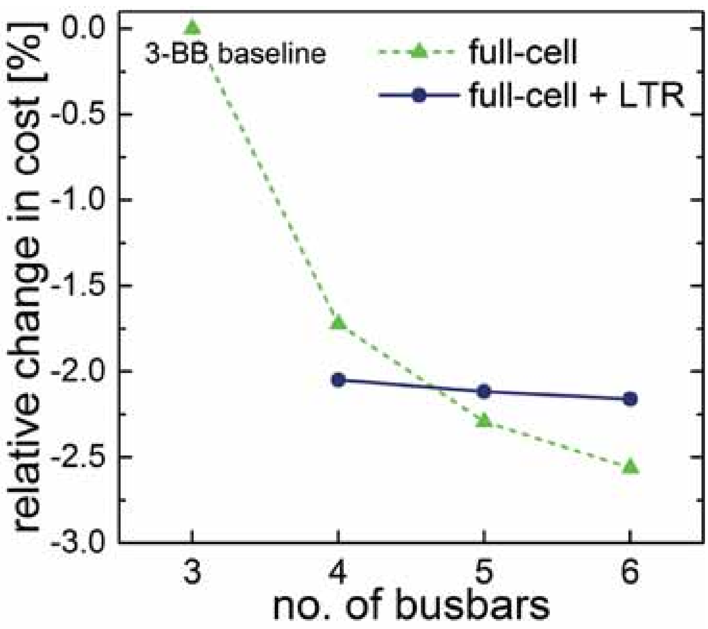


Figure 9. Cost-benefit analysis for module designs using multi-busbar and LTR approaches (full-cell). (A 3-BB module is chosen as the reference.)

About the Authors

Jai Prakash Singh received his Ph.D. in electrical and computer engineering from NUS. He works as a research scientist with SERIS at NUS, and has more than 10 years' experience in solar PV. His research focuses on the characterization, loss analysis and optimization of c-Si solar cells and modules.

Yong Sheng Khoo is the head of module development group at SERIS, and has more than five years' experience in PV module development and testing. He obtained his Ph.D. from NUS, and also holds B.S. and M.Eng. degrees in mechanical and aerospace engineering from Cornell University, USA.

Cai Yutian received his B.Eng. (Hons) in materials science and engineering. He is currently a research engineer at SERIS, where his research focuses on the prototyping of PV modules. Prior to joining SERIS, he worked as a process engineer.

Srinath Nalluri obtained his B.Eng. from NUS and has around three years' experience in the PV industry. He is a research assistant at SERIS, where he focuses on the fabrication of high-efficiency modules, PV module recycling, CAD modelling and numerical simulations.

Sven Kramer studied management and engineering at the Cooperative University in Stuttgart, Germany. After working as a project manager, he began a career as a sales engineer for solar module manufacturing equipment, before joining teamtechnik in 2015. As vice president of solar sales he is responsible for the worldwide sales activities of the stringer systems.

Axel Riethmüller studied mechanical engineering at the University of Stuttgart, Germany. After holding several leading positions in robotics and automation, he joined teamtechnik in 2002, where he was initially responsible for the assembly division. Since 2007 he has been head of the solar division, and in 2009 he was named a member of the board.

Yan Wang is the director of the PV module cluster at SERIS, and has professional knowledge of PV technology and hands-on manufacturing experience spanning various PV products. He obtained his Ph.D. in 2007 through a graduate study collaboration between Forschungszentrum Jülich, Germany, and Nankai University, China.

Enquiries

Jai Prakash Singh
Solar Energy Research Institute of Singapore

National University of Singapore
7 Engineering Drive 1
Building E3A, #06-01
Singapore 117475

Email: jaiprakash.singh@nus.edu.sg
Website: www.seris.nus.edu.sg

Photovoltaics International

Advertisers & Web Index

To advertise within Photovoltaics International, please contact the sales department: Tel +44 (0) 20 7871 0122

Renewable Energy India Expo
A UBM Event

Renewable Energy India 2017

Sincerely invite you to visit us at

Date: *Sep 20- Sep22*
Booth: *Hall10 10.96*
Venue: *India Expo Center, Greater Noida*

www.suntech-power.com

SUNTECH