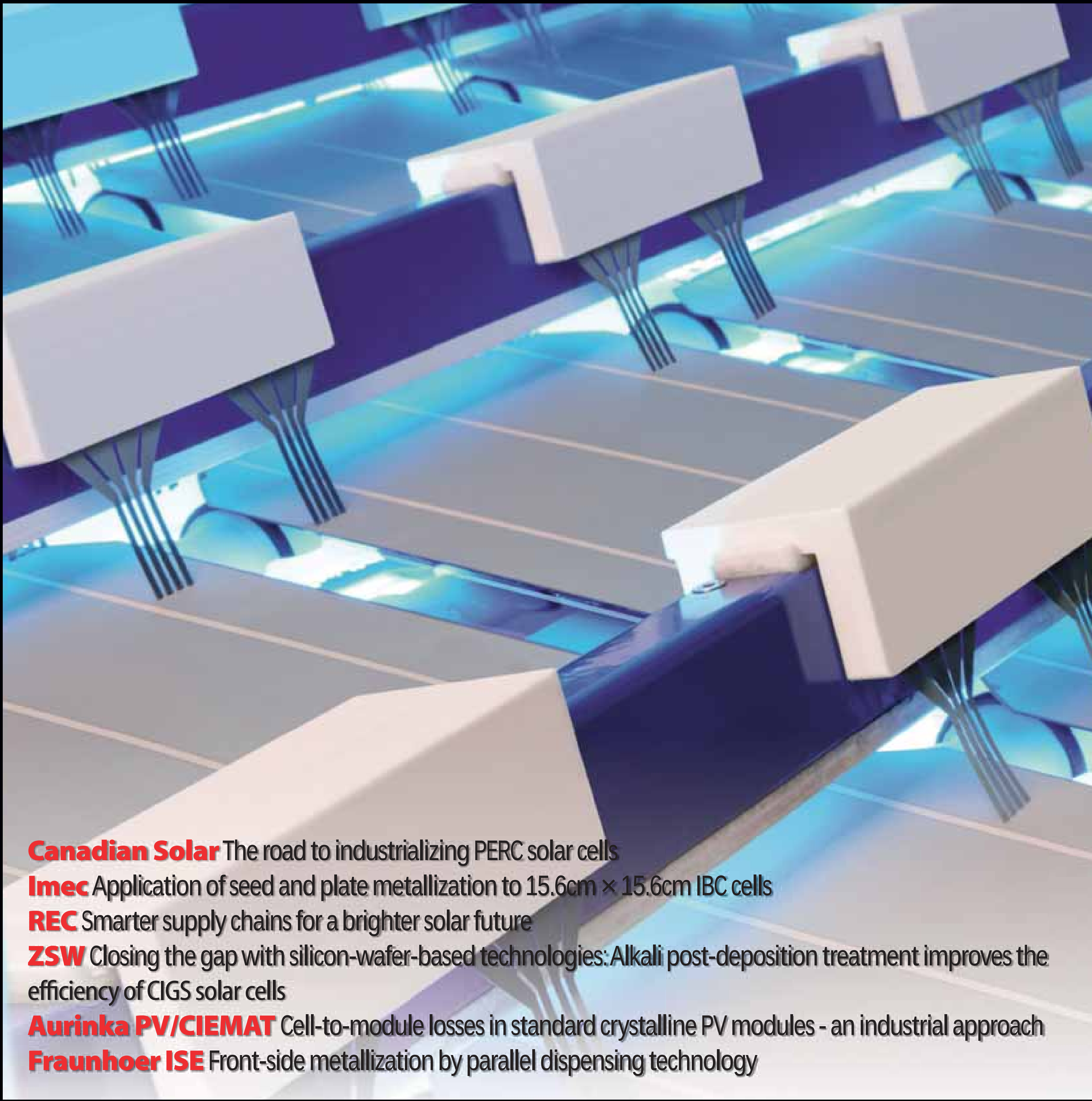
Photovoltaics International Twenty Ninth Edition 2015

Twenty Ninth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS



Canadian Solar The road to industrializing PERC solar cells

Imec Application of seed and plate metallization to 15.6cm × 15.6cm IBC cells

REC Smarter supply chains for a brighter solar future

ZSW Closing the gap with silicon-wafer-based technologies: Alkali post-deposition treatment improves the efficiency of CIGS solar cells

Aurinka PV/CIEMAT Cell-to-module losses in standard crystalline PV modules - an industrial approach

Fraunhoer ISE Front-side metallization by parallel dispensing technology

Third Quarter, September 2015

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Cover image: RENA's InCellPlate inline Cu plating technology keeping solar cell rear sides dry.

Image courtesy of RENA Technologies, Gütenbach, Germany.

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Foreword

Forecasting the evolution of a young, dynamic industry is by definition an uncertain business, and solar is no exception. Rarely, if ever, do the numbers broadcast by any of the various bodies involved in the PV prediction game tally, and even historical deployment rates remain the subject of hot debate. The paradox is that getting forecasts broadly right is going to become increasingly important over the next few years, particularly for those involved in producing the equipment that will support whatever levels of demand come to pass.

As discussed by Gaëtan Masson, director of the Becquerel Institute, on p.110 of this issue of *Photovoltaics International*, although global PV demand appears in rude health, complex political and economic conditions in many individual markets mean the question of how vigorously it will continue to grow in the coming years is less than clear. Yet for the upstream part of the industry, correctly forecasting PV market developments will be critical to ensure the right investments are made along the value chain in technologies that will help spur PV to new levels of competitiveness and thus drive continued demand.

For now at least, all the signs point to an upstream PV industry looking with some optimism to the future. One metric of this is the extent to which some of the industry's leading companies are beginning to invest again in research and development activity.

This is highlighted in our annual analysis of the 2014 R&D spend by 12 tier-one module manufacturers (p.12), a unique piece of market research within the industry. As this reveals, 2014 saw an increase of nearly US$100 million in the amount spent on R&D by the companies we track compared to US$422.6 million in 2013. This strong return to form took overall R&D investment by the sample companies last year to US$512.75 million, higher even than the US$510 million spent in 2011, when the PV industry was at the height of its last boom. It a strong indicator that after several brutal years of consolidation, companies are once more putting serious money and resource into the technologies of the future.

As always, *Photovoltaics International* brings together contributions from leading scientists in the field on the latest developments in PV technology. In this issue, the technical director of Canadian Solar's R&D operation in China discusses how PERC, the frontrunner in the current wave of emerging technologies, is being industrialized and incorporated into production lines (p.48). The paper demonstrates how PERC can be used to increase mono- and multi-silicon cell efficiencies by 1.1% and 0.7% respectively at volume-production levels.

A piece from Aurinka PV and CIEMAT from Spain takes up the industrialization theme, this time focussing on cell-to-module (CTM) losses (p.91). The power losses that can occur when cells are incorporated into modules are a major challenge for module manufacturers. The Aurinka/CIEMAT article explores how CTM losses in standard silicon cells occur in various stages of the module production process and how they can be minimized.

Other highlights of this issue include REC on PV manufacturing supply chain logistics (p.23), ZSW on using post-deposition treatment to boost CIGS thin-film cell efficiencies (p.82) and Fraunhofer ISE on new developments in front-side metallization (p.53).

Some of the team behind *Photovoltaics International* will be heading to Hamburg in September for the last outing of the EU PVSEC event before it combines with Intersolar Europe in Munich next June. We will be exhibiting at Booth C3 in Hall H, and very much hope to meet you there.

Ben Willis
Head of Content
Solar Media Ltd

Photovoltaics International

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

Editorial Advisory Board

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

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

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

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

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

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

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

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.

Jim Zhu, Chief Scientist, Wuxi Suntech

Jim Zhu has bachelor and master's degrees from Fundan University and a Ph.D. from the Shanghai Institute of Technical Physics of the Chinese Academy of Sciences. In 2007 he joined Suntech as group VP with responsibility for customer service, quality management and R&D. He has been the company's Chief Scientist since 2013.

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

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

Sam Hong, Chief Executive, Neo Solar Power

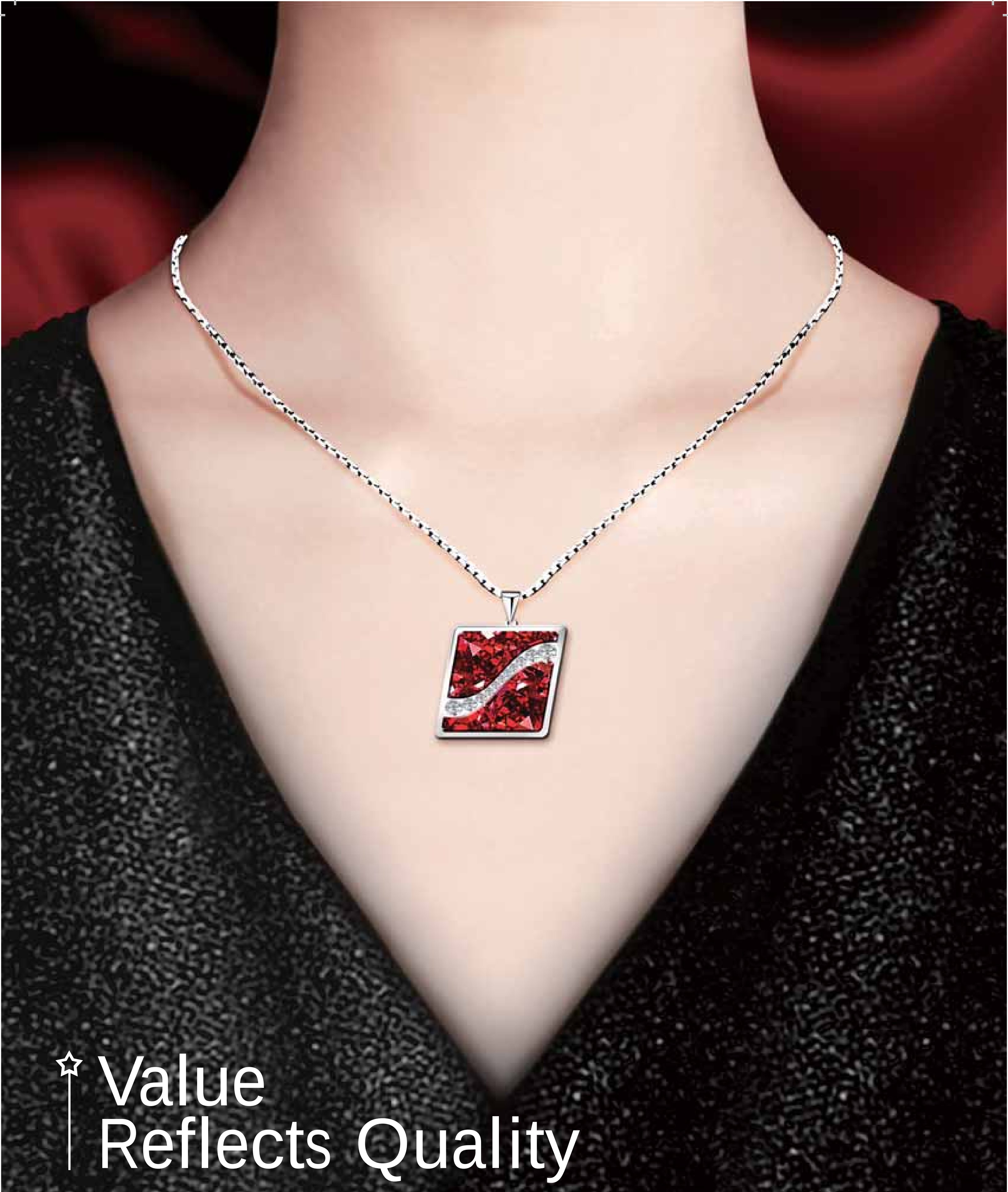
Dr. Hong has more than 30 years' experience in solar photovoltaic energy. He has served as the Research Division Director of Photovoltaic Solar Energy Division at the Industry Technology Research Institute (ITRI), and Vice President and Plant Director of Sinonar Amorphous Silicon Solar Cell Co., the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

Matt Campbell, Senior Director, Power Plant Products, SunPower

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

Ru Zhong Hou, Director of Product Center, ReneSola

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



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Fab & Facilities


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News

SolarCity ups R&D spend as gigafactory takes shape

SolarCity's Silevo gigafactory in Buffalo, New York State is taking shape with Governor Andrew Cuomo taking part in a "topping off" ceremony.

The 1GW fab will produce modules based on Silevo's high-efficiency cell architecture. The integrated manufacturing site will make the country's largest residential installer, also its largest domestic producer of cells and modules.

A recent SEC filing from SolarCity showed an R&D spending increase of more than 300% in the second quarter as work to equip the 1GW factory continues.

SolarCity said that the Bufallo fab was on schedule for completion before the end of the year and tool install completed by the end of the first half of 2016. The major production ramp to full capacity would occur in 2017. The Buffalo fab is being funded by a build-to-suit lease arrangement with the Research Foundation for the State University of New York, including US$350 million for the 1GW facility and US$400 million for manufacturing equipment.

SolarCity is responsible for equipment spending outside the fixed amount.

Source. Governor Andrew Cuomo, Flickr

SolarCity's new 1GW fab is on track for completion by the end of the first half of next year.

Chinese manufacturers go overseas

Seraphim Solar establishing 300MW module plant in Mississippi

China-based integrated PV module manufacturer Seraphim Solar System is scheduled be operational with a planned 300MW annual capacity solar module assembly plant in Jackson, Mississippi. Potential customers of the company, primarily in the US, were sent emailed letters in early May, announcing the facility was expected to be commissioned in August.

Several China-based tier-one module manufacturers, such as Yingli Green and Trina Solar, had previously touted plans to establish manufacturing in the US, but both have since dropped those plans.

Sunpa to invest in solar plants and panel manufacturing in Karnataka

China-based anchor investor Sunpa Group of Companies is to invest in solar power generation and panel manufacturing in the Indian state of Karnataka.

Sunpa will also invest US$1 billion in a proposed industrial park in the state.

Ratna Prabha, additional chief secretary of the Karnataka government, agreed "in principle" to devote 40 hectares of land in Vasanthnarasapura through the Karnataka Industrial Areas Development Board (KIADB) for the Chinese Industrial Park.

Sunpa said it will make investments in Karnataka for various other sectors including tele-medicine, manufacturing of medical equipment and accessories, and technology research.

Hareon Solar planning 1GW state-of-the-art solar cell fab in India

China-based PV manufacturer Hareon Solar has said its initial phase-one 160MW solar cell production plant in India is part of more ambitious plans to establish a 1GW state-of-the-art solar cell facility in a joint venture with Indian firm Dalmia Group.

Hareon Solar had said in a stock market statement that it had teamed with Dalmia Group on a 160MW solar cell plant and recently announced plans to team with India's ReNew Power to invest in a 72MW solar project in India.

The phase-one solar cell plant was expected to be operational by mid-2016, marking the company as the first major Chinese producer to announce a definitive agreement for setting up manufacturing in India.

From the lab

Hareon Solar's test lab gains TÜV SÜD qualification

In other Hareon Solar news, the company's product testing laboratory recently met TÜV SÜD's on-site testing standards.

The meeting of the TMP (Testing at Manufacturers Premises) laboratory qualification standards means Hareon Solar can shorten the testing period and authentication period for new product introductions as testing in-house is the equivalent of contracting with the likes of TÜV SÜD at outside facilities.

Hareon Solar's laboratory is expected to be equipped with the appropriate IEC61215/61730 testing capability. TÜV SÜD typically inspects qualified facilities on a regular basis to ensure standard testing procedures are being met.

Fraunhofer ISE expands research into 'complementary pillars of energy transition'

Fraunhofer ISE has opened a new centre in the institute's home city of Freiburg, Germany, committed to expanding its research and development activities in a range of technologies considered "complementary" to solar as key foundations of distributed, low emissions energy networks.

Work carried out there will focus on energy storage battery R&D, on producing hydrogen from renewables, solar thermal storage and heating and cooling building using heat pumps.

Capacity: expansions and constraints

Silfab Solar increases module production to 300MW

Module manufacturer Silfab Solar is to increase production and expand its PV module manufacturing facility in Toronto, Canada from 180MW to 300MW capacity.

Source: Fraunhofer ISE

Fraunhofer ISE is opening a new R&D centre in Freiburg looking at technologies that complement solar.

The plant expansion, which includes an upgrade of existing equipment to manufacture five-busbar modules, comes in order to meet strong demand from North American partners, the company claimed.

The expansion will be completed in the third quarter of 2015. The plant was opened in 2011 with a 90MW capacity, which was increased to 144MW in three years and then up to 180MW before the latest expansion. The plant operates on a 24/7 schedule, 362 days a year.

Motech refinancing after Topcell acquisition and capacity expansions

Taiwan-based merchant solar cell producer Motech Industries has secured NT$6.4 billion (US$196 million) in a new syndicated financing round.

Motech said that the three-year credit facility was to refinance its existing loans and to replenish working capital. The company recently acquired rival solar cell producer, Topcell, resulting in its nameplate solar cell capacity topping 3GW, making it the largest global merchant cell producer.

Motech had also announced that it was also investing further in its China-based manufacturing subsidiary Motech (Suzhou) Renewable Energy at a cost of RMB211 million (US$33 million) to expand capacity and improve its economies of scale at the facility.

REC Solar almost sold out for 2015

Singapore-based tier-one PV manufacturer REC Solar, part of Chinese investment firm Elkem Bluestar, has provided bullish business figures for the second quarter of 2015.

REC Solar said PV module sales reached US$168 million, up 12% from the prior quarter, driven by 130MW of module shipments to the US in the quarter, which accounted for 50% of total sales.

REC Solar is a key supplier to US installer SolarCity, which posted 189MW of installations in the quarter, up from 153MW in the first quarter of 2015.

The company is undergoing site selection analysis for its next major capacity expansion. REC Solar has been one of several PV manufacturers benefiting from having production outside China and Taiwan after the US strengthened its anti-dumping duties.

PV manufacturing in Brazil

Brazil's Pernambuco seeking two panel manufacturers to set up in state

The government of Brazilian state Pernambuco was reported to be in negotiations with two unnamed solar panel manufacturers to set up facilities in the state.

State energy secretary Eduardo Azevedo said the manufacturers could be attracted to Brazil by encouraging project winners of the state's solar-only auctions in December 2013 to buy equipment from the target manufacturers.

Five out of six winning projects have been delayed for completion until 2017, meaning that they still need to purchase solar equipment. However, legally they must still purchase a portion of their equipment from national suppliers.

Brazil wants investment in solar

The Brazilian Association of Photovoltaic Solar Energy (Absolar) has signed an agreement with the Brazilian Agency for Export and Investment Promotion (Apex-Brazil) to partner on attracting more foreign investment into the domestic solar industry. The partnership is a way for the Brazilian PV sector to increase its presence nationally and to present investment opportunities to major international investors.

It is also intended to give more visibility to opportunities available in the Brazilian PV market for manufacturers, project developers, international financing institutions and others.

The development of the sector will be focused on local markets, with local demand created by both large-scale PV auctions with large-scale PV projects and also small-scale distributed generation coming from net-metering systems.

Source: Ben Willis

Hanergy TF has cancelled plans for a 900MW production plant.

Company news

TSMC exiting CIGS thin-film market with closure of production plant

Taiwan-based CIGS thin-film module producer TSMC Solar, a subsidiary of leading semiconductor foundry Taiwan Semiconductor Manufacturing Corp, was due to close its manufacturing plant at the end of August and exit the solar PV market.

A statement by TSMC said that despite recent world-class conversion efficiencies achieved for its CIGS-based modules and expanded capacity to reach economies of scale, TSMC Solar had remained unprofitable since entering the market in 2012 and would remain so, despite any further attempts to aggressively lower production costs.

Hanergy TF and Hanergy Group cancel 900MW a-Si turnkey production plant plans

Amongst other recent controversies (see news, Thin Film, p.72) Hanergy Thin Film Power has cancelled a 900MW a-Si turnkey production plant with parent company, Hanergy Holding.

Initially announced in early May 2015, Hanergy TF said in a financial filing that "after arm's length negotiations", both parties agreed to cancel the plans, without providing further explanation.

The deal that was previously signed with Hanergy TF subsidiary Fujian Apollo for six complete production lines was said to be worth US$585 million, which included US$175.5 million for the equipment and a service contract totalling US$409.5 million. Timelines and location of the 900MW plant were never disclosed.

JinkoSolar increases 2015 module shipment guidance to as high as 4.5GW

Tier-one PV manufacturer JinkoSolar has raised its module shipment guidance for the full year. The company expects shipments to be in the range of 4.0GW to 4.5GW, up from previous guidance of 3.3GW to 3.8GW.

The increased guidance could catapult the company from being ranked fourth globally, based on shipments in 2014, to being ranked second behind Trina Solar, should it meet the high end of the revised guidance.

Rankings positions (based on 2014 shipments) 2 to 5 (Yingli Green, Canadian Solar, JinkoSolar and JA Solar) are converging towards the 4GW-plus range, setting the scene for further rankings shuffle later in the year.

JinkoSolar taps capital from China's Ex-Im bank for Malaysian fab

JinkoSolar has secured more than US$62 million in a loan agreement with The Export-Import Bank of China (TEIBC) to support long-term fixed assets and mid-term working capital for its recently started Malaysia facility. The company said it had already drawn down the US$62 million loan.

JinkoSolar also said it had secured a further RMB50 million (US$8.05 million) loan from TEIBC that would be used to support near-term working capital for the Malaysia facility.

JinkoSolar confirmed back in March, 2015 that its new Malasian fab would have an initial solar cell capacity of 500MW and 450MW of PV module capacity.

Aurora Solar's inline measurement system selected by SEMCO

Inline measurement equipment specialist Aurora Solar Technologies has started a collaboration with PV equipment supplier SEMCO Group, offering its 'Veritas' and 'Decima' products with SEMCO's 'LYDOP' and 'LYTOX' horizontal diffusion and annealing furnaces.

The partnership is intended to simplify purchasing requirements in respect of having an integrated quality control solution in cell fabrication for high yield and reduced product binning costs. This has becoming increasingly in focus with next-generation cell architectures and processes such as PERC (passivated emitter rear cell) and heterojunction (HJ) technologies.

As part of the partnership, both Decima and Veritas products will be installed and used for cell fabrication and customer demonstrations at SEMCO's IrySolar photovoltaic fabrication facility and laboratory in France.

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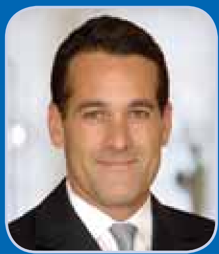

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R&D spending analysis of top PV module manufacturers in 2014

Mark Osborne, Senior News Editor, *Photovoltaics International*

ABSTRACT

R&D expenditure by major PV module manufacturers showed a remarkable turnaround in 2014. Previous reports had noted, especially in 2013, that R&D spending had not been immune to the PV industry's period of profitless prosperity and was deemed a discretionary spend by the majority of leading producers. A return to profitability for many in 2014 resulted in a year of new record spending. There was record spending from 11 of the 12 companies covered, with Hanwha Q CELLS' spending actually declining in 2014.

R&D spending patterns

The R&D expenditure in 2014 of 12 major Tier-1 PV module manufacturers that were historically tracked increased by almost US$100m from the previous year, to reach US$512.75m. Such is the rebound in spending that the total 2014 spend is at a new historical high, surpassing the previous historical high of US$510.4m set in 2011.

"The total 2014 spend is at a new historical high."

Dedicated crystalline silicon-related R&D spending (see Fig. 2) would have missed setting a new record by the slimmest of margins if there had not been a small contribution from First Solar's monocrystalline-based TetraSun. Without TetraSun's contribution, c-Si spending would have been US$368.85m, compared with US$369.9m in 2011; however, with TetraSun's contribution, the spending on crystalline R&D topped US$373.95m, another new record set in 2014.

The overall increase in spending in 2014 has also led to a breakout of several companies that have historically spent less than US$20m annually and had formed the largest cluster of companies in the analysis (by expenditure) since 2007. Notably, JA Solar and Trina Solar moved from the sub-US$20m annual spending cluster to the sub-US$40m cluster, which also includes SolarWorld.

On the basis of the trajectory of spending in 2014 (see Fig. 3), several companies (Jinko Solar and Wuxi Suntech) could also exit the lowest spending cluster in 2015, leaving (without drastic spending behaviour change) just Canadian Solar and Hanwha Q CELLS (formerly Hanwha SolarOne) in the sub-US$20m category.

Although the spending by REC Solar increased considerably in 2014, compared with the previous year, its acquisition by Chinese-owned Bluestar Elkem Investment in May 2015 has resulted in the company going private; it is therefore highly doubtful that it will be possible to continue tracking REC Solar's R&D spending behaviour. Several PV module manufacturers are currently being evaluated in order to backdate and start to include them in the 2015 analysis and beyond.

The increase in spending has also meant the sub-US$60m category holds only one company, ReneSola, in 2014, compared with three companies (ReneSola, SunPower, Yingli Green) in 2013. However, the sharp increase in spending by Yingli Green means it has elevated itself into the heights of the sub-US$100m category. Interestingly, only one other company, First Solar in 2010, has ever spent US$90m on R&D in any given year; indeed, the gap between First Solar and any rival covered remained relatively stable between 2010 and 2013. The increase in spending by Yingli Green and SunPower means that this is the first time since 2010 that the gap with First Solar has visually closed.

R&D staffing patterns

In line with the increase in spending, the number of employees designated to R&D activities has also gone up, as Fig. 4 shows. Having reached a headcount peak in 2011 of 3,575, R&D headcount numbers among the companies covered declined overall to 2,911 in 2013. Nine companies, however, increased R&D headcount in significantly varying degrees in 2014, while two companies (Hanwha Q Cells and SolarWorld) had very slight declines.

"In line with the increase in spending, the number of employees designated to R&D activities has also gone up."

Source: Hanwha Q CELLS.

Figure 1. R&D spending by some of the leading module producers bounced back in 2014 after two years of decline.

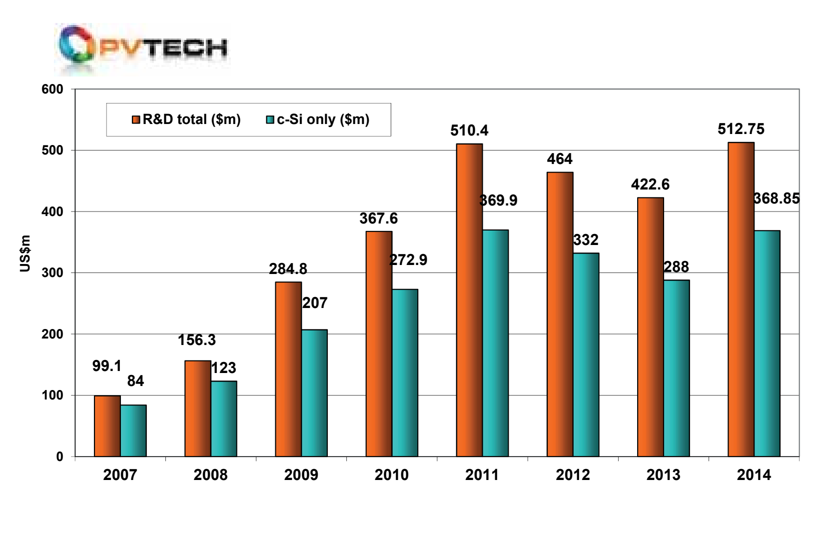

Figure 2. Key 12 PV module manufacturers' combined R&D spending (US$m).

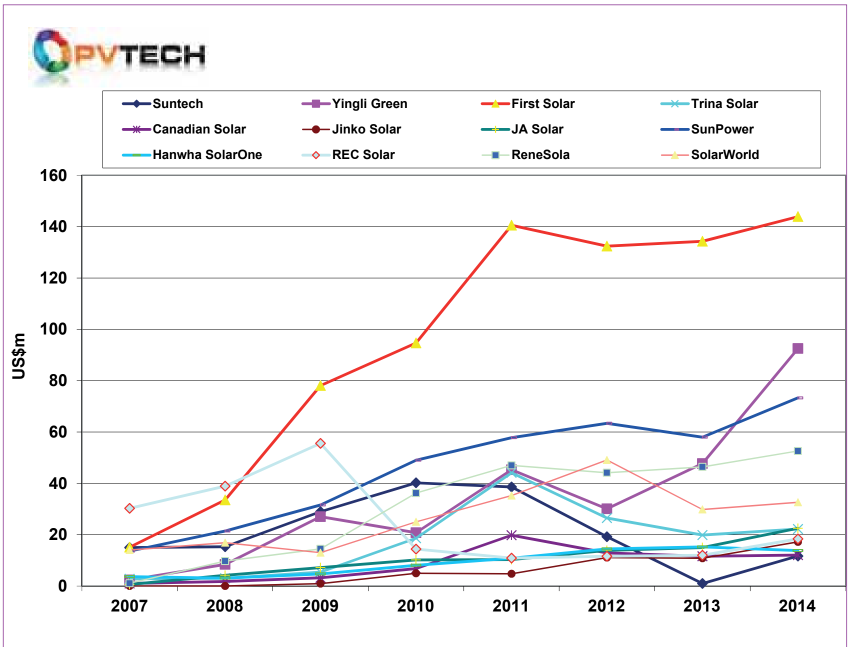

Figure 3. Key 12 PV module manufacturers' annual R&D spending (US$m).

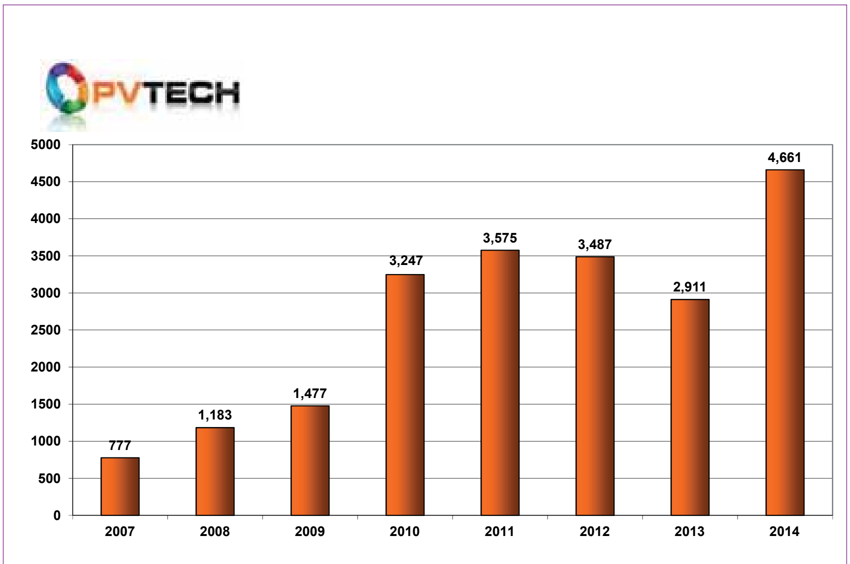

Figure 4. Key 12 R&D-spending PV module manufacturers' combined R&D headcount.

There is, however, an anomaly in these figures (see Fig. 5). Glaringly, Trina Solar has increased designated employees in R&D activities by around 1,398, bringing its total of R&D personnel to a massive 1,954. The company has confirmed the accuracy of this change, noting that a shift in its lab-to-fab approach had meant that those operating its pilot production line (called 'Golden Line' and housed in its State Key Laboratory Testing Center), as well as those carrying out traditional R&D activities, were categorized as R&D personnel. However, Trina Solar also confirmed that traditional R&D activities had retained staffing levels in line with 2013, which totalled 556.

A similar change took place at Yingli Green in 2010, with subsequent increases in R&D personnel through 2012. R&D personnel figures, however, have remained static for the last two years and reflect the company's lack of new capacity expansions. The company also has a State Key Laboratory of PV Technology, which has the same special status as the State Key Laboratory of Trina Solar.

Without the Trina Solar reclassification, the headcount figure would have been 3,263, still a decent increase from 2,911 in 2013. With Trina Solar and Yingli Green reclassifying a large number of manufacturing staff to R&D activities, not surprisingly both companies lead the pack in relation to R&D headcounts.

If R&D headcount figures from both these companies are excluded, however, JA Solar has shown the biggest increase in 2014, taking its R&D headcount to 290, up from 139 in 2013. JA Solar has also been one of the few companies covered that has incrementally added R&D staff since 2010, avoiding (unlike others) the temptation to trim staffing levels in 2012 and 2013.

ReneSola may not be adding new manufacturing capacity in 2015 but it has ramped up its R&D headcount in 2014. The company has both PV inverter and LED operations, which could partly explain the increase in headcount.

Also of note is SunPower, which is one of the few companies to have incrementally added R&D staff from 2007 onwards. In 2014 SunPower increased its R&D headcount from 300 to 337, ranking the company third behind Trina Solar and Yingli Green.

R&D spending rankings and analysis

Once again, First Solar led the pack in outright R&D spending in 2014 (Table 1). The CdTe thin-film firm has now

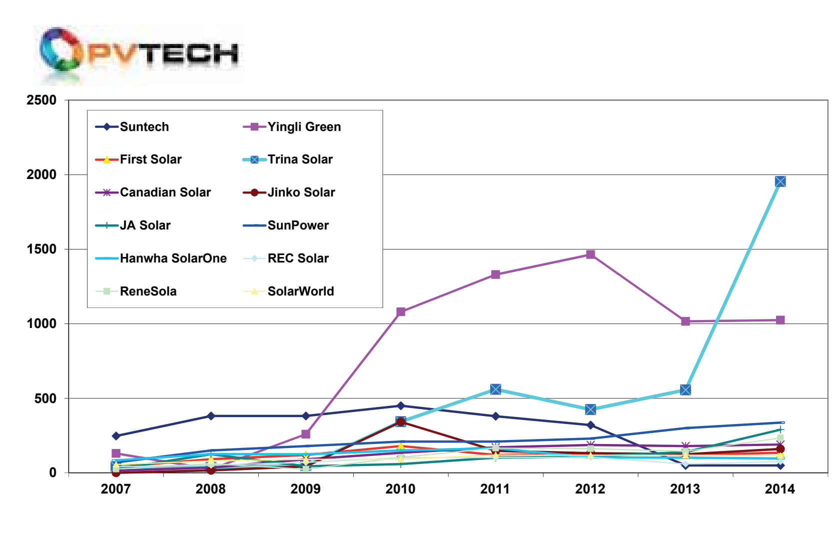

Figure 5. Key 12 PV module manufacturers' R&D headcount by company.

2011	2012	2013	2014	Ranking
First Solar	First Solar	First Solar	First Solar	1
SunPower	SolarWorld	SunPower	Yingli Green	2
REC	SunPower	SolarWorld	SunPower	3
ReneSola	ReneSola	Yingli Green	ReneSola	4
Yingli Green	REC	ReneSola	SolarWorld	5
Trina Solar	Yingli Green	Trina Solar	JA Solar	6
Suntech	Trina Solar	Hanwha Q CELLS	Trina Solar	7
SolarWorld	Suntech	JA Solar	REC Solar	8
Canadian Solar	Hanwha Q CELLS	Canadian Solar	Jinko Solar	9
Hanwha Q CELLS	JA Solar	REC Solar	Hanwha Q CELLS	10
JA Solar	Canadian Solar	Jinko Solar	Canadian Solar	11
Jinko Solar	Jinko Solar	Suntech	Suntech	12

Table 1. Top-ranked R&D spenders in 2014.

been ranked first for six consecutive years.

First Solar

First Solar allocated US$143.9m to R&D activities in 2014, up from US$134.3m in the previous year. Although the company splits spending between manufacturing and downstream modular power plant developments, there has been more emphasis in the last two years on thin-film module efficiency gains and line throughput increases in addition to its initial ramp-up at TetraSun.

The perennial heavy spending on R&D can be partly explained by the proprietary nature of its CdTe production equipment and processes; however, the benefit of acquiring GE's CdTe technology IP and co-development work has really started to pay back in module efficiency gains.

First Solar said in June 2015 that it had surpassed multicrystalline module conversion efficiencies for the first time, with its CdTe module efficiency achieving a record 18.6% and corresponded to the company's eighth major update since 2011. At the beginning of 2015, First Solar reported a research cell with a conversion efficiency of 21.5%.

Yingli Green

One of the big movers in ranking in 2014 was Yingli Green. The company was ranked fourth in 2013, spending US$47.7m on R&D; in 2014, however, Yingli Green increased spending to US$92.5m, catapulting it ahead of SunPower and SolarWorld.

Yingli Green has both multicrystalline and monocrystalline technology roadmaps that are designed to meet production average efficiency targets in 2020 of 19% and 23% respectively. The company is aiming to narrow the gap between lab results and actual volume production, with only a 1% difference in multi and mono technologies by 2020.

By the end of 2014, Yingli Green said it had achieved an average cell conversion efficiency rate of 19.8% for its monocrystalline PANDA cell on its commercial production lines, and a record cell conversion efficiency rate of 21.2% on its PANDA trial line. The company is also adopting ion implantation for its PANDA cells in 2015.

SunPower

Although SunPower significantly increased its R&D spending in 2014 to US$73.3m, up from US$58m in the previous year, it dropped one ranking position to third, because of Yingli Green's spending splurge. SunPower has persistently been ranked either second or third since 2008, underlining that proprietary technology requires additional investment as compared to standard mono or multi cell technology.

Being a major downstream PV project developer, SunPower also splits R&D activities, but it has also been developing its low-concentration CPV technology in recent years. The main focus, however, remains on the next-generation Maxeon cell, which is being ramped up at its dedicated cell plant in the Philippines

The company attributed a US$10.3m increase in R&D spending to the additional headcount and salary-related expenses in 2014. It also noted that some of the extra labour costs were also associated with consulting services in relation to its next-generation cell technology.

SunPower expects to achieve production module efficiencies of 23% in 2015 using a simplified, and therefore lower-cost, manufacturing process, while the company reported that it had produced its first solar cells with over 25% cell efficiency in the lab in 2014.

ReneSola

Up one ranking position from fifth to fourth was ReneSola, spending US$52.6m in R&D in 2014, up from US$46.4m in 2013. A special focus for the company has been improving its wafer quality, production cost reductions and yield improvements across both multi and mono wafer production. ReneSola has achieved a conversion efficiency rate of 17.8% on its A+++ wafer-based multicrystalline solar cells, as well as reporting monocrystalline solar cell efficiencies of 19.2% at the end of 2014.

SolarWorld

Two companies dropped two ranking positions in 2014 – SolarWorld and Canadian Solar. SolarWorld was ranked third behind First Solar and SunPower in 2013, but the increased spending by Yingli Green and ReneSola in 2014 negatively impacted SolarWorld's ranking position, as did the fact that the company only increased spending from US$29.8m in 2013 to US$32.6m in 2014.

Understandably, SolarWorld went through a major restructuring phase in 2014 and has not yet returned its R&D spending to the peak level of US$49.1m seen in 2012, when the company was ranked second. Interestingly, SolarWorld has had one of the most volatile R&D spending behaviours among the companies covered in this report, and since 2007 has occupied all positions from a lowest of eighth to a highest of second.

The company has focused on developing and migrating to PERC cell technology and migrating some of its production to five-busbar technology. With this technology, it has claimed to have achieved a cell efficiency of 21.51% on its crystalline p-type based wafer.

SolarWorld has also been involved with several EU-funded projects in recent years, to improve the cost competitiveness of monocrystalline wafer production.

JA Solar

JA Solar achieved its highest ranking position in 2014, having increased R&D expenditure from US$15m in 2013 to US$22.5m in 2014. It was ranked sixth, climbing two ranking positions from the previous year.

The company reported late in 2014 that it had achieved multicrystalline module efficiencies of 17.2%, generating 280W in a standard 60-cell format. Its p-type monocrystalline solar cells (PERCIUM) had also surpassed a conversion efficiency of 20.5% in late 2014. The company's high-performance multicrystalline RIECIUM series cell was reported to yield a conversion efficiency of over 18.8%.

JA Solar is continuing to develop cells using metal wrap-through (MWT) technology and n-type cell technology.

Trina Solar

The leading global PV manufacturer (by module shipments) in 2014 was Trina Solar, having surpassed Yingli Green. However, in terms of R&D spending, Trina Solar lost ground on that company, with a spending of US$22.2m, compared with US$19.9m in 2013. As a result of relatively low R&D spending and only a small incremental increase in 2014, Trina Solar was ranked seventh, down one position as JA Solar ramped up spending at a higher rate.

Despite the level of R&D spending, Trina Solar demonstrated some significant developments in 2014. The company announced that its Honey Plus modules were using multicrystalline PERC cell technology, with cell efficiencies said to be 18.7% on initial volume-production levels. It also said that its Honey M Plus monocrystalline module would have average power outputs of 285W and average cell efficiencies of 20.4%. The company also noted that its PERC cell technology for the Honey modules would also use an advanced five-busbar front-side contact for lower overall series resistance. At year-end Trina Solar announced that its Honey Plus p-type PERC cell had achieved an efficiency of 20.76%, independently confirmed by Fraunhofer ISE CalLab in Germany.

Trina Solar claimed to have set four new world records in 2014 for p-type PERC cells and modules. These include new records for large-area (156mm × 156mm) p-type silicon substrates, of 21.40% for monocrystalline and 20.76% for multicrystalline silicon solar cells, as well as new peak power output records for commercial PV modules, of 335.2Wp for monocrystalline and 324.5Wp for multicrystalline silicon solar cells.

REC Solar

A strong mover in 2014 was REC Solar, as its R&D spending increased from US$12m in 2013 to US$18.4m in 2014, propelling the company to eighth place, up two ranking positions from the

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previous year. This is also the first time since 2008 that REC Solar's ranking has not declined. When it was leading the field, the company was spending on fluidized bed reactor (FBR) technology for polysilicon production. The company split its polysilicon business and became a pure-play integrated PV module manufacturer in 2013, which explains its current ranking and R&D spending behaviour.

REC Solar focused on technology developments in ingot/wafering in 2014, with the aim of reducing wafer cost and significantly increasing cell efficiencies. The company had also been working on migrating lines to PERC, with several lines coming on stream in the first quarter of 2015.

The company has also developed and qualified a four-busbar cell technology and half-cut cell technology. Future-technology research work has been centred on low-cost and high-efficiency processes using monocrystalline wafers. Solar cell efficiencies in excess of 20% have been achieved, according to the company.

Jinko Solar

One of the big surprises in 2014 was the fact that Jinko Solar significantly increased R&D spending, attaining a new annual expenditure record that coincided with average solar cell efficiencies also reaching new heights. The company had been a laggard among its major rivals in R&D expenditure since the company started production and was only beaten to the bottom-ranked position within the 2013 analysis by Suntech because of the latter's bankruptcy. In 2014, R&D spending topped US$17.2m, up 62.8% from US$10.8m in the previous year.

Part of the significant increase in R&D expenditure was the increase in the number of employees dedicated to R&D activities: personnel had been cut to 125 in 2013 but expanded to 160 in 2014. Jinko Solar's peak R&D headcount occurred in 2010, when R&D staffing levels topped 342.

The company reported that the average conversion efficiency rate of its monocrystalline cells had increased to 19.6% by the end of 2014, up significantly by 100 basis points from 18.6% at the end of 2013. This is significant for the company, as its average monocrystalline cell efficiencies had been stagnant since 2012.

In contrast, Jinko Solar had only achieved minor incremental efficiency gains with its multicrystalline solar cells, taking average cell efficiencies from 17.6% in 2012 to 18.2% by the end of 2014. The company may be able to boost multicrystalline cell efficiencies at a faster pace in 2015, as a result of plans to add 450MW of high-efficiency PERC capacity at its new production plant in Malaysia.

The company has also recently announced a strategic collaboration agreement with DuPont for the implementation of next-generation metallization pastes, using DuPont's PERC-specific Solamet PV19x series pastes.

> "First Solar led the pack in outright R&D spending in 2014."

Hanwha Q CELLS

The only company to reduce R&D spending in 2014 was Hanwha Q CELLS, formerly Hanwha SolarOne before officially merging with sister company, Hanwha Q CELLS, in the first quarter of 2015. Hanwha SolarOne had spent US$15.2m in 2013, but its R&D spending fell to US$13.8m in 2014, causing the company to drop three ranking positions to tenth place; this was also the biggest drop among the companies covered in this analysis.

It is unclear why the company cut R&D spending in 2014, although the planned Hanwha Q CELLS merger may have been a factor because of Q CELLS' well-known R&D activities in Germany, which have in recent years been supporting Hanwha SolarOne's cell and module efficiency improvements. Q CELLS had not been public since its acquisition by Hanwha in 2012 and therefore R&D spending figures are not publicly available.

With the merger undertaken there is a strong probability, especially with plans to migrate to PERC technology, that R&D spending from the combined entities will increase significantly in 2015. Q CELLS' former R&D facility and personnel are also being retained after the merger and are included in a total of 350 personnel being retained at Hanwha Q CELLS in Germany.

At the end of 2014, Hanwha SolarOne's multicrystalline cells had achieved a conversion efficiency rate of 17.7%; however, Q CELLS' mono PERC cells had conversion efficiencies of 19.5%, and traditional BSF multi cells had conversion efficiencies of 18.8%.

Canadian Solar

Although the spotlight has been on Jinko Solar as a laggard in R&D spending, major PV manufacturer Canadian Solar has historically tracked along the bottom with Jinko Solar. Canadian Solar allocated only US$12.05m to R&D activities in 2014, up slightly from US$11.6m the previous year. With both REC Solar and Jinko Solar reporting a greater increase in R&D spending in 2014 than Canadian Solar, the latter fell two ranking places to eleventh.

Canadian Solar has historically focused on in-house cell technology advances, which could explain its persistent laggard status, yet the company has still achieved an increase in cell efficiency of 0.5% abs. per year over the past five years. However, it has also developed PERC cell technology in this time frame, which is associated with many other companies raising R&D spending in recent years.

Putting its R&D expenditure levels in perspective, Canadian Solar had full-year 2014 revenue of almost US$3bn and was the third-largest PV manufacturer (by module shipments) last year. The company also has ongoing initiatives in relation to n-type bifacial cells, with efficiency targeted at exceeding 22% by 2017; this is in addition to work on heterojunction cells and IBC cells, but R&D spending certainly seems at the moment to be spread thinly across many projects.

At the end of 2014, Canadian Solar's multicrystalline cells had achieved conversion efficiencies of 18%. The company is also planning to enter production with its ONYX (black silicon) cells with initial efficiencies of 18.31% in the first quarter of 2015. Later in the year, Canadian Solar is proposing to enter production with its ONYX II PERC cell, which is claimed to yield efficiencies of around 19%.

Wuxi Suntech

The good news for bottom-ranked Wuxi Suntech, since its acquisition by Shunfeng, has been the relaunch of R&D activities after its former bankruptcy. Suntech spent US$11.7m on R&D expenditure in 2014, up from US$2.2m in 2013.

Wuxi Suntech is expected to spend around US$16m in 2015. The migration to PERC cell technology is ongoing and the company recently launched its multicrystalline p-type SuperPoly module, said to also integrate an in-depth reflection technology and passivation process, yielding module efficiency rates of up to 16.7%.

Conclusion

R&D spending reached a new record high in 2014, fuelled by cell technology developments, primarily centred around PERC. This was supported by a record number of R&D personnel employed and a shake-up in the rankings, though First Solar remained ahead of the pack.

Quarterly analysis of PV manufacturing capacity expansion plans: 1H 2015

Mark Osborne, Senior News Editor, *Photovoltaics International*

ABSTRACT
In this quarterly report we will provide full first-half 2015 analysis that shows a massive shift in the geographical location of planned production plants, as well as details on key capacity announcements in the months of May and June. The analysis of April's capacity announcements were reported in the previous quarterly report. Despite April announcements being so low, May proved to be a blockbuster month. The return of meaningful solar cell capacity plans reiterates the strength in the recovery and the first attempts for many years by leading PV manufacturers to rebalance cell and module production as next-generation PERC technology leads the cell rebalancing act.

Total PV manufacturing capacity announcements topped 6.7GW in May 2015 (See Figure 1), setting a new monthly record for 2015 and surpassing any month in 2014. May announcements are more than double the 2.96GW announced in February and the 2.62GW announced in March.

The most significant trend from the May capacity expansion announcements was the significant 2.7GW of solar cell expansion plans, the highest in over three years and higher than the 2GW announced in May and November 2014. This was supported by a further 1GW of joint-venture integrated cell and module capacity announcements in India by Trina Solar.

Solar cell capacity expansions lagged module assembly announcements overall through 2014. The majority of solar cell announcements relate to high-efficiency multicrystalline passivated emitter rear cell (PERC) technology, driven by Trina Solar and Hanwha Q CELLS as well as high-end n-type mono heterojunction technology expansion plans by Panasonic.

However, crystalline module assembly announcements were also strong in May, totalling 2.1GW. Significantly, none of the announcements related to assembly expansions in China but included Thailand, Japan, India, South Korea, Brazil and the US. A more detailed analysis of regional trends is included in the first half of year analysis later in this report.

Lost in the noise of May announcements were plans by China-based integrated PV module manufacturer Seraphim Solar System to open a 300MW module assembly


Credit: JA Solar.

The first half of 2015 has seen the return of meaningful cell capacity expansion announcements.

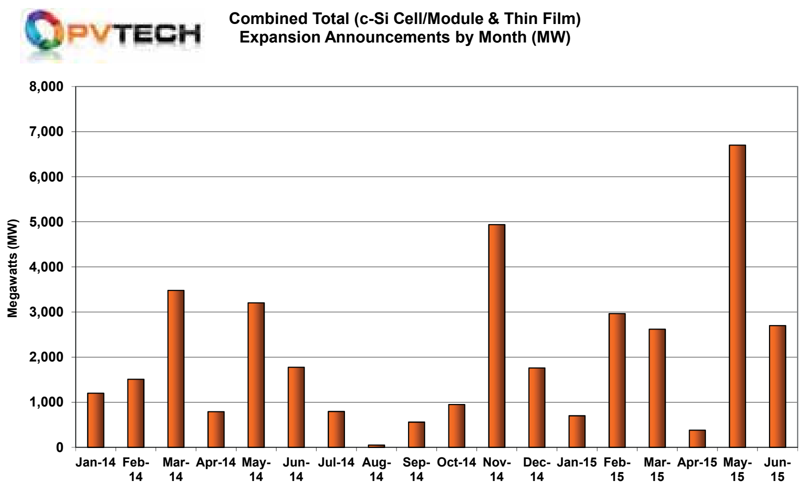

Figure 1: Combined total (c-si cell/module & thin film) expansion announcements by month (MW)

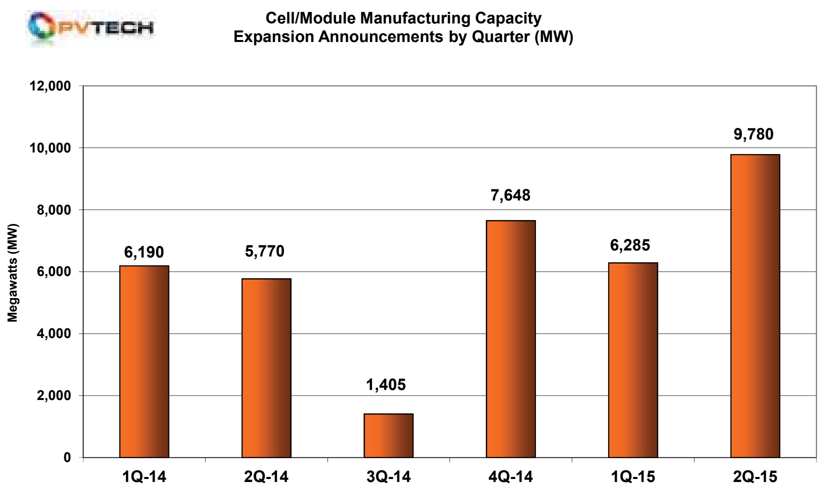

Figure 2: Cell/module manufacturing capacity expansion announcements by quarter (MW)

plant in Jackson, Mississippi in August 2015.

In recent years, several Asia-based PV manufacturers had closed down small-scale module assembly plants in the US due to chronic industry-wide overcapacity and massive ASP declines, but this was before the US imposed anti-dumping duties.

Several China-based tier-one module manufacturers, such as Yingli Green and Trina Solar, had previously touted plans to establish manufacturing in the US; both have since dropped those plans.

Recently, Trina Solar announced major capacity expansion plans in Thailand instead to avoid US import duties, while Yingli Green's financial state is dictating no added capacity in 2015 and has lowered planned module sales in the US this year.

Seraphim is therefore the first China-based module manufacturer to establish production in the US since Suntech Power Holdings operated a plant in Arizona. Suntech subsequently went bankrupt and the plant was closed in 2013.

Seraphim is also developing plans to double capacity of solar cell and module assembly production from 600MW in 2014 to 1,200MW by the end of 2015 at its highly automated 'Fab 1' in Changzhou China.

June exceeded expectations

With a lacklustre (380MW) of capacity expansion announcements in April and record-setting figures in May, expectations that June would prove to be muted proved unfounded. Instead, June recorded 2.7GW of new capacity announcements, similar in size to figures reported for February and March.

Perhaps not surprisingly there were no new dedicated solar cell capacity announcements made in June, following the bumper announcements made in the previous month. However, the surprising development was a massive 2.5GW of integrated capacity plans, driven by Trina Solar in India and China state-owned CNPV in South Korea.

The 2GW announced by Trina Solar should be treated with some caution, partly due to the few specific details made available and the fact the company had already announced 1GW of integrated production with two Indian firms in May. The decision by CNPV to build an estimated 500MW integrated plant in South Korea also lacks specific details.

Dedicated crystalline silicon module assembly announcements also fell to only 50MW, matching the lowest monthly figure, previously set in April 2014.

Second-quarter record

The May capacity expansion figures single-handedly helped the second quarter of 2015 exceed the 6.28GW of capacity announcements made in the first quarter.

The total new announcements made in the second quarter of 2015 topped 9.78GW (see Figure 2), again setting a new quarterly record.

Although 2014 was significant in ushering in the next major capacity expansion phase after three years of limited capital expenditures, the current and previous two quarters indicate a significant overall higher intensity to expansion plans, highlighted by the recent 1.5GW solar cell expansion by Hanwha Q CELLS.

The second quarter (see Figure 3) included 1GW of primarily a-Si thin-film expansions by Hanergy Group, 2.7GW of dedicated next-generation solar cells and 2.5GW of crystalline module assembly expansions,

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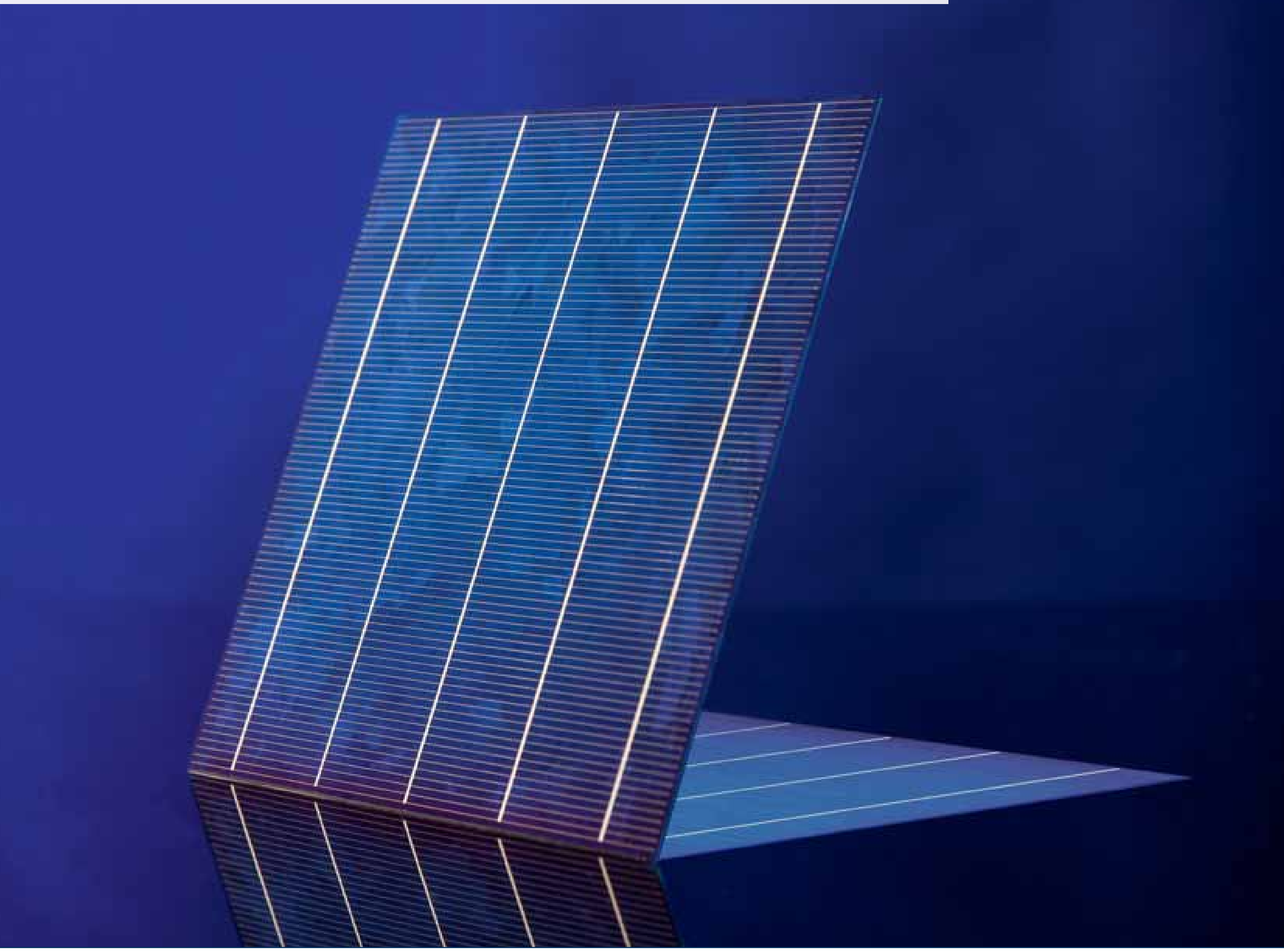

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*Gain in energy depending on rear side illumination and module mounting.

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Country	MW
China	2,710
Japan	300
South Korea	3,050
Taiwan	450
Malaysia	1,710
Thailand	2,250
Indonesia	60
India	4,360
Germany	1,200
Holland	70
Spain	1
USA	300
Mexico	200
Cuba	15
Brazil	570
Egpt	50

Table 1: PV manufacturing capacity announcements by country only (MW) 1H 2015

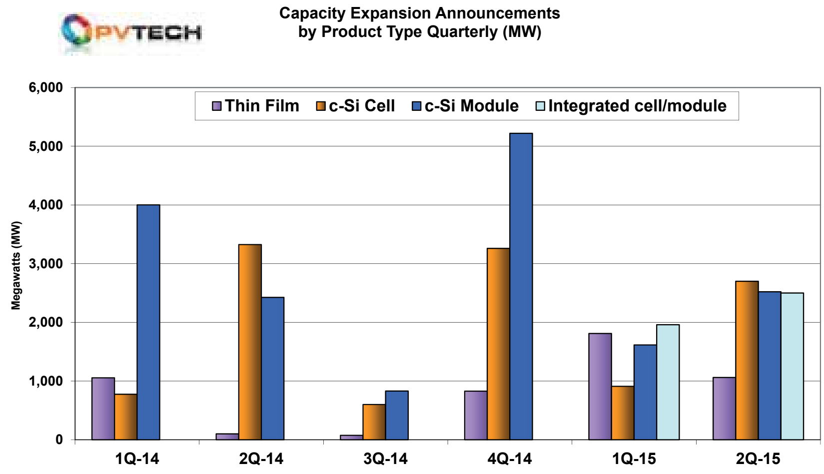


Figure 3: Capacity expansion announcements by product type quarterly (MW)

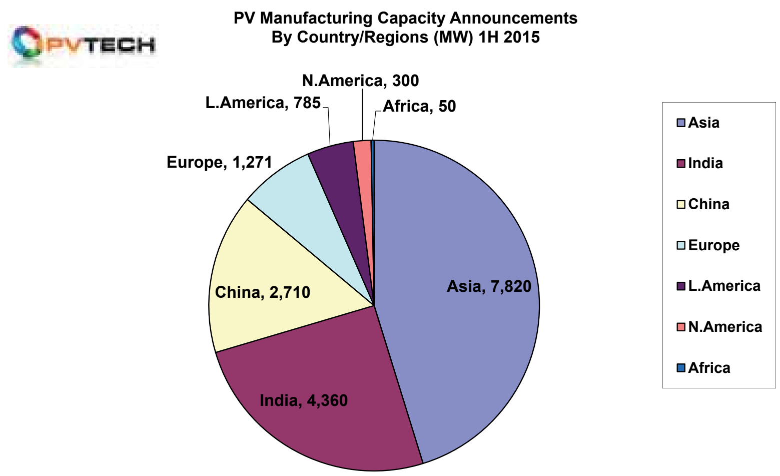


Figure 4: PV manufacturing capacity announcements by country/regions (MW) 1H 2015

predominantly outside China. Integrated production announcements also gained momentum over the first quarter (1.96GW), reaching 2.5GW in the second quarter of the year.

Not all the capacity announcements in the last two quarters are expected to be implemented in 2015. Initial analysis of all the announcements made in May indicate that around 2GW of the 6.4GW planned was highly unlikely to ramp until 2016 onwards. Those made in June, especially related to India, carry significant uncertainty until more specific developments take place. This also applies to the announcements from Hanergy, which are further analysed below.

Seismic shift

Analysis of global PV manufacturing expansion plans for the first half of 2015 on a geographical basis (see Figure 4) indicate that little if any meaningful or 'effective' new plans were announced by Chinese producers for production in China, representing a major shift in Chinese producers' plans.

Figure 4 classifies Asia to include key countries such as Japan, South Korea, Malaysia and Thailand, but excludes China to better show the location changes, while Table 1 provides individual country breakouts for the first half of 2015.

Instead of China, Chinese crystalline silicon-based PV manufacturers announced more than 6.7GW of planned capacity expansions in a number of overseas countries (see Table 1), including India, Malaysia, Thailand, South Korea, Brazil and the US.

To put this in perspective, Chinese crystalline silicon-based PV manufacturers dominated the 19GW of new capacity plans announced in 2014 for production in China (see Figure 5).

The first half of 2015 has seen several of the same tier-one companies that announced new production plans in China last year, such as Trina Solar, JinkoSolar and JA Solar, lead an exodus overseas. This has been driven by US anti-dumping duties as well as plans to become major players in emerging markets such as India and Latin America.

The lack of new capacity expansions in China contrasts with over 12GW of new announcements in 2015 for other regions across Asia, with Chinese producers accounting for just over half of the capacity announcement figures.

Southeast Asia attracted nearly 4.5GW of new PV manufacturing capacity plans in the first half of 2015, led by Thailand with over 2GW announced and over 1.5GW announced for Malaysia. This included

Company	Announcement Date	Manufacturing location	New Nameplate Capacity (MW)	Production Product Type
Jetion Solar	Jan-15	Thailand	200MW	Integrated c-Si Cell/Module
Renovasol	Jan-15	Brazil	70MW	Multi c-Si Module Assembly
Hanwha Q CELLS	Jan-15	Cyberjaya, Malaysia	230MW	(Relocated) PERC multi c-Si solar cell
Hanwha Q CELLS	Jan-15	Cyberjaya, Malaysia	130MW	(Relocated) Multi c-Si Module Assembly
PT Len	Jan-15	Indonesia	60MW	Integrated c-Si Cell/Module
Surana Solar	Jan-15	Fab City, Hyderabad India.	110MW	Multi c-Si solar cell
SolarPark Korea	Feb-15	South Korea	600MW	Integrated c-Si Cell/Module
LG Electronics	Feb-15	South Korea	200MW	N-type bi-facial mono c-Si cells and modules
Zhongli Talesun	Feb-15	Rayong, Thailand	500MW	Integrated PERC c-Si Cell/Module
Silevo/SolarCity	Feb-15	California, USA	32MW	(Relocated) Pilot & R&D line
Waaree Energies	Feb-15	Surat, Gujarat, India	750MW	Multi c-Si Module Assembly
Empresa de Componentes Electrónicos	Feb-15	Cuba	15MW	Multi c-Si Module Assembly
Tainergy Tech	Feb-15	Taiwan	300MW	Multi c-Si solar cell
Hanergy Thin Film/Shangdong Macrolink New Resources Technology	Feb-15	China	600MW	a-Si Thin Film BIPV plant
SolarWorld	Mar-15	Arnstadt, Germany	500MW	mono c-Si ingot production
SolarWorld	Mar-15	Arnstadt, Germany	700MW	Upgrade PERC cell production
Vietnam Government	Mar-15	Hanoi, Vietnam	20MW	Multi/Mono c-Si Module Assembly
Ener Brazil	Mar-15	Brazil	50MW	Semi-automated c-Si PV module assembly plant
JA Solar	Mar-15	Penang, Malaysia.	400MW	Integrated c-Si Cell/Module
JinkoSolar	Mar-15	Malaysia	500MW	Multi c-Si PERC solar cell
JinkoSolar	Mar-15	Malaysia	450MW	Multi c-Si Module Assembly
"Hanergy Thin Film/Inner Mongolia Manshi Investment Group"	Mar-15	China	600MW	a-Si Thin Film BIPV plant
Hanergy Thin Film/Baota Petrochemical Group	Mar-15	China	600MW	a-Si Thin Film BIPV plant
Flextronics	Apr-15	Ciudad Juarez, Mexico	200MW	Multi/Mono c-Si Module Assembly
Eclipse Brasil	Apr-15	Limoeiro do Norte, Ceará, Brazil	100MW	Multi c-Si Module Assembly
Orange Solar Power	Apr-15	Netherlands	70MW	15MW 'Monoflex' & 55MW Multi c-Si Module Assembly
Hanergy Thin Film	Apr-15	Wuhan, China	10MW	Thin Film GaAs R&D/Pilot Line
Onyx Solar	Apr-15	Spain	1MW	c-Si BIPV
Hanergy Thin Film/ Hanergy Group	May-15	China	900MW	a-Si Thin Film BIPV plant
Trina Solar	May-15	Rayong, Thailand	700MW	Multi c-Si solar cell (PERC)
Trina Solar	May-15	Rayong, Thailand	500MW	Multi c-Si Module Assembly
Gintech Energy	May-15	Thailand	350MW	Multi c-Si solar cell (inc,PERC)
Seraphim Solar System	May-15	Jackson, Mississippi, USA	300MW	Multi c-Si Module Assembly
Intéling soluções inteligentes	May-15	Bento Gonçalves, Brazil	?	Multi c-Si Module Assembly
Panasonic Corp	May-15	Shimane, Japan	150MW	HJ mono c-Si cell
Panasonic Corp	May-15	Shiga, Japan	150MW	HJ mono c-Si Module Assembly
JA Solar/ Essel Group JV	May-15	India	500MW	Integrated c-Si Cell/Module
Trina Solar/ Welspun JV	May-15	India	500MW	Integrated c-Si Cell/Module
Vikram Solar	May-15	India	250MW	c-Si mono/multi Assembly
Vikram Solar	May-15	India	250MW	c-Si mono/multi Assembly
BYD Company	May-15	São Paulo, Brazil	400MW	Multi c-Si Module Assembly
Hanwha Q CELLS	May-15	South Korea	250MW	Multi c-Si Module Assembly
Hanwha Q CELLS	May-15	Jincheon, South Korea	1,500MW	Multi c-Si PERC solar cell
Sunprism Energy	Jun-15	Cairo, Egypt	50MW	Multi c-Si Module Assembly
CNPV Power	Jun-15	Saemangeum, South Korea	500MW(E)	Integrated c-Si Cell/Module
Trina Solar	Jun-15	India	2,000MW	Integrated PERC c-Si Cell/Module
Hulk Energy Technology	Jun-15	Taiwan	150MW	CIGS thin film

PV manufacturing capacity expansion announcements in 2015

the relocation of production lines by Hanwha Q CELLS from Germany to Malaysia and also plans by Taiwan-based solar producer Gintech, in establishing production in Thailand.

The seismic shifts did not stop in China as South Korea re-emerged with new PV manufacturing expansion plan announcements estimated to be in the region of 3GW.

Both Hanwha Q CELLS and SolarPark Korea significantly contributed to the 3GW total in just the first half of the year, potentially marking a renaissance in PV manufacturing in South Korea and enabling Korean firms to fill the module demand void in the US left by many Chinese competitors.

In contrast, the renaissance in PV manufacturing announcements in the US that was noted last year has waned significantly. In 2014, the US had over 1.8GW of new capacity plans announced but has so far slumped to around 300MW, driven by a single Chinese producer, Seraphim.

Although much speculation still surrounds India and its ability to meet a highly ambitious 100GW of PV installations by 2022, around half of over 4GW of capacity expansion plans announced in the first half of 2015 include Indian and Chinese firms via joint ventures.

This is in contrast with only around 1.4GW of announcements that were made for India in the whole of 2014, with little of that figure yet to materialise in actual production.

Indian and other companies such as US-based SunEdison and JVs between Japan's SoftBank and Taiwanese OEM Foxconn have made pledges to build PV manufacturing plants in India that equate to significant capacity additions. But the vast majority have remained outside the scope of this analysis until more definitive announcements are made.

Meaningful capacity expansion announcements in the first half of 2015 have not been restricted to Asia alone, although its geographical dominance clearly remains.

Analysis of manufacturing capacity announcements made in this period for Latin America indicate the milestone of over 1GW of planned production in the region was surpassed in the first half of the year and took less than 18 months to achieve.

Key to the 1GW target being reached was the planned module assembly plant in Brazil by China-based BYD.

Latin America is forecast to install 2.2GW of PV in 2015, a 352% increase from 625MW in 2014, according to GTM Research. However, like India, raising capital is a major issue and has slowed production projects getting to the line, especially without overseas JV involvement.

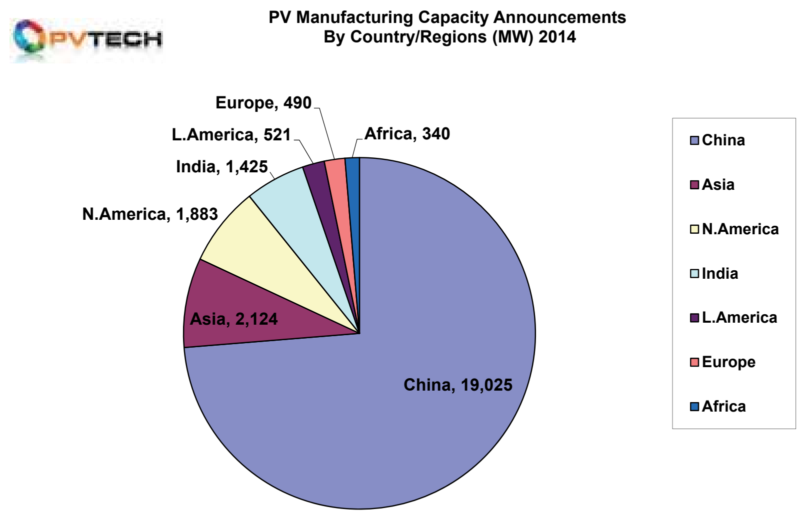


Figure 5: PV manufacturing capacity announcements by country/regions (MW) 2014

The only potential discrepancy in the first-half year analysis is whether the 2.7GW of primarily new a-Si thin-film capacity announced by Hanergy Thin Film should be recognised.

Remarkably, Hanergy TF actually accounted for all of the new capacity announcements for China in the first half of the year.

Hanergy TF only announced another 900MW expansion for its parent company, Hanergy Group, in May, yet while the company remains under investigation by Hong Kong securities and its share trading halted it announced the contract had been cancelled, without providing any explanation.

Hanergy TF previously made three other a-Si thin-film manufacturing contract announcements this year, totalling a further 1.8GW to companies with no prior PV involvement. A key omission from the contract announcements was the locations for the production plants.

It should be noted that in excluding Hanergy TF announcements of plants in China, no new capacity expansions were effectively made for China in the entire first half of the year.

Of course, capacity expansions announced last year for China are ongoing and a number of tier-two Chinese producers are benefiting from some OEM outsourcing deals and increased domestic demand, pushing utilization rates higher. However, new capacity announcements from this sector are often not easy to detect or decipher from higher utilisation rates.

Elsewhere, PV manufacturing capacity expansion plan announcements in Europe, North America and Africa remained limited and down to primarily one individual company in each region.

In the case of Europe, SolarWorld announced major line upgrades to PERC and the restart of monocrystalline ingot/wafer production. The increased cell efficiencies boost line megawatt capacity but it is unclear by how much. We have listed these cell developments but as such they are not new capacity announcements, highlighting the lack of activity in Europe as a whole in the first-half of the year.

Conclusion

The first-half year analysis highlights that with 16GW of announcements made, compared to around 12GW in the prior year period, overall momentum has been building. Greater emphasis is being placed on next-generation solar cell capacity expansions compared to 2014 and a more balanced approach, highlighted by further integrated capacity announcements.

The significant change in geographical location has been the most surprising aspect to the first half of 2015, although whether this trend continues into the second half of the year remains to be seen as does the question of whether the intensity of capacity expansion announcements will continue.

Smarter supply chains for a brighter solar future

Jen Tan, VP of APAC Sales and Energy Solutions (and former Global Planning and Logistics VP) & **Agnieszka Schulze**, Global PR Manager, REC, Singapore

ABSTRACT
As other entrants in the solar industry scramble to build greater efficiencies into their supply chain, the leading companies focus on manufacturing strengths such as zero-defect quality along the entire supply chain. When it comes to supply chain excellence, the solar industry as a whole is playing catch-up. However, there are players who have already made substantial progress here, having already adopted 'lean' practices to eliminate inefficiencies at source. REC, the largest European brand of solar panels and a world leader in the industry, is maintaining its strong position. The company's practices and principles are explained in detail in this paper.

Introduction

When industry parameters change and competition heats up, previous inefficiencies at an operational level are suddenly laid bare. The solar industry provides an unfortunately apt example. Following unprecedented demand for solar installations around the world at the start of the millennium, and generous feed-in tariffs in many countries to sweeten investment, innumerable new entrants rushed in to snap up a piece of this lucrative market. Global manufacturing capacity increased exponentially until 2011, and the market space grew more crowded. We know what happened next.

System prices have tumbled by over 50% in the past six years. And to make an already challenging competitive situation even tougher, many countries have slashed incentives for solar investment. Even in Germany, traditionally a flagship for the global solar industry, cutbacks in feed-in tariffs are making themselves felt (with new surcharges on commercial and industrial self-consumption). In an industry that has turned frosty for many contenders, the companies that are making a success of their solar business are those which can derive competitive advantage from every element of their supply chain. It is also a matter of competitive advantage for the entire industry: cost savings aside, the ability to reduce system costs for end users will make solar a more competitive energy source and expand the market for every stakeholder.

> "The global solar industry loses up to US$500m every year through deficiencies in its supply chain practices."

Figure 1. REC's products consistently rank among the best in quality.

Other industries lead by example

For many established industries, the need for smart, efficient supply chains has long been acknowledged. Not so in the solar industry. According to the International PV Equipment Association (IPVEA), the global solar industry loses up to US$500m every year through deficiencies in its supply chain practices. Some shipments are delayed, or even lost altogether; others arrive at their destination damaged. Inventory goes missing. Products are stockpiled unnecessarily in warehouses. The IPVEA estimates that losses could exceed the one billion dollar mark by 2018 if the industry fails to change its ways. Wasteful practices that would be unthinkable at car manufacturers – who also operate in a global industry with global supply chains – are common in the solar world, and the solar industry might do well to look to car manufacturers for a lead.

Toyota's famous 'lean manufacturing' transformed the entire industry with its principles of waste avoidance, low inventory, continuous problem solving and respect for people. The automotive industry has over time created an approach to achieving operational excellence that other, unrelated sectors now look to for inspiration.

REC experiences near-zero delay in its shipments and achieves near-zero-defect product quality, and its claims rate is among the lowest in the industry. While REC's products consistently rank among the best in quality, they are also competitively priced; the company is also bankable and considered a 'safe bet' on the Bloomberg New Energy Finance (BNEF) bankability survey (published in February 2015). But like any other player in the solar industry, REC is renewing efforts to further boost demand as system prices continue to fall. So what is REC doing differently to maintain its success? How has it adopted the principles of 'lean' into the solar world?

Rather than short-term, tactical initiatives focusing on short-term cost-cutting gains, REC has always taken the longer view, steadily building – and staying in control of – an effective supply chain that is focused on collaboration with qualified partners.

The quintessence of supply chain excellence

At the heart of REC is the REC Business System (RBS), REC's standard operating system for improving and sustaining safety, quality and productivity (see Fig. 2). With this system, REC has looked to numerous models for inspiration on best practice. RBS is a marriage of Toyota's 'Lean Philosophy', Motorola's 'Six Sigma' (for process excellence) and other world-class manufacturing concepts, combining the best of REC's own business system and that of REC's new parent company, Elkem. It provides the techniques that enable REC to fulfil its mission: to create value through efficient and sustainable solar products and services, and to do so together with partners.

It is no coincidence that the RBS is built like a house – strong only if the roof, walls and foundations are strong. The structural elements are the principles and practices that run through every aspect of REC's business. Customer satisfaction – with the best safety and quality, the shortest lead time and the lowest cost – is at the peak of

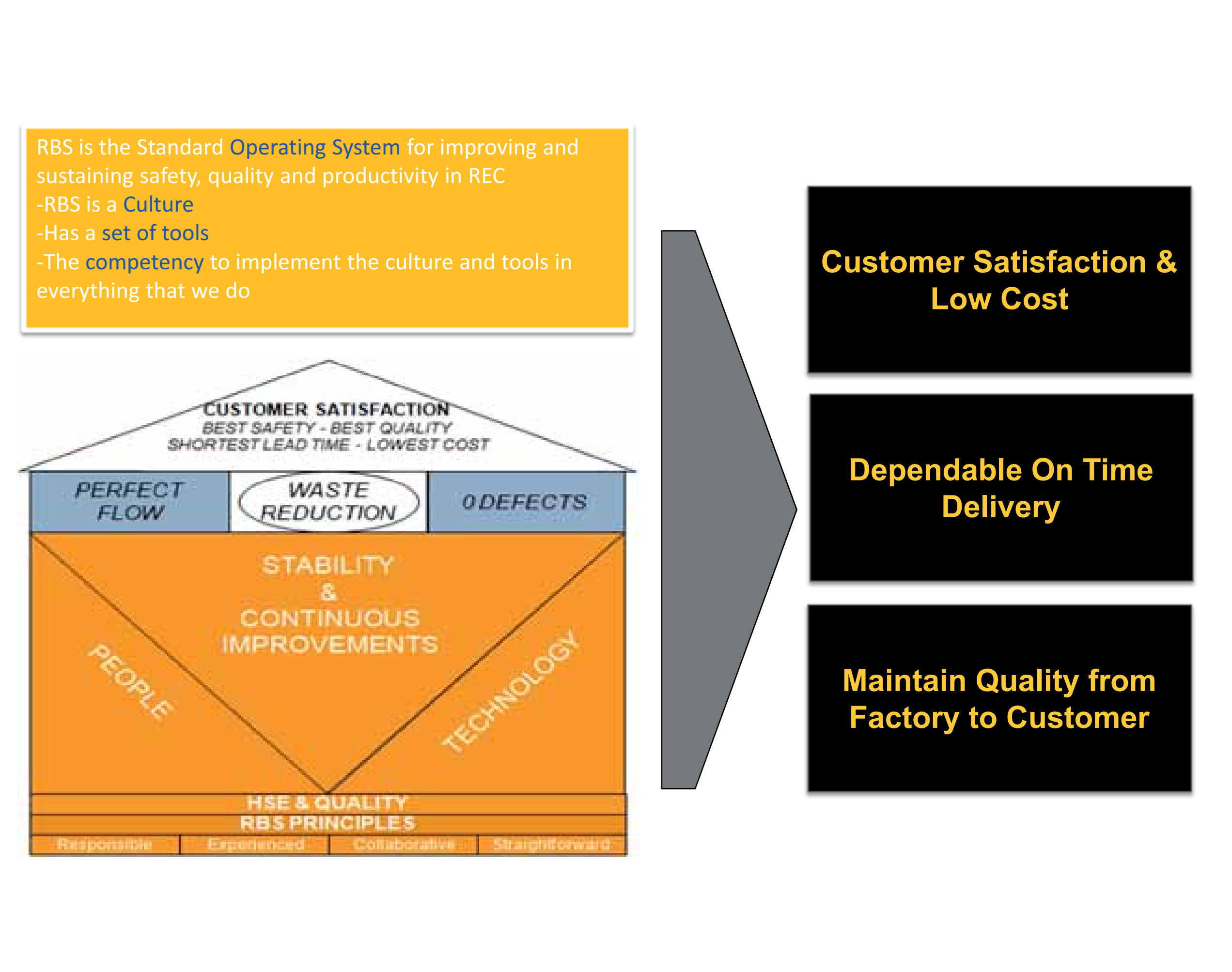
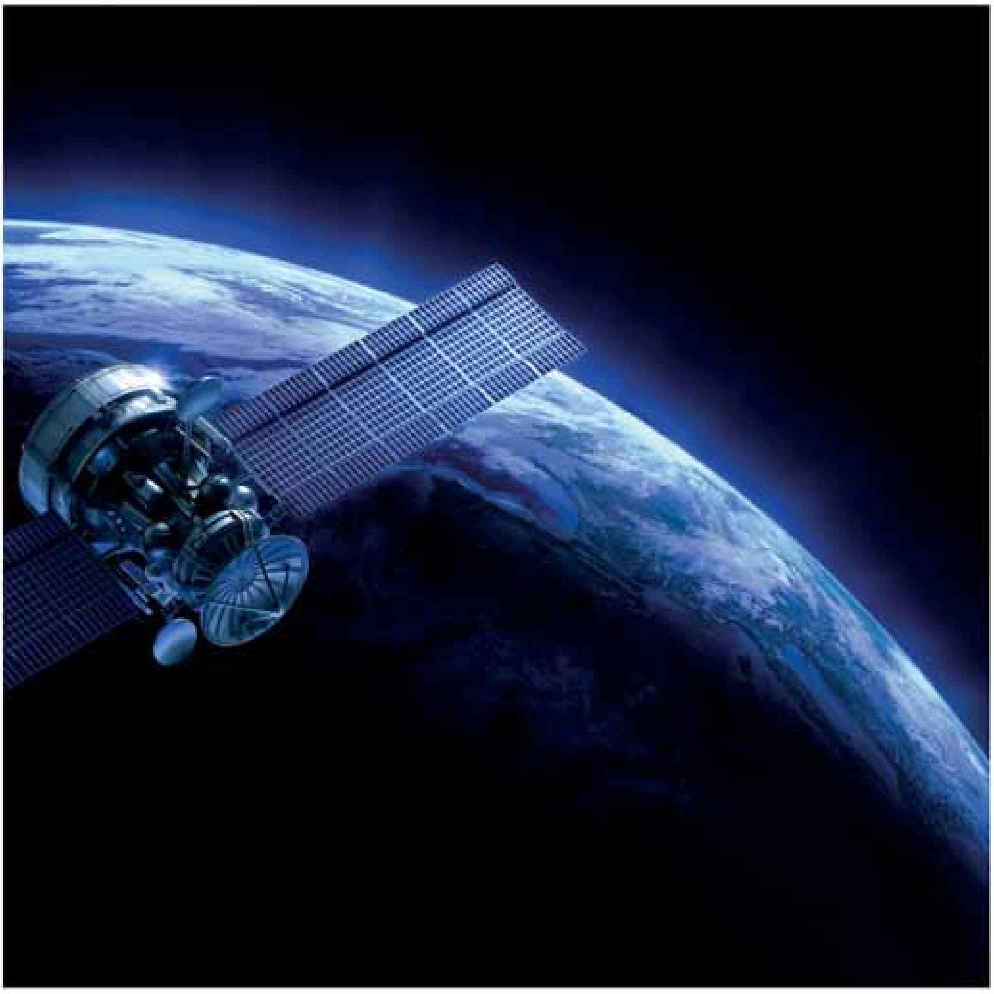


Figure 2. The REC Business System (RBS).



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this aspiration. This is the 'roof' of the RBS house, and is what REC always has in mind as the ultimate target.

Core values and principles

At the top of the house is the quality of the output which leads to customer satisfaction; the base foundation also comprises the qualities or values of people. These common qualities – being responsible, disciplined and straightforward, applying experience and collaborating with others – energize the measures that deliver excellence in the supply chain, and ultimately deliver cost efficiencies and zero-defect quality.

Moving up a floor, next come the RBS principles, which frame and inform everything REC does.

Principle 1 – Understand your business case

REC starts with the facts, figures and targets of the business case, and how activities affect safety, quality, lead time and cost.

Principle 2 – Organize your people

This is about how people and their roles are organized, ensuring that everyone engages with what is happening. In a vertically integrated organization such as REC, it is important to have teams that combine every relevant section of the value chain to ensure a big-picture view of workflows and processes. A lack of clear directions, or a lack of understanding of roles and responsibilities, is unproductive. In addition, zero physical harm on the job is paramount. If an employee's job is not safe and healthy, a company can forget about establishing an atmosphere of trust and respect for everything else it is trying to build. REC believes that accidents, injuries and occupational illnesses are preventable. The company's target is to ensure zero harm to employees, contractors, partners, customers and members of the public, and also to act with responsibility for the health of the planet.

Principle 3 – Design and improve your system

This is about continuous improvement of the systems. Technologies change, for example REC's own new floating solar solution; so do situations in the wider market, for example the reductions in feed-in tariffs that have altered the ROI calculations of investors. The agility to adapt is more important than ever for a true leader when conditions outside one's own sphere of influence change.

To design and improve a business system in the most straightforward way, REC has implemented four core rules (see Fig. 3).

Rule 1 – Standardize

Of these rules, standardization arguably delivers the most quantifiable benefits. To change or improve a process, it is necessary to know at the nuts-and-bolts level exactly how it works today. Standardization enables REC to achieve reliability and repeatability in its processes, which in turn lead to consistency in product quality and a strong commitment to deliveries on time and to contracts. Nothing is left to chance. The content, sequence, timing and outcome of every process are part of in-house

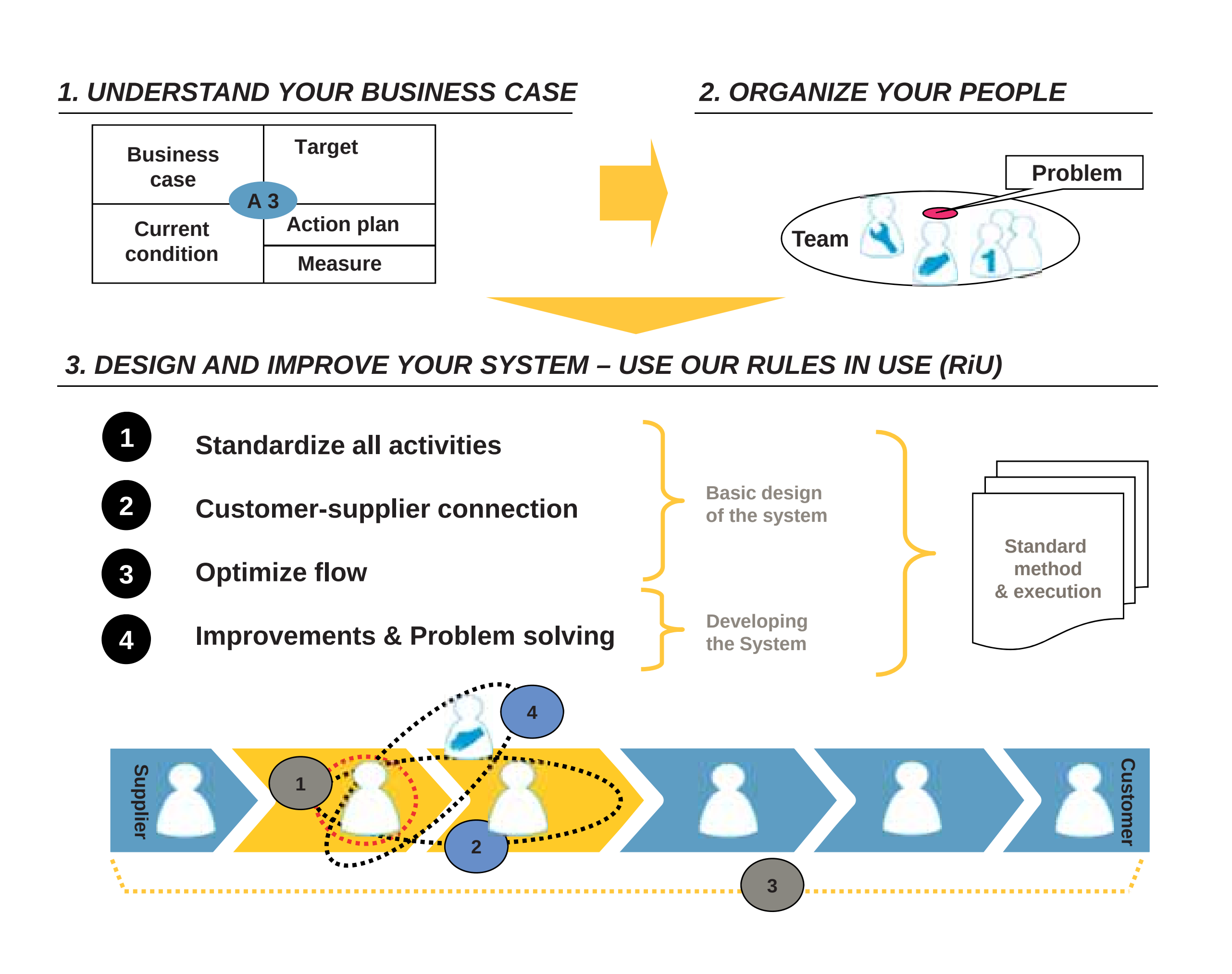

Figure 3. REC's principles and rules.

knowledge. If the results of a process are not exactly as expected, it is known exactly where to make adjustments. The payoff of standardization is in fact not just cost savings – it also provides the agility to respond quickly when changes are required.

Rule 2 – Maintain effective connections

Because standardization is in place, it is possible to specify what we want the previous stage to deliver to us, and what the next stage expects of us. Clarity and safety are key, with direct lines of communication between REC and the customer, and accurate input from customers about what is required, when and at what level of quality. This does not just apply to customers, in order to achieve optimum customer satisfaction; internal understanding, with effective connections within the company, also helps to improve productivity and efficiency.

> "Anything that does not add value to the product is waste."

Rule 3 – Understand and optimize flow

Anything that does not add value to the product is waste: in the form of overproduction, for example, this could be unnecessary conveyance of work in progress, waiting, or even overprocessing with a higher quality than needed. All production lines or process sequences are set up so that every product or service flows along a simple prespecified path, without forks or loops that can stall efficiency. People should never be uncertain about what step to take next. In the factory, product and process are aligned as closely as possible, with as little waste as possible. This attitude has to be apparent along the entire value chain, not just in production. For example, inefficient transportation routes, or the late (or non-) arrival of shipping documentation, will interfere with efficiencies in the supply chain (and are responsible for a chunk of the US$500m going to waste through supply chain inefficiencies). REC ensures that optimal flow is maintained throughout.

Rule 4 – Make improvements

RBS is about always challenging the current situation. There is always a better way – and often a need to respond to a specific challenge on the horizon. REC became part of Elkem Group in early 2015, and is therefore now able to make even more improvements to its leading energy payback time and CO_2 footprint by increasing the share of Elkem Solar Silicon in its manufacturing. As REC expands production in its factory, it is also introducing new 'flexilines' that can each be used to manufacture several different products.

Assuring the quality of output

Values and principles are one thing – applying them effectively in practice is another. Actual quality is a function of combination of the processes and the product that emerges from this process chain. By designing and deploying its RBS system, REC has taken the strategic steps to make certain that the product itself is consistently excellent and that the perfect flow, zero-defect production and zero waste which are declared objectives within the RBS system are accomplished.

Products are designed specifically to permit as much recycling and as little waste as possible. Between 2012 and 2014, the share of recyclable components increased from 40% to 75%, well above the industry average. Very little material is left over: at REC's Singapore manufacturing facility, instead of spacious hoppers to receive waste from the production line, there are receptacles which are more shoebox-sized.

While many companies routinely outsource virtually all of their manufacturing, this comes at a cost of loss of control. REC is following the vertical integration route, de-commoditizing the components and products that make up a system. All REC solar panels come from the company's own production facility in Singapore, which opened in 2010. Capacity has been steadily expanded to keep pace with growth, and by the end of 2015 will reach 1.3GW.

Through automation and vertical integration in production, with the manufacture of silicon wafers, cells and PV modules all at one site, REC gains technology, quality and expertise advantages as well as better reliability and repeatability, as evidenced by REC's strong performance in tests and bankability audits. (Accolades received by REC include the Frost and Sullivan Customer Value Enhancement Award for the Solar Industry and the Top Brand PV Seal from EuPD Research.)

REC modules are designed and engineered to deliver reliable long-term power output over their entire lifetime, and come with a 25-year warranty. Of the four million solar panels the company produces every year, less than 400 – one in ten thousand of the company's total annual output, or under 100 ppm – have to be returned owing to defects. To offer this reliability (and longevity), REC's product qualification process is substantially more stringent than the industry demands. REC develops products to pass its own internal standards, rather than pass a set of minimum requirements; IEC, UL and JET compliance is the starting point rather than the end goal. Any major design change undergoes an extended qualification process, during which panels are tested well beyond normal industry standards. This extreme testing, with harsh environmental conditions and brutal stressing, ensures that panels can perform in the most severe surroundings. REC's solar panels have passed water tests to prove they maintain performance and standards, even for installations on freshwater bodies; they also have desert accreditation, confirming that they can withstand the sandstorms and searing heat of desert regions.

Ownership of upstream process quality: sourcing

Factors influencing product quality extend far beyond the factory doors, of course, and taking real ownership of the supply chain has the potential to make a huge difference. As well as vertical integration at its own manufacturing facility, REC retains control and ownership of every stage of the process upstream and downstream.

Components are also procured from outside suppliers. With its stringent supplier qualification programme, REC regards sourcing as a continuous practice rather than a one-off initiative, and places sourcing at the centre of a strategic framework. This ensures that the supply chain is energized by suppliers with the competencies and cost efficiencies to help REC deliver on its mission. The sourcing strategy also includes analysing the global supply market to understand cost drivers and scout out new developments. Local sourcing is also key: by moving its factory to Singapore, REC now has access to the dynamic and competitive sourcing markets in the Asian region. Between 2010 and 2013, REC reduced its solar panel costs by half; of these savings, two-thirds were down to factory and operational efficiencies, and one-third was the result of reduced material costs.

Downstream: on-time delivery

Trying to manage a global supply chain without knowing where the cargo is, what condition it is in and who has custody of it, or even when an event occurs, is asking for trouble. It is certainly not the way to guarantee on-time delivery. REC partners with Hellmann Worldwide Logistics, a specialist provider of solar energy logistics, to explore strategic approaches, innovations and value-added services to re-invent, optimize and maintain full control of the global supply chain from factory to customer, and – at the most basic level – to ensure that products are delivered on time and in pristine condition.

Shipping conditions are optimized to ensure that zero damage is suffered in transit. Temperature and humidity are carefully controlled and shocks minimized while the products are travelling to their destination. Thanks to a carrier space guarantee, which protects against peak season surcharges and general rate increments, REC does not risk paying penalties for late delivery and achieves up to 50% savings during peak season.

REC selects shipping providers based not just on price, but also on the strength of the provider's global network, reliability, consistency and responsiveness. As a result, REC has best-in-class transportation costs, 15% lower than the market average. Likewise, REC saves on storage cost by genuinely delivering 'just in time'. Instead of stockpiling inventory, REC uses shipping containers for storage, and its products spend their time en route rather than in store. Accurate planning along the entire value chain – from sourcing and production to freight scheduling in line with the customer's requirements – means that the company is nearly always sold out from one quarter to the next.

The last mile: customer satisfaction based on strong partnerships

REC does not simply hand over responsibility for the product once it reaches the installer. The partners through which REC solar panels are sold globally are also part of the REC value chain and key to ensuring customer satisfaction. The company is strongly committed to long-term partnerships with distributors, integrators, project developers and promoters. In October 2011 REC launched its Partner Program with a range of benefits, support and rewards to help partners take their business to the next level. REC now has 30 Platinum and Gold Partners worldwide.

Installation quality is also vital to solar projects' meeting and exceeding expectations. Complementing its Partner Program, REC has also rolled out a certified installer programme, and also trains and certifies installers through the REC Solar Professional Program. In total REC has 700 certified installers worldwide.

Continuous improvement

Even if they are already leaders, the best companies continue to evolve their supply chains in order to better manage risks, anticipate changes and identify and exploit new opportunities. REC scrutinizes every facet within the supply chain for cost-saving opportunities; for example, shipping routes are continuously reviewed to ensure that the best choices are made. REC also recently improved its packaging, partnering with packaging experts and carrying out continuous engineering and testing. The result is a double-stack pallet instead of a single stack. This seemingly minor tweak has in fact improved REC's sea freight container loading by 25%, enabling the company to reduce shipping charges to customers without any impact on module quality.

Outlook for supply chain excellence in the solar industry

Analysts at Fraunhofer Institute and Agora predict that solar will be the world's most common energy source by 2050, powering 40% of the world's electricity needs, at generation costs as low as 2 to 4 eurocents per kWh. The evidence does point in this direction: in 2014 a record volume of solar capacity was installed worldwide, and the total capacity now adds up to 100 times the level of that in 2000. There is therefore everything to play for in an industry that looks set to be one of the most important on our planet within the lifetimes of many of us. It is a global imperative that the industry smarten up its supply chains to deal with demand at this level.

In the more immediate future, efforts to improve supply chains will probably be driven by necessity. System prices are too low to permit the luxury of letting half a billion dollars simply slip through the cracks. These efforts, if successful, will benefit every stakeholder in the industry (not just panel producers) by lowering solar costs all round. Apart from enhancing the perception of reliability of PV suppliers, greater cost efficiency in the supply chain will have a positive impact on the competitiveness of solar energy, and increase the number of countries in which solar has achieved grid parity with other energy sources.

> "Greater cost efficiency in the supply chain will have a positive impact on the competitiveness of solar energy."

As REC shows, supply chains work effectively when ownership of quality and knowledge is retained, and the supply chain reflects the company's wider approach to doing business. Zero-defect quality, the importance of long-term strategic partnerships, just-in-time logistics and reliable shipping are the outputs of a robust value system. The danger of a rush to optimize supply chains in the solar industry is that enterprises will over-focus on mining obvious efficiency potential in individual operational processes, losing sight of the need to approach their supply chains in strategic rather than tactical terms. Cost-cutting and short-termism are unlikely to be the route to sustaining success. The most successful enterprises – in the solar industry as in others – are those that can leverage their supply chains into activities that genuinely unlock value, and translate their corporate strategy into effective processes at the operational level.

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News

EU increases anti-dumping rates on Chinese solar glass

Chinese solar glass imports into the EU face stiffer duties.

Source: Flickr, Alex Gulbord

The EU has increased anti-dumping duties on Chinese solar glass to a maximum of 75.4%. The highest original anti-dumping tariff was 36.1%.

The review was requested by EU ProSun Glass in November 2014 with the EU reopening its investigation in December that year. The group is led by manufacturer Interfloat.

In an official release, the European Commission said it had found that export prices among the companies it investigated had continued to fall, even after the first set of tariffs had been applied.

The highest anti-dumping rate of 75.4% was applied to Xinyi PV Products.

Most companies have been given rates of around 60%. Countervailing duties remain unchanged from the original case.

SolarWorld, the complainant in the EU-China cell and module trade cases, publicly opposed the reopening of the solar glass case.

When the first [glass] case started there was a legitimate case to be answered but since then 50% of Europe's glass supply has disappeared," Milan Nitzschke, president of EU ProSun said.

Wafers

Fraunhofer ISE reveals kerfless wafer spin-off company

A new spin-off from Fraunhofer ISE is targeting kerfless solar wafer production, having developed high-throughput equipment that is touted to produce high-quality, low-cost wafers using atmospheric pressure chemical vapour deposition (APCVD) technology.

Start-up NexWafe GmbH in Freiburg, Germany is led by Stefan Reber, formerly head of crystalline silicon – materials and thin-film solar cells at Fraunhofer ISE. The start-up is being supported by an undisclosed amount of initial seed funding from Fraunhofer Venture.

Kerfless wafer production has previously been pioneered in volume production for semiconductor 'silicon on insulator' wafers by the likes of Soitec.

However, low-cost, high-throughput systems in line with PV market dynamics have proved elusive.

Comtec Solar seeing increased demand for 'Super Mono' wafers

Monocrystalline wafer producer Comtec Solar Systems Group has completed the qualification processes to supply two existing customers headquartered in the US and Japan from its Malaysia-based wafer production plant.

Comtec Solar says it has also completed the qualification process with a new undisclosed Japanese customer for its n-type monocrystalline 'Super Mono' products, which included pilot shipments that had started in the second quarter of 2015. Unspecified volume shipments were expected to start in the second half of 2015.

As of mid-June, the company was also in the process of qualification for Super Mono wafers with potential new customers in the US, Japan, Korea and Taiwan.

Polysilicon sales

Wacker's polysilicon sales down 10% in Q2 on weaker demand and ASP decline

Wacker's polysilicon sales may have reached a new peak for the first time in three years in the first quarter of 2015, yet they declined almost 10% in the second quarter, held up significantly by further penalty payments by customers on terminated long-term supply deals.

Wacker reported its Polysilicon division sales reached €261.3 million in the second quarter of 2015, down from €289.4 million the previous quarter and down from €273.2 million in the prior-year quarter.

The company said that the sales decline was due to PV customers reducing inventory levels following "robust demand" for polysilicon in the first quarter of 2015.

Hemlock's polysilicon sales declined in first half of 2015

Dow Corning has said its polysilicon sales, via its majority-owned subsidiary Hemlock Semiconductor, declined in first half of 2015. CFO J. Donald Sheets said first-half results were "impacted by fewer polysilicon shipments to long-term contract customers".

Sheets said these customers' contracts "have a degree of variability when customers take their product and recent order patterns have resulted in customer orders being concentrated late last year". Dow Corning also noted its earnings had been impacted by the strong US dollar. Group sales were US$1.42 billion, down 8% from the previous year period. Net income was US$113 million.

REC Silicon hit by China poly trade row

REC Silicon will halve production at its Moses Lake facility in Washington State as a result of the ongoing polysilicon trade dispute with China.

The cut in the fluidized bed reactor (FBR) production has taken 2000MT off its 2015 production guidance. It also announced that planned expansions at the facility are on hold. The company is facing a 57% duty to access the Chinese market.

There will be no job losses as a result of the temporary shutdown with existing staff replacing contractors for maintenance duties, ensuring the plant is ready for a restart and lowering costs.

Source: Applied Materials

Applied Materials is closing its wafering wire saw business and solar ion implant operation.

Daqo hit by big fall in polysilicon ASPs

China-based polysilicon producer Daqo New Energy's financial results were impacted by a sharp decline in polysilicon prices in the second quarter of 2015.

Daqo reported second quarter revenue of US$34.3 million, down from US$41.9 million in the prior quarter.

The sales decline was primarily attributed to polysilicon ASPs declining from US$18.09/kg in the first quarter of 2015, to US$15.95/kg in the second quarter.

Polysilicon production volume was 1,734MT in the second quarter, compared to 1,801MT in the prior quarter. Polysilicon sales volume was 1,363MT in the second quarter, compared to 1,502MT in the first quarter.

Company news

Applied Materials withdraws from solar ion implant and wafer sawing sectors

Semiconductor equipment supplier Applied Materials (AMAT) is to close its Precision Wafering Systems (PWS) wire saw business, headquartered in Switzerland. The company will also stop development on its 'Solion' ion implant product, saying that it will "shift some internal resources to other opportunities". AMAT will continue support for existing Solion customers.

The PWS business was formed from its acquisition of HCT Shaping Systems for US$475 million in June, 2007, while the Solion ion implant business came from the acquisition of Varian Semiconductor, which had around 80% of the semiconductor market for ion implantation tools and had launched its first ion implant tool for solar cell applications. Applied announced its acquisition of Varian in May 2011 at a cost of US$4.9 billion.

Heraeus files patent infringement lawsuit against Giga Solar Materials

Heraeus has filed a patent infringement lawsuit against Taiwan-based PV materials specialist Giga Solar Materials Corp for allegedly infringing a patent held by Heraeus over front-side metallization paste materials used for solar cells.

In its complaint filed at the Intellectual Property Court in Taipei, Taiwan, the company claimed that Giga Solar sold three series of its patented front-side silver pastes to cell manufacturers in Taiwan.

The patent covers the use of leaded and lead free tellurium glasses in the production of metallization pastes.

Andreas Liebheit, head of Heraeus Photovoltaics' Global Business Unit, said Heraeus invests heavily in developing innovative metallisation pastes and said the advances made by the company benefits the PV industry by improving solar cell technology.

CEO of GTAT Tom Gutierrez resigns

Long-standing CEO of silicon PV and sapphire materials equipment supplier GT Advanced Technologies (GTAT), Tom Gutierrez, has resigned all positions at the company, which continues to operate under Chapter 11 bankruptcy.

The new CEO will be its former EVP and general manager of its Polysilicon and Photovoltaic business, David Keck. Keck also joins a newly established Office of the Chairman, overseeing ongoing Chapter 11 progression, reporting to the Restructuring Committee of the Board. Before joining GTAT, Keck operated his own consulting business relating to the silicon industry and served as VP of business development for Advanced Silicon Materials Incorporated (ASIMI), now known as REC Silicon.

Financial news

Solexel's lightweight mono PV attracts Saudi funding

The venture capital investment arm of

King Saud University of Saudi Arabia has contributed to a funding round for Solexel, a US manufacturer of thin monocrystalline solar.

With IP-protected high-efficiency cells and panels, Solexel aims to compete with silicon solar on efficiency, but with thin-film on flexibility and versatility.

Analyst Finlay Colville of Solar Intelligence said the latest funding showed another external source of financing coming into what he described as Solexel's "prolonged start-up phase".

Commercializing the technology will represent an integrated production challenge that other PV manufacturers have not taken on, Colville said – producing much thinner wafers than the industry has become accustomed to.

Polysilicon plant project in Qatar boosts centrotherm's 1H sales

PV and silicon equipment specialist centrotherm photovoltaics reported increased sales in the first half of 2015, driven by revenue generated from the often delayed polysilicon plant project in Qatar for Qatar Solar Technologies (QSTec).

Centrotherm reported first-half revenues of €85.9 million (US$100 million), compared to €78.09 million (US$86.4 million) in the prior-year period. PV sales in 2014 were €90.6 million, up from €70.1 million in 2013.

In its Silicon segment, primarily comprising subsidiary SiTec, sales reached €40.09 million, including €31.8 million directly from the QSTec polysilicon project.

QSTec is a JV between Qatar Solar, owned by the Qatar Foundation for Education, Science and Community Development, SolarWorld and the Qatar Development Bank. QSTec has a 29% shareholding in SolarWorld.

Meyer Burger guides huge sales target for second half of year on new order intake

Meyer Burger has reported group sales of CHF124.4 million (US$127 million) for the first half of 2015, guiding full-year sales of around CHF400 million (US$408 million).

Meyer Burger reported PV segment sales of around CHF91 million (US$92.9 million) in the first half of 2015.

PV segment new order intake was dominated by advanced solar cell technology purchases, including heterojunction (HJ) cell coating equipment, PERC technology on the MAiA 2.1 platform as well as orders for wafer and module measurement technologies.

Source: Meyer Burger

Meyer Burger has seen sales rebound and has guided a large sales target for the second half of 2015.

PV encapsulant producer STR Holdings battles losses

STR Holdings is battling continued losses, lacklustre sales and a second warning from NYSE regarding de-listing.

STR has been threatened with delisting from NYSE, due to its share price trading below the US$1.0 threshold for more than 30 consecutive trading days.

In January, the company undertook a reverse stock split to regain compliance. Not surprisingly, STR noted that it did not plan a second reverse stock split at this time.

STR has around six months to address the US$1.0 threshold, but must also meet an average market capitalisation of US$15 million on a 30 day consecutive trading timeframe, under NYSE rules.

Partnerships

GET adding 1GW of outsourced ingot/wafer capacity

Green Energy Technology (GET), Taiwan's largest wafer producer, has signed an outsourcing agreement for ingot growing and wafer slicing with another Taiwan-based producer, Eversol.

GET said it would be purchasing a total of around 1GW of multicrystalline wafers, including around 400MW from Eversol, while retaining its in-house capacity at 2.2GW. GET has secured further production partnerships and will provide on-site technical support to Eversol's production facilities to ensure product quality.

Its latest 'Victoria' series multicrystalline wafers used with conventional cells can achieve conversion efficiencies of 17.8% to 17.9%.

Yingli and LONGi to partner on monocrystalline value chain

Yingli Green and leading monocrystalline wafer producer Xi'an LONGi Silicon Materials are to cross-use their products from wafers to modules.

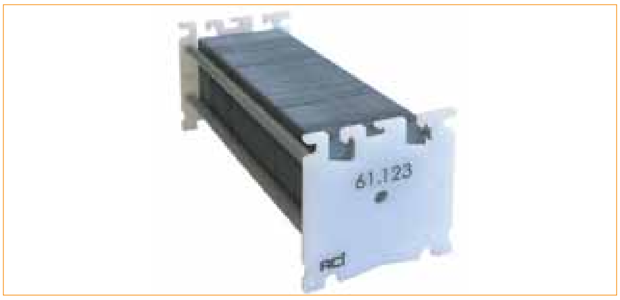
LONGi had previously stated its intention to move downstream and support the expansion of production of monocrystalline wafers by producing monocrystalline PV modules.

Under the new deal with Yingli Green, LONGi is expected to become a preferential wafer supplier to the integrated PV manufacturer, while providing its latest low-cost production techniques to Yingli Green, which has a relatively small capacity of monocrystalline silicon wafer production.

The deal would also reduce development and cost reduction expenditures for Yingli Green in respect to monocrystalline wafers production.

Product Reviews

ACI



ACI's 'ecoCarrier' improves wafer/cell handling in automated loading and unloading processes

Product Outline: ACI, a cleaning and automation specialist, has introduced its new 'ecoCarrier' designed for carrying and handling monocrystalline and polycrystalline wafers/cells. Compared to the conventional cleaning media used in wafer and cell manufacturing, cleaning with ozone and water offers several advantages. However, ozone places high demands on work piece carriers.

Problem: Lower costs, better cleaning results and compatibility with the environment are the main reasons why ozone is being increasingly used by the solar industry as a cleaning medium in wafer and cell manufacturing processes. However, the allotrope of oxygen reacts very aggressively with a wide range of materials, such as polypropylene .

Solution: Made from polyvinylidene fluoride (PVDF), the new ecoCarrier from ACI AG is not only resistant to ozone but its smooth surface and increased stability also aid process optimization. The ecoCarrier features further attributes, such as an optimized slot form for automated handling, torsional stiffness and a resistance to high temperatures. Even if temperatures fluctuate by 40°C, its dimensions remain so stable that work pieces can be loaded and unloaded without any risk of damage.

Applications: Handling of wafer/cells in standard substrate sizes of 156 x 156mm and 125 x 125mm and can be adapted to other formats as well as wafer thicknesses of 130µm.

Platform: The ecoCarrier's combination of an optimum slot form and high chemical resistance make it ideal for long-term automated loading and unloading processes. The low dimensional tolerance of just 0.1mm means that placement systems don't have to be readjusted each time for a new carrier or batch – regardless of whether it's the start-up of production or later purchase of workpiece carriers. The slot form also ensures that very thin wafers/cells, e.g. with a thickness of 130µm, can be processed easily without adhering to one another.

Availability: Currently available.

GCL

GCL-Poly's S4 wafer offers higher cell efficiencies for PERC cell architectures

Product Outline: GCL-Poly has launched its high-efficiency 'GCL Multi-Wafer S4' polycrystalline wafer. Trial data from customers was said to have shown that the average conversion efficiency for the S4 wafer has reached 18.33% for a conventional polycrystalline solar cell line, 0.22% higher than that of its previous high-efficiency wafer, the S3, pictured above.

Problem: High solar cell conversion efficiencies require higher purity solar wafers. Production process improvements are constantly required to meet next-generation cell architectures such as PERC.

Solution: The GCL Multi-Wafer possesses three prominent technical features. First, the use of GCL's new high-efficiency pure crucible can effectively solve the problem of deploying contacts on the back side of multicrystalline wafers and significantly enhance the conversion efficiency. Second, the platform of growth technology further enhances the conversion efficiency, and the output power of solar modules can be effectively enhanced through the optimized design of the size of wafers. Thirdly, the contribution of the new co-doping technology is claimed to solve the issue of light-induced degradation (LID) of solar cells, providing for high-efficiency cell processes including passivated emitter rear contact (PERC) solar cells.

Applications: High-efficiency polycrystalline solar cells including PERC.

Platform: The GCL Multi-Wafer S4 is produced from upgraded DSS furnaces and high-purity crucibles. This means no surface damage, stains, water marks, or contamination and wire saw marks limited to ≤ 15µm.

Availability: Available since April 2015.

Comprehensive analysis of strength and reliability of silicon wafers and solar cells regarding their manufacturing processes

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ABSTRACT

The mechanical strength of monocrystalline and multicrystalline silicon wafers is mainly dictated by the cracks induced during the wire-sawing process. Different sawing technologies, such as diamond-wire- or slurry-based processes, lead to different strength behaviours of as-cut wafers. Furthermore, the strength is strongly influenced by texturization, and at this stage can be interpreted as the basic strength of a solar cell. The metallization and firing processes determine the final strength and reliability of a solar cell, with the metallization contacts being the root cause of breakage of solar cells, depending on the particular cell concept. This paper gives a comprehensive overview of the typical ranges of strength for as-cut wafers, textured wafers and solar cells, for the two different sawing technologies. Around 100 batches with 4,253 samples were evaluated in the study.

Introduction

Diamond-wire-sawn wafers have been receiving more attention during the last few years because of the potential for higher cutting speeds, less wire consumption and the use of cheaper cooling fluids, in comparison to the standard slurry process [1]. Diamond-wire sawing is expected to gain market share at the expense of slurry-based wafering over the next 10 years [2]. As well as the challenges in cutting and texturization for multicrystalline wafers, the comparatively low strength of diamond-sawn wafers is perhaps the most critical aspect in the solar cell production process. Because the wafer makes up 33% of the overall module cost [2], this strength is very important in order to ensure small breakage rates. The questions therefore arise as to how the strength changes within the solar cell production processes, and what the differences are between diamond-sawn and standard slurry-sawn wafers.

The strength of silicon solar cells is defined by defects on the silicon surface, depending on the manufacturing of the wafers and cells [3]. For as-cut wafers, the related defects are mainly cracks induced by the sawing process [4]. Besides the type of material used (multicrystalline or monocrystalline silicon), the major factor affecting wafer strength is the sawing technology, which leads to different cracks, and therefore to different strength behaviours. In the processes at the start of cell production, the wafer surface is then altered again by saw-damage removal and texturization processes.

> "Besides the type of material used, the major factor affecting wafer strength is the sawing technology."

This paper reports on the strength behaviour of diamond- and slurry-sawn wafers and gives a comprehensive overview of the typical ranges of strength values for as-cut wafers, textured wafers and solar cells. In the study 2,207 as-cut wafers, 743 textured wafers and 1,303 solar cell samples were tested and evaluated at Fraunhofer CSP.

Methods for testing strength

The failure of wafers and solar cells arises when critical loading is reached, which is defined by the most critical defect, according to the weakest link theory for brittle materials [5]. With the use of fractography techniques, fracture origins for slurry- or diamond-sawn wafers and solar cells were found on the surface, as shown in Fig. 1; this correlates with the assumption that the sawing process induces the dominant damage on the wafer surface. The kinds of defect, however, vary between slurry and diamond-wire sawing: cracks of different shapes and depths occur on the surface, which govern the strength of the wafer. With solar cells, the fracture origin for the back side is mostly found in the overlapping region of the different metallization pastes.

Although there are different optical methods for detecting cracks in the millimetre range that have been induced on the wafer surface after the sawing process [6], there is still no reliable industrial method for characterizing the cracks that define the as-cut wafer strength, which are in the tens of micrometres range [7]. Because of this fact, fracture tests are the only way to determine the strength of as-cut/textured wafers and solar cells.

Fig. 2 shows the most frequently used fracture test methods, categorized by uniaxial and biaxial testing [8]. The uniaxial fracture tests are used for evaluating edge and surface defects on small or large samples. The four-point bending (4PB) is preferred over the three-point bending (3PB) method, because of the larger constantly loaded area between the upper two rollers with 4PB, instead of just one line under the upper roller in the case of 3PB. The 3PB can be used for very small samples or as a method for finding the fracture origin (see Klute et al. [7]).

The biaxial fracture tests are mainly used for the evaluation of surface strength of small samples if the edge defects need to be suppressed, such as for laser-cut specimens. In general, the ring-on-ring test should be preferred over the ball-on-ring test, since the loaded area is larger. However, because of the small thickness of photovoltaic wafers, the ring-on-ring test is limited to small ring geometries, as otherwise the stress field would become highly nonlinear [9]; for this reason, the ball-on-ring test is mostly used for thin semiconductor materials.

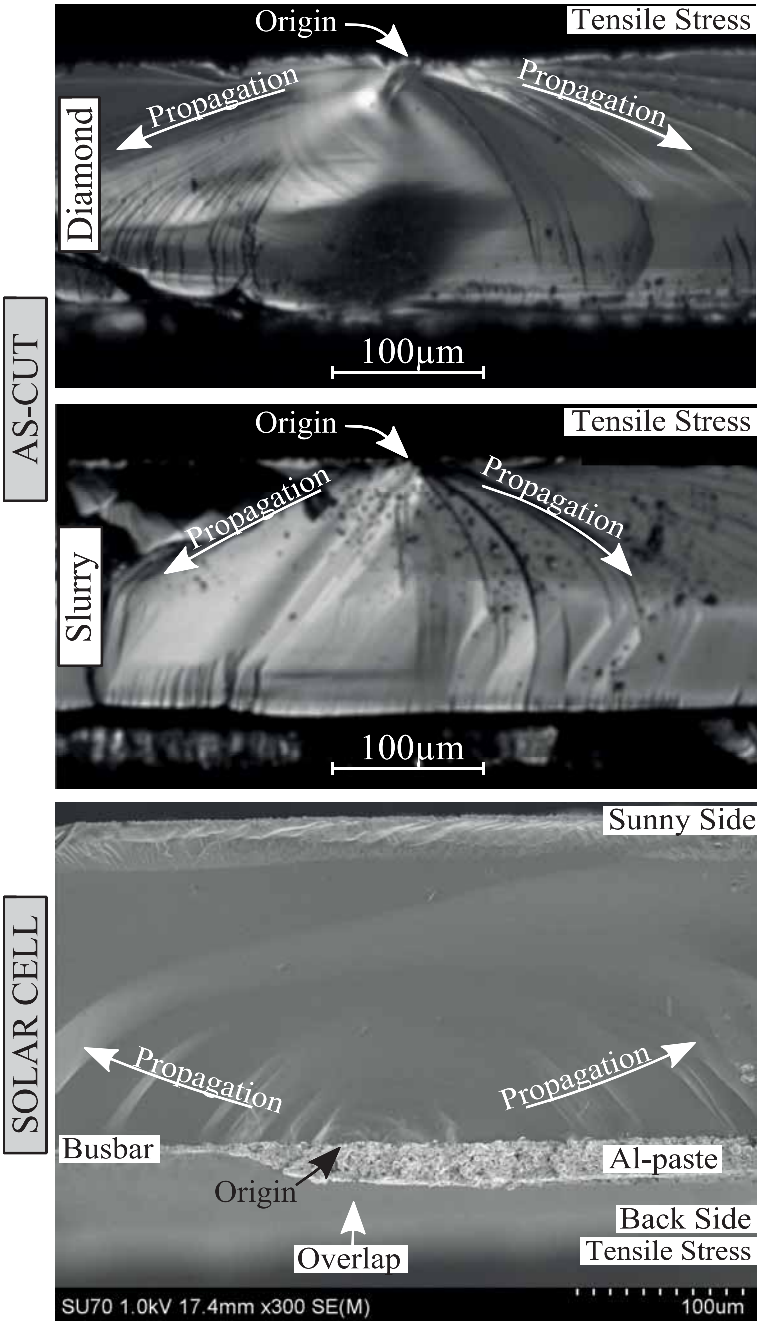

Figure 1. Fracture origins from optical and scanning electron microscopy (SEM) at the surface of diamond- and slurry-sawn monocrystalline wafers and of solar cells from samples after a four-point bending (4PB) test (a cross-sectional view of the fracture surface is shown).

For an evaluation and comparison of the biaxial and uniaxial tests, a numerical model is required in order to accurately calculate the fracture stresses and effective size. In this paper only the results from 4PB are used, because the area evaluated is the largest, and edge defects are considered.

Statistical evaluation and size effect on strength

After the tests were performed, it was necessary to calculate the fracture stresses using finite element models, which consider nonlinearities as large deflections and contacts between sample and rollers [3]. These stresses were then evaluated statistically using a two-parameter Weibull distribution [5,10]:

$$P = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_\theta}\right)^m\right] \qquad (1)$$

where σ is the loading, σ_θ is the characteristic fracture stress at which 63.2% of all samples fail, and m is the Weibull modulus, which represents the scattering of the fracture stresses. A high Weibull modulus represents a small variation and vice versa.

In fracture tests of brittle materials another important fact is the effect of size on strength [5,8]: the measured strength depends on the sample area or volume. With increasing volume, there is a greater likelihood of finding a critical defect in this volume, which results in a smaller fracture stress. Different sample sizes and load cases therefore mean that results from uniaxial and biaxial fracture tests cannot be directly compared. Thus, because of the effect of size on strength, the size of the samples or loaded geometry needs to be taken into consideration.

If surface-related breakage is assumed, the area of the wafer needs to be analysed; an effective area A_{eff} is therefore calculated for the different samples and test geometries. This effective area is influenced by the sample size, test parameters and Weibull modulus. For an effective area A_{eff}, the size-independent scale parameter σ_θ can be determined from the equation:

$$\sigma_0 = \sigma_\theta {A_{eff}}^{1/m} \qquad (2)$$

Fig. 3 shows the relationships between the effective area, Weibull modulus, characteristic fracture stress and test geometry for two different 4PB configurations. The effective area for the 4PB configuration can be calculated by:

$$A_{eff,4PB} = b\frac{m\, l_1 + l_2}{1+m} \text{ for } t \ll b \qquad (3)$$

where b and t are the length and thickness of the sample, and l_1 and l_2 are the spans of the inner and outer rollers. It can be seen that different test configurations can lead to different results in experimentally measured characteristic fracture stresses.

For the study reported in this paper all characteristic fracture stresses from different sample sizes and test configurations were converted to an effective area of 9,116mm^2, which represents a 4PB with standard test conditions (l_1 = 55mm, l_2 = 110mm), a wafer size of 156mm × 156mm and a Weibull modulus of m = 15.

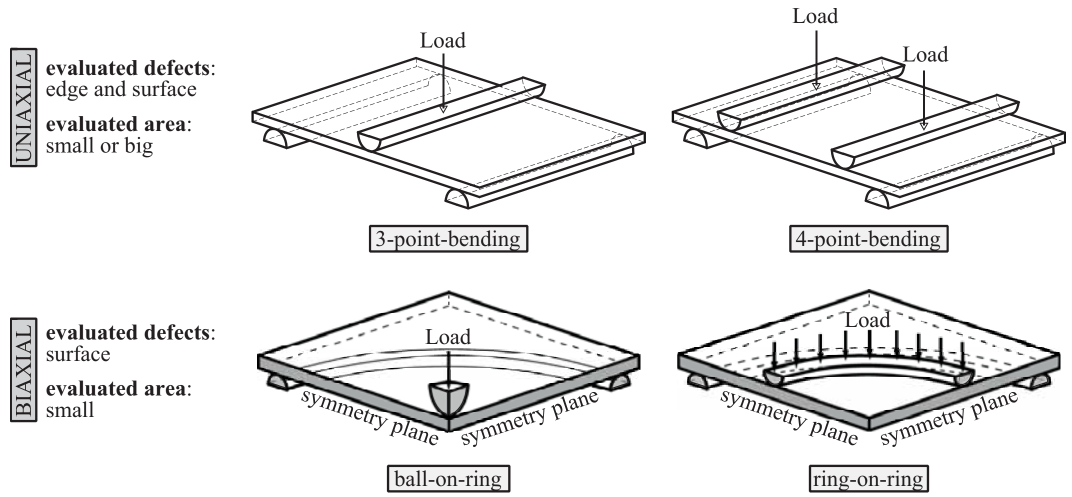

Figure 2. Different fracture test methods for determining the strength of as-cut/textured wafers and solar cells.

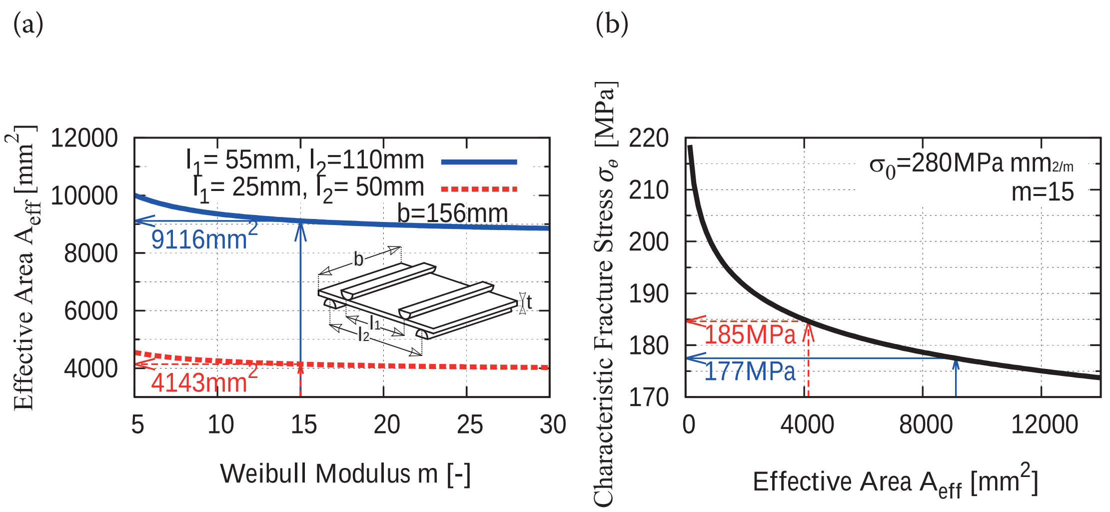

Figure 3. (a) Dependence of the effective area A_{eff} on the Weibull modulus *m*. (b) Influence of the effective area on the characteristic fracture stress σ_θ.

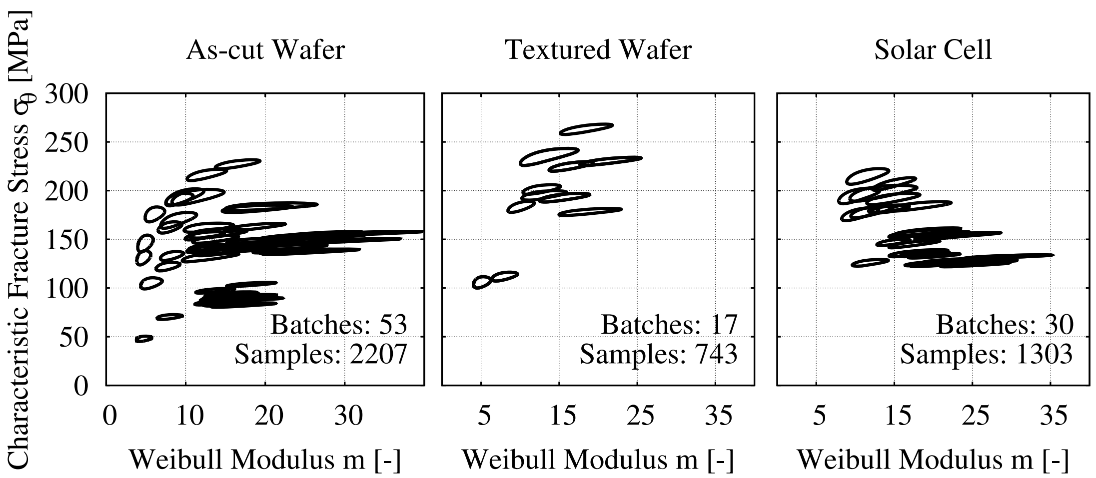

Figure 4. Strength results for as-cut/textured wafers and solar cells, tested in 4PB at Fraunhofer CSP, each ring (MLE 90% confidence ring) representing one strength test with an average of 42 wafers per test.

Overview of typical ranges of strength

Although the strength of silicon wafers is influenced by many parameters of the sawing process, the intention of this paper is to give an overview of the typical strength-range results. The data obtained from strength testing over the past few years, with 100 batches and over 4,250 samples tested in 4PB at Fraunhofer CSP, is used (see Fig. 4).

Because of the effect of size on strength, all data from 4PB experiments with as-cut wafers were converted to an effective area of A_{eff} = 9,116mm^2 and then sorted by material, sawing process and loading direction. An overview of parallel and perpendicular loadings to the saw marks is shown in Fig. 5. The boxes represent the outer limits of the Weibull parameters based on the experimental data, considering the limits of the confidence bounds; the values are shown in Table 1. In general, for every material and sawing technology, lower strength is demonstrated with parallel loading than with perpendicular loading, but the difference between diamond-sawn wafers and slurry-sawn wafers is greater in the former.

Material

In initial results multicrystalline diamond-sawn wafers demonstrate lower strength than monocrystalline ones. In the case of slurry-sawn wafers, however, the strength range for multicrystalline wafers is similar to that of monocrystalline wafers, although the monocrystalline wafers exhibit less variation in strength. Monocrystalline wafers tend to a higher Weibull modulus than multicrystalline ones; they also have a lower scattering in fracture stress, except for monocrystalline diamond-sawn wafers under perpendicular loading.

> "In initial results multicrystalline diamond-sawn wafers demonstrate lower strength than monocrystalline ones."

For analysing the strength of quasi-mono slurry-sawn wafers, only a few data points in parallel loading were acquired, but they seem to fit within the range between monocrystalline and multicrystalline wafers.

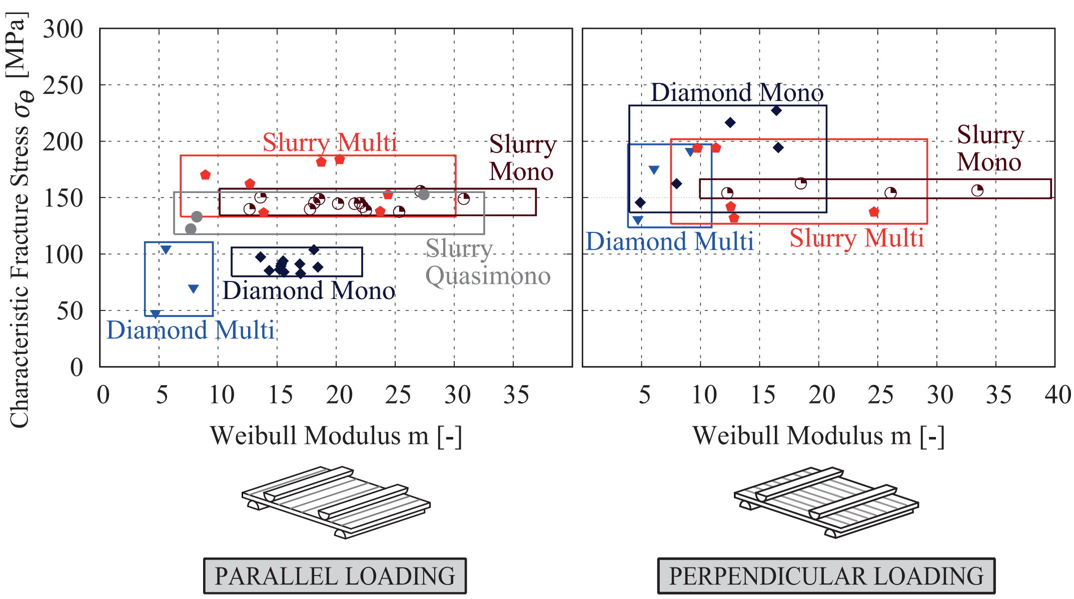

Figure 5. Overview of typical ranges of strength for as-cut wafers tested in 4PB (A_{eff} = 9,116mm^2) for different sawing technologies and material types with loading parallel and perpendicular to the saw marks.

Sawing technology	Material	Loading	Weibull modulus m	Characteristic fracture stress σ_θ [MPa]
Slurry	Mono	Parallel	10–37	134–158
		Perpendicular	10–40	149–166
	Multi	Parallel	7–30	133–187
		Perpendicular	8–29	127–202
Diamond	Mono	Parallel	11–22	80–106
		Perpendicular	4–21	137–232
	Multi	Parallel	4–10	45–111
		Perpendicular	4–11	124–197

Table 1. Overview of typical ranges of strength for as-cut wafers tested in 4PB (A_{eff} = 9,116mm^2) for different sawing technologies and material types, with parallel and perpendicular loading to the saw marks.

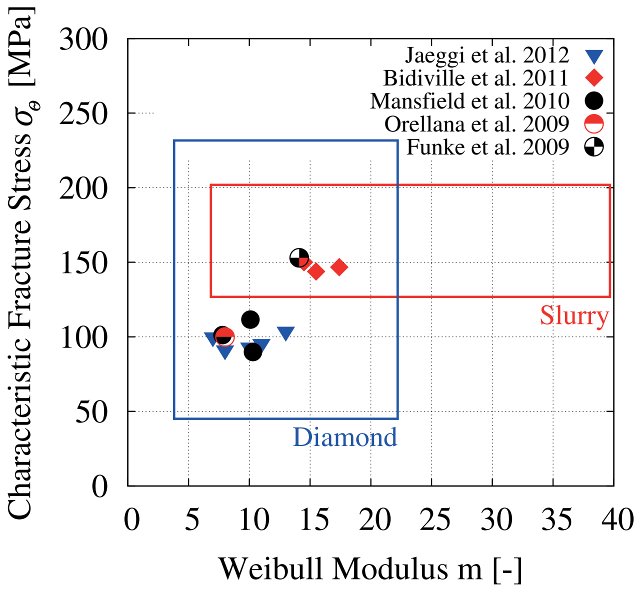

Figure 6. Overview of the typical ranges instrength of diamond- and slurry-sawn wafers (material and both types of loading combined), compared with strength values given in the literature [11–15].

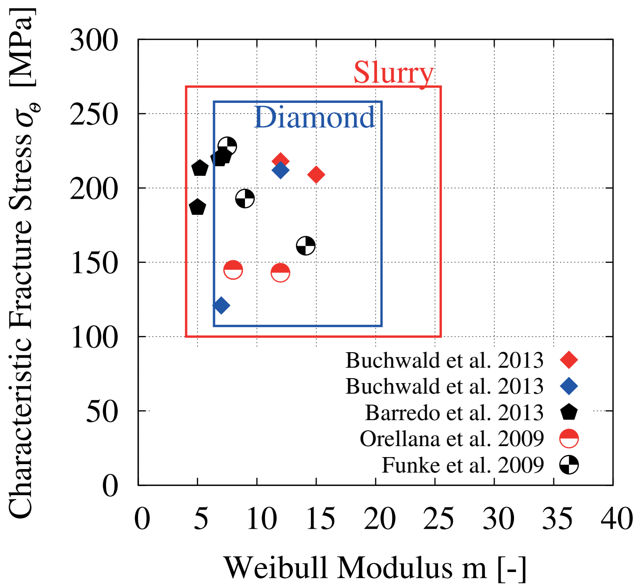

Figure 7. Overview of the typical ranges in strength of diamond- and slurry-sawn wafers after texturization (material and loading combined), compared with strength values given in the literature [11,12,16,17].

Sawing technology

The sawing process itself introduces strength-limiting cracks in the wafer surface; thus the wafer strength heavily depends on the sawing technology. Compared with slurry-sawn wafers, the strength of diamond-sawn wafers is always lower in a parallel-loading configuration, and in the same range, or higher, with perpendicular loading. It can also be observed that the slurry-sawn wafers tend to higher Weibull moduli (less scattering) than in the case of diamond-wire-sawn wafers.

In Fig. 6 the strength results for different materials and loadings have been combined and are compared with values from the literature [11–15]. The red and blue dots indicate slurry- and diamond-sawn wafers respectively, while the black dots show strength values for an unknown sawing technology. Apart from Orellana et al. [12], the literature values fit within the ranges presented. The tendency for higher characteristic fracture stresses and Weibull moduli in the case of slurry-sawn wafers can also be observed from the values in the figure.

Effect of etching and solar cell process

During the initial cell processing steps for the solar cell (saw-damage etch and texturization), the wafer surface is altered and the strength behaviour is affected. In Fig. 7 the strengths of textured wafers for different materials and loadings are combined and compared with values in the literature values [11,12,16,17]. The red and blue dots indicate slurry- and diamond-sawn wafers respectively, while the black dots show the strength values for an unknown sawing technology. It can be seen that the strength of textured diamond-sawn wafers is within the range as for slurry-sawn wafers; however, the strength limit of slurry-sawn wafers is higher than that of diamond-sawn wafers for current etching procedures.

The typical strength range for as-cut/textured wafers and solar cells with the most critical loading is shown in Fig. 8. For as-cut or textured wafers, critical loading is when the rollers are parallel to the saw marks; in the case of solar cells, the most critical loading means that the back side is in tension and the rollers are perpendicular to the busbars [3]. In addition, the data from monocrystalline and multicrystalline samples were grouped together in the analysis. Several different solar cells concepts – such as aluminium back-surface field (Al-BSF), passivated emitter rear cell (PERC) and interdigitated back contact (IBC) – were also evaluated. Typical strength-range values are given in Table 2.

For both diamond-wire- and slurry-sawn wafers, the strength is significantly increased as a result of the texturization process, but slurry-sawn wafers are still stronger than diamond-wire-sawn ones. After the solar cell processing, the strength decreases again for all tested solar cells, independent of the sawing technology. The critical area for cells is the back side with small- or large-area metallization and where the metallization overlaps. It can therefore be assumed that the metallization changes the silicon surface and the defects, and induces new defects or residual stresses for all tested types of solar cell [3,18]. The front side of a solar cell is stronger, and the strength is governed by the textured surface, with influences from the small areas of metallization. This means that, by focusing on the mechanically weakest region, no differences in slurry-sawn or diamond-sawn wafers can be observed after solar cell processing.

Fig. 9 shows the mean values from all experiments for the Weibull

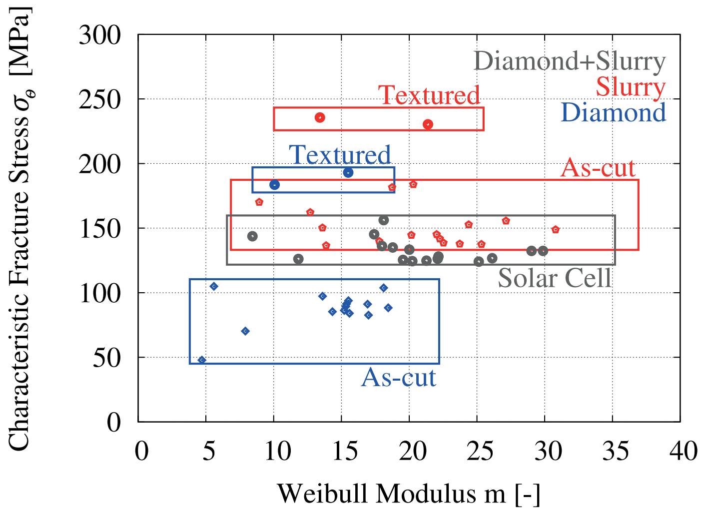

Figure 8. Overview of typical strength ranges for as-cut/textured wafers and solar cells tested in 4PB (A_{eff} = 9,116mm^2). The data are based on the most critical loading (parallel to saw marks for wafers, perpendicular to busbars for solar cells).

parameters and a predicted probability of breakage for a loading of σ = 70MPa. The Weibull modulus (Fig. 9(a)) decreases slightly after texturization (fracture stresses increases), and increases again after the final solar cell production steps. Texturization increases the characteristic fracture stress (Fig. 9(b)) by 53% for slurry-sawn wafers and 116% for diamond-sawn ones; this effect of higher strength with higher scattering after texturization is commonly known for increasing surface strength [19].

After most of the surface damage has been eliminated, the defects are smaller and fracture stresses increase; consequently, comparatively larger defects can be easily induced, causing lower fracture stresses and overall a higher scattering of strength. Before texturization the characteristic fracture stress of slurry-sawn wafers is 75% higher than that of diamond-

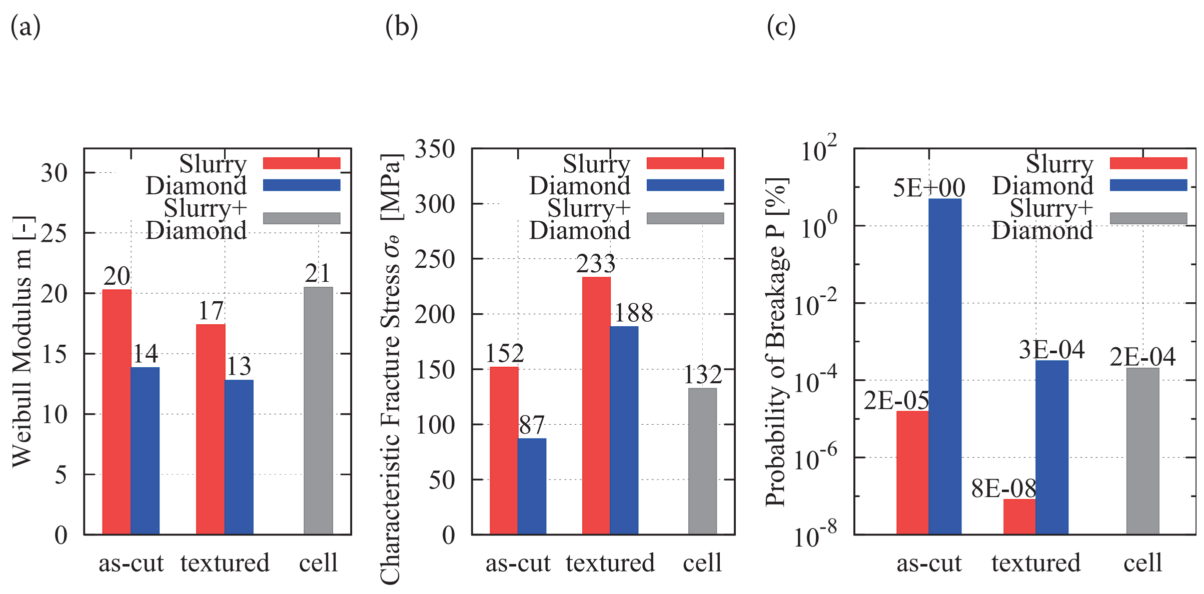

Figure 9. Changes occurring during solar cell production for slurry- and diamond-sawn wafers, for a loading of σ = 70MPa and A_{eff} = 9,116mm^2: (a) Weibull modulus *m*; (b) characteristic fracture stress σ_θ; (c) probability of failure *P*.

Sawing technology	Material	Loading	Weibull modulus *m*	Characteristic fracture stress σ_Θ [MPa]
Textured wafers				
Slurry	Mono+multi	Parallel	10–25	226–243
Diamond	Mono+multi	Parallel	8–19	178–197
Solar cells				
Slurry + diamond	Mono+multi	Back-side tension, busbars perpendicular to rollers	7–35	122–160

Table 2. Overview of the typical ranges of strength for as-cut/textured wafers and solar cells tested in 4PB (A_{eff} = 9,116mm^2). The data are based on the most critical loading (parallel to saw marks for wafers, perpendicular to busbars for solar cells).

sawn wafers; after texturization it is still 24% higher. After the final step of cell production is completed, the characteristic fracture stress decreases by 43% and 30% for slurry-sawn and diamond-sawn wafers respectively.

> "The smallest risk of breakage is demonstrated by textured slurry-sawn wafers."

Using the statistical Weibull parameters one can predict the probability of failure – in other words, the systematic breakage rate of wafers and cells [20]. The breakage rate depends on the load and the loading area; here, it is assumed that the full wafer is stressed by 70MPa. The resulting failure probabilities are shown in Fig. 9(c). For the given load example, the diamond-wire-sawn wafers show the highest breakage rate of around 5%. As-cut slurry-sawn wafers and solar cells are in the lower range of breakage probability, at less than 0.001%. The smallest risk of breakage is demonstrated by textured slurry-sawn wafers; these are the strongest wafers within the cell process.

Conclusions

Strength is an important parameter of not only the wafer substrates but also the solar cells: it governs the reliability or breakage rate in the process and in photovoltaic modules. The strength changes, however, as the wafer progresses to cell manufacturing, mainly because of the wafering, texturization and metallization processes. This paper has given a comprehensive overview of the mechanical strength behaviour of diamond-sawn and slurry-sawn as-cut/textured wafers and solar cells in 4PB tests.

For slurry- and diamond-sawn wafers the fracture origin is always found at the wafer surface; surface defects are therefore strength-limiting defects. For as-cut wafers, it was observed that, except for monocrystalline diamond-sawn wafers in the case of loading perpendicular to the saw marks, the scattering of strength is higher for multicrystalline wafers than for monocrystalline ones. Diamond-wire sawing is a promising technology, with several advantages over standard slurry sawing. A limiting factor for diamond-sawn wafers, however, is still the smaller strength values than in the case of slurry-sawn wafers. For critical loading with the rollers parallel to the saw marks, the strength for slurry-sawn wafers before texturization is 75% higher than for diamond-sawn wafers, and it is still 24% higher after texturization. The wafering process itself and subsequent process steps therefore influence each other and need to be optimized with respect to surface damage and wafer strength.

In the case of solar cells, the back-side metallization dominates the strength, because crack origins can be found near the busbars at overlapping regions between the aluminium and silver paste. The metallization process changes the surface of the silicon and induces new defects, which lead to values of strength below the texturization strength of diamond- or slurry-sawn wafers. Thus, the difference in strength based on the wire-sawing process vanishes, but only when attention is focused on the weakest area in the solar cell. In summary, in order to achieve reliable solar cell manufacturing, the processes from wafering to cell manufacturing need to be investigated as regards their overlapping influence on the strength of silicon wafers and solar cells.

Acknowledgements

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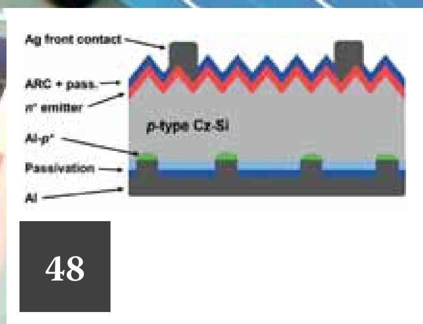
Cell Processing



News

Record solar R&D spending in 2014: First Solar leads the pack

R&D expenditure in 2014 increased by almost US$100 million from the previous year to reach a new record of US$512.75 million from 12 major tier-one PV module manufacturers, according to the annual R&D spending report by Photovoltaics International and its sister website PV Tech.

Previous reports, especially in 2013, found that R&D spending had not been immune from the PV industry's period of profitless prosperity and was deemed a discretionary spend by the majority of leading producers. However, the improving business conditions last year, coupled to increased momentum in pushing solar cell conversions efficiencies were the key drivers to the spending increase for 11 out of the 12 companies tracked.

In tandem with the increase in spending was a significant increase in R&D personnel, which reached a new record of 4,661, up from 2,911 in 2013. R&D headcounts had previously peaked in 2011 at 3,575. Once again First Solar allocated more financial resources to R&D activities in 2014 than its nearest rivals, taking expenditure to US$143.9 million.

The full Photovoltaics International R&D spending report can be read on p.12.

Source: First Solar

First Solar has once been the leading tier-one manufacturer in R&D spending over the year.

Records

Imec tops n-PERT cell efficiency of 22.5%

Nano-electronics research centre imec has achieved a record cell conversion efficiency of 22.5% for its large area (six-inch) n-type PERT (passivated emitter, rear totally diffused) Cz-Si solar cell.

The new record was the highest efficiency achieved for a two-side-contacted solar cell which had been processed on six inch commercially available n-type Cz-Si wafers, without the use of passivated contacts. The record efficiency was calibrated at ISE CalLab.

The cells feature Ni/Cu/Ag front contacts, rear local contacts, a diffused front surface field (FSF) and a rear emitter. The cells achieved an independently confirmed open-circuit voltage (Voc) of 689mV, a short-circuit current (Jsc) of 40.3 mA/cm2, and 80.9% fill factor.

Suntech boosts 'HyPro' silicon solar cell efficiencies to 20.82%

PV manufacturer Wuxi Suntech, a subsidiary of Shunfeng International Clean Energy (SFCE), has reported verified solar cell efficiency gains for its recently introduced monocrystalline and multicrystalline 'HyPro' silicon solar cells.

Its monocrystalline solar cell efficiencies had reached 20.82%, while its multicrystalline cells achieved 19.11% conversion efficiencies. Both cell types had efficiencies verified by the National Center of Supervision and Inspection on Solar Photovoltaic Products Quality (CPVT), in Wuxi, Jiangsu. China.

The efficiency gains came shortly after the company reported its HyPro monocrystalline silicon cells using passivated emitter rear cell (PERC) technology with four busbars had achieved 20.5% efficiencies on average in volume production.

SolarWorld touts 21.7% PERC world record efficiency

Germany-headquartered PV manufacturer SolarWorld has had a record efficiency for a PERC solar cell of 21.7% independently verified by the photovoltaic calibration laboratory (CalLab) of Fraunhofer ISE.

SolarWorld was the first company to rely on PERC technology in its production, upgrading around 800MW of its production lines to the new format in a ramp up which began in March.

PERC architecture includes a passivation layer to the back of the cell which reflects light which would otherwise be lost, effectively increasing the amount of light that can be captured and converted into electricity, typically resulting in conversion efficiencies in excess of 20%. This layer is usually formed via a PECVD or ALD process.

Orders

SoLayTec garners repeat ALD orders from China for PERC production

Atomic layer deposition (ALD) equipment specialist SoLayTec, a subsidiary of Amtech Systems, has secured orders from two China-based PV manufacturers.

SoLayTec has received its first follow-on order for its modular InPassion system from an existing customer, since first evaluating ALD technology in 2011. The customer entered volume production using the technology in 2014, resulting in a repeat order for production later in 2015. Tool delivery was planned for June.

The second order is for an R&D evaluation with a new client with the expectation of taking the technology from lab to fab in the future.

SEMCO wins post-ion implant anneal technology order on its DF6200 platform

PV equipment specialist SEMCO Group is to supply its latest LYTOX technology to an unidentified solar cell producer to carry out post-ion implantation damage annealing.

The latest design of SEMCO's DF6200 high-throughput furnace platform equipped with the LYTOX reduced pressure post-implant activation and passivation technology also included its high throughput cassette-to-cassette wafer transfer automation system that enables the loading of 1,400 horizontal wafers per furnace tube for high-volume production, typically n-type monocrystalline and bifacial solar cells.

Having recently teamed with process measurement specialist, Aurora Solar, the order includes Aurora's resistance measurement system and software.

VITRONIC supplying 150 'VINSPECsolar' optical inspection systems to Korea

Machine vision manufacturer VITRONIC secured a major order for its 'VINSPECsolar' optical inspection systems from a leading Korean PV manufacturer.

The 150-unit order was received in July and came to "several million euros" in value and will be installed at the Korean PV manufacturers new production facility in the country, according to the company.

The company's industry division had set a new order record in the first half of 2015, having received in February a large order from a major China-based solar cell producer to retrofit production lines with its VINSPECsolar inspection systems.

The optical inspection system detects inactive areas, weak active cells, cracks effecting electrical performance, micro-cracks and grid line interruptions.

Meyer Burger wins heterojunction cell business from EcoSolifer

Major PV manufacturing equipment supplier Meyer Burger has secured a CHF29 million (US$29.5 million) order from Swiss/Hungarian silicon thin-film equipment and technology firm EcoSolifer for a 90-100MW heterojunction (HJ) solar cell line.

Ecosolifer was planning an 80MW module assembly plant in Brazil, using its proprietary amorphous silicon deposition technology on monocrystalline wafers produced at its plant in Csorna, Hungary.

Meyer Burger won its order after an extensive six-month technical evaluation process. The HJ cell line equipment will be delivered to EcoSolifer's plant in Hungary in late 2015. EcoSolifer plans to begin industrial manufacturing in the first quarter 2016.

Company news

Amtech reports best sales quarter since 2011 as solar sales rebound

PV manufacturing equipment specialist Amtech Systems has reported its best quarterly results since 2011, backed by significant sales in its solar segment.

Amtech reported total fiscal third quarter revenue of US$40 million with solar contributing to over half the total at US$22.9 million.

Revenue from the solar segment increased 427%, due primarily to increased sales of plasma-enhanced chemical vapour deposition (PECVD) equipment, as well as solar diffusion systems in the quarter.

Amtech is also selling the majority of its stake in subsidiary Kingstone Technology to China-based venture capital firm, Suzhou Zhuo Jing Investment Center for around US$13.6 million.

Neo Solar Power's July sales slide

Taiwan-based merchant solar cell producer Neo Solar Power (NSP) reported preliminary July 2015 sales of NT$1,713 million (US$54.15 million), down around 5% from the previous quarter, which has been the highest sales month for the company in 2015.

NSP retained high utilisation rates comparable with the prior month as sales overall in 2015 have slowly trended upwards on higher demand, despite the impact from US anti-dumping duties, which have hit sales significantly since mid-2014.

NSP is expecting a gradual increase in solar cell demand in the second half of the year. The company is also increasing its focus on the downstream PV power plant business and plans a yieldco IPO on the Hong Kong stock exchange.

Source: Meyer Burger

Meyer Burger has secured a sizeable order for its heterojunction solar cell line technology.

Source: Solartech

Solartech's sales have improved on the back of its shift to PERC technology.

Motech continues strong recovery on record July sales

Merchant solar cell producer Motech Industries continues to demonstrate increased monthly sales.

Motech reported record sales in July 2015 reaching NT$2,286 million (US$71.3 million), up around 7% from the prior month and up 91.19% year-on-year.

Second quarter gross margin was 1.75%, up from -2.9% in the previous quarter.

Motech reported second quarter loss of NT$291 million (US$9 million), down from US$16.1 million in the previous quarter. The company reported second quarter shipments of 536MW, up from 415MW in the previous quarter.

Solartech's sales rebounding on PERC cell technology shift

Taiwan-based solar cell producer Solartech Energy Corp has seen its monthly sales rebound strongly in the last few months as the company continues to shift production to PERC cell technology.

Solartech reported May 2015 revenue of NT$708 million (US$22.9 million) an increase of 18.25% from the previous month.

Sales have yet to recover from the most recent peak in January when the company reported revenue of NT$826 million (US$26.1 million). However, a shift in production to Malaysia as part of its stake in Tek Seng Holdings, a small module manufacturer in the country, could explain the lower revenue in the first quarter as production ramps.

China's Tongwei takes 10% stake in Gintech

Chinese conglomerate Tongwei Group has taken a 10% stake in Taiwanese cell manufacturer Gintech.

The private share placement is worth NT$850 million (US$27 million) and will align Gintech with a vertically integrated solar manufacturer.

Tongwei, which focuses on agriculture, animal feed and renewable energy, is looking to expand its PV business internationally. Tongwei Solar currently has 2.3GW of cell capacity making it the third largest cell producer in the world. When combined with Gintech's 1.8GW of cell capacity, the two companies claim they will be the largest producer globally.

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Product Reviews

CENTROTHERM

Centrotherm's one-step PERC AlOx/SiNx stack PECVD solution provides 20.6% cell conversion efficiency

Product Outline: centrotherm photovoltaics is offering a one-step PECVD aluminum oxide (AlOx/SiNx) process upgrade for advanced solar cell concepts such as PERC.

Problem: Driven by the pursuit of increased conversion efficiencies, solar cell manufacturers are turning towards more complex cell architectures for higher performance. PERC technology has emerged as the next generation of industrial silicon solar cells. Prerequisite for a successful implementation is a highly efficient surface passivation of front and rear sides. Aluminum oxide (AlOx) with its excellent passivation properties and high negative fixed charge density is perfectly suited to achieve this.

Solution: The centrotherm AlOx process shows best passivation properties at thickness <20nm (further reduction is expected) also on uneven surfaces and low surface recombination velocity on p-type wafer surfaces. Furthermore, these stacks are deposited in one run and in one step, by just changing the recipe. This is an advantage compared to ALD systems where only the AlOx layer is deposited and the capping layer needs to be added in another system (mainly also by PECVD).

Applications: AlOx/SiNx stack and capping layer deposition on PERC solar cell rear side for mono and multicrystalline cell processing.

Platform: Compared to inline systems the centrotherm batch system offers a more than 5% higher uptime and a continuous wafer flow without regular downtimes for reactor cleaning at a low cap-ex.

Availability: Upgrade solution ready for shipment with short delivery times.

RENA

RENA's 'InCellPlate Cu' platform offers cost savings at high efficiency levels

Product Outline: RENA's 'InCellPlate Cu' inline equipment for direct plating of a Ni/Cu/Ag stack on silicon, when combined with laser ablation of the silicon nitride layer and subsequent inline anneal, is said to provide complete front-side metallization for solar cell manufacturing. Compared with screen-printing, the technology allows cell production costs to be cut by US$0.06 per cell and offers potential for cell efficiency improvement.

Problem: Conventional screen printing of the front contacts remains among the most costly processes in solar cell manufacturing and limits the achievable finger width and emitter sheet resistance and so limits the overall cell performance.

Solution: Direct plating on silicon with RENA's InCellPlate Cu eliminates the need for screen-print paste on the front side. It further replaces most of the silver with cheaper copper, which is claimed to reduce costs per cell by US$0.06 per cell. The technology also allows the formation of thinner fingers (≤30 µm) and contact formation to emitters with higher sheet resistance (≥120 Ohmsq.), thus enabling higher currents and voltages while keeping the fill factor high. RENA has already used the technology to reach 20.8% efficiency on Cz-PERC cells (verified by ISE Cal-Lab).

Applications: Solar cell processing, front-side contact formation.

Platform: RENA's patented technology allows single-side plating of the cell's sunny side while keeping the rear side dry. This reduces the drag-out of electrolyte and associated production costs, avoids undesired plating of the contacts and excludes the risk of degradation of the aluminum paste by contact with the electrolyte.

Availability: Currently available.

VITRONIC

VITRONIC's retrofit optical inspection system enables reliable defect detection

Product Outline: VITRONIC's latest development for the PV industry is the VINSPECsolar CTS Retrofit Inspector for integration into cell testers.

Problem: Manual visual inspections are unable to compete with the latest machine vision technology from either a qualitative or a cost perspective. However, PV manufacturers can only hold their ground on the market by offering high-quality, clearly classified products. Optical quality inspection is required during PV production especially on more advanced cell designs such as PERC to obtain and maintain high yields.

Solution: The new VINSPECsolar CTS is claimed to achieve highest detection and classification performance in equipment where transport mechanics and data communications are not easily adaptable for line-scanning but high resolution and high performance are mandatory. This addition to the VINSPECsolar product range is a standstill version suited for retrofitting sorters using walking beam or other non-linear transportation mechanisms. VITRONIC's CTS Retrofit Inspector utilizes a high-brightness dynamic range, combined with a 31µm resolution for detection of all relevant print and color deviations. It detects surface defects in low reflection coatings (mono and multicrystalline) as well as small interrupts and flaws in highly reflective print (metallization) with narrow grid (fingers).

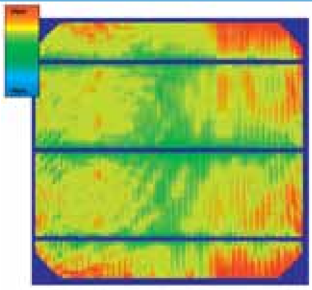
Applications: Optical inspection solar cells with edge lengths of up to 8" and for a range of different formats, e.g. pseudo square and full square as well as various crystalline structures including PERC.

Platform: The retrofit inspector features easy integration into standard equipment. It fits to all testers and sorters.

Availability: Currently available.

Product Reviews

ISRA VISION



ISRA's new 'PRINT-Q 2.0' inspection technology handles PERC & HIT fine-line cell requirements

Product Outline: ISRA VISION/GP SOLAR has responded to the need for improved cell inspection with their new inspection technology 'PRINT-Q 2.0,' providing solutions for higher efficiency solar cell and module concepts such as PERC or HIT, notably deploying extreme thin contact fingers and new wire contacting. The system was said to have been successfully installed at several manufacturing sites, generating more than 1.5GW of advanced cells.

Problem: During the metallization process when conductive fingers and busbars are attached to the solar cell, defective solar cells are identified by inspecting the quality of the metal grid on a solar cell. Moreover, the quality of the grid also provides insight as to the cause of the defect.

Solution: PRINT-Q offers an innovative print inspection solution, providing state-of-the-art matrix camera technology for optimal metrology. The system is said to provide the highest resolutions down to 25µm with matrix camera technology for optimal metrology at cycle times lower than one second, coupled with the highest claimed detection rate and lowest false rejects. The system's inline matrix high resolution inspection combined with the CHROME+ technology for multiple wavelength imaging catches automation inaccuracies, and is said to be easy to integrate into any modern screen printer equipment.

Applications: Advanced PERC and HIT cell metallization inspection.

Platform: PRINT-Q 2.0 is designed to achieve both profitable and competitive solar cell production with <= 3.600 pieces/hr throughput and 0% defect tolerance rate. PRINT-Q .Cam thoroughly inspects the print quality of solar cells. Solid process monitoring is guaranteed by a specific system in which a PRINT-Q FS.Cam inspects the front side of the solar cell, and one PRINT-Q RS.Cam each inspects every printing step on the rear side. Using the new 'Advanced Rear Side Inspection' system, not only are red images analyzed, but UV images are also analyzed separately.

Availability: Available since May 2015.

HORIBA

HORIBA provides advanced POCl3 delivery system for high-volume solar cell processing

Product Outline: HORIBA has developed a phosphorus oxychloride (POCl3) delivery system that is being implemented for atmospheric and low pressure diffusion furnaces in Europe and Asia.

Problem: POCl3 is delivered in 1-litre quartz vessels that typically require more than 200 exchanges in a 200MW line each year. Most quartz bubbler exchanges are performed at a height where there is always a risk to the health of operators and to the process itself. In addition to these risks there is also two hours' downtime to consider for each exchange. Poor process results and additional downtime maybe incurred if the exchange is not performed well. Each quartz bubbler vessel typically can be used down to 10% of POCl3 remaining before the process becomes less stable. This 'waste' POCl3 cannot be used and needs to be disposed of.

Solution: POCl3 is delivered in 20-litre canisters reducing exchanges from 200 to just 10 tank exchanges per year. Tank exchange is claimed to be safer as the canister is constructed from ETFE-lined stainless steel and the exchanges are performed at ground level. Furnace downtime is eliminated as production continues even when the bulk POCl3 tank is being exchanged. When combined to the HORIBA Advanced Bubbler, the fragile quartz bubbler vessel is replaced by a fixed robust PFA bubbler vessel where the POCl3 level is maintained to guarantee full saturation and deliver stable and repeatable sheet resistance. Financial and environmental benefits are also delivered as POCl3 waste is reduced from 10% to less than 2%.

Applications: Atmospheric and low pressure diffusion furnaces for the delivery of POCl3 or BBr3 to produce n-type and p-type solar cells and semiconductor devices.

Platform: HORIBA has designed a robust refill system featuring fully automatic purge and safety check with integrated gas and liquid leak detection and full containment. The refill system is connected via dual containment tubing to up to 20 HORIBA advanced bubblers.

Availability: August 2015 onwards.

The road to industrializing PERC solar cells

Xusheng Wang & **Jian Wu**, Canadian Solar Inc., Suzhou, China

ABSTRACT

The passivated emitter and rear contact (PERC) cell design is gaining acceptance in solar cell manufacturing because of its potential for high efficiency with p-type wafers and its easy integration into existing production lines. In terms of PERC mass production, an effective and reliable AlO_x deposition tool is the most important aspect that needs to be considered. Light-induced degradation (LID) is a cell efficiency bottleneck because of bulk recombination, even if the silicon surface is well passivated. This paper examines the combination of cell efficiency, AlO_x tool choice and LID regeneration as a route to industrializing PERC technology.

Introduction

With the PERC design, a ~0.6–1.0% gain in cell efficiency is achievable for p-type mono solar cells, while ~0.5–0.8% is possible for multi cells, which is very attractive to the industry. Batch cell efficiencies of 19.0% for multi PERC and 20.70% for mono PERC solar cells have been reported in a pilot run.

Atomic layer deposition (ALD) and inline plasma-enhanced chemical vapour deposition (PECVD) AlO_x are currently the only two choices on the market for AlO_x deposition. A comparison of these two tools, with regard to passivation effect and cell efficiency, shows little difference between them, although ALD seems slightly better. On the other hand, high-deposition rate PECVD AlO_x has the advantage of higher throughput and uptime, which is more appealing to customers.

The boron–oxygen (B–O) complex is the origin of light-induced degradation (LID) in solar cells. Cell efficiency is limited by the bulk recombination, even if the silicon surface is well passivated; in other words, the extra efficiency gained by the excellent surface passivation of PERC cells will be reduced by bulk material LID. In this paper the results of an LID-regeneration evaluation test by thermal and light illumination are reported. Tests at the cell level have revealed that, after LID regeneration, the relative degradation is around 2.0% for mono PERC and 1.1% for multi PERC, which are acceptable results.

Purpose of the work

PV technologies are under challenge to reduce the cost of solar cells and increase their efficiency. Most state-of-the-art industrial solar cells use p-type Si as the base material; featuring an aluminium back-surface field (Al-BSF) on the rear surface, these cells suffer from rear-surface recombination and a low internal reflectance. Additionally, the bowing induced as a result of the thinness of the wafers limits the amount by which the silicon material used at the wafer level can be reduced. In order to achieve a higher conversion efficiency, however, the quality of the rear-surface passivation and reflectance needs to be higher than what Al-BSF can provide.

> "PERC structures allow an increase in efficiency and at the same time a decrease in wafer thickness."

The application of passivated emitter and rear contact (PERC) structures (see Fig. 1) to industrial solar cell production, therefore, would allow an increase in efficiency and at the same time a decrease in wafer thickness. In a PERC cell, the full-area aluminium is replaced by a dielectric film covered with an aluminium film. The dielectric layer is then locally opened, to provide contact between the Al and the Si wafer.

A wide range of materials can be used for the rear-surface dielectric [1] (SiO_2 [2], a-Si [3], a-SiC_x [4]). Recently, AlO_x layers deposited by lab-type plasma-enhanced chemical vapour deposition (PECVD) [5] and high-deposition rate PECVD [6] have demonstrated that excellent surface passivation is provided with p-type surfaces too, eliminating the throughput restrictions of conventional atomic layer deposition (ALD) systems. Alternatively, very thin ALD Al_2O_3 capped by PECVD SiN_x or PECVD SiO_x, which also show very good surface passivation quality [7], could be used for industrial production.

A PERC process for mono and multi silicon material will be presented, cell efficiency evaluated, and the passivation effect and cell efficiency of ALD and inline PECVD AlO_x tools compared in order to determine any differences in passivation. An LID regeneration evaluation test by thermal and light illumination will also be discussed.

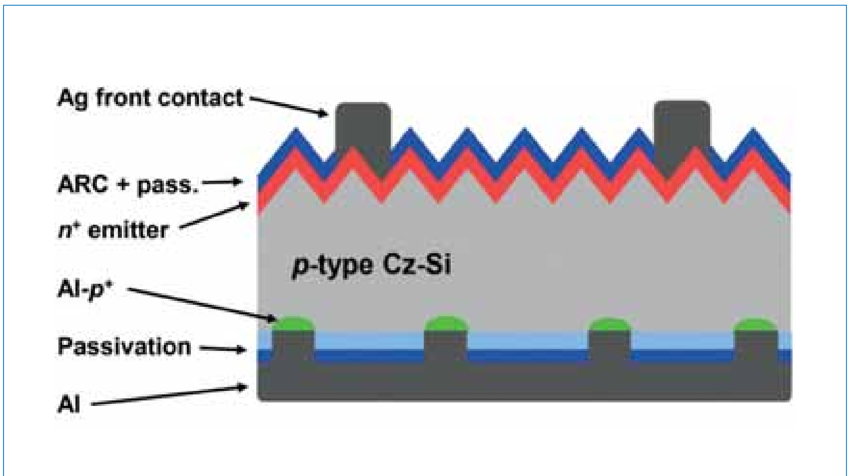


Figure 1. Schematic of a PERC solar cell.

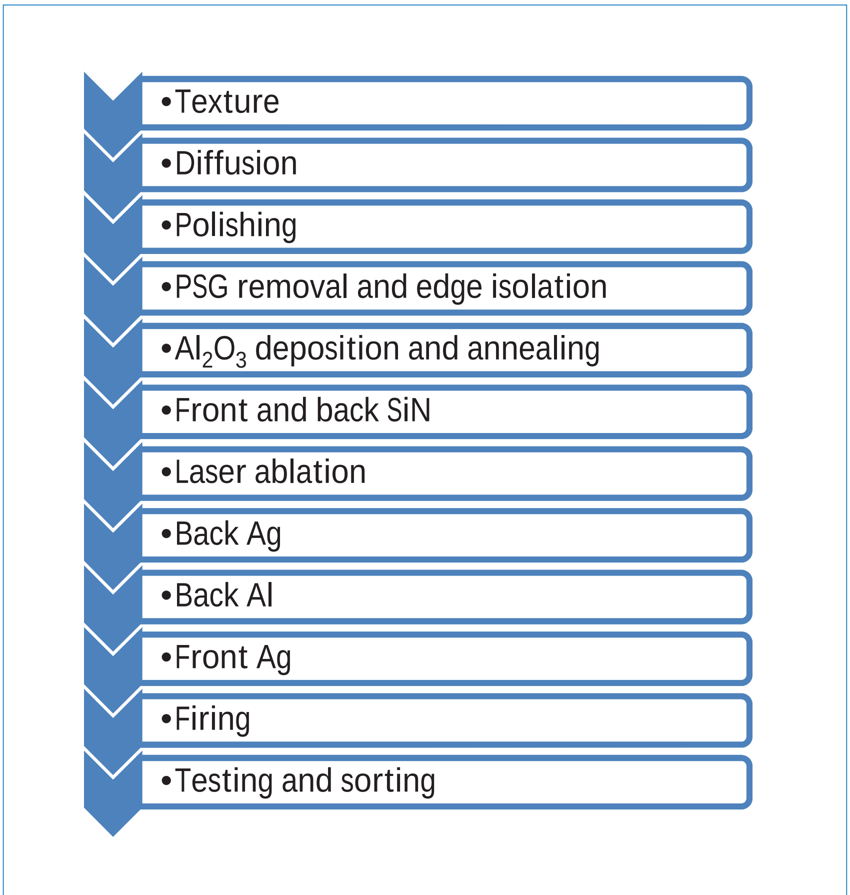


Figure 2. PERC process flow.

Approach

Cell efficiencies of mono and multi PERC solar cells

For the fabrication of the PERC solar cells, several thousand mono and multi wafers were processed in the pilot line. Fig. 2 shows the process flow sequence, more details of which can be found in previous publications [1,6].

The as-cut wafers passed through a conventional acid solution to create the textured surface. One step of single-side $POCl_3$ diffusion was then used to form a lightly doped homogeneous emitter. The rear surface was polished for the preparation of the PERC structure, followed by phosphor-silicate glass (PSG) removal. A thin layer of ALD Al_2O_3 was deposited on the rear surface, and PECVD SiN_x was deposited on both the front and the rear surfaces. After deposition, a green laser (532nm) was used for the local opening on the rear dielectric stack layers. Finally, screen printing and co-firing, as the metallization steps, were carried out to form the emitter contact and BSF field.

Cell efficiency reached around 19% with the PERC approach for multi silicon wafers, while the reference group reached 18.3% with traditional processing; an efficiency gain of ~0.7%

Lot	V_{oc} [mV]	I_{sc} [A]	FF [%]	R_s [mΩ]	R_{sh} [Ω]	Eff [%]	I_{rev1} [A]
Reference	634.5	8.761	80.11	1.7	123.69	18.30	0.18
PERC-1	642.4	9.131	78.9	2.34	72.19	19.02	0.21
PERC-2	642.4	9.122	78.87	2.43	80.7	18.99	0.213
PERC-3	644.3	9.129	78.78	2.49	106.07	19.04	0.165

Table 1. PERC cell efficiency for multi wafers.

Lot	V_{oc} [mV]	I_{sc} [A]	FF [%]	R_s [mΩ]	R_{sh} [Ω]	Eff [%]	I_{rev1} [A]
Reference	639.8	9.26	80.47	1.59	171.9	19.63	0.10
PERC-1	659.4	9.603	78.72	2.66	141.9	20.53	0.18
PERC-2	659.7	9.594	78.61	2.74	141	20.49	0.19
PERC-3	659.9	9.610	79.31	2.33	164.2	20.71	0.12

Table 2. PERC cell efficiency for mono wafers.

was therefore achieved at the cell level (see Table 1). For mono cells, the efficiency reached around 20.7% with the PERC approach, while the reference group yielded 19.6%; this equated to an efficiency gain of ~1.1% at the cell level (see Table 2).

AlO_x tool evaluation

For PERC mass production, an effective and reliable AlO_x deposition tool is the most important factor that needs to be considered. ALD and inline PECVD AlO_x tools are currently the only two choices available on the market; in this section their passivation behaviours and PERC efficiencies will be compared.

First of all, a non-contact capacitance–voltage (CV) measurement was performed in order to extract the total fixed charge density (Q_{fix}) and the interface defect density (D_{it}). The results are given in Table 3; these data demonstrate a good field passivation in both cases.

To examine the Al_2O_3 passivation further, the effective minority-carrier lifetime was characterized using the Sinton QSSPC method. With the measured lifetime data, the effective surface recombination velocity (SRV) S_{eff} is given by:

$$S_{eff} = \frac{W}{2}\left(\frac{1}{\tau_{eff}} - \frac{1}{\tau_{bulk,intrinsic}}\right) \qquad (1)$$

where W is the wafer thickness, τ_{eff} is the effective lifetime and $\tau_{bulk,intrinsic}$ is the bulk lifetime. The effective SRV S_{eff} was calculated using Equation 1 for the polished wafers passivated by ALD AlO_x/SiN_x and by PECVD AlO_x/SiN_x. After the firing process, the calculated S_{eff} was 12cm/s for ALD AlO_x/SiN_x and 20cm/s for PECVD AlO_x/SiN_x (at a carrier injection level of $\Delta n = 1\times10^{15}cm^{-3}$).

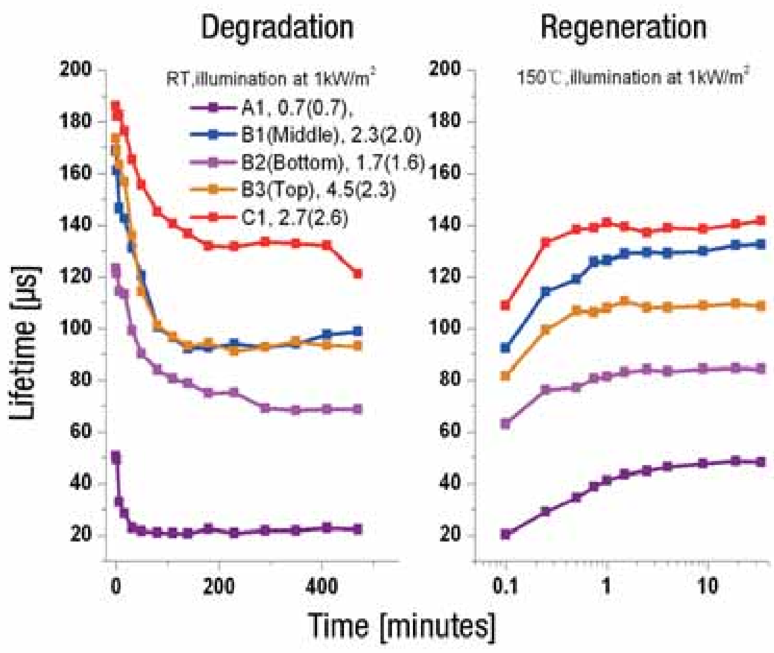


Figure 3. LID and regeneration lifetime–time curve for various resistivities (A, B, C refers to different ingots). The data in brackets are the resistivities measured after the oxygen thermal donor dissolved.

Passivation	Q_{fix} [cm^{-2}]	D_{it} [$cm^{-2}ev^{-1}$]
PECVD AlO_x/SiN_x	-3.61×10^{12}	1.13×10^{12}
ALD AlO_x/SiN_x	-3.95×10^{12}	9.44×10^{11}

Table 3. Total fixed charge (Q_{fix}) and interface defect density (D_{it}) for PECVD and ALD AlO_x/SiN_x stack layers.

Lot	V_{oc} [mV]	I_{sc} [A]	FF [%]	R_s [mΩ]	R_{sh} [Ω]	Eff [%]	I_{rev1} [A]
ALD	659.9	9.588	79.0	2.15	150.5	20.59	0.14
PECVD	659.2	9.575	79.0	2.14	147.5	20.53	0.14

Table 4. PERC cell efficiency for mono wafers using ALD and inline PECVD AlO_x tools.

To verify the passivation effect even further, two groups of mono PERC cells (manufactured following the process flow sequence in Fig. 2) were used to demonstrate the differences in cell efficiency; the details are given in Table 4. Only very slight differences in passivation effect and cell efficiency were found between the ALD and PECVD passivation methods. The high-deposition rate PECVD AlO_x, however, has the advantage of a higher throughput and uptime, which is more appealing to customers.

Light-induced degradation and regeneration

As mentioned earlier, the source of light-induced degradation (LID) in solar cells is the B–O complex. Cell efficiency is limited by bulk recombination, even if the silicon surface is well passivated; in other words, the extra efficiency gained by excellent surface passivation of a PERC cell will be reduced by bulk material LID.

The total light-generated B–O pairs are directly proportional to the boron concentration and to the square of the oxygen concentration. The generation rate, however, is only related to the boron concentration, which is the reason why much of the efficiency gain is lost in the case of mono silicon material, thus preventing it from entering into mass production.

LID can be reduced by regenerating the silicon bulk lifetime through directly passivating the generated B-O complex, but only if the H-rich sample is simultaneously annealed at an elevated temperature [8–10]. Hydrogen is believed to play a key role in the B–O deactivation process. The regeneration rate is also limited by high boron or oxygen concentrations.

Fig. 3 shows the lifetime regeneration data for different zones in an ingot, taken from a previous study [11]; from this it can be inferred that a portion of the lifetime recovery is achieved by light illumination at an elevated temperature. To allow further verification, more mono and multi PERC cells were fabricated and tested initially using an *I–V* tester. After the light regeneration and subsequent degradation tests under 1 sun illumination for 72 hours, the relative degradation data shown in Table 5 were obtained.

> “LID in the cell could be comfortably less than 3% rel. for mono PERC cells, and less than 2% rel. for multi PERC.”

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Cell	State	Efficiency	Relative degradation
Multi	Before	18.98%	1.07%
	After	18.78%	
Mono	Before	20.59%	2.00%
	After	20.18%	

Table 5. PERC cell efficiency before light illumination and after LID regeneration and light illumination.

Table 5 indicates that the LID in the cell could be comfortably less than 3% rel. for mono PERC cells, and less than 2% rel. for multi PERC. The implementation of the approach could therefore be industrially feasible, provided the degradation can be controlled to within a reasonable range, say ~2–3%, at the module level.

Conclusions

A PERC approach for both mono and multi silicon material has been presented, with efficiency gains of 1.1% and 0.7% being demonstrated at the mono and multi cell levels respectively. ALD and inline PECVD AlO_x show only very slight differences in passivation effect and cell efficiency; however, high-deposition rate PECVD AlO_x is more appealing to customers because of its higher throughput and uptime. An LID regeneration process can help to address LID issues, by reducing the loss in efficiency to less than 3% rel. for mono PERC cells, and to less than 2% rel. in the case of multi PERC. The approaches outlined above constitute one direction that can be taken towards the industrialization of PERC technology.

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Front-side metallization by parallel dispensing technology

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ABSTRACT

Parallel dispensing technology as an alternative front-side metallization process for silicon solar cells offers the possibility of increasing cell conversion efficiency by 2% rel. by the use of commercial silver pastes designed for screen-printing technology. This efficiency gain is achieved through a significantly reduced finger width, and hence reduced shading losses, in combination with substantially improved finger homogeneities and high aspect ratios that guarantee sufficient grid conductivity at reduced paste lay-down. In this paper Fraunhofer ISE's development of a parallel dispensing unit that is integrated into an industrial, inline-feasible platform made by ASYS is discussed. A possible industrial application of the dispensing technology is supported by latest results from pilot processing as well as by basic economic considerations.

Introduction

Silicon solar cell metallization is still dominated by screen-printing technology, which offers a robust contact formation and proven long-term stability. Due to pressure from a rapid decline in retail module prices, however, it became necessary to significantly reduce Ag-paste consumption [1]. Consequently, paste and process development was motivated to achieve printed line widths of less than 50µm, but known issues – such as mesh marks, line spreading or screen wear – have not yet been overcome. Various thick-film technologies – for example stencil printing [2], pattern transfer printing [3] and co-extrusion [4,5] – are promising and have already reached significantly high technology-readiness levels. Nevertheless, some remaining challenges – including fragile and expensive stencils, additional consumable costs, and the competition of the fast-emerging screen-printing technology – have so far prevented a market breakthrough.

Dispensing technology, as described by Specht et al. [6] and illustrated in Fig. 1, offers a contactless, single-step metallization process that significantly reduces finger width and thus shading losses. Furthermore, a substantially improved homogeneity of dispensed fingers compared with screen-printed front-side contacts results in more-efficient metal paste usage [7]. In 2011 record cell efficiencies of 20.6% for 125mm × 125mm FZ p-type material using dispensing technology on metal wrap-through passivated emitter and rear cell (MWT-PERC) devices were presented by Lohmüller et al. [8]. Within the GECKO public research project, dispensing technology has been developed, in collaboration with industry partners ASYS, Heraeus and Merck, with a goal of industrial application.

"Dispensing technology offers a contactless, single-step metallization process that significantly reduces finger width and thus shading losses."

Print head development

In order to compete with industrially established metallization processes, standard throughput rates needed to be achieved (i.e. 1,600 wafers/hour per printing tool [9]). One possibility for increasing the throughput is by parallel dispensing multiple fingers. Various approaches concerning this topic have been reported in the past [10,11].

Chen et al. [12] introduced a parallel dispensing unit incorporating several nScrypt SmartPumps [13] in parallel, each individually feeding two or three nozzles. With this approach, contact lines of only 47µm in width and a height of 34µm were reached at traverse speeds of up to 500mm·s^{-1} [14]. However, the number of contact

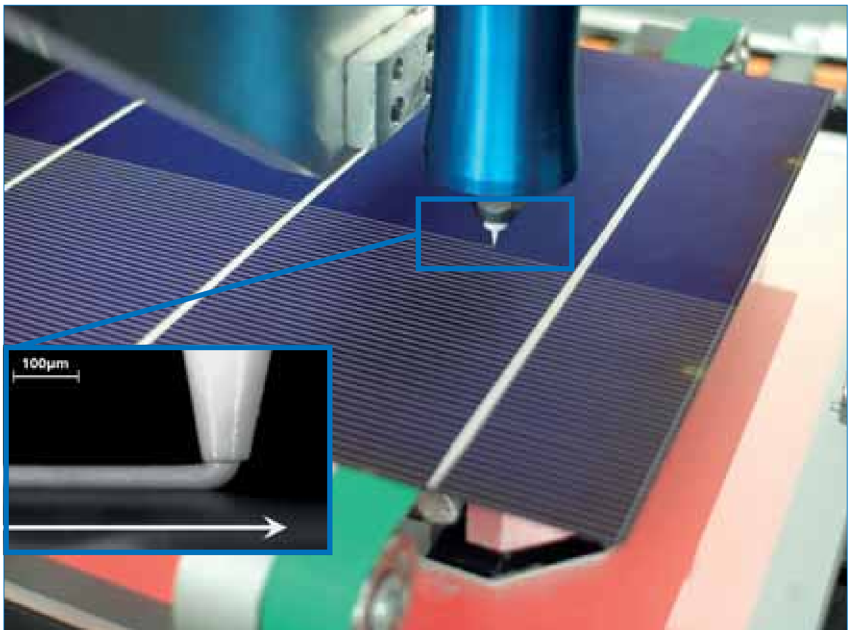

Figure 1. Single nozzle dispenser as used for initial process investigations.

fingers necessary on the front side increases with decreasing line width, since sufficient grid conductivity has to be provided. To allow the highest throughput rates, one nozzle per contact finger had to be possible, and the finger pitch needed to remain variable with only minor adaptation of the system. A modular set-up was therefore chosen, comprising a central paste supply unit and an exchangeable part containing ten nozzles with an opening diameter of 40µm and an initial pitch of 1.56mm, as necessary for a 100-finger grid.

At first, the central supply unit was developed by setting up a computational fluid dynamics (CFD) simulation of the system [15] that allows the description of paste flow inside any geometry in steady-state operation. Because of their high solid content, silver pastes support the formation of slip layers on solid walls and shear bands, as well as regions of plug flow, where the local shear stress does not surpass the yield stress and the paste remains in a solid state. Hence, a detailed rheological investigation of the metal pastes involved had to be conducted before setting up the CFD model. The central supply unit was then optimized until a homogeneous paste distribution to all nozzles could be ensured, despite the previously discussed issues concerning the yield stress metal paste.

The influence of fabrication tolerances (Fig. 2) on the dispensing process was isolated by sequentially changing the nozzle diameter of, for example, only one nozzle, thereby gaining an indication of the robustness of the solution [15]. The result was a ten-nozzle print head (Fig. 3), which had so far been applied to multiple cell

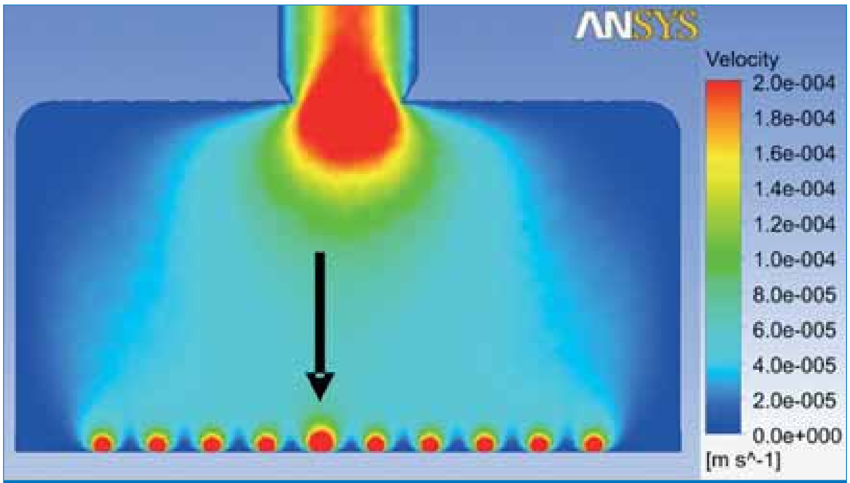

Figure 2. Velocity distribution of central paste supply unit over ten nozzles. Nozzle five was enlarged to simulate fabrication tolerances [15].

Figure 3. Ten-nozzle print head during solar cell metallization. With this system, process speeds above 600mm·s⁻¹ can be realized.

Figure 4. Novel inline-applicable dispensing platform developed by ASYS, to be equipped with multi-nozzle print heads and auxiliaries.

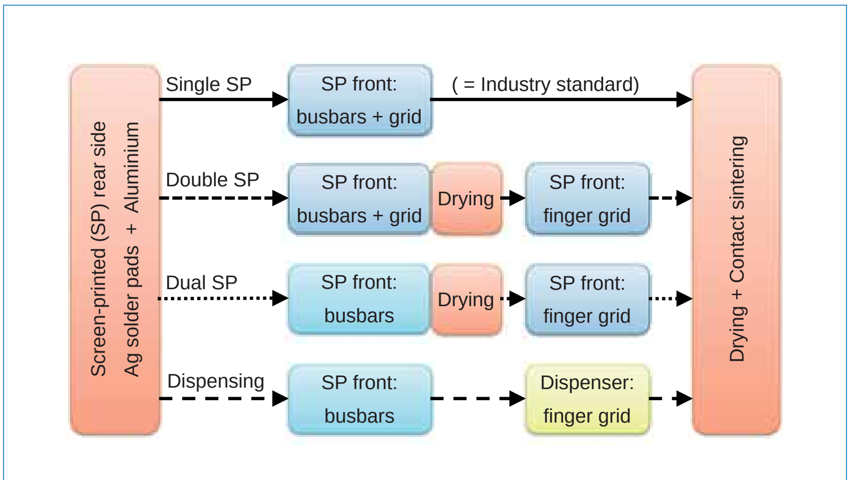

Figure 5. Possible integration of the dispensing platform into an existing back-end production line. Compared with screen- or stencil-based printing process, dispensing provides a simple drop-in replacement, since it does not require an additional post-print inspection or drying step [7].

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processing in recent years [7,16,17]. Industrial feasibility further required the development of an enlarged version of the print head, which covers the whole width of an industrial silicon wafer in order to dispense one cell within the required cycle time of a maximum of two seconds. This brand-new version has now been launched and will be presented at the 31st EU PVSEC in Hamburg [18].

Solar cell production process using dispensing technology

Besides the enhancement of parallel print heads at Fraunhofer ISE, ASYS developed an inline-applicable dispensing platform that has the same footprint as an ordinary screen-printing unit [7] (see Fig. 4). Equipped with the latest wafer alignment system that is also used in screen printers to ensure precise overlay alignment, this platform contains (among various other features) all the necessary interfaces to allow it to be directly integrated into a conventional solar cell production line.

Compared with other known enhancements of back-end metallization lines, the investment required for an inline integration will be low, since the dispensing unit can directly replace the post-print inspection unit in a conventional single-screen-printing line. The existing screen printer is then used for the application of the busbars following the dual-printing approach [19]. This allows a reduction in silver consumption and damage to the passivation layer underneath the busbars.

A second dryer between the two printing steps, as required for conventional dual or double (i.e. print on print) printing approaches, is not necessary (Fig. 5), since dispensing allows a contactless application of silver pastes, which can be deposited on already printed, wet busbars.

Rheological paste characterization

As mentioned earlier, a detailed rheological investigation was required beforehand in order to set up the CFD model during print head development. Because of the non-contact printing process, dispensing further offers the possibility of varying paste rheology over a much wider range than in the case of other thick-film printing technologies. The shape of the resulting contact fingers on the wafer can therefore be adjusted with respect to an optimum trade-off between cross-section area, shading and electrical contacting behaviour [20]. The main reason for this is that highly filled, thixotropic and shear-thinning silver pastes quickly regain their internal structure and return to a solid-like state after being exposed to high shear at the nozzle outlet. This already leads to higher aspect ratios than with conventional screen-printing, independent of the

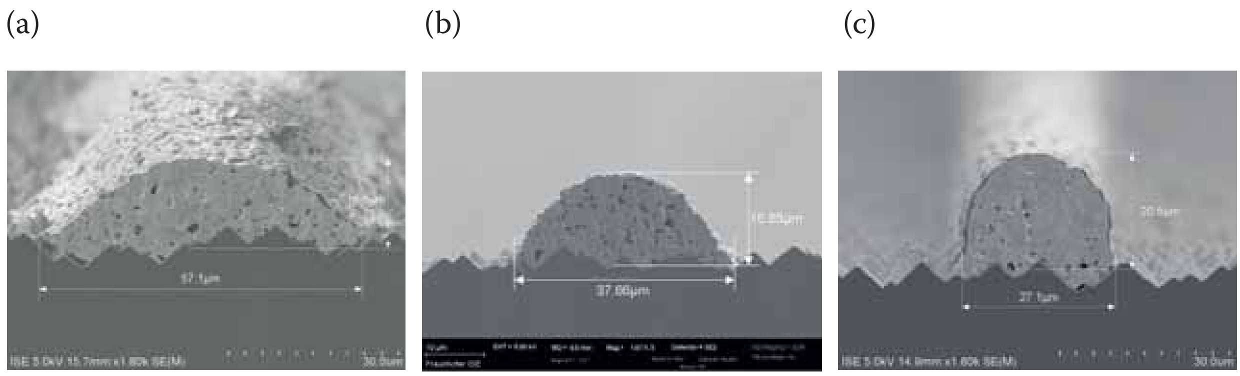


Figure 6. SEM images of printed and dispensed finger cross sections: (a) single-screen-printed reference; (b) dispensed sample when a screen-printing paste is used [7]; (c) dispensed sample when a rheologically adapted printing paste is used in order to increase yield stress and finger aspect ratio [16].

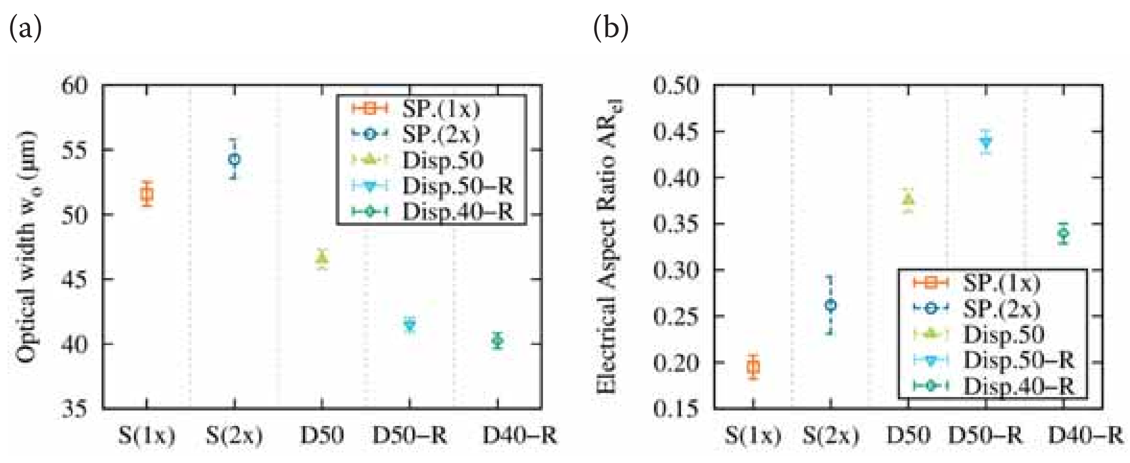
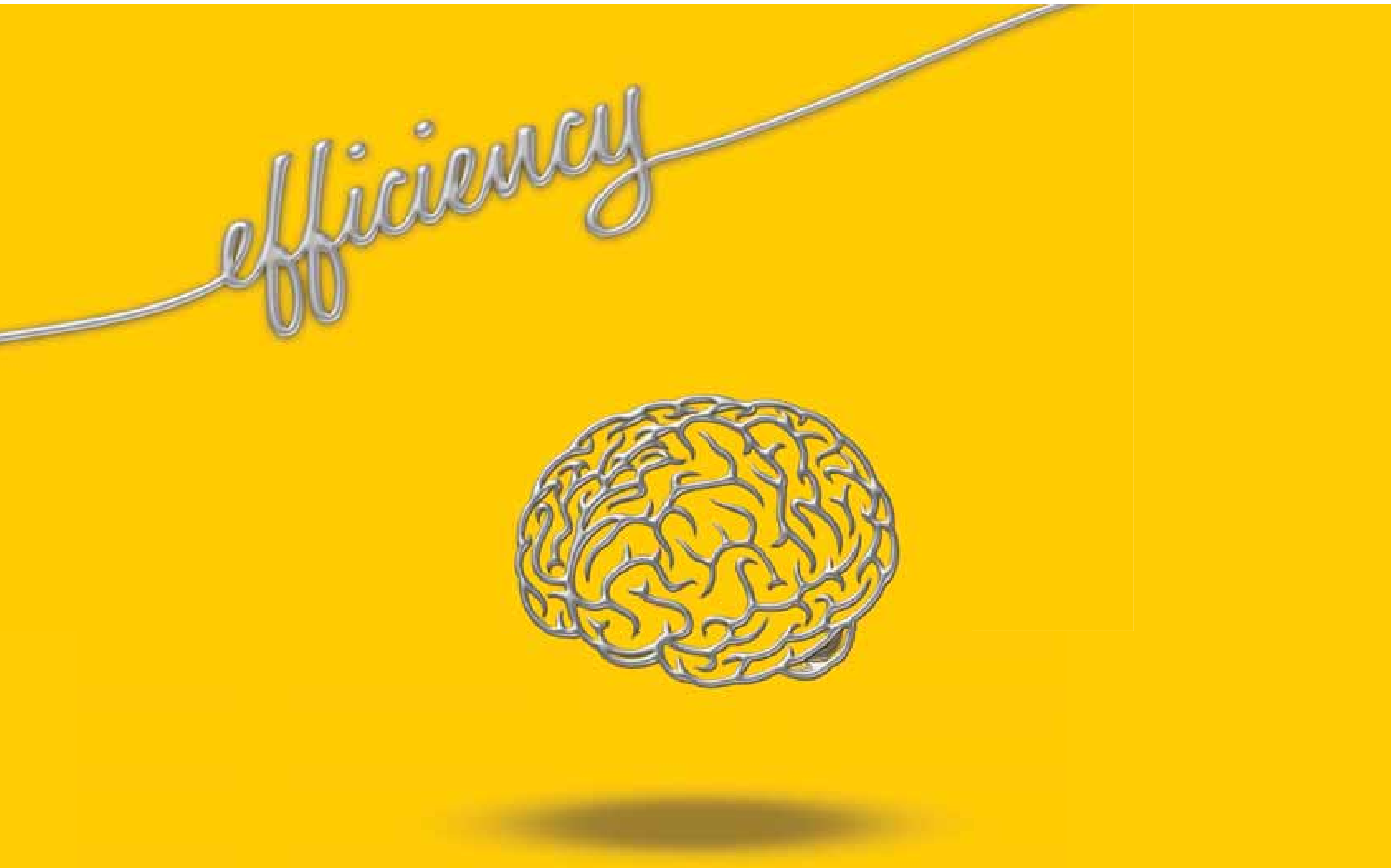


Figure 7. Resulting contact finger geometries for industrial Cz 156mm × 156mm material: (a) the optical finger width, which comprises the complete metal covered contact width of the finger; (b) the electrical aspect ratio, which describes the ratio between average finger height and optical finger width.

Heraeus



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applied paste, as indicated in Fig. 6. The characteristic shape of fine-line-dispensed contact fingers then changes drastically with increasing yield stress τ_y towards higher aspect ratios. A more detailed rheological description of this phenomenon has already been given in the literature [16,20].

Cell Processing

> "Dispensing also offers the possibility of varying paste rheology over a much wider range than in the case of other thick-film printing technologies."

Analysis of contact finger geometries

Throughout the whole process development, printed and dispensed contact geometries were measured using an Olympus LEXT4000 laser confocal microscope; this allowed an in situ determination of confocal and height information within a finger section of approximately 256µm in length. An analysis of these geometrical data was performed using the Matlab-based software developed in-house, as mentioned in Pospischil et al. [17]. In the latest experiment, single SP(1×) and double SP(2×) screen-printed contact grids with screen openings of just 45µm and 40µm, respectively, were used as references. The dispensing group was divided into one with a nozzle opening of 50µm (D50), using exactly the same metal paste as the reference groups, and two that used a rheologically adapted paste with 50µm and 40µm nozzle opening diameters, i.e. D50-R and D40-R. Fig. 7 shows the plots of the resulting contact widths and the electrical aspect ratios for each of the five groups.

All dispensed samples exhibit a significantly reduced finger width and an increased aspect ratio. A comparison of the D50 and D50-R groups reveals that the rheologically adapted paste (-R) leads to a significant increase in aspect ratio, and thus to a further decrease in finger width, when the same nozzle diameter is used. Furthermore, as demonstrated by applying spectrally resolved light-induced current measurements (SR-LBIC), an increase in aspect ratio also improves internal reflective effects, thus allowing even smaller effective widths [7] and hence yielding further reductions in shading losses.

Interestingly, the aspect ratio for the last group, D40-R, is again lower than that for the D50-R group; this can be explained by the higher shear load inside the nozzle due to the smaller diameter in the former groups. Consequently, the finger width of the corresponding solar cells is still larger than 35µm, although a record finger width of 27µm has already been demonstrated with the same nozzle configuration but with a rheologically adapted paste of the previous generation [16] having an even higher yield stress.

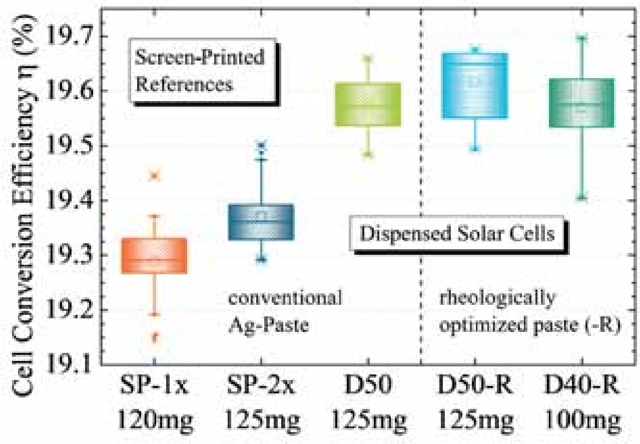

Figure 8. *I–V* results and wet paste lay-down for three different dispensing groups in comparison to single- and double-screen-printed reference cells. All dispensed groups show significantly increased cell efficiencies compared with both reference groups. The application of a nozzle diameter of only 40µm (last group) allows a substantial reduction in wet paste consumption compared with single-screen-printed samples. The application of a rheologically optimized printing paste should be considered in order to gain maximum cell efficiencies. A total of 270 cells on industrial preprocessed 156mm × 156mm Cz Al-BSF material were used in the experiment.

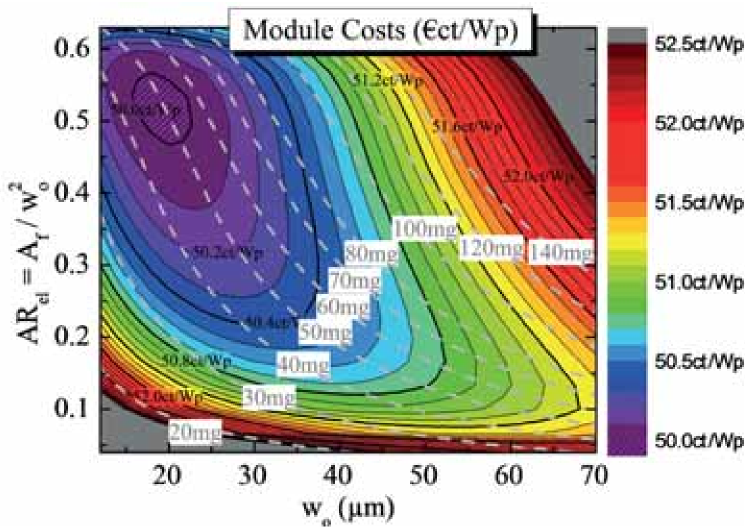

Figure 9. Simulation of estimated module costs as a function of finger width and electrical aspect ratio. Similar amounts of wet paste consumption are indicated by dotted lines. The data imply a homogeneous contact finger shape for any contact geometry. Each data point refers to the ideal number of contact fingers per cell from a cost perspective. For the simulation, a Cz p-type silicon wafer material, with industrial emitters of R_{sh}~90Ω/sq. and three dual-printed busbars (w_{BB} = 1.2mm), was assumed. (Data on cell manufacturing costs taken from Nov. 2014.)

Latest solar cell results for standard Al-BSF solar cells

Latest developments now permit the application of printing pastes designed for screen printing to the parallel dispensing prototypes. This improvement ensures the required contacting behaviour of the dispensed grids in combination with the previously discussed geometrically advantages of these ultrafine contact fingers that are applied at production speeds above 600mm·s^{-1}.

In the latest batch of industrial Cz Al-BSF solar cells, all the dispensing groups showed significant increases in efficiency of up to +0.4% abs. compared with the screen-printed references (see Fig. 8). Top values of 19.7% demonstrated the potential of the technology as an alternative metallization concept. This efficiency gain is mostly due to the significantly smaller finger width and thus higher values in J_{sc} and V_{oc}. For the first time, fill factors above 80% were demonstrated for all groups, the highest values being achieved for samples dispensed with a 50µm nozzle opening.

A detailed analysis of the series resistance revealed that all groups showed similar contact behaviour. The differences in R_s could therefore be directly attributed to differences in the finger grid resistance R_f. In this case, the dispensed groups using a nozzle opening of 50µm feature a value of R_f which has decreased by up to 28% compared with the value for the double-printed reference (SP-2×), which has the same wet paste consumption, but suffers from geometric inhomogeneities, such as mesh marks and paste spreading. Consequently, substantially improved homogeneity of dispensed contact fingers leads to more efficient usage of the applied silver paste and thus significant material savings. The total wet paste consumption, including contact fingers and busbars, for solar cells dispensed with 40µm nozzles was reduced by approximately 15–20% compared with that for both of the screen-printed reference groups, whether single or double printed. At the same time, efficiency increases of 0.3% abs. for the 40µm group were recorded.

Economic considerations

In order to optimize paste rheology and dispensing set-up in respect of cell efficiency and production cost, the Gridmaster analytic tool [21] was enhanced to handle extensive parameter studies by means of efficient, nested interval algorithms [17]. Here, the optimum number of necessary contact fingers is calculated on the basis of a combination of two independent input parameters, which are preferably chosen to be finger width (w_o) and aspect ratio (AR_{el}) for comparing screen-printed and dispensed contact grids.

An actual calculation is given in Fig. 9, which shows the expected module production costs as a function of the aforementioned input parameters; lines of equal wet paste lay-down are also indicated. If the geometrical results of Fig. 7 are taken into consideration, a cost-saving potential of approximately €ct1/Wp compared with single screen printing becomes apparent when dispensing technology is used, because of its high aspect ratio. Note that, in this case, differences between the technologies regarding the relative effective finger width and geometrical inhomogeneities, as well as additional influences, such as consumable and investment costs, yield losses and device throughput rates, have not been considered at this stage.

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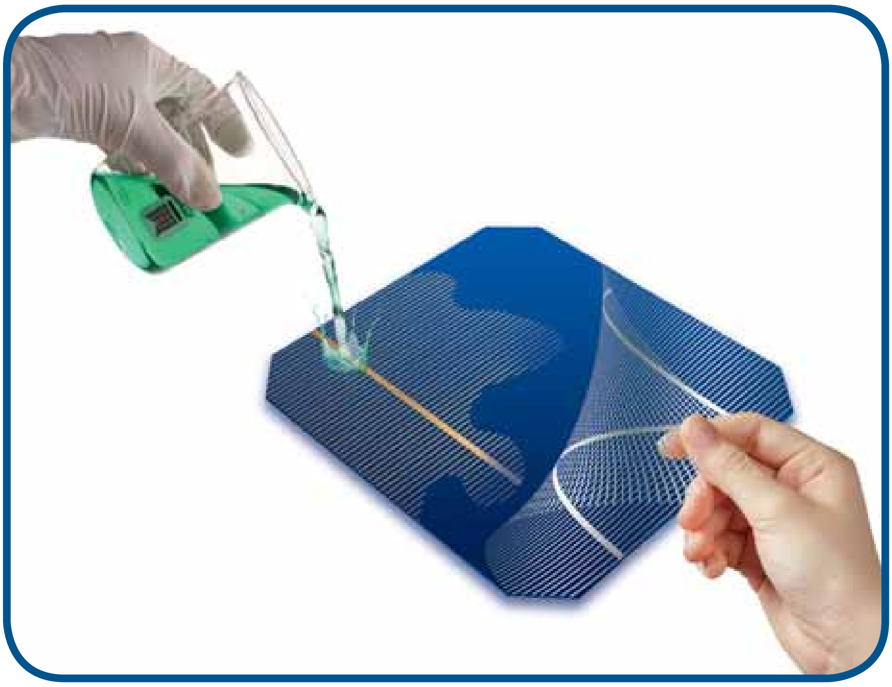

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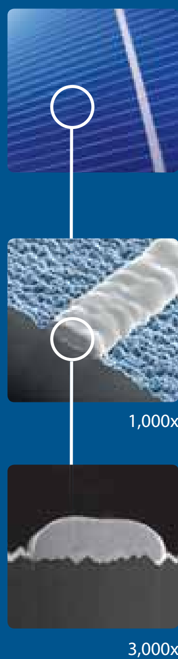

Chemicals Make the Connections

Conclusions and outlook

Fast-emerging thick-film printing technologies remain a dynamic challenge for any kind of alternative metallization technology. The possibility of directly applying screen-printing pastes, however, allows the enhancement of dispensing technology with regard to industrial cell processing. State-of-the-art contacting behaviour was therefore demonstrated on parallel dispensed solar cells, since the same screen-printing paste was printed and dispensed.

Dispensed grid lines offer a substantially more homogeneous contact shape and require 15–20% less silver than screen-printed fingers to obtain similar grid resistances. In the case of a rheological adaptation of the incorporated dispensing paste in order to achieve high aspect ratios, there is the additional benefit of smaller finger widths and reduced shading losses, as well as additional light reflected from the grid geometry at the module level. This fact, in combination with a substantially improved finger homogeneity, allows greater cell currents and fill factors, and at the same time a reduced silver paste consumption, compared with screen-printed reference solar cells. Parallel dispensing at production speeds above 600mm·s^{-1} on an industrially feasible platform means that the introduction of the process to industrial back-end lines would allow a further increase in cell efficiencies at lower production costs in the mid term.

"Dispensed grid lines offer a substantially more homogeneous contact shape and require 15–20% less silver than screen-printed fingers to obtain similar grid resistances."

Once the 6″ dispensing print head has been launched, the focus will be on the biggest challenge – the development of a dispensing process that operates intermittently. This will include the optimization of all the components involved, especially the valve systems, in order to meet the requirements of this highly dynamic system.

Acknowledgements

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Maximilian Pospischil studied mechanical engineering at the Technical University of Munich and at Delft, and received his diploma degree from the former in 2009. In 2010 he joined Fraunhofer ISE as a Ph.D. student, and is currently a project leader within the printing technology group. His Ph.D. thesis topic concerns the development of an industrial front-side metallization process for silicon solar cells, based on dispensing technology.

Markus Klawitter completed his training as a tool mechanic in 2005. He received his B.Eng. degree from Konstanz University of Applied

Science, Germany, and is experienced in the fields of computational fluid dynamics and rheology as well as special solar-driven water pump development. Since 2012 he has been working as a research engineer at Fraunhofer ISE, developing the dispensing process.

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Raphael Efinger studied printing technology at the University of Printing and Media in Stuttgart and graduated in 2008. From 2009 to 2011 he worked at Day4 Energy Inc. as a research scientist in the field of cell-to-module integration using the multi-wire busbar approach. He has been working as a research engineer at Fraunhofer ISE since 2012.

Angel Padilla studied electronic engineering with a focus on embedded systems at the Universidad Autonoma de Baja California (UABC) in Mexico. During a one-year exchange programme at the Ruhr-Universität Bochum, Germany, he completed his studies with an internship at Fraunhofer ISE, after which he continued his development work as part of the dispensing team.

Harald Gentischer received his engineering diploma from Johannes Kepler University in Linz in 2007. While pursuing his education and after graduation, he worked on R&D, at Fraunhofer IPA and its spin-off companies, in automatization technologies for semiconductor production. In 2011 he joined Fraunhofer ISE to support the development of dispensing technology, and is now involved in materials science, developing next-generation battery materials.

Markus König received his Ph.D. in materials science, with a research topic of sintering of nanoscale zinc oxide particles and thin films, from the Technische Universität Darmstadt in 2011. Since 2010 he has been working for Heraeus Deutschland GmbH & Co. KG as an R&D project manager for metallization pastes for silicon solar cells. His research interests are contact formation and high-temperature processes, paste rheology and solar cell physics.

Matthias Hörteis received his Ph.D. in physics from the University of Constance in Germany. He joined Fraunhofer ISE in 2005 and worked on the metallization of solar cells. Since 2011 he has been at Heraeus Precious Metals, where he is involved in the development of screen-printing pastes for PV devices.

Lars Wende is director of Advanced Technologies at ASYS Group. He has a master's in physics from the Technical University of Darmstadt, and received his Ph.D. in semiconductor physics from the University of Berlin in 1995. The research work for his Ph.D. concerned the intrinsic defects in semiconductor materials at the Hahn Meitner Institute in Berlin.

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Daniel Biro studied physics at the University of Karlsruhe, Germany, and at UMASS Amherst, USA, after which he received his Ph.D. from the University of Freiburg in 2003. He joined Fraunhofer ISE in 1995, and in 2004/2005 he coordinated the design and ramp-up of the Fraunhofer ISE production technology lab PV-TEC. He is now head of the high temperature and printing technology/industrial solar cell structures department.

Ralf Preu received his diploma degree in physics in 1996 from the University of Freiburg, Germany, and a Ph.D. degree in electrical engineering in 2000. He also has a diploma degree in economics, awarded by the University of Hagen in 2003. He joined Fraunhofer ISE in 1993 and is currently director of the PV production technology and quality assurance division.

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Application of seed and plate metallization to 15.6cm × 15.6cm IBC cells

Sukhvinder Singh[1], **Barry O'Sullivan**[1], **Manabu Kyuzo**[2], **Shruti Jambaldinni**[1], **Loic Tous**[1], **Richard Russell**[1], **Maarten Debucquoy**[1], **Jozef Szlufcik**[1] & **Jef Poortmans**[1,3,4]

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ABSTRACT

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Increasing the fill factor could be partly solved by increasing the metal thickness [4]. Large-area IBC cells (15.6cm × 15.6cm) with a fill factor of up to 78.5% using PVD metallization have been reported by ISFH/Bosch [14], possibly with a much higher Al thickness. In the authors' opinion, increasing the metal thickness by sputtering could lead to increased bowing and also breakage of wafers.

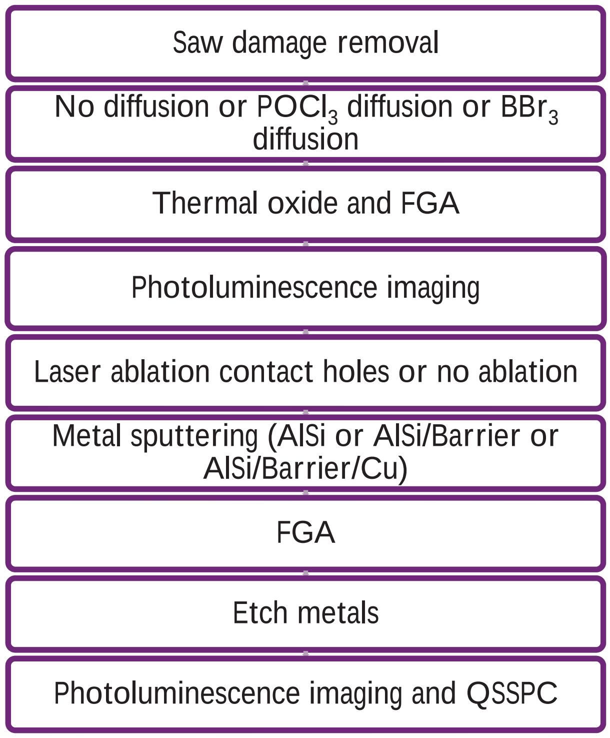

Figure 1. Process flow for the investigation of sputtering damage and barrier properties of the seed layer stack.

Additionally, the sputtering of thick AlSi is neither commercially viable nor readily compatible with cell interconnection [15]. There is therefore a need for an alternative, commercially feasible and module-integration-compatible, thick metal stack for large-area IBC cells.

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- Good ohmic contact to both p^+- and n^+-doped silicon regions
- High rear-surface reflection
- A barrier for Cu diffusion into the Si
- A suitable layer on top to enable subsequent plating

This thin stack could be easily deposited by sputtering because of the various advantages of the method, such as uniformity, maintaining stoichiometry and conformity [16]. This PVD stack can be less than 500nm thick, clearly less than when a metallization with only PVD is envisaged. A thicker Cu layer can be plated on top of the seed layer.

The sputtering of metal layers, however, has been reported to cause damage to the underlying passivation layer and silicon substrate as a result of bombardment of the surface by photons in the soft X-ray regime [17–19]. For sputtered AlSi layers this damage can be effectively recovered by forming gas annealing (FGA); however, in some cases (e.g. sputtering of metals such as NiV and NiCr), it has been shown that the damage cannot be fully recovered, even after FGA [19].

The results of a study of a seed layer stack for Cu plating and its barrier properties, as well as a detailed investigation of sputtering damage and its recovery by FGA, are presented in this paper. This

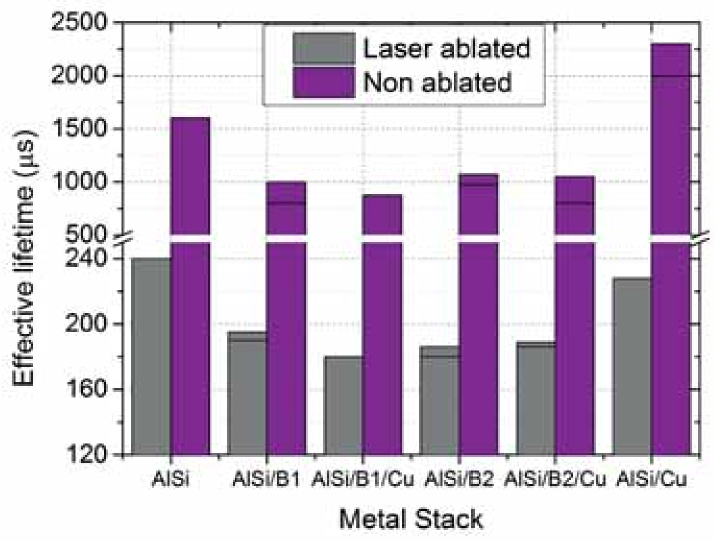


Figure 2. Effective lifetimes (at an injection level of 1E15cm^{-3}) of wafers following the full process flow listed in Fig. 1, without the $POCl_3$ or BBr_3 diffusion.

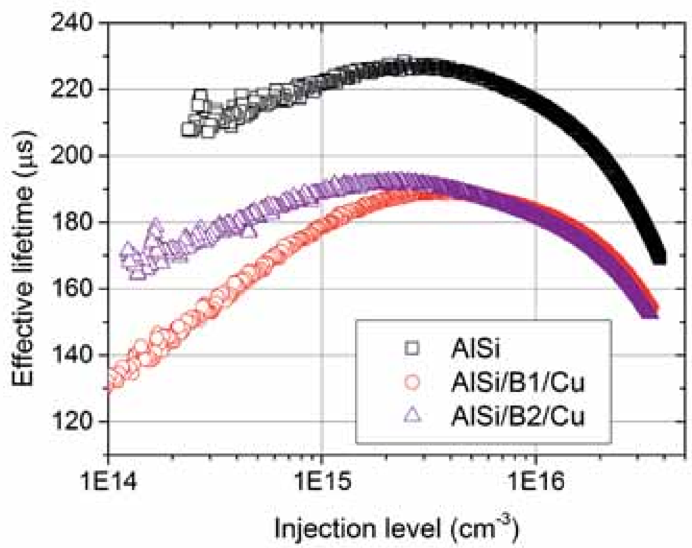


Figure 3. Injection-dependent lifetime of typical samples with different metals stacks.

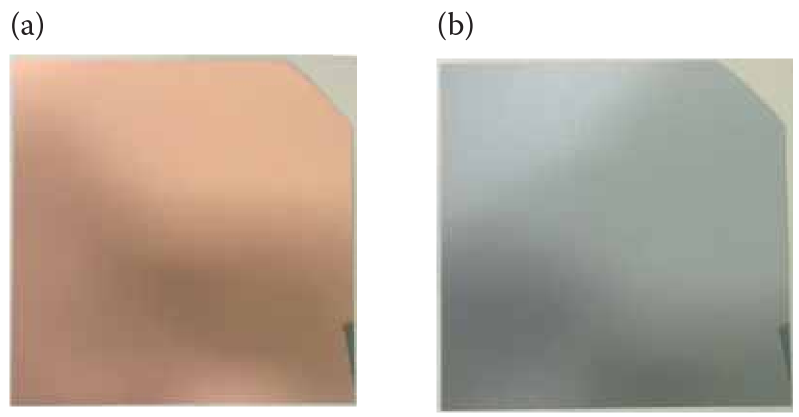


Figure 4. Images of samples with AlSi/Cu: (a) before, and (b) after FGA at 400°C.

seed layer stack and the subsequent Cu-plating process are then integrated in large-area solar cells.

Process flow for sputtering damage investigation

The process flow used for investigating the sputtering damage is illustrated in Fig. 1. Semi-square n-type 15.6mm × 15.6mm CZ silicon wafers first undergo a saw damage removal etch step, then are cleaned, and subsequently either proceed to direct thermal oxidation or undergo emitter (BBr_3) or BSF ($POCl_3$) diffusion. The passivation/dopant activation is carried out by thermal oxidation.

This is followed by FGA and quasi-steady-state photoconductance (QSSPC) measurements. Next, contact areas are defined by laser ablation on part of the wafers, followed by various thin metallization stacks, including two titanium-based barriers, namely B1 and B2. These contact areas also allow the investigation of possible Cu diffusion into the silicon through the barrier. The wafers then receive an FGA, followed by a metal etch and photoluminescence imaging and QSSPC lifetime measurement. In order to analyse the surface defect density *p*, n-type polished and oxidized wafers were used for capacitance voltage (CV) measurements; for these measurements the metallized areas were defined by photolithography after a blanket metal process and subsequent etch of the underlying seed layer.

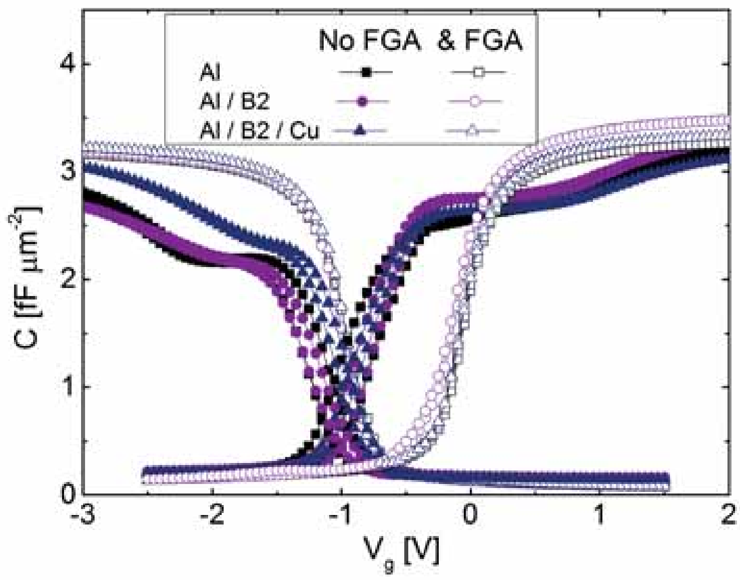
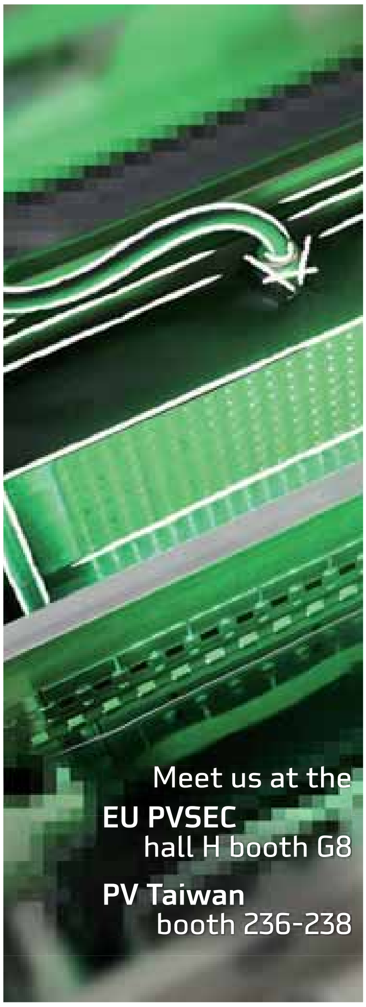


Figure 5. CV measurements for thermally oxidized p- and n-type samples.

Lifetime and CV studies of wafers without BBr_3 or $POCl_3$ diffusion

It is observed from Fig. 2 that samples having undergone laser ablation



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demonstrate significantly lower lifetimes than samples without ablated surfaces; this is because there is clearly no passivation present in the laser openings. It is also seen that samples with AlSi/B1 (and B2) display lower lifetimes (≤1ms) than those with only AlSi (>1.5ms), which indicates higher sputtering damage on samples with either of the barriers. It may be noted that in the process flow described above, the metal stack is etched only after FGA in order to retain the benefits from the well-known Alneal effect upon sintering [20]. This is in contrast to the process flow listed elsewhere in the literature [19].

Next, the samples with AlSi/B1/Cu and AlSi/B2/Cu display similar lifetimes as respective samples (AlSi/B1 or B2) without Cu, indicating that the Cu deposition and the FGA at 400°C do not lead to Cu diffusion through the barrier layers, or that such a Cu diffusion has no further negative effect on the lifetime. AlSi/B1/Cu, however, exhibits lower lifetimes in the low injection regime than AlSi/B2/Cu, as seen in Fig. 3.

Barrier B2 was therefore chosen for further investigations on samples with emitter/BSF diffusion. Surprisingly, non-ablated samples with AlSi/Cu demonstrate higher lifetimes (≥2ms) than corresponding samples with AlSi only. This shows that Cu does not cause any significant sputtering damage and possibly results in enhancing the lifetime by an effect similar to the 'alneal' effect [20]. However, this does not imply that no barrier layer would be required, as the laser-ablated AlSi/Cu samples display lower lifetimes than samples with only AlSi, which could be a sign of Cu diffusion in the laser-ablated regions. Furthermore, the discoloration seen in Fig. 4 is visual evidence that Cu could diffuse into AlSi. Various phases of Cu and Al are possible after sintering at 400°C [21], emphasizing the need of a barrier layer to prevent the diffusion of Cu. This discoloration is not observed in the samples with AlSi/barrier/Cu.

Capacitance–voltage profiling (CV) measurements carried out on p- and n-type polished and thermally oxidized silicon wafers are shown in Fig 5. Immediately after the seed layer sputtering step, a large shoulder is present in the CV curves in the region between accumulation and depletion for both n-Si and p-Si substrates. This is consistent with the presence of high densities of silicon dangling-bond defects at the Si/SiO_2 interface, at energy levels between the valence band edge and the mid-gap (p-Si), and from the mid-gap to the conduction

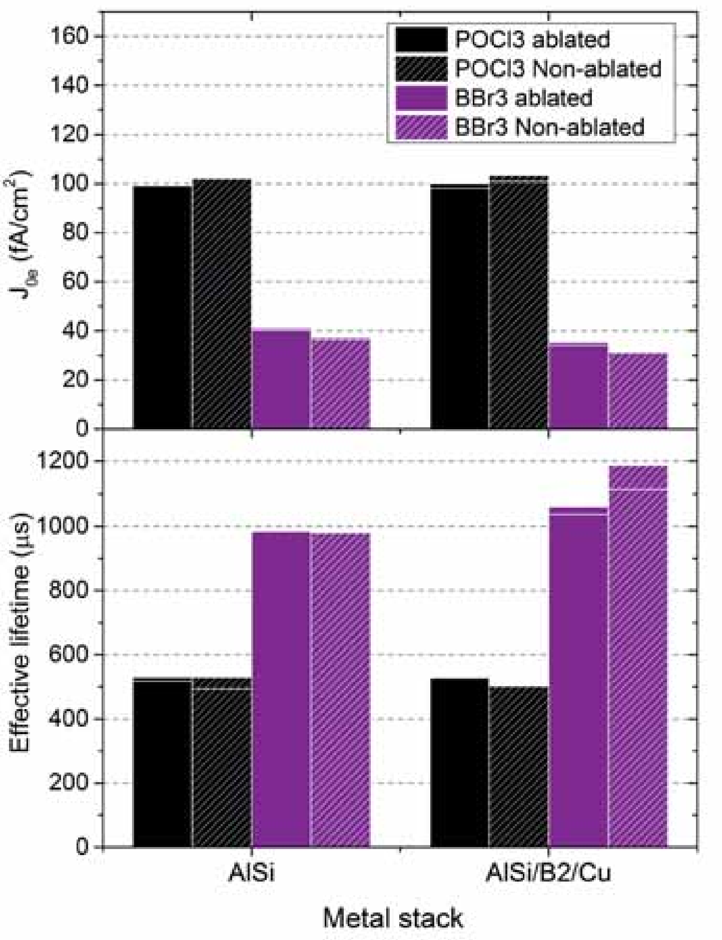
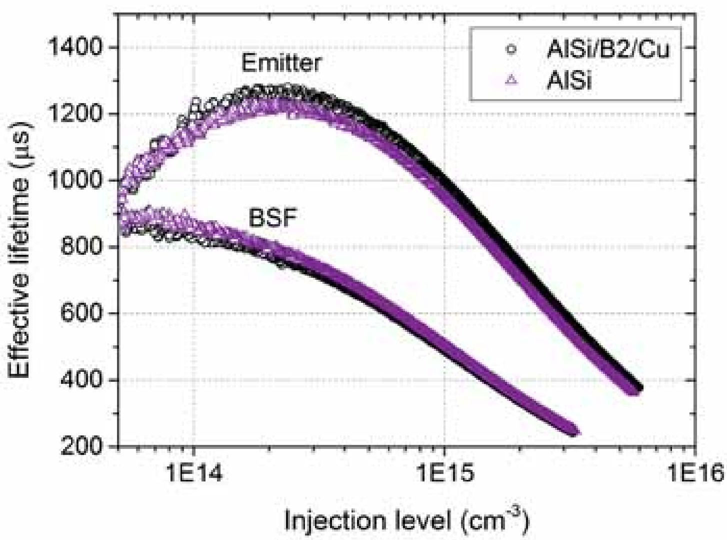


Figure 6. Effective lifetime and J_{0e} for BBr_3-diffused (emitter) and $POCl_3$-diffused (BSF) samples.



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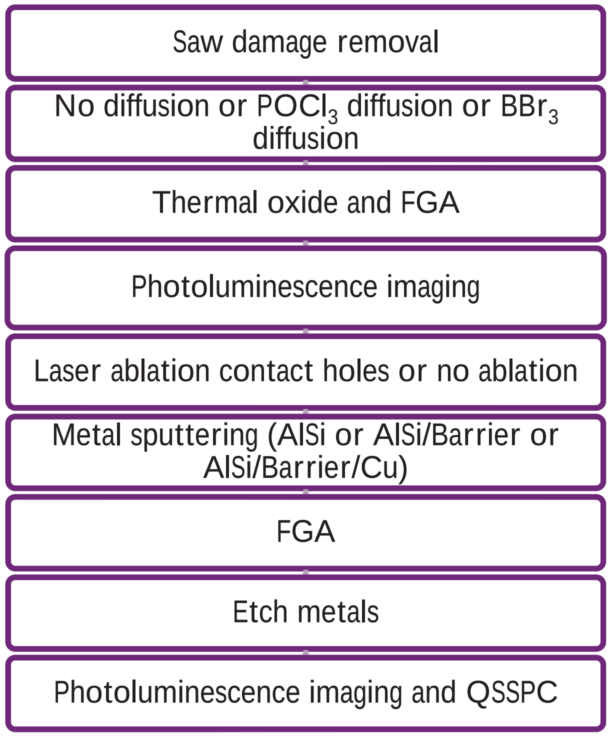

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- A barrier for Cu diffusion into the Si
- A suitable layer on top to enable subsequent plating

This thin stack could be easily deposited by sputtering because of the various advantages of the method, such as uniformity, maintaining stoichiometry and conformity [16]. This PVD stack can be less than 500nm thick, clearly less than when a metallization with only PVD is envisaged. A thicker Cu layer can be plated on top of the seed layer.

The sputtering of metal layers, however, has been reported to cause damage to the underlying passivation layer and silicon substrate as a result of bombardment of the surface by photons in the soft X-ray regime [17–19]. For sputtered AlSi layers this damage can be effectively recovered by forming gas annealing (FGA); however, in some cases (e.g. sputtering of metals such as NiV and NiCr), it has been shown that the damage cannot be fully recovered, even after FGA [19].

The results of a study of a seed layer stack for Cu plating and its barrier properties, as well as a detailed investigation of sputtering damage and its recovery by FGA, are presented in this paper. This

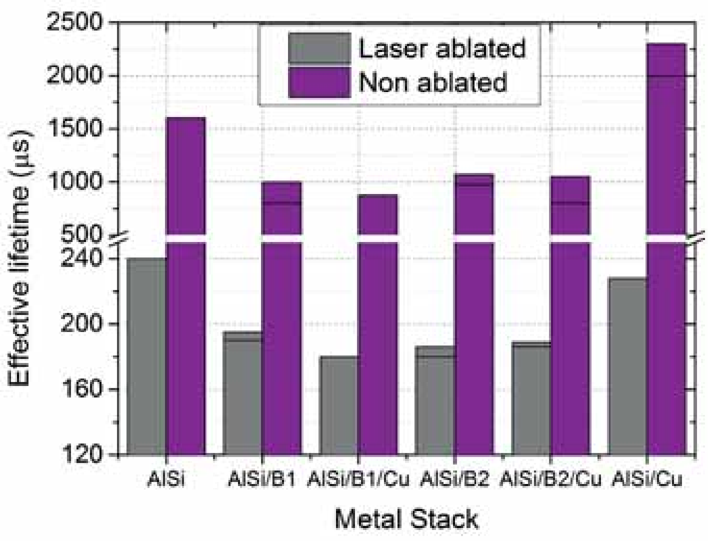


Figure 2. Effective lifetimes (at an injection level of 1E15cm^{-3}) of wafers following the full process flow listed in Fig. 1, without the $POCl_3$ or BBr_3 diffusion.

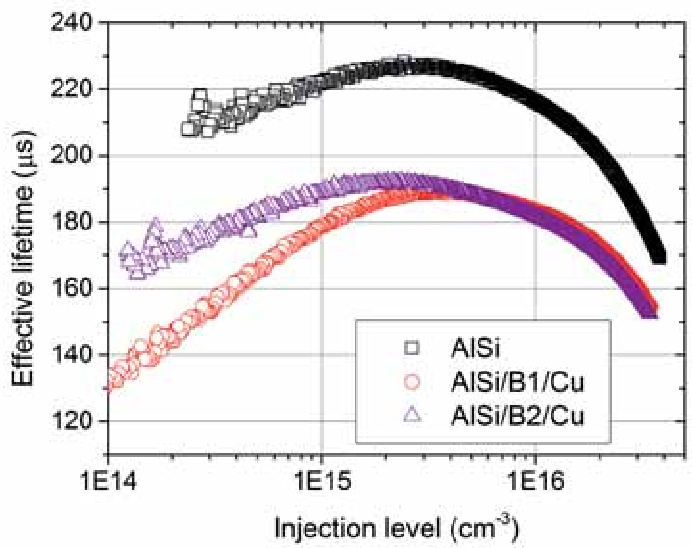


Figure 3. Injection-dependent lifetime of typical samples with different metals stacks.

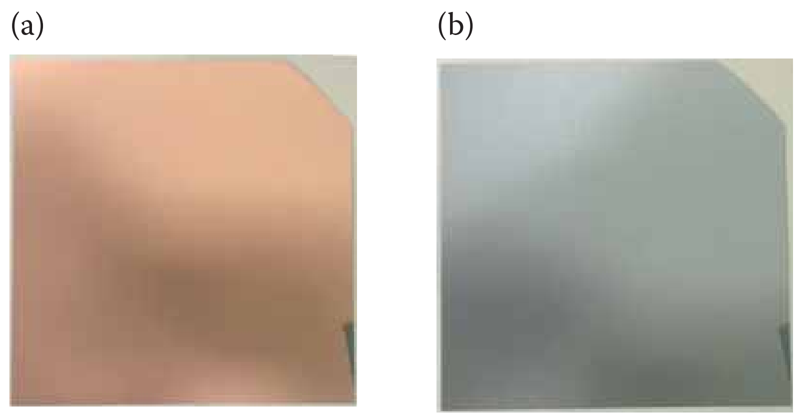


Figure 4. Images of samples with AlSi/Cu: (a) before, and (b) after FGA at 400°C.

seed layer stack and the subsequent Cu-plating process are then integrated in large-area solar cells.

Process flow for sputtering damage investigation

The process flow used for investigating the sputtering damage is illustrated in Fig. 1. Semi-square n-type 15.6mm × 15.6mm CZ silicon wafers first undergo a saw damage removal etch step, then are cleaned, and subsequently either proceed to direct thermal oxidation or undergo emitter (BBr_3) or BSF ($POCl_3$) diffusion. The passivation/dopant activation is carried out by thermal oxidation.

This is followed by FGA and quasi-steady-state photoconductance (QSSPC) measurements. Next, contact areas are defined by laser ablation on part of the wafers, followed by various thin metallization stacks, including two titanium-based barriers, namely B1 and B2. These contact areas also allow the investigation of possible Cu diffusion into the silicon through the barrier. The wafers then receive an FGA, followed by a metal etch and photoluminescence imaging and QSSPC lifetime measurement. In order to analyse the surface defect density *p*, n-type polished and oxidized wafers were used for capacitance voltage (CV) measurements; for these measurements the metallized areas were defined by photolithography after a blanket metal process and subsequent etch of the underlying seed layer.

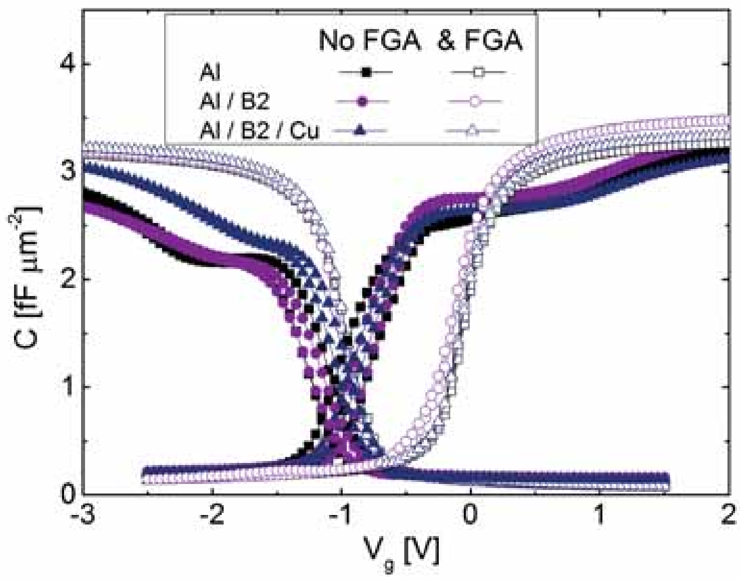
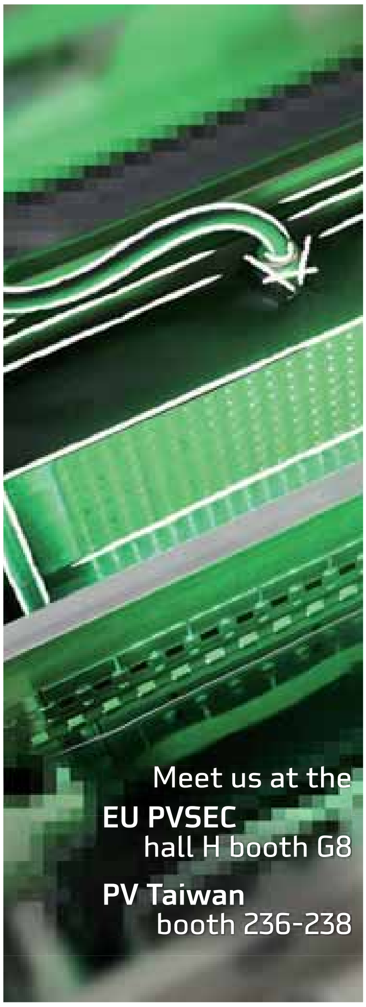


Figure 5. CV measurements for thermally oxidized p- and n-type samples.

Lifetime and CV studies of wafers without BBr_3 or $POCl_3$ diffusion

It is observed from Fig. 2 that samples having undergone laser ablation



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demonstrate significantly lower lifetimes than samples without ablated surfaces; this is because there is clearly no passivation present in the laser openings. It is also seen that samples with AlSi/B1 (and B2) display lower lifetimes (≤1ms) than those with only AlSi (>1.5ms), which indicates higher sputtering damage on samples with either of the barriers. It may be noted that in the process flow described above, the metal stack is etched only after FGA in order to retain the benefits from the well-known Alneal effect upon sintering [20]. This is in contrast to the process flow listed elsewhere in the literature [19].

Next, the samples with AlSi/B1/Cu and AlSi/B2/Cu display similar lifetimes as respective samples (AlSi/B1 or B2) without Cu, indicating that the Cu deposition and the FGA at 400°C do not lead to Cu diffusion through the barrier layers, or that such a Cu diffusion has no further negative effect on the lifetime. AlSi/B1/Cu, however, exhibits lower lifetimes in the low injection regime than AlSi/B2/Cu, as seen in Fig. 3.

Barrier B2 was therefore chosen for further investigations on samples with emitter/BSF diffusion. Surprisingly, non-ablated samples with AlSi/Cu demonstrate higher lifetimes (≥2ms) than corresponding samples with AlSi only. This shows that Cu does not cause any significant sputtering damage and possibly results in enhancing the lifetime by an effect similar to the 'alneal' effect [20]. However, this does not imply that no barrier layer would be required, as the laser-ablated AlSi/Cu samples display lower lifetimes than samples with only AlSi, which could be a sign of Cu diffusion in the laser-ablated regions. Furthermore, the discoloration seen in Fig. 4 is visual evidence that Cu could diffuse into AlSi. Various phases of Cu and Al are possible after sintering at 400°C [21], emphasizing the need of a barrier layer to prevent the diffusion of Cu. This discoloration is not observed in the samples with AlSi/barrier/Cu.

Capacitance–voltage profiling (CV) measurements carried out on p- and n-type polished and thermally oxidized silicon wafers are shown in Fig 5. Immediately after the seed layer sputtering step, a large shoulder is present in the CV curves in the region between accumulation and depletion for both n-Si and p-Si substrates. This is consistent with the presence of high densities of silicon dangling-bond defects at the Si/SiO_2 interface, at energy levels between the valence band edge and the mid-gap (p-Si), and from the mid-gap to the conduction

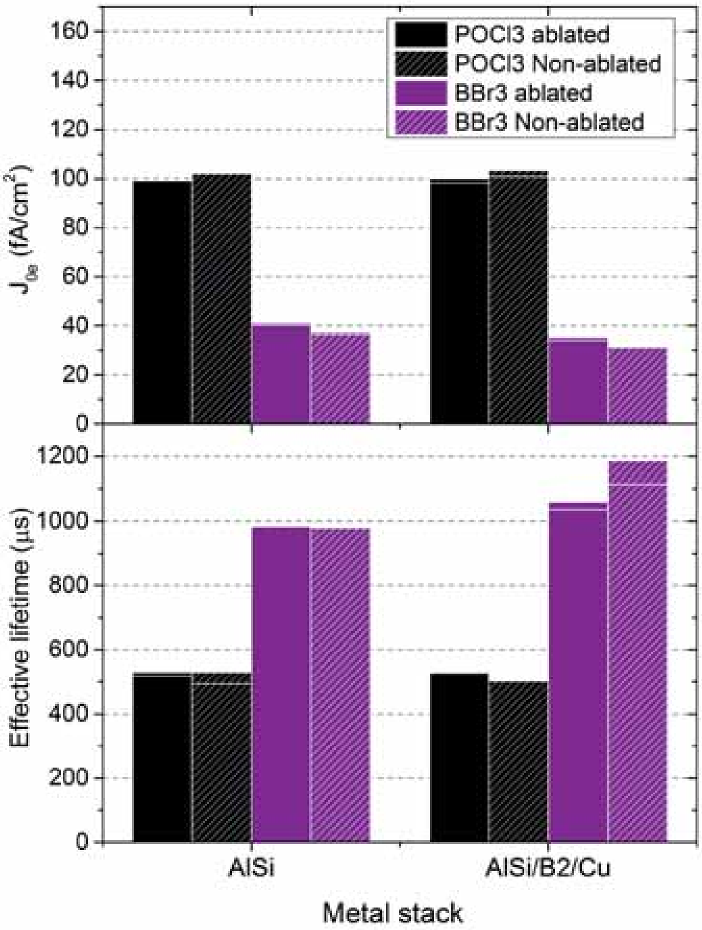

Figure 6. Effective lifetime and J_{0e} for BBr_3-diffused (emitter) and $POCl_3$-diffused (BSF) samples.

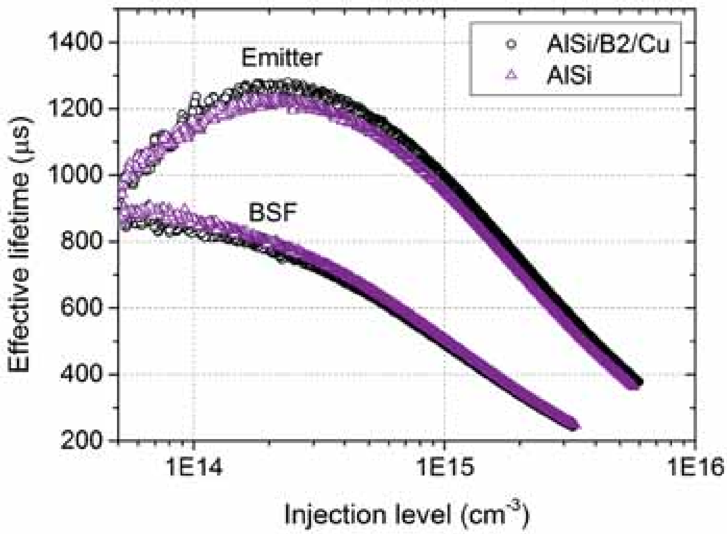

Figure 7. QSSPC curves for BBr_3-diffused (emitter) and $POCl_3$-diffused (BSF) samples.

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band minimum (n-Si). These features are removed by FGA, indicating the successful passivation of the interface defects. Negligible hysteresis indicates low densities of trap/defects in the SiO_2 layer after FGA for all samples with AlSi, AlSi/B2 and AlSi/B2/Cu.

"The differences in effective lifetimes of samples with and without a barrier layer are not related to any remaining surface damage but could be related to the shallow damage below the Si/SiO_2 interface."

It has been reported [22] that sputtering introduces damage near the interface, and that these defects move deeper into the substrate at temperatures above 275°C. These defects were shown to be present up to a depth of 0.5μm. This results in the important conclusion that the differences in effective lifetimes of samples with and without a barrier layer are not related to any remaining surface damage but could be related to the shallow damage below the Si/SiO_2 interface.

Lifetimes studies of wafers with BBr_3 or $POCl_3$ diffusion

In order to understand the effect of sputtering damage on the open-circuit voltage V_{oc} and pseudo fill factor pFF of IBC cells, samples with symmetrical emitter (BBr_3) and BSF ($POCl_3$) doping were prepared. The samples were sputtered with AlSi, AlSi/B2 and AlSi/B2/Cu layers. Lifetime and emitter saturation current (J_{0e}) values measured on these samples with AlSi and AlSi/B2/Cu after FGA (and metal etch) are shown in Fig. 6.

First, it is observed that there is only a very small difference in lifetimes between laser-ablated and non-ablated samples for these diffused wafers (contrary to the case of samples without and with doping, shown in Fig. 2). This can be attributed to the field-effect passivation from the diffused regions masking the surface passivation damage caused by laser ablation.

Second, for BSF-diffused samples, no measurable difference in lifetime or J_{0e} is observed between AlSi and AlSi/B2/Cu. Although the samples with emitter diffusion show slightly better lifetimes for those with AlSi/B2/Cu than the corresponding ones with AlSi, it was found that this is related to the difference between the effective lifetimes of the wafers measured before metal sputtering rather than to the sputtered layers themselves.

These results are also in contrast to the results shown in Fig. 2 for non-diffused samples. QSSPC measurements at low injection (see Fig. 7) do not show any significant difference in effective lifetimes at all injection levels down to less than 5E13/cm^3. It was concluded from these studies (as well as from CV measurements) that additional sputtering damage caused by the barrier layer below the surface is possibly situated in the (highly) doped region of emitter and BSF diffusion. This is also supported by the fact that for the samples with emitter diffusion (shallower doping), the lifetime at low injection levels decreases, whereas for samples with BSF diffusion (deeper doping), it does not.

It is noted that BSF doping profiles are much deeper than emitter doping profiles and extend more than 1μm in depth [9], accommodating all the sputter-damaged region. This is also

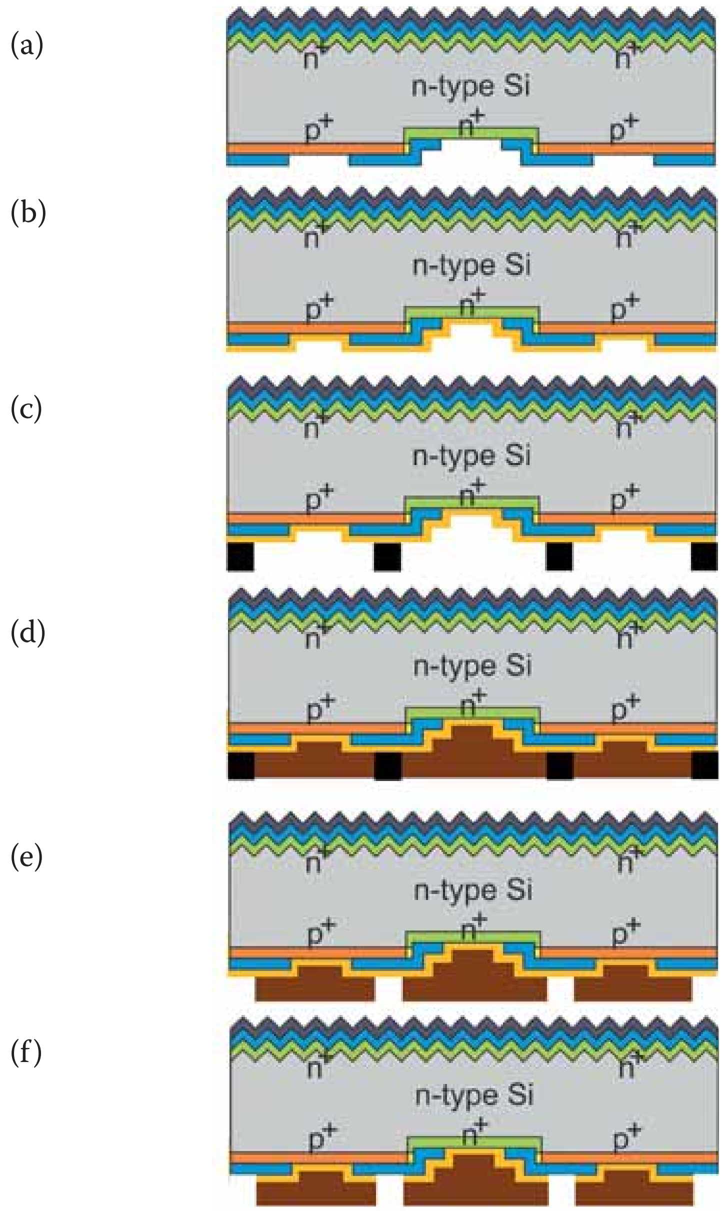

Figure 8. IBC cell metallization flow.

Metal	Size [cm^2]	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	Eta [%]	pFF [%]
Cu-plating	239.1	40.64	682	79.0	21.9	83.0
AlSi-PVD	239.1	40.80	686	77.1	21.6	83.6

Table 1. Best *I–V* results for $239cm^2$-area IBC cells with Cu-plating and AlSi-PVD metallization.

in line with the above-mentioned fact that the doped regions could screen the surface defects. Therefore, even if this sputtering damage is present, it does not affect the measured effective lifetime and J_{0e}.

Cu-plating process implementation for IBC cells

The chosen seed layer stack AlSi/B2/Cu has been implemented in the IBC cell process – the process flow is depicted in Fig. 8. The previously developed process [9,13] is followed until the opening of the contact areas by laser ablation (Fig. 8(a)). Metallization is carried out by PVD AlSi/B2/Cu blanket deposition (Fig. 8(b)). Emitter and BSF metallized regions are defined by screen printing a resist (Fig. 8(c)), followed by the plating of more than 5µm Cu on the non-masked regions (Fig. 8(d)). Next, a resist strip (Fig. 8(e)) and metal seed etch (Fig. 8(f)) are performed. During the metal seed etch, plated Cu acts as a mask, so the seed layer is only etched in the regions without Cu, which are the regions where the resist was printed. FGA is then carried out, after which *I–V* measurements are taken; Table 1 lists the cell results obtained.

As expected from the lower line resistance of the Cu metallization, cells with Cu-plating metallization displayed a higher fill factor than with 3µm AlSi-PVD metallization. Although the J_{sc} values were similar in both cases, the measured values of V_{oc} were slightly lower in the case of Cu-plated cells; this is being investigated further.

Very high pseudo fill factors were observed for Cu-plated samples, indicating the absence of shunts in metallization; this confirms that the developed seed layer (barrier) is effective against Cu diffusion and substantiates the potential for such a metallization scheme. Finally, an efficiency of 21.9% measured over the full area of $239.1cm^2$ cells was achieved with Cu-plated IBC cells.

Conclusions

A review of different metallization schemes for IBC cells – such as screen-printed pastes, PVD metal and plated Cu with a seed layer – has been presented. The firing-through of screen-printed metal pastes is a simple process, but it can limit the efficiency potential of IBC cells, because of the high recombination at the metal–silicon interface; moreover, it can be expensive because of the use of Ag paste. In the authors' view, PVD metallization – such as the sputtering of thick AlSi – is neither commercially viable nor readily compatible with cell interconnection.

"The developed seed layer and Cu plating process has been integrated for large-area IBC cells, resulting in cell efficiencies of up to 21.9% on the full area of the cells."

Owing to its various advantages, a thin seed layer followed by Cu plating was therefore chosen and investigated in detail. This metallization stack satisfies the various requirements of high-efficiency large-area industrial IBC solar cells; these requirements include low contact resistance to both n^+- and p^+-doped regions, limited influence on the passivation of the doped regions, good compatibility with module incorporation, and cost effectiveness. The developed seed layer and Cu plating process has been integrated for large-area IBC cells, resulting in cell efficiencies of up to 21.9% on the full area of the cells. To the best of the authors' knowledge, this is the highest efficiency measured for IBC cells of 15.6cm × 15.6cm with Cu-plating metallization.

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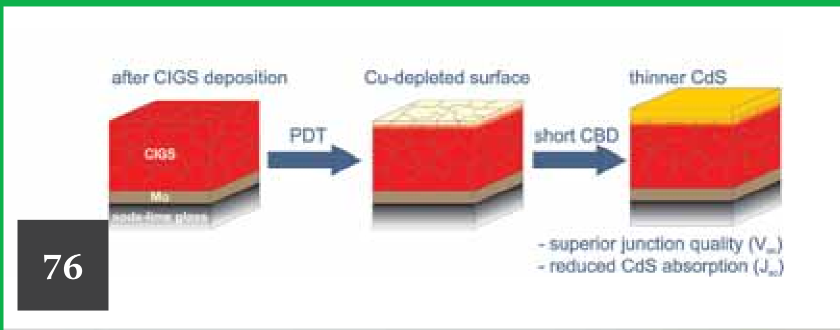
Thin Film


after CIGS deposition
CIGS
Mo
PDT
Cu-depleted surface
short CBD
thinner CdS
- superior junction quality (V)
- reduced CdS absorption (J)
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82

News

3GW shipment milestone for Solar Frontier shows CIGS 'can work'

The head of Japan-headquartered thin-film manufacturer and project developer Solar Frontier has offered a robust defence of thin film technology in an interview with Photovoltaics International's sister website PV Tech.

Atsuhiko Hirano said thin film is better suited to compete across all market segments with its conventional rivals than ever before, despite generally recording lower conversion efficiencies.

"We have a strong belief – and we've been proving – that thin-film CIS is applicable for all market segments including residential, commercial rooftop and utility," Hirano said.

"But there were some perceived views that, because of the lower conversion efficiency, we may be inferior against monocrystalline silicon in a limited space area."

Solar Frontier CEO Atsuhiko Hirano.

Source: Solar Frontier

The company's CTO, Satoru Kuriyagawa, also claimed thin film could have a better chance of achieving cost reductions than competing technologies.

Solar Frontier passed a "milestone" of 3GW in module shipments in July.

Analyst Finlay Colville of Solar Intelligence, part of Photovoltaics International publisher Solar Media, said that despite an often turbulent journey to get there "Solar Frontier's milestone is…a confirmation that CIGS can work".

Thin-film fabs

Ascent Solar terminates plans for CIGS thin-film plant in China

Flexible CIGS thin-film producer Ascent Solar Technologies has dropped plans to build an initial 25MW plant in Suqian, Jiangsu Province, China.

In an SEC filing, Ascent Solar noted that the joint venture with the Municipal City of Suqian that would have led to 100MW of capacity had mutually been agreed to be terminated, due to "short supply of needed technical skills in the Suqian area and other factors affecting the long term viability of the partnership", including the slow progress of the planned manufacturing project.

CIGS module producer Hulk planning 200MW expansion by year-end

CIGS thin-film producer Hulk Energy Technology (Hulk) is planning a single 200MW line expansion by the end of 2015, due to growing demand in Europe and the expectation of establishing a strong market in the US.

The Taiwan-based start-up has differentiated itself on several key fronts, notably its founder and president, Brian Sung, has been instrumental in the development of its key process technology and equipment as well as a unique clip together racking system for rooftops.

In early July, the company also achieved a new record power output for a commercial CIGS thin-film module, 324W, confirmed by German testing house Fraunhofer ISE.

Hulk said the power gains had been picked up through a number of improvements including better spectral response, lower temperature coefficient and a lower impact from shading.

Ecosolifer planning heterojunction cell module assembly plant in Brazil

Swiss/Hungarian silicon thin-film equipment and technology firm Ecosolifer has been reported to be planning an 80MW module assembly plant in Brazil, using its proprietary amorphous silicon deposition technology on monocrystalline wafers produced at its plant in Csorna, Hungary.

The company has yet to decide a location for the assembly plant and the heterojunction cells would be supplied to the assembly beginning in April 2016.

An initial investment in the assembly plant was said to be around US$8.7 million, indicating small-scale module production.

Orders

LPKF continues to expect thin-film laser system order inflow in 2016

Laser systems specialist LPKF Laser & Electronics expects lean new order bookings in its solar segment for the remaining half of 2015.

LPKF noted that its large thin-film laser systems order of €15 million (US$16.7 million) back in early 2014 had been completed in the second quarter. Billings continued for this order through the first half of 2015, but management noted this would not carry through to the rest of the year.

Management noted that its solar segment revenue and profit would be down for the year. However, major orders are expected in 2016 and subsequent years based on "current projects".

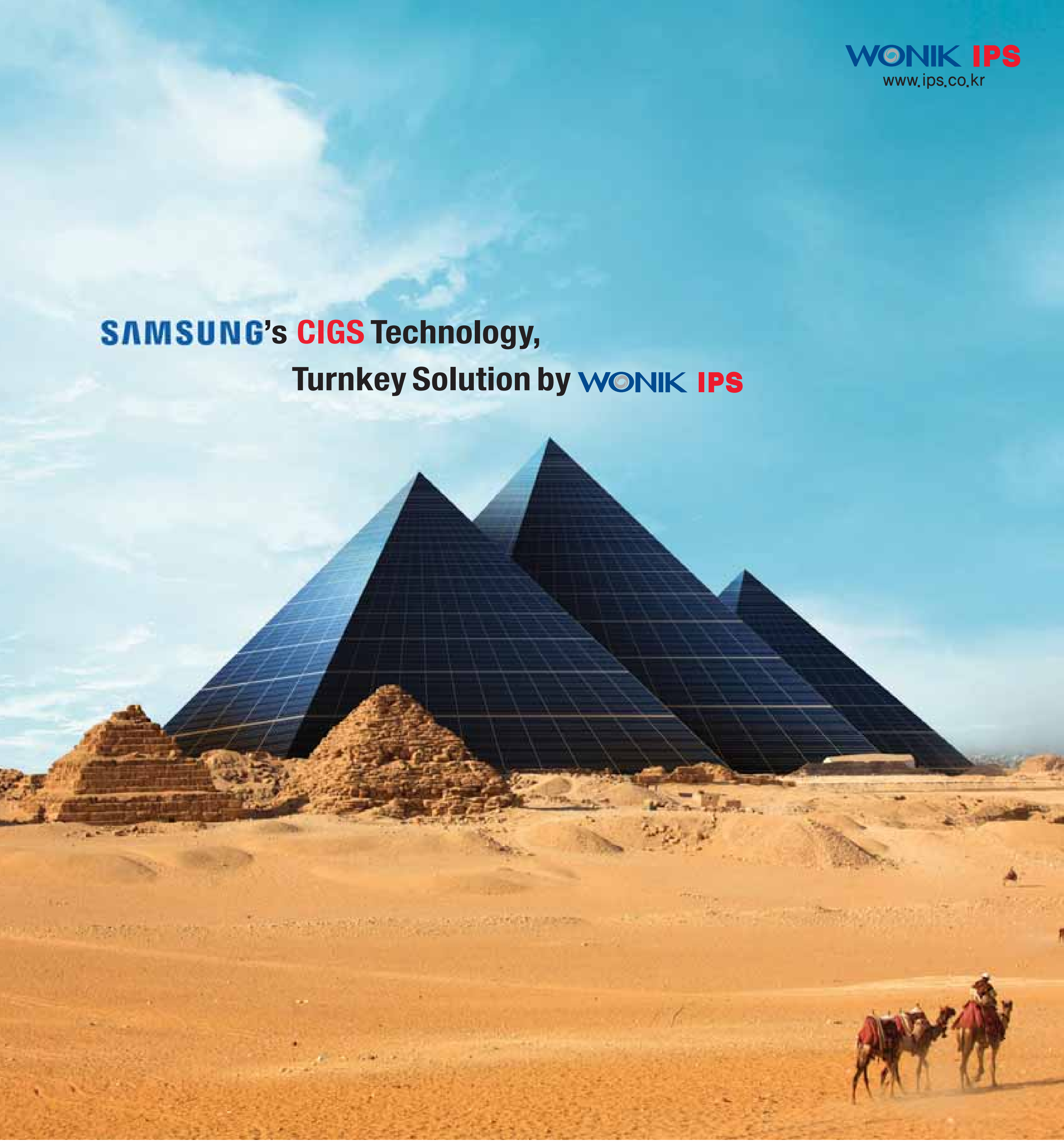
LPKF reported group revenue of €42.4 million (US$47.2 million) for the first six months of 2015, down 7% from the previous year level.

New order intake at Singulus tops €73.1 million in the first half 2015

PV manufacturing equipment specialist Singulus Technologies has reported new order intake for the first half of 2015 topped €73.1 million (US$80.2 million), significantly up from €25.2 million (US$27.7 million) in the prior year period.

Singulus reported preliminary first half 2015 revenue of €29.2 million (US$32.0 million), inline with the prior year period of €30.1 million (US$33.0 million). The earnings before interest and taxes (EBIT) improved slightly from a negative EBIT of €12.5 million (US$13.7 million) in the prior year period to negative €9.8 million (US$10.8 million).

The company noted its order backlog



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Lower cost and higher efficiency become the leader of PV market with infinite potential.

WONIK IPS will lead you to advance mass production faster

CIGS Turnkey solution eliminates the barrier to entry CIGS business from R&D to mass production with core equipment and process technology.
Our proven technology promises best performance as well as minimizing capital investment and risks.

- Efficiency 16%
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Source: Manz Solar

Manz has reported lower sales in the first half of 2015.

as of June 30, 2015 stood at €57.9 million (US$63.5 million).

Management noted that expected orders within its Solar and Optical Disc divisions in the next few weeks would determine meeting sales guidance for the full year.

Innovations and efficiencies

ZSW leading EU-funded CIGS thin-film 'Sharc25' project to 25% conversion efficiencies

An EU funded R&D project has been launched to achieve commercially viable CIGS (copper indium gallium (di)selenide) thin-film cells with 25% conversion efficiencies.

The Sharc25 project includes 11 research partners from eight countries and is being coordinated by The Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), a record holder for CIGS thin film cells on glass.

The ambitious aim is to threaten the dominance of multicrystalline solar cells from Asia.

Imec claims more 'important breakthroughs' in commercialisation of perovskite thin-film

Belgian nanoelectronics research group imec says it has made a "breakthrough" in developing perovskite-based thin-film photovoltaics (PV), recording an active area efficiency of 11.9% with its module.

The organometal halide perovskite module's aperture conversion efficiency was recorded at 11.3%, using an aperture area of 16cm2. Imec says these efficiencies are the best recorded for perovskite modules to date and followed the company's own previous best of 8%, announced just a month earlier.

Imec claimed its PV module can still achieve 9% aperture area efficiency when a linear coating technique is applied to its solution based layers through the conventional lab scale spin coating process. The cells have a geometrical fill factor of 95%.

Company news

Manz sales subdued on order delays

Manz AG reported lower first-half 2015 sales as orders from several business segments were said to have been delayed or cancelled.

The company reported Solar segment sales of around €10.5 million (US$11.5 million) for the first six months of 2015, up 3.9% from the same period of 2014.

However, overall Manz group sales totalled €121.9 million (US$134.3 million) during the first six months of 2015, compared to €163.6 million (US$180.3 million) in the prior year period.

Manz appointed a new COO, Martin Drasch, who was previously in the automobile industry, in July. The company has also said that it wants to increasingly use the "synergies" between its diverse manufacturing locations, highlighting in particular the growing importance of Manz's manufacturing presence in China.

First Solar guides 2015 shipments of almost 3GW

First Solar has guided 2015 PV module shipments almost double those of 2014. The CdTe thin-film leader expects shipments to be in the range of 2.8GW to 2.9GW. First Solar reported the second quarter 2015 sales of US$896 million, an increase of US$427 million from the first quarter of 2015.

The company also guided 2015 net sales to be in the range of US$3.5 billion to $3.6 billion, achieving a guided gross margin of 21 to 22%.

In June, First Solar surpassed multicrystalline module conversion efficiencies for the first time with its CdTe module efficiency reaching a record 18.6%. The company said the 18.6% aperture area efficiency corresponds to a full area conversion efficiency of 18.2%, measured and certified by the U.S. National Renewable Energy Laboratory (NREL).

First Solar recently also made several internal management changes, including a new US regional president and chief operating officer (COO).

Hanergy TF looking at only US$25 million income in Q2

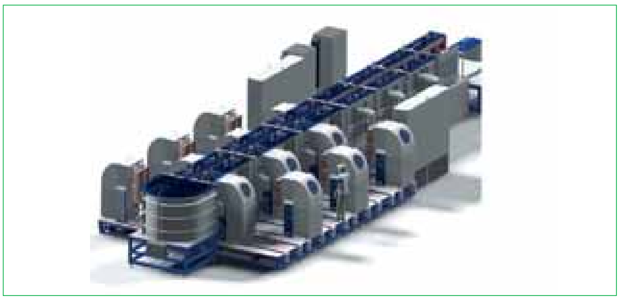
Hanergy Thin Film Power issued a profit warning for its first half 2015 results as its primary customer Hanergy Group recently cancelled a major connected transaction to appease a Hong Kong stock market investigation into Hanergy TF's viability when the majority of a sales go through its privately held parent company.

Hanergy TF said it expected income in the first half of the year to be around US$25.8 million, compared to revenue of around US$413.2 million in the prior-year period.

Various contracts signed with Hanergy Group have been cancelled or put on hold since the investigation, and the stock of Hanergy TF has not traded on the exchange since mid-May.

Product Reviews

SINGULUS



Singulus' inline sputtering systems enable CIGS, CdTe and heterojunction cell thin-film deposition

Product Outline: Singulus Technologies has added to its product family of vacuum coating systems for use in solar technology with an inline sputtering system for CIGS and CdTe thin-film solar cell production.

Problem: Cost-effective thin-film deposition requires uniform coating thicknesses and highly homogeneous coatings to provide the highest cell performance, while maximizing sputter target and material usage with minimum downtime.

Solution: The VISTARIS system with vertical substrate transport and the HISTARIS system with horizontal transport have been designed to enhance the efficiency of thin-film solar cells, while cutting production costs. The machines bring the user the advantage of uniform coating thicknesses and highly homogeneous coatings. Cell performance is appreciably improved, according to the company. This significantly reduces the production area taken up and therefore cuts the investment outlay. High reliability and the easy-to-service design principle boost uptime and slash production costs. With the HISTARIS sputtering system, contact layers on heterojunction cells can be deposited on the front and rear of the wafers without the need to turn the wafers between coating processes. By using cylindrical sputtering magnetrons, a high target exploitation rate is achieved.

Applications: Anti-reflection and barrier coatings, buffer and precursor layers such as copper-gallium, indium, and i-ZnO, but also different metallic layers like Mo, Al, Cu, Ag, and NiV, as well as transparent conductive oxide layers like ITO, AZO, which are necessary for new heterojunction cell technology.

Platform: The systems are available with vertical as well as horizontal substrate transport and can be configured for various substrate sizes and are ideally suited for challenging layer stacks and flexible product mixes. The systems use an inline process in which the substrates are transported on a specially designed conveyor system on flat carriers through the system. The carriers can be configured flexibly for different substrate formats and materials such as solar wafers. Different automation options for loading and unloading are available. Thanks to their modular structure the systems are versatile to use, and are especially noted for their compact design.

Availability: Available since July 2015.

WONIK

Wonik providing turnkey CIGS production lines with 19% efficiency roadmap

Product Outline: Korean-based equipment supplier Wonik IPS has developed a turnkey CIGS thin-film technology from previous collaborations with Samsung. Wonik IPS has taken over all of the CIGS technology and IP acquired by Samsung SDI during its intensive and long-running CIGS R&D development phase.

Problem: Manufacturing CIGS modules creates a higher barrier to entry than with c-Si modules, usually requiring greater investments in terms of R&D and upfront cap-ex costs. There is a lack of proven equipment and reliable processes for CIGS manufacturing, and CIGS manufacturers often have to develop proprietary systems with the above related costs. In addition, there is the challenge of achieving large area uniformity with four-component materials and process monitoring and control. Prices can be prohibitive due to high initial investments and commissioning periods.

Solution: Wonik IPS is providing a proven turnkey solution leading to mass production with full technology transfer, including a selenization furnace and MOCVD for TCO and sputtering. Wonik operates an existing pilot line that is claimed to reduce time from R&D to customer volume production with high efficiencies.

Applications: Turnkey CIGS volume production.

Platform: Wonik IPS CIGS turnkey manufacturing solution creates a shortcut to the market by offering a tried and tested manufacturing platform with known module performance at 16% highest current efficiency (TUV confirmed) in 900x1,600mm module format and a claimed roadmap for 19% conversion efficiency and US$0.2/W module manufacturing costs. All equipment is provided, including support for reaching full production output at the stated efficiency.

Availability: Currently available.

Closing the gap with silicon-wafer-based technologies: Alkali post-deposition treatment improves the efficiency of $Cu(In,Ga)Se_2$ solar cells

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ABSTRACT

With the introduction of the alkali post-deposition treatment (PDT) for the absorber layer in $Cu(In,Ga)Se_2$ (CIGS)-based solar cells, new efficiency records approaching 22% have become feasible. After gallium incorporation, sodium doping and the three-stage process, this is the next milestone on the CIGS roadmap. In this paper the current understanding of how PDT alters the CIGS surface and affects device parameters is illustrated. A comparative study of cell device parameters from ZSW and the evolution of efficiencies from other institutes and companies with and without PDT is presented.

Introduction

Every once in a while there is a leap forward in technology with the introduction of a new technological development. For CIGS thin-film photovoltaics, the incorporation of Ga to increase the band gap [1], the discovery of Na doping [2], and the three-stage process [3], among others, should be mentioned. The efficiency 'learning curve' in Fig. 1 historically groups these and other advances in CIGS process technology.

The latest of such efficiency-boosting milestones is a further development of the NaF post-deposition treatment (PDT), which was originally designed to provide CIGS layers on Na-free substrates with Na after the growth of the CIGS has finished [4]. The PDT process was then extended to KF to dope alkali-free CIGS layers with potassium [5]. The application of this KF-PDT to already Na-doped CIGS layers has subsequently led to a significant boost in efficiency [6].

Further optimization of the CIGS devices including the alkali PDT has led to new record efficiencies in CIGS laboratories all around the world [7–9], the latest being 21.7% from the group at ZSW [10]. The certified solar cell characteristic (current vs. voltage, *I–V*), device parameters (efficiency, open-circuit voltage (V_{oc}), fill factor (FF), short-circuit current density (J_{sc})) and quantum efficiency (QE) of this cell with a total area of $0.5cm^2$ are shown in Fig. 2(a) and (b). The same efficiency for three neighbouring cells [10] has been certified, and since then, more than 100 cells exceeding 21% have been made, demonstrating the potential scalability and reproducibility of the PDT process. Fig. 2 also compares the data to the previous 20.3% ZSW record cell without PDT [11].

It should be noted, however, that several improvements, including the alkali PDT, led to the new record efficiency of 21.7%. (For a comparative study of cells differing only in ZSW's alkali PDT, see Fig. 4(a) and (b); for an evolution of record efficiencies from ZSW and others, see Fig. 5.) Only mini-module results have so far been published [12], but ZSW believes that there are no basic or technical obstacles to PDT entering into production.

"Several improvements, including the alkali PDT, led to the new record efficiency of 21.7%."

The next section gives a brief overview of the PDT process and how it affects the device parameters of CIGS solar cells. A direct comparison of an ensemble of CIGS cells prepared with and without the alkali PDT at ZSW is then presented, followed by a discussion of the influence of the alkali

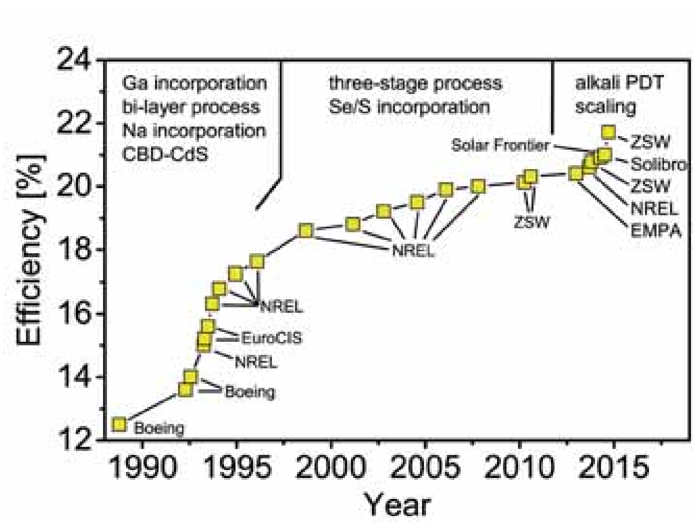


Figure 1. CIGS efficiency 'learning curve', attributing the advances in efficiency to developments in CIGS processing technology.

PDT on different CIGS deposition technologies. Finally, potential future improvements of the CIGS process are examined.

PDT process

The current understanding of the alkali PDT is still incomplete and is steadily evolving as more and more groups implement the process in their CIGS processing lines. In standard cells a molybdenum-coated glass substrate supports the CIGS absorber layer grown either by co-evaporation of the elements Cu, Ga, In and Se at elevated temperatures or by a sequential process, where precursors are deposited at a low temperature in a first step and heated in the presence of Se in a second. Typical precursors are, for example, sputtered layers of Cu, In and Ga or nanoparticle inks.

Both deposition techniques form intrinsically p-type absorbers. If the substrate is soda-lime glass, the absorber already contains a certain amount of 'intrinsic' sodium and potassium which diffuse from the glass during the high-temperature growth phase [7,13]. Some groups employ flexible substrates, such as polyimide, steel foils or glass with a diffusion barrier, all of which need an 'extrinsic' sodium doping, for example via a NaF-PDT [4]. Both kinds of sodium doping lead to high efficiencies and have been known for many years.

The importance of other alkali elements like potassium came into focus when CIGS solar cells on K-rich enamelled steel substrates performed better than the reference samples on soda-lime glass substrates [13]. However, a PDT turned out to be a more effective and versatile technique for introducing alkali elements [5,6] than relying on out-diffusion from a given substrate. A PDT with additional alkali elements clearly improves the efficiency of CIGS solar cells,

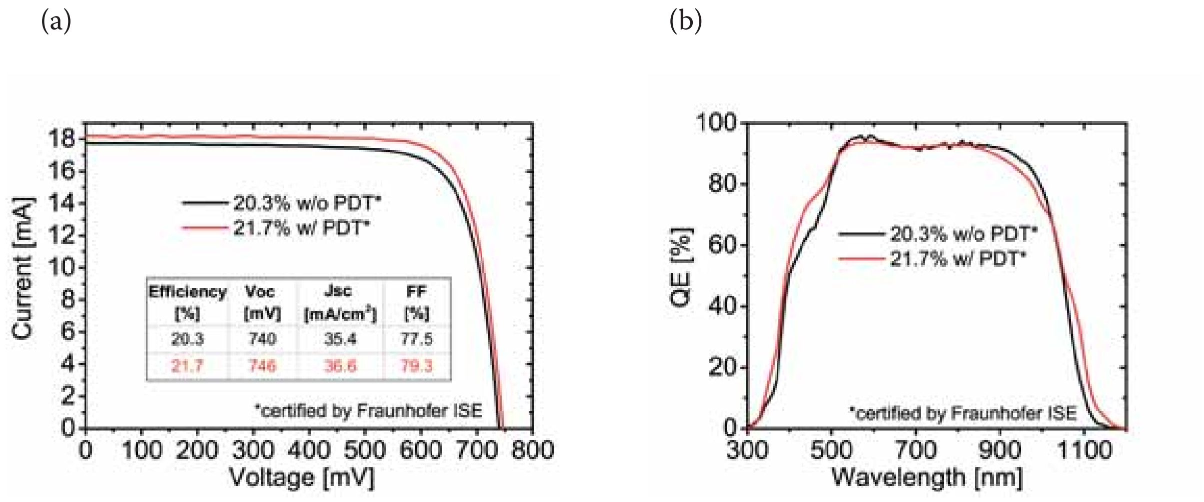


Figure 2. (a) Certified *I–V* curve for the 21.7% ZSW CIGS record cell employing ZSW's alkali PDT (w/PDT) and other improvements (red). The inset table shows the device parameters [10]. (b) QE curve of the same cell (red). The data are compared with the 20.3% ZSW record cell without (w/o) PDT from 2011 (black) [11].

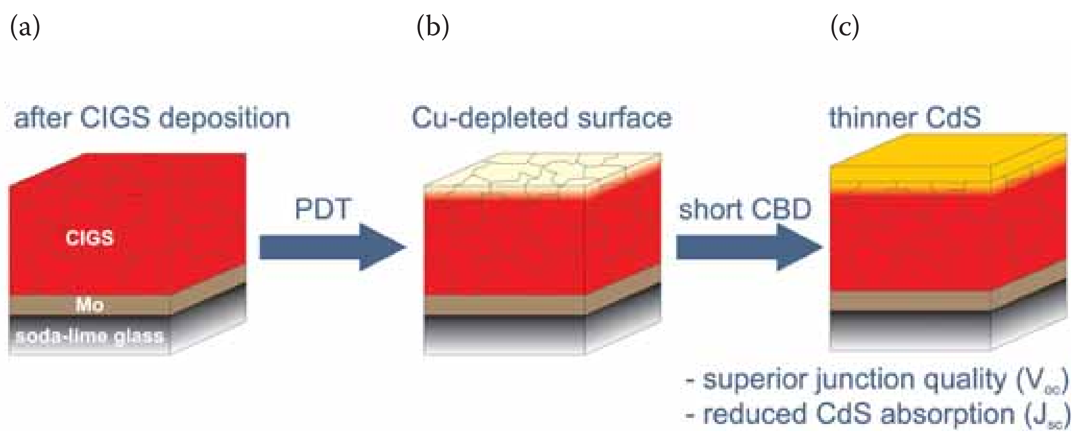


Figure 3. Effect of the alkali PDT on the CIGS/CdS heterojunction: (a) The CIGS layer has an initial alkali content through the diffusion of alkali elements from the glass substrate. (b) After the PDT process the alkali content has been modified and the surface is Cu depleted. (c) The improved diffusion of Cd or Zn during CBD buffer deposition enables better junction formation, improved coverage during initial growth, and higher efficiencies with thinner CdS layers.

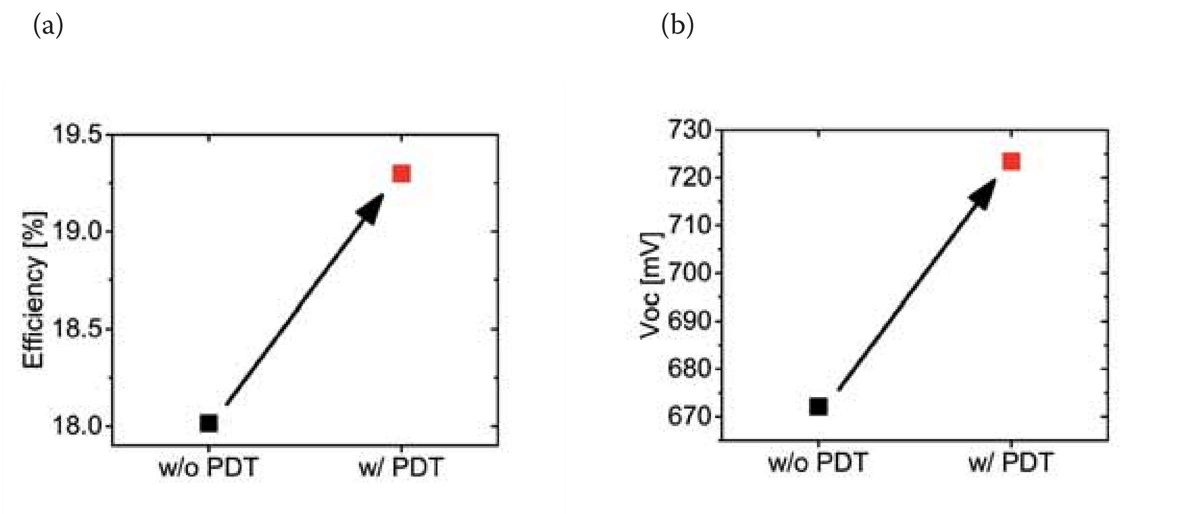


Figure 4. (a) Average efficiencies and (b) average V_{oc} values for an ensemble of about 50 cells. The ensemble was split into two groups after the CIGS process: approximately one-half received an alkali PDT (w/ PDT, red symbols), and the other half did not (w/o PDT, black symbols). Subsequent processes for buffer and window layers were essentially the same for all samples.

regardless of the choice of substrate.

The process in the case of CIGS grown on soda-lime glass is illustrated in Fig. 3. Alkali elements diffuse into the CIGS layer from the substrate during film growth. After CIGS deposition, the post-deposition adjusts the alkali content from the CIGS surface. PDT involves the evaporation of alkali-containing species in the presence of Se and heating to drive the diffusion processes. The alkali elements are found to displace Cu and thus induce a Cu-depleted surface with a depth of a few nanometres [6]. The residual compounds are water-soluble and are therefore washed off in the subsequent chemical bath deposition (CBD) process of a buffer layer, typically CdS. This step forms the heterojunction of the cell, and here the positive impact of a PDT unfolds: Cd ions can more easily diffuse into the Cu-depleted surface and form a junction of superior quality (better V_{oc}) compared with the CBD on CIGS without PDT. This is implied by the continuous transition as marked from red to yellow in Fig. 3(c). It has been suggested that the position of the p-n junction (the location where n = p, n and p being the electron and hole densities, respectively) is located within the absorber layer, thereby forming a buried junction with less interface recombination [14].

For CIGS-based solar cells with PDT, the coverage of the CdS layer appears to improve in the nucleation phase, as indicated by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) measurements [15]. It has been shown experimentally that high V_{oc}s can be maintained with a thinner buffer layer (20–30nm) than with standard CBD-CdS layers (40–50nm) [6,10]. A thinner CdS layer improves J_{sc}, since parasitic absorption is reduced. The surface adjustment induced by PDT also increases V_{oc} for Cd-free buffer layers, such as CBD-Zn(O,S) [15].

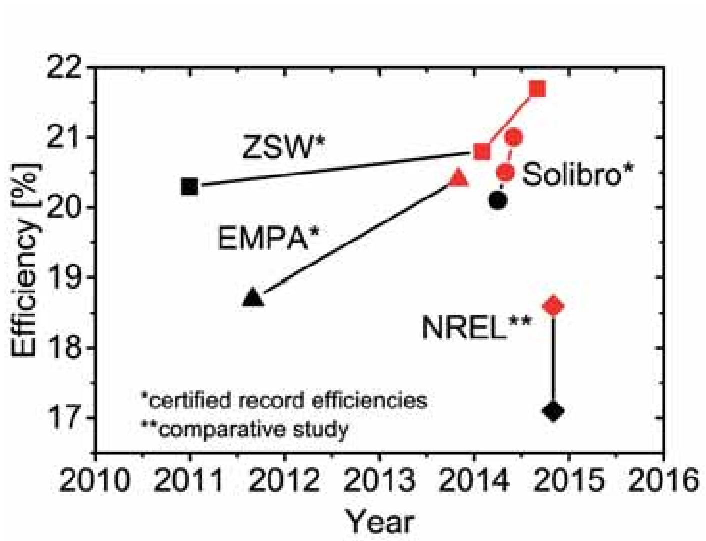


Figure 5. Evolutions of record cell efficiencies from ZSW (squares) [7,10,11], Solibro (circles) [8,9,16] and EMPA (triangles) [6,17]. Red symbols indicate the use of an alkali PDT. The data from NREL (diamonds) are from a comparative study about the effectiveness of an alkali PDT on sequential CIGS absorber layers [18].

Comparison of ZSW device parameters

Fig. 4 shows average device parameters (efficiency and V_{oc}) for an ensemble of about 50 CIGS cells which were deposited by a multistage process under very similar conditions, except that approximately one-half received ZSW's alkali PDT, whereas the other half did not. The complete layer sequence was soda-lime glass/Mo/CIGS/CdS/i-ZnO/ZnO:Al/grid. The cell size was ~0.5cm^2, as defined by mechanical scribing. No anti-reflection coating was applied.

As expected, with PDT the efficiency and V_{oc} increased by ~1.3% abs. and ~50mV respectively; the gain in V_{oc} can be clearly attributed to the alkali

PDT. No significant changes in FF as a result of PDT were observed and the corresponding plot is omitted. J_{sc} was also similar for all samples, since the thickness of the CdS layer was kept constant in this comparative study, as mentioned above.

Impact on other CIGS deposition technologies

The evolutions of certified record efficiencies from ZSW, EMPA and Solibro are shown in Fig. 5. Red and black symbols indicate respectively the implementation of alkali PDT or no implementation. ZSW [7,10,11] and Solibro [8,9,16] both use a high-temperature co-evaporation process on glass substrates, whereas EMPA employs a low-temperature co-evaporation process on flexible substrates [6,17].

The results from a comparative study by NREL for a sequential selenization process on glass substrates are also included in Fig. 5 [18]. Remarkably, an efficiency improvement due to PDT was observed even when the CIGS layer was stored in dry nitrogen for two months after deposition (not shown). It is evident that all mentioned CIGS deposition technologies benefit from the alkali PDT.

No data of the effect of alkali PDT upon sulphur-containing, sequentially processed $Cu(In,Ga)(S,Se)_2$ (CIGSSe) absorbers have so far been published. Many commercially available modules from, for example, Avancis, Solar Frontier and TSMC possess a gallium-poor and sulphur-rich surface by using a combination of selenization and sulphurization step. It is not clear how an alkali PDT affects this surface and whether or not it is beneficial.

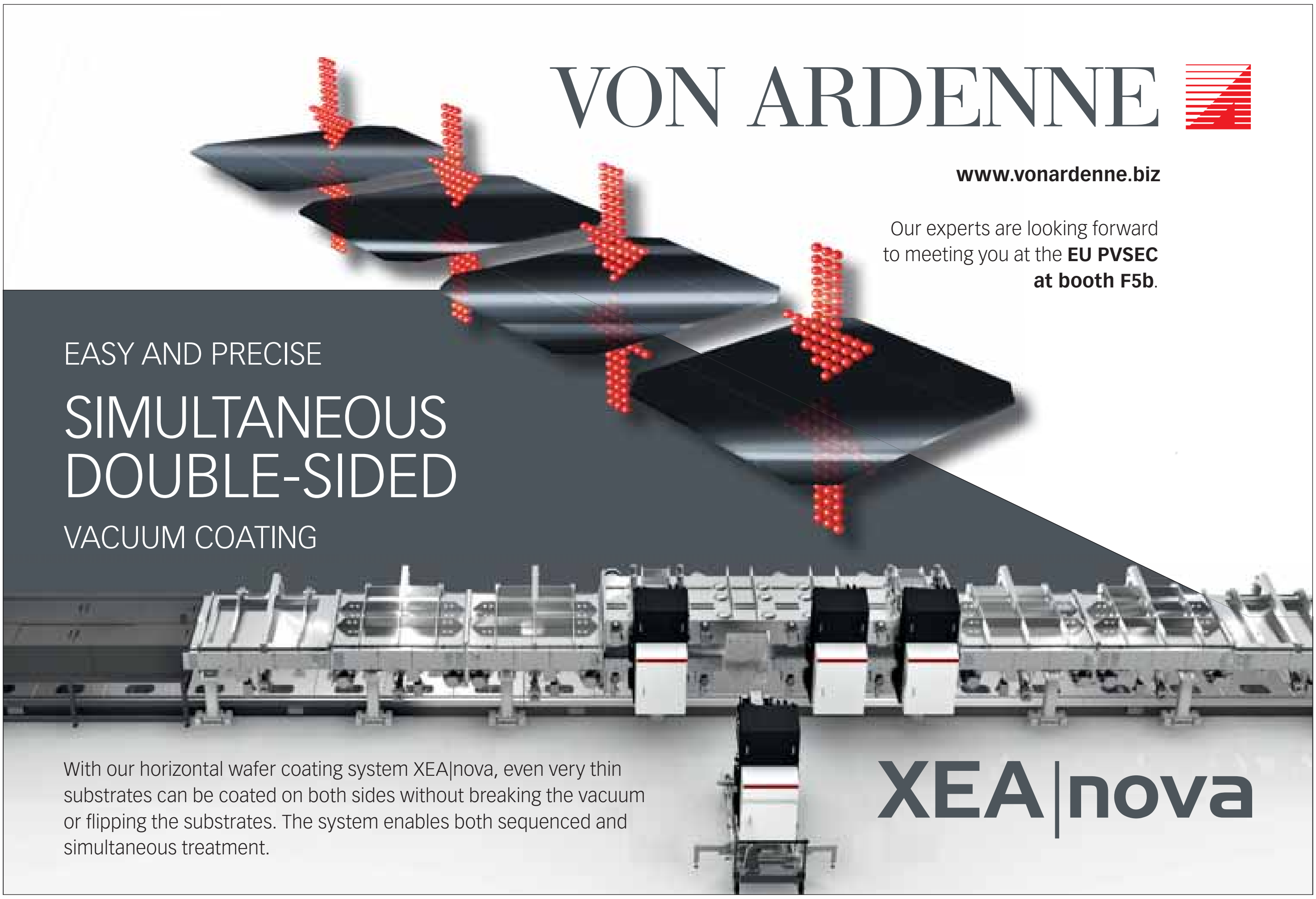
Future potentials

At the laboratory level, the 21.7% CIGS cell efficiency already exceeds the record of 20.4% for polycrystalline Si wafer-based cells [19]. The high V_{oc}s of 740–750mV are even on a par with the currently best monocrystalline-Si-based cells from Panasonic (heterojunction with intrinsic thin layer – HIT) [20]. Thus, a similar low V_{oc} temperature coefficient is also expected, since the band gaps of Si and CIGS are comparable. Two potential directions to take to further close the efficiency gap with Si technology are pointed out in the following sections. Since Si solar cells have had a 'head start' compared with the much younger CIGS technology, the authors are confident that it is only a matter of time before CIGS catches up.

The buffer layer

As regards the photocurrent of CIGS solar cells, the potential for improvement still exists. The reduced QE below 500nm for the 21.7% cell in Fig. 6 is due to absorption inside the thin CdS buffer layer. To minimize the loss, the goal of many research efforts has been to replace this layer by a Cd-free alternative with a higher band gap. Up until now, efficiencies for different kinds of alternative buffer layer (Zn(O,S), In_2S_3, etc.) have not been able to keep up with record devices employing CdS from a CBD process.

When ZSW's PDT-optimized CIGS was combined with a solution-grown Zn(O,S) buffer layer, a certified cell efficiency of 21% was achieved [15]. This result is the current world record for Cd-free buffer layers and reduces the gap towards CIGS with CBD-CdS to just 0.7% abs. The certified QE curve of this cell is shown in Fig. 6 and compared with the QE of the 21.7%



cell. The gain in photocurrent below 500nm is evident but is partly offset by losses in the visible region. The authors are confident that these losses can be further minimized (for example by adjustments in the anti-reflection coating), and thus the efficiencies will come to match, or even exceed, CdS-buffer-based record efficiencies.

Grain boundaries

Another potential source of improvement may be to minimize the polycrystalline structure and the resultant grain boundaries of the CIGS absorber. The SEM cross-section in Fig. 7 shows a remarkable density of grain boundaries perpendicular to the current flow and many different grain sizes (~0.5–2µm). However, they cannot be critical, as this image was taken from the 21.7% record cell. Further passivation of these grain boundaries or the growth of larger grains together with back surface passivation layers could lead to an improved diffusion length and corresponding current collection, especially in the long wavelength region; this would generate a more rectangular shape of the QE curve around 1000nm (see Fig. 6).

> "All CIGS deposition technologies benefit from the alkali PDT."

Summary

In this paper the technological advances that led to the current CIGS solar cell world record of 21.7% efficiency have been summarized. The direct beneficial effect of PDT on V_{oc}, and also the indirect improvement of J_{sc}, have been explained. The former was demonstrated by a comparative study of ZSW cells from the same CIGS run, either with or without PDT. Except for sulphur-containing absorbers, where no data are available, all CIGS deposition technologies benefit from the alkali PDT. Current advances with Cd-free devices yielding almost the same efficiencies as CIGS cells with CdS buffer layers, as well as further passivating grain boundaries and the back surface, are potential routes to meeting ZSW's efficiency goal of 25% in the near future.

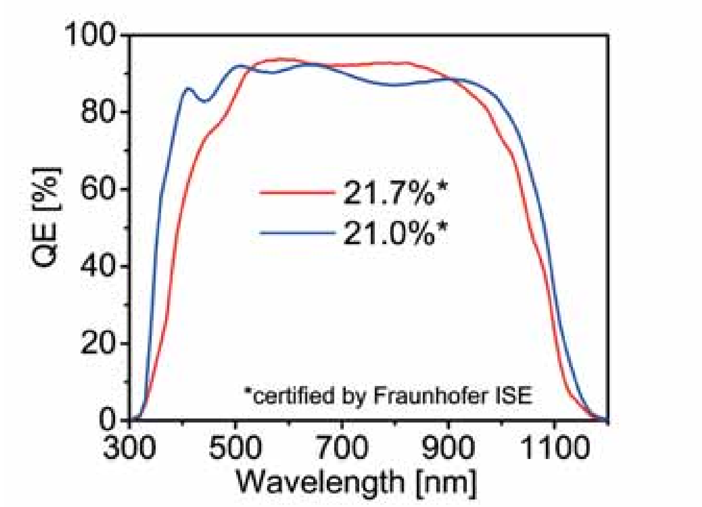


Figure 6. Certified QE curves of the 21% Cd-free world-record cell [15] compared with the 21.7% world-record cell with a CdS buffer layer [10]. Parasitic light absorption below 500nm has been reduced as a result of a CBD-Zn(O,S) buffer layer. In both cases, CIGS films had an alkali PDT.

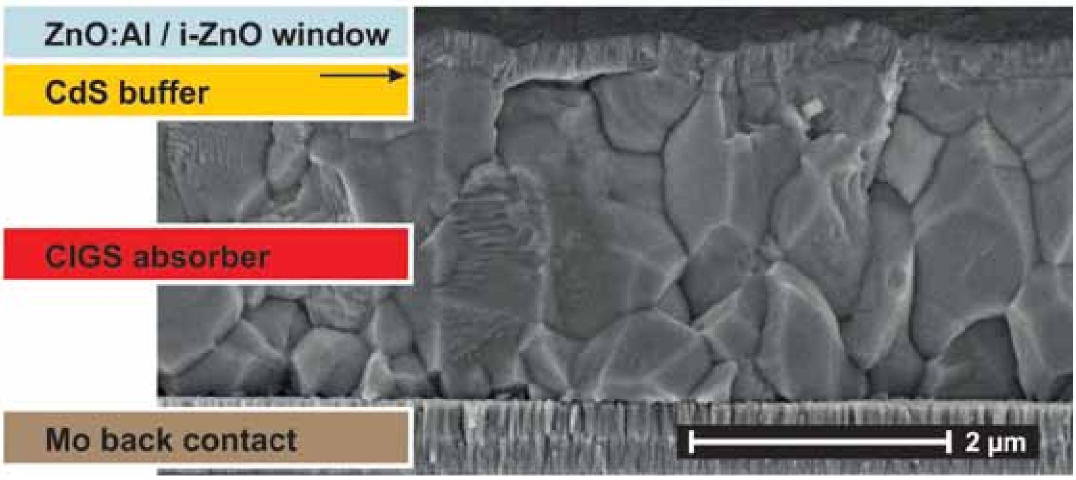


Figure 7. SEM cross-section image of the 21.7% CIGS record cell. The ZnO:Al / i-ZnO, CIGS and Mo layers (from top to bottom) are visible (the CdS buffer layer is too thin to be observed). The remarkable density of grain boundaries leaves room for improvement (CIGS grain boundaries perpendicular to the current flow, if not sufficiently passivated, are potentially detrimental to current collection).

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Philip Jackson studied physics at the University of Tübingen. For the past 13 years he has worked as a research scientist on Cu(In,Ga)Se_2 solar cells, both at the Institute for Physical Electronics (IPE), University of Stuttgart, and at ZSW in Stuttgart.

Dr. Dimitrios Hariskos received his diploma in chemistry from RWTH Aachen University and his Ph.D. from the Technical University of Darmstadt. He has been a researcher at ZSW in Stuttgart since 1998, and has worked on the up-scaling of CIGS technology from small-area cells to full-size commercial modules. His research interests focus on the development of high-efficiency Cd-free CIGS devices.

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Fabrication of high-power CIGS modules by two-stage processing, and analysis of the manufacturing cost

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ABSTRACT

Of the various copper indium gallium diselenide (CIGS)-formation processes, a so-called 'two-stage process', consisting of sputtering and selenization, has been successfully applied in large-scale production thanks to its stable process scheme and high-fidelity production equipment. A CIGS module with a power of 231W, corresponding to a total area-based efficiency of 16% for 902mm × 1,602mm, was demonstrated when this two-stage process was employed in a pilot production line at Samsung (although all the technology concerning CIGS production has now been transferred to Wonik IPS, whose main business is to provide production equipment for the semiconductor and display industry). The high-power module suggests significant potential for CIGS modules to compete with multicrystalline Si modules in terms of both cost and performance. This paper addresses the important process technologies for achieving high efficiency on large-area substrates, and presents a cost analysis using the data obtained from the operation of the pilot production line. As a result of the synergistic effect of low material cost and high efficiency of the two-stage process, the CIGS manufacturing cost is expected to be reduced to US$0.34/W.

Introduction

Owing to the rapid cost reduction in the production of crystalline silicon (c-Si) PV modules, the thin-film PV industry has unexpectedly been adversely affected. At the moment, US$1/W is the target system cost for c-Si PV systems. Copper indium gallium diselenide (CIGS) is the only thin-film module technology that is expected to supersede c-Si in the near future.

In recent years there has been considerable progress in the performance of CIGS thin-film solar cells: cells of this type with power conversion efficiencies of almost 14% have been commercialized in the PV market [1]. Moreover, CIGS systems are among the most promising absorber materials for the fabrication of low-cost solar cells. The highest efficiencies reported thus far have already exceeded those of polycrystalline Si-based solar cells, while pioneering research groups and industries are striving to further increase the efficiencies by employing various alternative substrates [2–4].

There are two conventional methods for creating CIGS absorber layers:

1. The simultaneous evaporation of metallic elements in the presence of vaporized selenium (co-evaporation).

2. Heat treatment of metal precursors in H_2Se gas (two-step process) [5–7].

A large number of studies have focused on the formation of CIGS absorber layers by the co-evaporation process; the best efficiencies have always been reported for cells fabricated that way. On the other hand, several studies on CIGS absorber layers fabricated via the two-step approach have been carried out by various industries, in particular the Institute of Energy Conversion (IEC) at the University of Delaware, with the aim of commercializing this method.

"With the two-step process, total area efficiencies of 17.9% and 16% for modules of 300mm × 300mm and 902mm × 1,602mm respectively have been achieved at Samsung's pilot line."

The two-step process has been under development for seven years at Korea University and Samsung/Wonik IPS for application to large-area modules. The large-area equipment for the production processes was designed and manufactured in collaboration with equipment providers. With the two-step process, total area efficiencies of 17.9% and 16% for modules of 300mm × 300mm and 902mm × 1,602mm respectively have been achieved at Samsung's pilot line; this excellent module performance is due to the synergistic effect of the high-efficiency process technology and the capability of large-area processing [8].

Despite the rapid progress in the performance of the two-stage process, no detailed cost analysis has been reported so far. The authors therefore

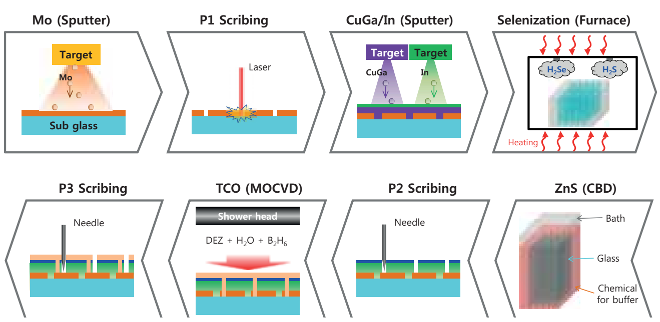

Figure 1. Process flow for CIGS module production using the two-stage process.

recently conducted an analysis of the CIGS manufacturing cost using the accumulated data from the pilot line at Samsung; the results are presented in this paper. Besides the evaluation of the cost-effectiveness of CIGS modules, the various cost elements of CIGS PV modules are broken down in detail, and the possibility of utilizing technological improvements for further cost reduction in the manufacturing process are highlighted.

Materials and methods

The key steps for CIGS module production by the two-stage process are shown in Fig. 1. For a monolithically integrated module, the Mo layer is scribed with a high-power laser (P1) after deposition of the Mo back electrode by the sputtering method. The width of the P1 scribing is optimized according to the desired current density and the thickness and quality of the transparent conducting oxide (TCO) layer.

After the Cu–Ga/In precursors are deposited on the P1-scribed Mo layers, CIGS absorber layers with a thickness of ~1.6µm are formed via the reaction of the precursors with H_2Se and H_2S gases. The element sodium (Na) is essential for high-performance CIGS solar cells and its quantity should be carefully controlled. The amount of Na from the glass substrates can be controlled by employing SiO_2 as the barrier layer before sputtering the Mo back contact, or by the sodium-containing Cu–Ga (Cu–Ga:Na) layer deposited on the Mo back contact.

The thickness and deposition conditions of the precursor layers are freely modified by the glass transfer speed, plasma power and pressure of the Ar gas. The reaction process is optimized with respect to temperature and time range. To induce the reaction process, the chamber is heated to 480–500°C and filled with H_2Se/N_2 gas. The first selenization step is then carried out for 25–35min. In the second step, the selenized film is exposed to H_2S/N_2 gas at 550–600°C for 60–90min. The chamber is cooled down to 300–350°C under a H_2S/N_2 atmosphere, and then purged with N_2 gas. The reaction takes place in a specially designed reaction chamber that can endure the highly corrosive H_2Se gas environment.

The buffer layer, used to reduce the number of shunt paths and to increase the interface quality, is grown on the absorber layer by a chemical bath deposition (CBD) process. The Zn(OH,O,S)-based buffer layer is deposited onto the CIGS absorber layer using $ZnSO_4$, NH_4OH and thiourea (CH_4N_2S) as sources in deionized (DI) water. Pre-rinsing is done using DI water at room temperature. The buffer layer is grown at the deposition-bath temperature of 60°C; its thickness is about 3–5nm.

The openings for the series connections between the unit cells separated by P1 are formed by mechanical scribing (P2). The gap between P1 and P2 is minimized to reduce the percentage of dead area within the total module area.

Boron-doped ZnO (BZO) is used as the TCO layer, deposited by low-pressure metal–organic chemical vapour deposition (MOCVD). The thickness and sheet resistance of the TCO layer are 950nm and 11–13Ω/sq. respectively.

The next step, for separating the unit cells, is done by the mechanical scribing process P3. After the P3 step, the Mo/CIGS/buffer/TCO multilayer films are removed along the glass edges to electrically isolate the active cell regions from the outside and to ensure hermetic sealing of the module. This process is called *edge deletion* or *edge trimming*; typically, the width of the deleted border is 8–9mm.

Electrical contacts are created by charge-collection tape (CCT) between the first and the last cell. The specific contact resistance between CCT and $MoSe_2$/Mo was calculated from transmission line measurements (TLM) to be much lower than 10mΩ·cm^2.

Hot, molten butyl sealant is dispensed around the glass edge for sealing, before the lamination process is carried out at 155°C for 18–20min. The EVA (film using evaporated a-Si) used in this process is a commercially available standard fast-cure EVA film. The gel-content test is the most appropriate method for measuring the percentage of cured EVA; the value of the gel percentage was in the range of 85–92%.

Finally, the junction box and rails are attached to the back side of the substrates using adhesive. The junction box enables a module to be electrically connected to other modules.

Fig. 2 shows a completed CIGS module (left) using this process, along with a conventional c-Si module (right). It is noted that the frameless modules passed the standards IEC 61646 ('Design qualification and type approval') and IEC 61730 ('Photovoltaic (PV) module safety qualification').

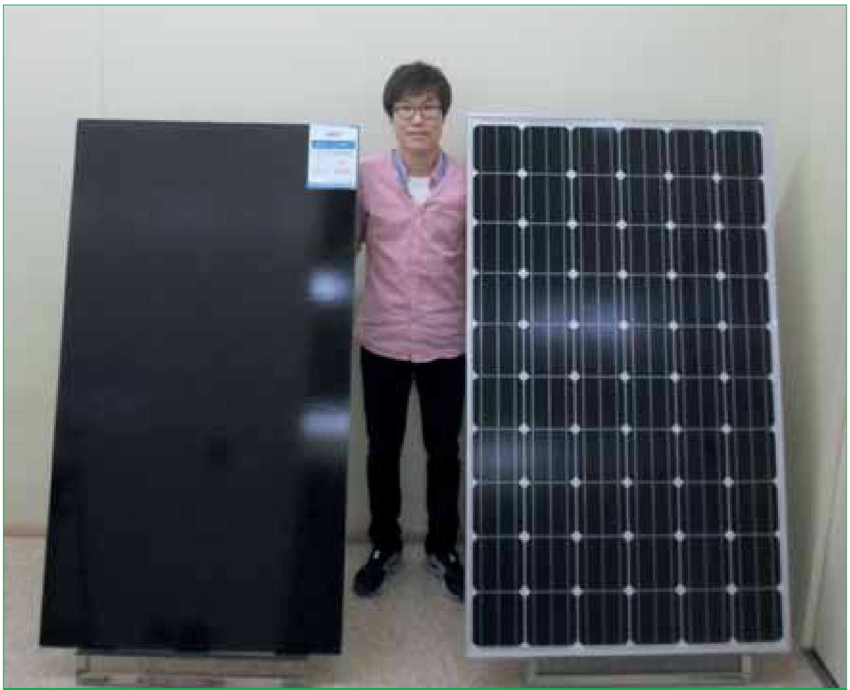

Figure 2. The CIGS module (left) fabricated at Samsung SDI in collaboration with Wonik IPS, and the c-Si module (right).

Development history

Fig. 3 shows the performance history of CIGS modules developed at Samsung, along with the *I–V* characteristics measured at TÜV Rheinland, Germany, in the case of a 902mm × 1,602mm module. All processing steps have been optimized to maximize the module output power, as well as to satisfy reliability requirements. After the development of small cells of 5mm × 5mm in 2008, the module size was gradually increased to 300mm × 300mm in the first pilot line.

Thin Film

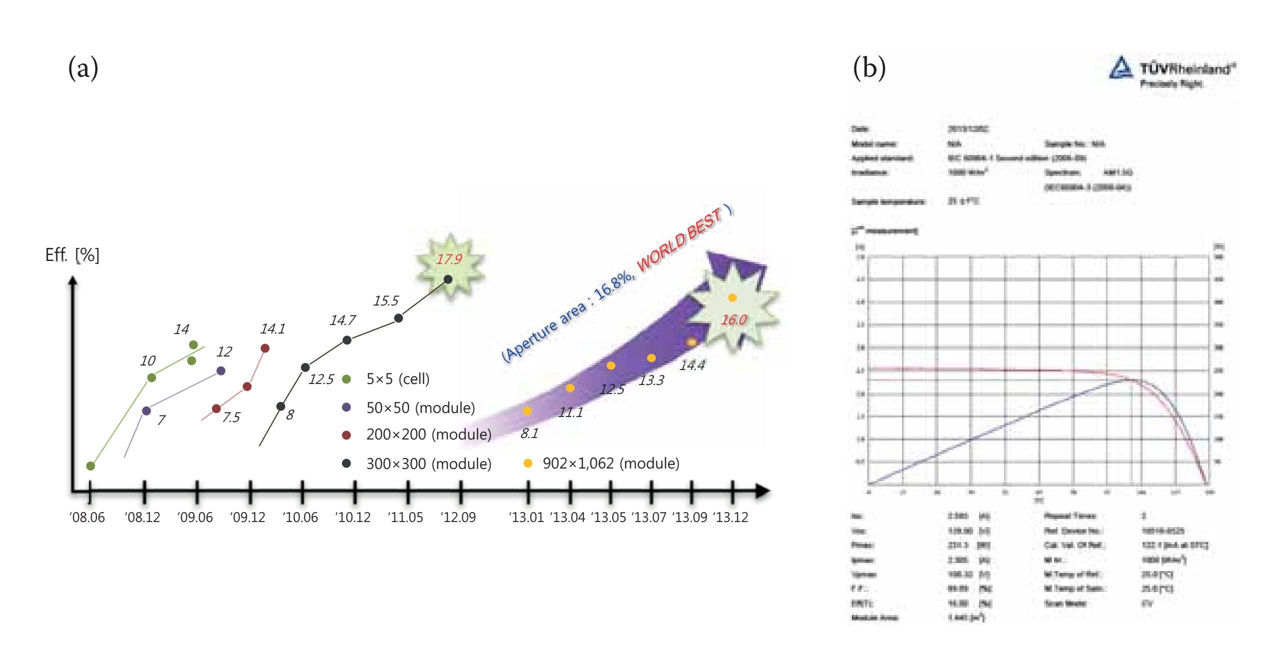

Figure 3. (a) History of efficiency improvements – small cells (5×5) to large-area modules (902×1,602). (b) The performance certification from TÜV Rheinland, Germany (902×1,602).

"It is encouraging that it was possible to enhance module efficiency from 8.1% to 16.0% within one year."

Following the achievement of a maximum module efficiency of 17.9% with 300mm × 300mm modules, a second pilot line was established to develop large-area modules of size 902mm × 1,602mm. The width and length of the modules were decided by taking into account factors such as the balance of system (BOS) cost, mechanical strength, weight and compatibility with c-Si modules.

All the tools for the second pilot line were designed to handle 1.8-mm thick, 902mm × 1,602mm glass substrates and to conduct uniform and reproducible processes. The specifications of the process tools were decided with the aim of achieving processing conditions similar to those developed for the first pilot line. Most of the key process tools – including the sputter system for the Cu/Ga and In precursors, the selenization furnace, the MOCVD system and the CBD system – were constructed in order to evaluate their suitability for a 200MW production capacity.

Fig. 4 shows the set-up of the four main process tools in the pilot production line for large-area CIGS modules. It is encouraging that it was possible to enhance module efficiency from 8.1% to 16.0% (Fig. 3(a)) within one year for a glass size comparable to that of a crystalline module. The rapid progress in efficiency enhancement of the large-area modules indicates that the two-stage process is favourable for increasing the substrate size and matching the parameters of different process tools.

Results and discussion

Analysis of the CIGS production cost

For the manufacturing-cost analysis of the CIGS modules, every input item of the cost-analysis template used previously for determining the manufacturing cost of crystalline silicon cells at Samsung was upgraded. A detailed analysis was conducted of the manufacturing costs on the basis of the data acquired from the operation of the CIGS pilot line for a period of more than a year. Material costs and capital expenditure for the equipment were aggregated using the data provided by the material and equipment suppliers. Cost calculations were performed for a three-year period and based on forecast technology improvements.

The basic assumptions for the manufacturing cost calculations were as follows:

- Module efficiencies are 15.2%, 15.9% and 16.3% in 2015, 2016 and 2017 respectively.
- The thickness of the absorber layer is 1.6µm until 2016 and then reduces to 1.3µm in 2017.
- The yields in module manufacturing remain constant at 97%.
- Plant utilization is 90%.
- The location of the production site is in China.
- The 1GW plants produce 5.5, 5.6 and 5.7 million modules a year in 2015, 2016 and 2017 respectively.
- The module structure is glass-to-glass without a frame. Four aluminium rails are attached onto the back side of the modules for installation.
- The depreciation period is assumed to be seven years for the cell-production equipment, and ten years for the module-production equipment and the entire plant, corresponding to the assumptions used for the Greentech Media report [9].

"The production of CIGS seems to be feasible below $0.4/W from Q4 2016 onwards, while mc-Si might still stay above $0.40/W."

Comparison with the production cost of multicrystalline Si modules

Table 1 shows the CIGS cell-to-module manufacturing cost per watt for the next three years (Q4 2015–Q4 2017). It is assumed that multicrystalline Si modules are produced through the procurement of wafers and the manufacturing process of cells and modules. The *CIGS cell process* is defined as all the process steps starting from substrate cleaning and finishing with P3 scribing, so that

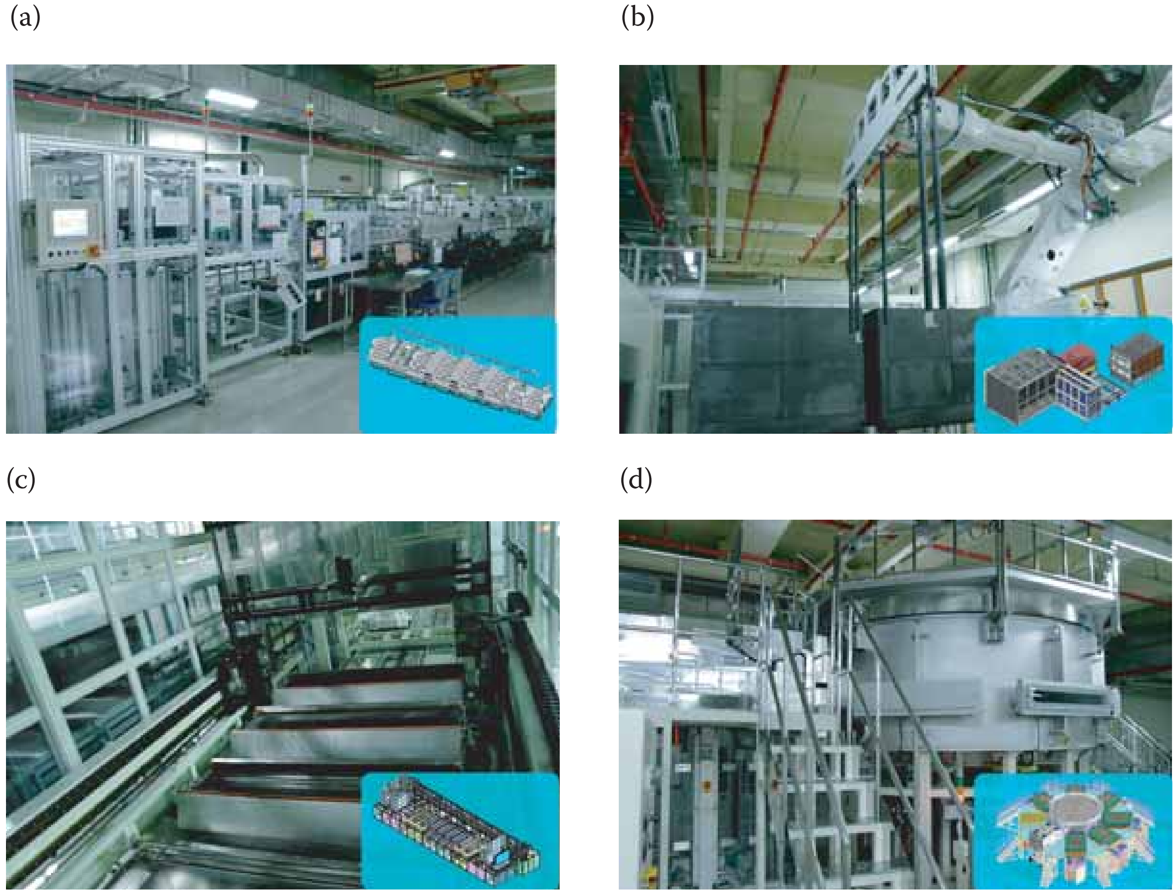
(a) (b) (c) (d)

Figure 4. Set-up of the main process tools in the pilot production line for large-area CIGS modules: (a) sputter system for Mo deposition; (b) selenization furnace; (c) CBD system; and (d) MOCVD system.

comparisons with the silicon-cell process can be made; however, there is no clear separation between cell and module in the case of CIGS.

The cost is broken down into six components: material cost in the cell process (such as substrate glass, target and H_2Se for the CIGS production), material cost in the module process (such as cover glass, junction box and EVA), capital (depreciation), labour, utilities and yield loss. As a result, the unit cost of CIGS in Q4 2015 is $0.404/W, which is about 13% less than in the case of mc-Si ($0.465/W). The cost gap between CIGS and mc-Si will increase over one year: the cost ratio of CIGS to mc-Si is expected to be 83% in Q4 2016 and 79% in Q4 2017. The production of CIGS seems to be feasible below $0.4/W from Q4 2016 onwards, while mc-Si might still stay above $0.40/W.

Cost element	Q4 2015E [$/W]	Q4 2016E [$/W]	Q4 2017E [$/W]
Materials (cell)	0.133	0.119	0.104
Materials (ex-cell)	0.109	0.101	0.095
Depreciation	0.088	0.072	0.063
Labour	0.010	0.010	0.010
Utilities	0.045	0.052	0.051
Yield loss	0.019	0.018	0.017
Total cost	0.404	0.372	0.340

Table 1. Estimated cell-to-module manufacturing cost ($/W) of CIGS, broken down according to the individual cost elements.

Cost element	Q4 2015E [%]	Q4 2016E [%]	Q4 2017E [%]
Materials (cell)	32.80	31.95	30.64
Materials (ex-cell)	27.03	27.10	27.92
Depreciation	21.80	19.42	18.49
Labour	2.58	2.81	3.06
Utilities	11.13	13.98	14.97
Yield loss	4.66	4.74	4.92

Table 2. Estimated percentage cell-to-module manufacturing cost of CIGS, broken down according to the individual cost elements.

The material costs account for 58–60% in CIGS (see Table 2), whereas they are forecast to be well above 80% in mc-Si for the next three years. A significant portion of the materials cost is substrate glass, cover glass, target, junction box and H_2Se gas. It appears that the operating rate of the glass-production capacity could have a significant impact on the substrate-glass price. Current worldwide CIGS production is not sufficient to consume all the substrate glass from a single glass-production line of 70,000 tons/year. Even though mc-Si owes its high ratio of material cost to the assumption of procuring wafers, it is obvious that mc-Si has a much higher share of material cost than CIGS.

CIGS requires much more intensive capital and slightly less intensive labour than crystalline Si. The CIGS production line has precursor deposition and selenization equipment for the absorber layer, whereas silicon-based cell and module manufacturers purchase the silicon wafers that correspond to the CIGS absorber layer. The depreciation expense in CIGS is therefore higher than in mc-Si, making up to 18–22% of the total manufacturing cost. The depreciation ratio in CIGS is expected to gradually decrease to 19.42% in 2016 and to 18.49% in 2017 due to economies of scale.

The lower labour cost of CIGS is attributed to the large-area, automated production. For example, labour-intensive processes, such as interconnection and lay-up in the case of crystalline silicon modules, can be carried out by the fully automated system in the CIGS production line. The labour-portion cost in CIGS is therefore lower than in mc-Si, constituting 2–3% of the total manufacturing cost.

Electricity constitutes the biggest utility-cost portion because of the CIGS formation process, which includes precursor deposition and annealing. The second-largest factor is nitrogen gas, related to the operation of vacuum equipment.

Greentech Media [9] states that the decrease in silicon price and the increase in module efficiency have significantly contributed to the fall in the manufacturing costs of silicon-based modules. It was found that efficiency improvement is also one of the biggest cost-reduction factors for CIGS. From the authors' internal model calculations regarding efficiency improvement, it seems that cell efficiency can be increased to 17% without major changes in cell architecture. It is interesting to note that the production cost structure of CIGS is quite similar to that of LCDs (liquid crystal displays). Considering that LCD TV prices have dropped to one-fifth in 10 years, it is expected that the CIGS module manufacturing cost could be reduced to half of the authors' estimated cost within five years, if the industry could enjoy the benefit of 'economy of scale', as experienced in the display industry.

Conclusions

Because CIGS development has been pushed forward to the manufacturing level, a few equipment players, such as Wonik IPS, will have turnkey business, leveraging the equipment and manufacturing technology from universities and institutes. The turnkey Si providers have contributed to reducing the module manufacturing cost by propagating and standardizing screen-printing manufacturing technology. In this way they could reduce the entrance barriers to cell- and module-manufacturing businesses, and induce technology improvements, by supplying a new technology to the manufacturers through linking the R&D accomplishments from institutes or universities to the manufacturing companies. Unlike in the crystalline Si industry, although many different CIGS production technologies have been tried, only Solar Frontier has successfully entered the GW production scale employing the two-stage process, by overcoming problematic issues, such as low yield, low power, low efficiency and high manufacturing cost.

> "The manufacturing cost of CIGS has the potential to be reduced to far below that of multicrystalline Si."

As discussed in this paper, the performance of CIGS modules is approaching that of multicrystalline Si, and the manufacturing cost of CIGS has the potential to be reduced to far below that of multicrystalline Si. If a few more companies join the CIGS business and start production on a GW scale, the benefit from 'economy of scale' will contribute to cost reduction throughout the CIGS supply chain, resulting in a boom in the CIGS industry similar to that experienced in the crystalline Si industry during the last few decades.

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Mr. Jeong Min Lee received his master's in engineering in 2006 from Korea Aerospace University, majoring in MOSFET (metal gate and dielectrics) technology. In 2010 he joined Wonik IPS, where he has worked on R&D in PECVD, ion implantation for crystalline solar cells, and MOCVD for CIGS. He is currently involved with business planning and cost analysis for CIGS.

Dr. Dong Seop Kim received his Ph.D. on CdS/CdTe solar cells from KAIST in 1994, and has more than 26 years' experience in both academia and industry with regard to PV research, including Cu(InGa)Se_2, crystalline silicon and CdTe. He worked on CIGS and c-Si solar cell development as director of the PV R&D team at Samsung SDI for seven years, and recently joined Wonik IPS, where he leads the CIGS development and turnkey business.

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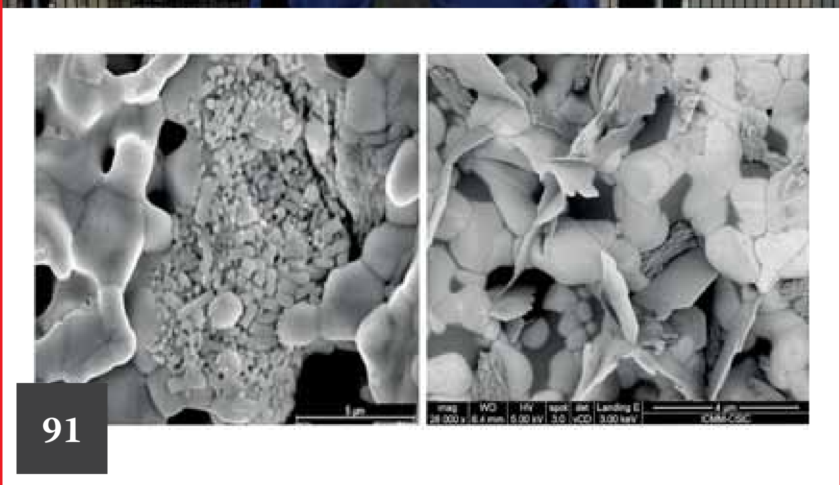
PV Modules



News

No clear winners in revised US-China solar duties

Source: SolarWorld

SolarWorld has welcomed changes to US duties on Chinese solar imports, though some companies appear to have benefited.

Revised US trade duties on Chinese solar panels have created further ambiguity with SolarWorld welcoming the changes, even though the world's top two producers appear to have benefitted from the changes.

The review of the 2012 tariffs increased the countervailing duties (CVD) to 20.9%. For many tier-one manufacturers, this increase was wiped out by decreases in the anti-dumping rates.

The 2012 case deals with modules classed as Chinese while the 2014 case targets Chinese modules with Taiwanese cells. Any imported module is subject to one or the other set of tariffs.

An investor note circulated by Deutsche Bank analyst Vishal Shah said the new changes to the 2012 duties were unlikely to impact Chinese firms' pricing in the US.

"We view this development as a positive for the Chinese suppliers like Trina and Yingli. While the effect on market pricing is unlikely to be substantial (at most, a few cents likely), the Chinese should be able to achieve improved margins in the US market given strong demand trends at least through the end of 2016," he said.

Orders

First Solar to supply modules for 200MW ACWA Power and TSK plant in Dubai

First Solar has signed an agreement to supply modules for the 200MW second phase of the Mohammed bin Rashid Al Maktoum Solar Park in Dubai.

The plant will use 2.36 million First Solar modules over 450 hectares. The first 13MW phase of the park used 152,880 First Solar modules.

A consortium led by Saudi-based energy developer ACWA Power and Spanish engineering and construction company TSK was selected earlier this year by the Dubai Electricity and Water Authority (DEWA) to develop, construct, own and operate the IPP project. It won the tender process with a bid of US$0.0584/kWh, one of the lowest costs per unit of solar electricity ever. The consortium claimed this reduced the cost of solar electricity by over 20%.

Trina Solar reveals Malaysian OEM supplying 500MW of modules

Trina Solar has refuted reports that its manufacturing plans in Malaysia were opposed by government officials, but in the process revealed previously undisclosed details of the scale of its Malaysian OEM module deal.

Trina Solar's cooperation with a local Malaysian partner would result in 500MW of module capacity for the company and 400MW available, specifically in 2015.

Trina Solar has guided PV module shipments in 2015 of being in the range between 4.4GW to 4.6GW.

The company has guided capital expenditures in 2015 to be around US$370 million, up from only US$70 million actually spent in 2014.

Risen Energy to invest and supply modules to 118MW PV power plant in India

China-based PV manufacturer Risen Energy is to co-develop and finance a 118MW PV power plant in the Ramnad district of the state of Tamil Nadu, India, with Raasi Green Earth Energy (RGEE), part of diversified company, Raasi Group.

According to Risen Energy a memorandum of understanding signed to jointly invest and develop in the project is the "first majority direct and the largest foreign investment by a Chinese company, in the Indian solar PV market".

RGEE would however hold a 51% stake in the project and be responsible for land acquisition through to electricity sales agreements.Future joint PV power plants in Karnataka, Telun Gan Magne and Andhra Pradesh were being discussed.

Hanwha Q Cells to supply 70MW of solar modules to Adani Group

Tier-one PV manufacturer Hanwha Q CELLS has signed a 70MW module supply contract with Ramnad Solar, a subsidiary of Indian conglomerate Adani Group.

The modules will be installed in the state of Tamil Nadu. Construction will begin in October this year with completion expected by February 2016.

M.Y. Kim, seniour vice president of Hanwha Q CELLS in India said: "Hanwha Q CELLS is pleased to have partnered with Adani Group, one of India's major energy companies. Solar has received increased support from the government and India has now become one of the more interesting emerging markets."

Legal

Canada rubber stamps duties on Chinese solar

Trade duties on Chinese modules and cells have been approved by the Canadian International Trade Tribunal (CITT).

The tribunal found that there was a threat to the domestic solar industry but did not find evidence that they had "caused injury" to the sector thus far.

In March this year the Canadian Border Services Agency (CBSA) announced preliminary duties on Chinese manufacturers ranging from 9.1% to 286.1%.

Wuxi Suntech loses ZKenergy module court case

Module manufacturer Wuxi Suntech has lost a lawsuit filed by renewable energy developer ZKenergy in a dispute over a RMB206 million (US$33.17 million) sales contract.

ZKenergy filed the lawsuit in September last year, alleging that Wuxi Suntech failed to deliver a shipment of modules ordered by the firm.

ZKenergy requested that it be repaid the total amount paid under the contract and be liable for breaching the sales agreement. The Jiangsu Province Higher People's Court ruled in favour of ZKenergy and ordered Wuxi Suntech to repay the total RMB206 million plus interest and penalties for the period running 31 March to 31 December 2014 up to a total added sum of RMB30.9 million (US$4.9 million).

Court-appointed administrators see 'no future' for QSolar

Module manufacturer QSolar has "no viable go forward business plan", according to court-appointed directors in Canada.

The new board took control in April after trading in shares of the company was put on hold. The interim board will now resign. It emerged QSolar used fake TÜV SÜD certificates on some its products.

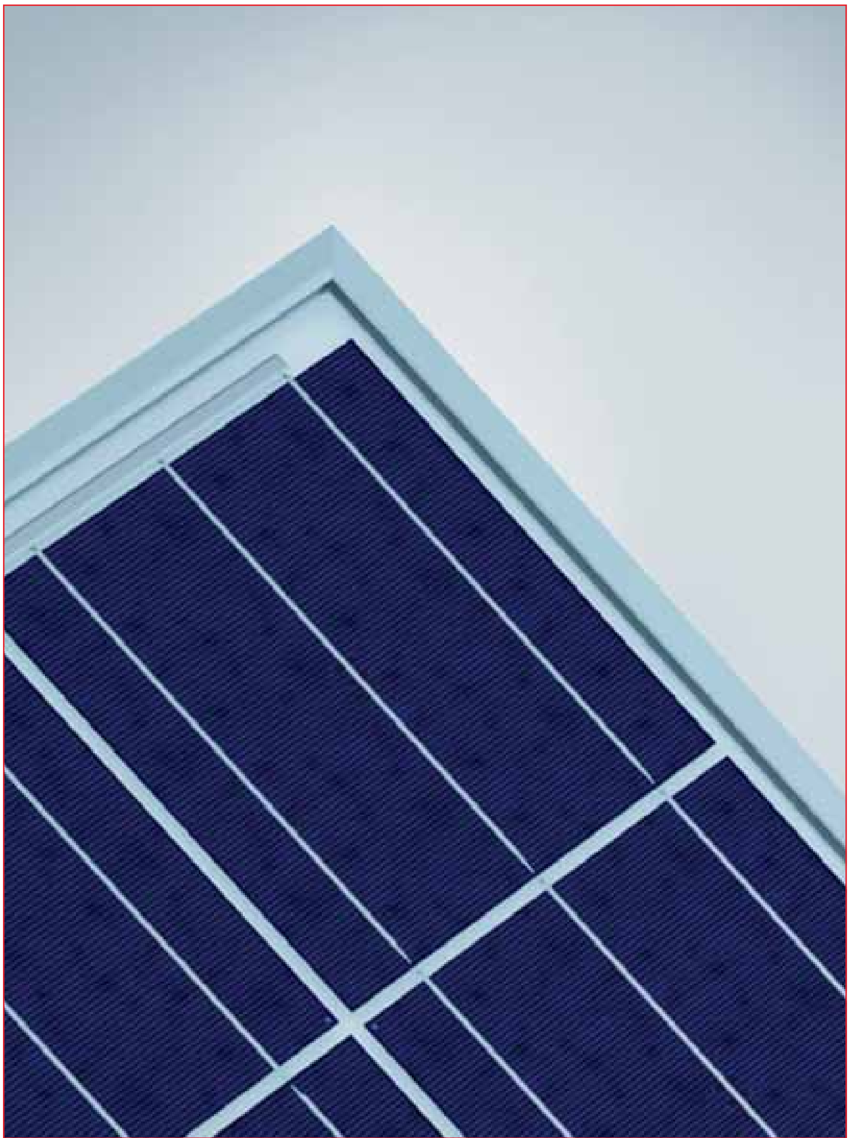
A bank of complaints from customers developed, with one customer sharing shared photos of a TÜV SÜD kite mark on the back of a badly degraded 175W module branded QSolar, and carrying a Calgary address.

Business and finance

Yingli Green receives official NYSE de-listing notice

Major tier-one PV manufacturer Yingli Green Energy has said it received an official notice from the NYSE on 13 August 2015 that it was not in compliance with the minimum US$1.0 share price threshold.

Yingli Green was at threat of receiving the de-listing notice after trading below the threshold for 30 consecutive trading days. Yingli Green expected to notify the NYSE of its intent to comply with the ruling within the six-month 'cure' period but did not state what the strategy would be.



Source: Hanwha Q CELLS

Hanwha Q CELLS is offering shares totalling US$500 million.

Shunfeng acquires majority stake in Suniva for US$57.8 million

Clean energy firm and PV developer Shunfeng International Clean Energy (SFCE) has acquired a majority stake (63.13%) in US-based solar cell and module manufacturer Suniva with an investment of US$57.76 million.

Shunfeng, which owns module manufacturer Wuxi Suntech, will make a cash contribution of US$12 million to Suniva with the remainder of the US$58 million to be settled through the issuance of more than 70 million shares. The cash and shares will be used for "US market expansion".

Shunfeng said the acquisition "could further strengthen the company's global position in high efficiency cells manufacturing at affordable costs, and more importantly enable the company to reap the huge potentials of the solar market in the United States".

Hanwha Q CELLS plans US$500 million share offering

Tier-one PV manufacturer Hanwha Q CELLS has issued a prospectus for offering American depositary shares (ADS) totalling a maximum of US$500 million.

The company recently issued plans to undertake a reverse stock split of its ADS shares. Hanwha Q CELLS said in the prospectus that the funds from the stock offering would be used for general corporate purposes.

Plans to build a 1.5GW solar cell facility in South Korea were also recently announced. However, Hanwha Group is providing the capital for the major capacity expansion via a wholly owned subsidiary.

SolarWorld buys back solar module line from JV partner

Integrated PV manufacturer SolarWorld has re-purchased a PV module assembly line from JV partner and major shareholder Qatar Solar Technologies (QST).

According to SolarWorld's first half year 2015 financial report, QST sold back to SolarWorld the assembly line for €1.3 million. The company did not say what the line capacity was of the repurchased equipment.

The company noted that it needed the production line due to increased demand for modules in the US. SolarWorld reported sales to the US in the first half of the year accounting for around 52% of total sales in the period.

Product Reviews

SPIRE

Spire's '5100SLP' sun simulator exceeds IEC 60904-9 Class AAA specifications

Product Outline: Spire Corporation has launched what it claims is a cost-competitive, high-performing PV module sun simulator system, the 'SPI-SUN SIMULATOR' 5100SLP.

Problem: Continued PV module cost reduction requirements, coupled to increased global production, has led to greater emphasis on cost-competitive, high-performing PV module sun simulator systems.

Solution: The SPI-SUN SIMULATOR 5100SLP is based on Spire's successful Single Long Pulse ("SLP") series. The system delivers better than Class A spectral/spatial/temporal performance in combination with superior measurement repeatability. The 5100SLP focuses on reducing the cost of ownership with a single lamp and small footprint design that integrates easily into any factory environment. A totally new approach to the internal optical design has resulted in improved optical efficiency without thermal problems or power limitations. The new optical design is also claimed to make the system well suited as a measurement instrument for leading national metrological and certification bodies and organizations with restricted budgets.

Applications: High-volume production testing of solar modules.

Platform: The 5100SLP exceeds IEC 60904-9 Class AAA specifications for irradiance spectrum, spatial uniformity and temporal stability. It provides better than Class A irradiance from 400nm-1100nm, which replicates true sunlight conditions and is critical for getting every watt out of high efficiency c-Si and thin-film modules.

Availability: Available since June 2015.

LUVATA

Luvata's 'Sunwire Calculator' online tools help PV module manufacturers optimize solar ribbon usage

Product Outline: Luvata has launched an online solar ribbon calculator called the Sunwire Calculator, enabling PV module manufacturers to make more informed decisions concerning their solar ribbon needs such as weight, ribbon length per spool and ribbon length per solar panel.

Problem: As PV module manufacturers look to reduce usage of silver paste in cell metallization, this can increase the number of interconnecting ribbons. This offers lower costs, while improving the efficiency of the solar cells. Understanding solar ribbon is critically important to solar module efficiency and lifecycle. Solar ribbon width and thickness have to be carefully adapted to accommodate the limitations of module materials. In addition, the yield strength, thickness and width of solar ribbon can directly influence production yields and decrease cell-to-module losses by 20-30%.

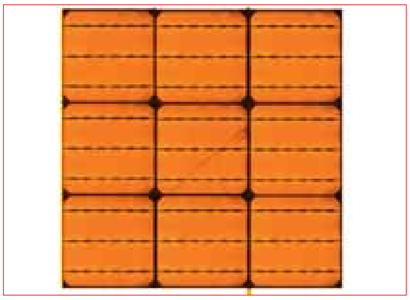
Solution: With the introduction of the Luvata Sunwire Calculator, PV module manufacturers can optimize the amount of Sunwire ribbon per spool to accommodate the speed of tabbing machines and shift changes. It provides the opportunity to further refine module materials and Sunwire ribbon for improved module efficiency and reduce overall material costs.

Applications: Online tool to optimize solar ribbon usage.

Platform: The Sunwire Calculator requires a few simple details to determine the solar ribbon weight, the ribbon length per spool and even the ribbon length per solar panel. The results are made available immediately and can be emailed directly to an email address.

Availability: Available since June 2015.

ISRA VISION



ISRA's PV module inspection tool suite provide 100% automatic defect classification

Product Outline: ISRA VISION/GP SOLAR are providing a suite of PV module inspection systems that can provide 100% automatic defect classification and help optimize costs throughout PV module production.

Problem: High-quality PV modules demand extremely accurate performance data while seeking the lowest possible production cost. Subsequently, the PV industry is looking for the highest possible throughput and reliability rates in module production. Quality inspection for process control, handling control and detection of defective parts are the keys to process optimization and cost efficient production.

Solution: Inspection solutions from ISRA VISION/GP SOLAR enable the detection of defective parts early in the process and enable rework in order to increase productivity, reduce the scrap rate and save costs. The MOD-Q EL (electroluminescence) inspection system is used on modules to show defective parts, process problems and indicate possible warranty issues.

Applications: PV module assembly inspection.

Platform: MOD-Q EL can be supplied in automatic or manual, inline or offline configurations with cycle times down to <30 sec for high throughput and resolutions down to <100 µm for detection of the smallest defects. MOD-Q VISION provides automatic optical inspection of modules at resolutions down to 25µm/pixel. ISRA's STRING-Q EL and EL + Vision inspect the soldering of the cells to strings, identifying common features such as breakage, misalignment, and bad contacts.

Availability: Available since June 2015.

Cell-to-module losses in standard crystalline PV modules – An industrial approach

Eduardo Forniés, Aurinka PV Group SL, Madrid, & **José Pedro Silva**, CIEMAT – División de Energías Renovables, Madrid, Spain

ABSTRACT

One of the main concerns of module manufacturers is the power loss that takes place when the solar cells are incorporated in PV modules. This power loss, known as *cell-to-module (CTM) loss*, results from the influence of many factors which occur during module production. Some of these factors lead to a gain in power at the end of the process; on the other hand, some are responsible for a loss of power and offset the positive effects of other ones, resulting in a net power loss. In this paper the CTM losses will be addressed from an industrial point of view and for standard crystalline PV modules. The focus will first be on some of the most frequent issues detected in production lines and their influence on module power loss. More extensive research is then carried out to arrive at an explanation of their origin. This paper describes some of the mentioned factors along with the different ways of detecting them.

Introduction

During the last few decades the producers of PV modules have reduced their costs, thus contributing to making PV energy a realistic option for obtaining not only clean but also profitable energy. This cost reduction has been addressed using different approaches: improving solar cell efficiencies, reducing material costs, optimizing production processes, etc. Among these, the reduction of the gap that exists between cell power and module power is being studied by many researchers; Haedrich et al. [1], in particular, have done an interesting overview of all of these investigations. The power gains and losses occurring in the module are classified as follows:

- **Optical losses:** due to glass reflection and absorption, encapsulant reflection and absorption [2], and shading of tabbing ribbon.
- **Optical gains:** due to refractive index matching between encapsulant and anti-reflection coating (ARC), and the back reflection of light rays from the fingers, tabbing ribbon, cell area and cell spacing area (backsheet reflection) [3,4].
- **Electrical losses:** due to an increase in series resistance (R_s) and contact resistance [5] generated from string formation and cable assembly.
- **Mismatch losses:** due to a scattering of the electrical parameters of solar cells [6,7].

This paper will focus on the causes of different events along the PV module

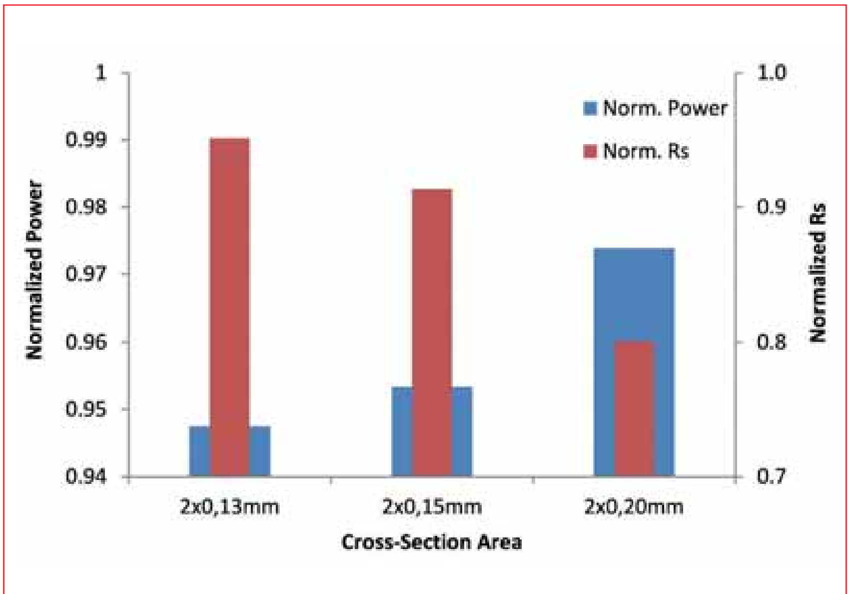


Figure 1. Module power and series resistance vs. tabbing ribbon thickness.

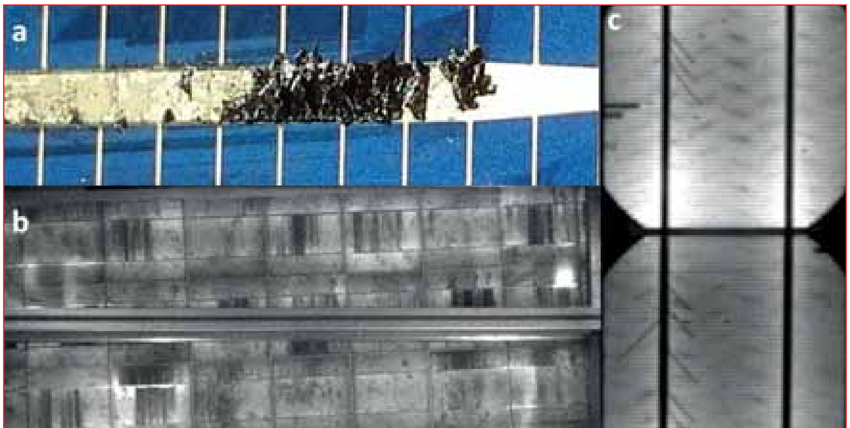


Figure 2. Effects of crystal damage: (a) view of the solar cells affected by crystal damage after the peeling test; b) EL image of a module with several cells affected by crystal damage; (c) V-shape breakage patterns of single-crystal solar cells, caused by shear stress after the soldering process.

production chain that give rise to CTM losses/gains and how they can be addressed.

"The reduction of the gap that exists between cell power and module power is being studied by many researchers."

CTM losses due to cell interconnection

Ribbon and cell design

In standard module manufacturing, once the solar cells have been classified they are soldered to make a series connection between them. This is performed by connecting the negative side of one cell with the positive side of the adjacent cell. For making that contact, a copper tabbing ribbon, coated with an alloy of Sn/Pb (or Ag/Sn/Pb), is used. There is a distinct increase in R_s because of the tabbing ribbon to cell interconnection process, but this resistance can be reduced by increasing either the number of busbars or the cross section of the tabbing ribbon.

Adding busbars

The addition of more busbars to the cells increases the number of collectors for current transport through the module, thus reducing the current density per busbar. Nowadays, for a 156mm × 156mm cell, the standard number of buses is three; however, some new technologies, which can achieve efficiencies of up to 19–22%, use a higher number of buses – in some cases up to five. New interconnection concepts, such as smart wiring, are being developed, but are not yet fully integrated in the industry.

Increasing the number of busbars introduces additional shadowing of the cell, consequently reducing the photogenerated current. This effect is minimized by a higher charge-carrier transport efficiency, as the charge carriers have to travel less distance through the cell to reach a collector, thus leading to a net increase in efficiency up to a point where the busbar shadowing predominates over the influence of current transport [8].

Increasing tab–ribbon cross section

Increasing the width of the tabbing ribbon [5] reduces the R_s of the module, but extends the shadow projected on the cell surface; the width can therefore be increased up to a certain point, always taking into consideration the width of the cell buses. The next option is to increase the thickness of the tabbing ribbon. In the last ten years the thickness has been increased from 0.12mm to 0.23mm (or higher), as the efficiency and size of the cells demanded a greater tabbing ribbon cross section to extract the maximum power available in the cells. Consequently, the power output of modules increased as a direct result of the reduction in R_s.

To clarify the influence of tabbing ribbon thickness on power output, 82 modules were manufactured with the

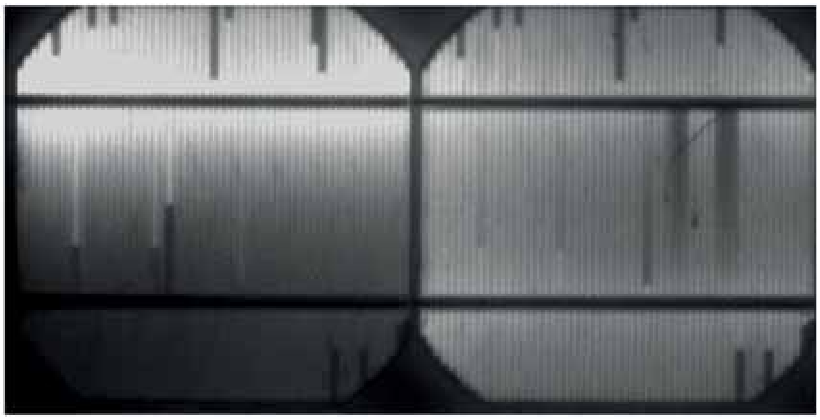


Figure 3. EL image of a module affected by an unsoldered tabbing ribbon – the cell affected is on the left side. The lower busbar is unsoldered and shows up as a dark busbar, whereas the upper busbar, which is forced to transport all the module current, appears brighter.

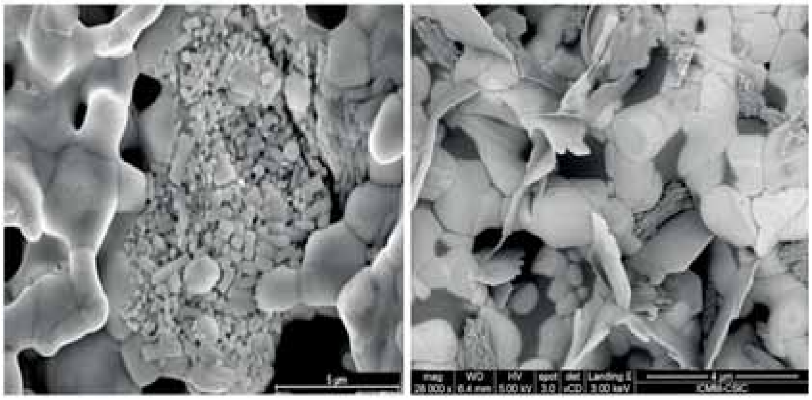


Figure 4. Scanning electron microscope (SEM) images of front busbars that presented adherence failure in the peel test. Formations different from those of a silver microstructure can be observed.

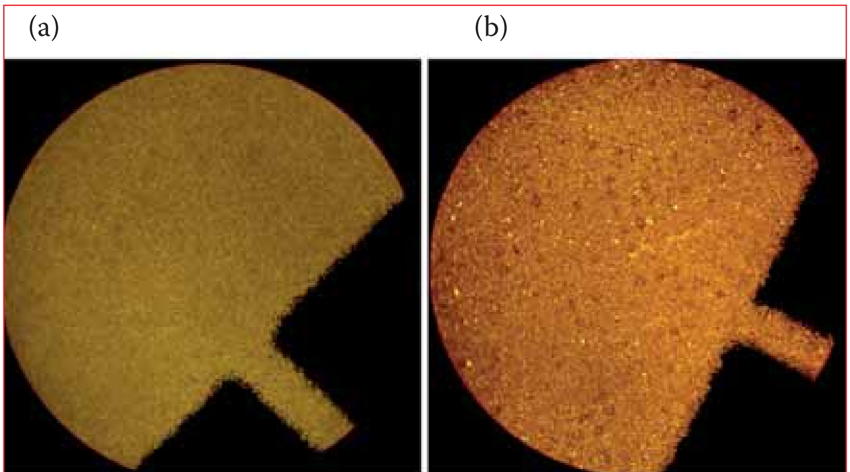


Figure 5. (a) Optical microscope image of a normal front busbar. (b) A front busbar affected by bright spots.

same materials and solar cells. Multicrystalline solar cells of dimension 156mm × 156mm and two busbars were assembled in a 10 × 6 configuration; the solar cell efficiency was the same for all the modules. Three different tabbing ribbon thicknesses were used in the experiment. Fig. 1 shows the average power and R_s of the modules: the average power has been normalized to the sum of the nominal power of 60 cells, and R_s has been normalized to the maximum R_s. An increase in module power inversely proportional to the series resistance was obtained experimentally.

The thickness of tabbing ribbon nevertheless has a direct influence on the silicon just below the bus: because of the different thermal expansion coefficients (TECs) of copper and silicon, breakages occur during the soldering process, leading to what is called *crystal damage*, as shown in Fig. 2(a). This defect can result in a serious lack of contact, which is exacerbated during thermal cycling once the module has been installed. If the crystal damage is extensive, it can easily be detected by electroluminescence (EL) imaging (Fig. 2(b)), and the module rejected; however, if the defect does not extend very far, the module may pass the quality controls and then be installed. In this situation, under outdoor thermal cycling, the module may be subjected to a high power loss due to the propagation of the defect. To counteract this effect the yield strength of the tabbing ribbon has been reduced from 90N/m to 30N/m, reducing the crystal damage, also known as *rip-out*.

It has been observed that multicrystalline silicon solar cells are more susceptible to this defect, while single-crystal solar cells, under high shear stress, tend to break in a V-shape fracture, as seen in Fig. 2(c).

Mismatch

The dispersion in the electrical parameters of solar cells (also known as *mismatch)*, and its relation to relative power loss (RPL) when the cells are associated in series to form a module, have also been widely studied [9–14]. Recent work [6,7] has shown that under standard cell classifications, the RPL, although it exists, is below the detection limits of solar simulators. This could lead to a re-evaluation of cell sorting: for example, cell classification may be carried out using wider ranges of electrical parameters to improve production yields. In module production environments it would no longer be recommended to sort 100% of the cells, resulting in savings in the capex and the breakages associated with this practice. However, it is advisable to perform at least the measurement of a certain population of cells as a quality control. Nevertheless, during module production, the manufacturer may follow certain practices that deviate from the standard production process, leading to an increase in RPL due to mismatch.

> “The tabbing–stringing process is the most critical process of module production in terms of failures.”

Soldering

The tabbing–stringing process (soldering the solar cells to each other) is the most critical process of module production in terms of failures. During soldering, the solar cells are subjected to high thermal shear stress [5,15,16]; as a result, most manufacturing failures occur during this process. The following sections discuss

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different failure modes and explanations of why these occur, derived from direct experience and research in industrial environments.

Adhesive failure between tabbing ribbon and busbar

The contact resistance also affects the overall module series resistance. Problems related to contact resistance mainly take place at the silicon–busbar interface and at the busbar–tabbing ribbon interface. As regards the busbar–tabbing ribbon interface, the contact failures occur during the soldering process. For example, bad storage conditions of solar cells or a prolonged period of time that the cells are on the production line without encapsulation can lead to the creation of an oxide film on top of the busbar; this reduces the soldering effectiveness and consequently leads to a lack of contact or even a complete peeling of the ribbon.

The flux is also a direct agent, which plays an important role during soldering. An eventual clogging of the flux dispensers leaves the cell buses without flux just before soldering. This gives rise to unsoldered cells in the module, which translates to a loss of power (Fig. 3). In this case, the current generated by the module is forced to pass through the soldered buses, which leads to a brighter appearance under EL testing (upper busbar in Fig. 3).

In the case of problems arising from solar cell manufacturing, contaminants in silver paste have a strong influence. A poor-quality silver paste, in which elements different from those related to glass frit formation or conductivity purposes are present, may have a negative effect upon the adherence strength of both cell and tabbing ribbon. In Fig. 4, different solar cells originating from failing lots in the soldering process were analysed. Several microstructures were detected, of which the main components were metal oxides. The soldering failures derived from those structures were not only adhesive but also cohesive.

The most common way of carrying out contact deposition is the screen-printing process, in which the silver paste of the front and back contacts is printed onto the silicon. After the printing, the solar cells are subjected to a thermal process that is responsible for triggering the drive-through of the silver through the ARC. If the thermal process is not done correctly, the coalescence of silver grains may occur and pure silver flakes are formed on the busbar surface; these flakes are called *bright spots* because of their brightness when exposed to light. Aurinka PV Group inspected a batch of solar cells from the same manufacturer and the same lot; some of these were found to have the bright spots (Fig. 5(b)). During solar simulator testing, modules with affected cells demonstrated 3% less power than those made from 'normal' cells.

After automatic soldering, an adherence test was carried out. The

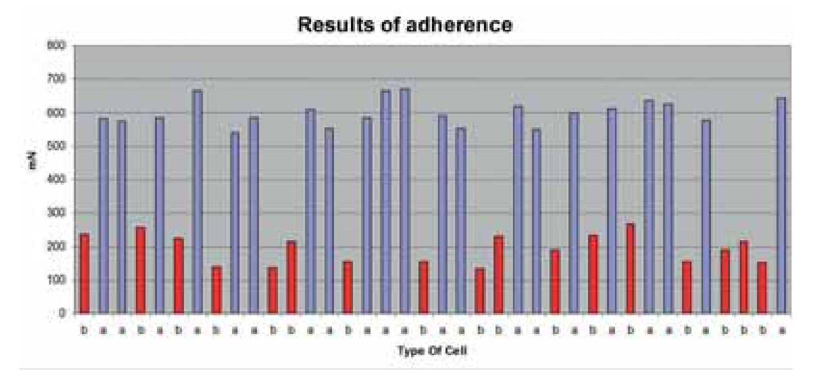

Figure 6. Red columns: adherence test carried out on cells affected by bright spots (see Fig. 5(b)). Blue columns: adherence test results for cells without bright spots (see Fig. 5(a)) from the same lot.

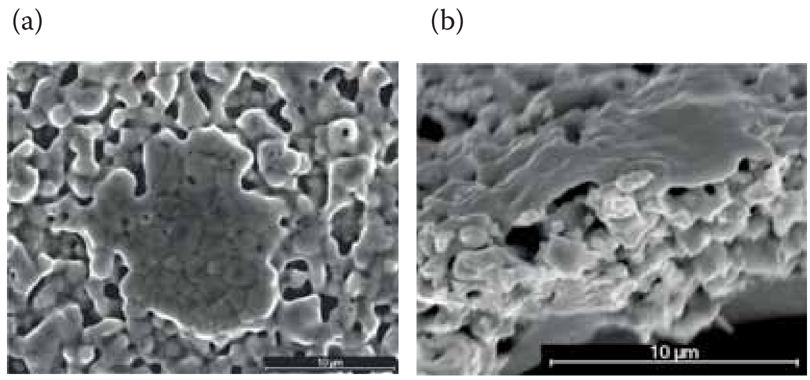

Figure 7. (a) Surface SEM picture of the microstructure of one 'bright spot.' (b) Tilted SEM picture of a busbar cut through a bright spot.

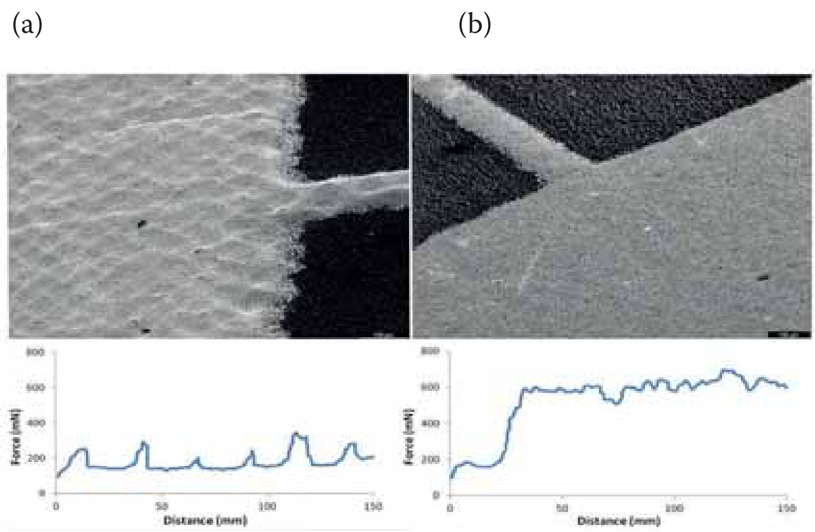

Figure 8. (a) SEM image of a front busbar with the topography derived from the mesh of the screen-printing process (top), and the corresponding adherence test result for one of the soldered buses (bottom). (b) SEM image where the mesh topography is absent (top), and the corresponding adherence test result for one of the soldered buses (bottom).

results, presented in Fig. 6, reveal the poor adhesion of cells with bright spots in comparison with those not affected by this issue.

For a more detailed explanation of the problem, the cells were inspected using a scanning electron microscope (SEM). The flake-shaped grains that have formed on top of the busbar have a softer surface than the silver paste surrounding them (Fig. 7); this makes the reflection of light more intense, resulting in the appearance of bright spots. An energy dispersive X-ray (EDX) analysis revealed that those grains are surface structures formed by pure silver (Ag), whereas the area surrounding them is mainly formed by silver as well as other metals and oxygen. The adherence of the tabbing ribbon onto the silver busbars depends on the number of flakes per mm^2. Because of the flat area of the flakes, there is a detrimental effect on adherence.

Changes in silver paste composition, busbar design or the mechanical parameters of the tabbing ribbon have a strong influence on the soldering process. The composition of silver pastes as well as the busbar geometry and distribution is under ongoing development in order to improve solar cell efficiencies and to reduce production costs. Nevertheless, any modifications to solar cell elements, although necessary, need to be realized in full collaboration with module producers, as the changes may have a direct effect on module performance and manufacturing processes.

Concerning busbar geometry, because of the soaring price of silver, solar cells producers have found different ways of saving silver by making discontinuous busbars, which also affect the soldering process. On the one hand, the solderability of silver pads is affected for many reasons: different contact pressures for silver pads than for aluminium (in rear buses) or for silicon (in front buses); inhomogeneous distribution of heat along the busbars; inhomogeneous distribution of shear stress; and so on. On the other hand, because of discontinuities the contact area is reduced. Although it has been reported that the contact resistance between the tabbing ribbon and the cell is constant and negligible in the case of sufficient solder spots having been achieved [17], the fact that the soldering process window narrows must be taken into account.

The composition or viscosity of the silver paste also affects the soldering. Around six years ago, there used to be Al in the silver paste composition for the back buses, which enhanced the solderability of the tabbing ribbon onto the back busbar; however, Al is no longer present in the back buses, causing a reduction in solderability as well as in the soldering process window. Some manufacturers are trying to reduce, or even eliminate, the Pb content in silver pastes in order to meet future environmentally friendly requirements. Normally those new silver pastes use Bi as an alternative to Pb, but this replacement of Pb by Bi also has an influence on the soldering process, leading to a decrease in adhesion force.

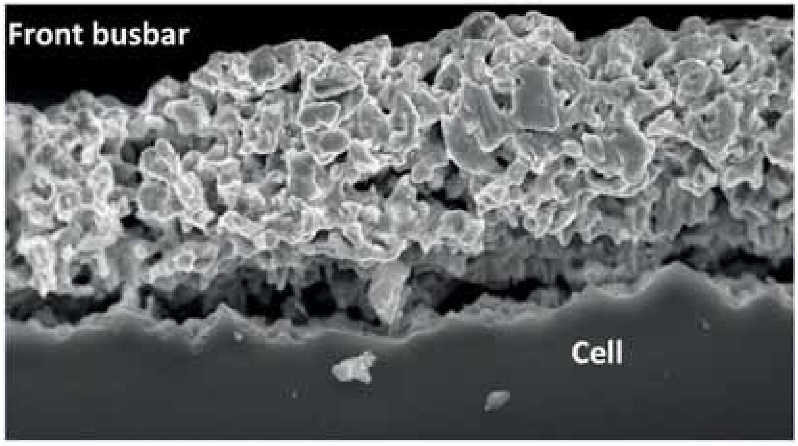

Figure 9. Front busbar of a cell affected by a bad contact: total delamination is observed.

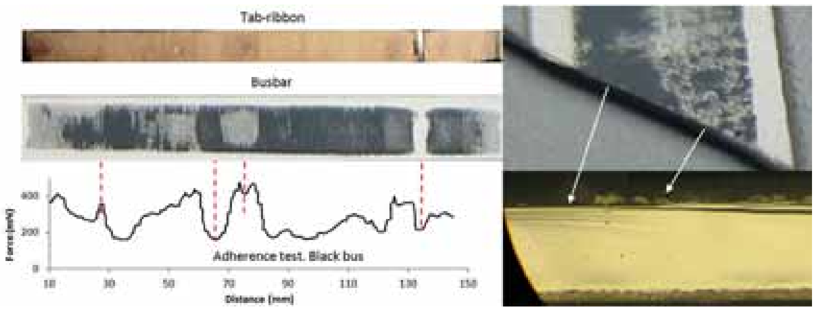

Figure 10. Top left: inner part of the tabbing ribbon after the peel test. Middle left: busbar of a cell exhibiting the 'black bus' effect after the peel test. Bottom left: peel force vs. busbar length. Top right: section view of the busbar after the peel test. Bottom right: optical microscope section view of the same busbar – the absence of silver in the black area is evident.

Regarding silver paste viscosity, a correlation between the macroscopic topography of the busbar and the adhesion has also been detected. The topography of fired silver paste is determined by paste properties (viscosity, emulsion thickness, etc.) and screen dimensions (i.e. wire diameter of the mess). During in-line quality control of the soldering process (peel test), an adhesion failure was detected in a certain lot of cells from the same supplier (Fig. 8, bottom left). The topography of a group of cells, with good and bad results during the peel test, was analysed by SEM: the difference between them shows up very clearly (Fig. 8, top). A distinct topography with a mesh-shaped pattern (arising from the mesh of the screen-printing process) is present in those cells that suffered adhesion failure, while the busbar surface of 'good' cells appears to be flat and soft. Several modules were manufactured using solar cells that demonstrated the above-mentioned busbar patterned topography and using solar cells with a soft busbar surface. The materials used and the soldering conditions were the same. The modules affected by the pattern issue produced 2% less power than those made using 'normal' cells.

Busbar-to-cell adhesive failure

The adhesion force between the silver paste and the cell is also an important factor that influences the final CTM losses. The origins of this kind of failure are diverse: poor-quality silver paste, inefficient drying or co-firing processes in solar cell production, storage of wafers in bad conditions, inappropriate handling of silicon wafers, etc. All of these result in deficient contact between cell and silver paste, and can even lead to busbar flaking, as shown in Fig. 9.

Eventually, in some of the steps of solar cell production prior to screen printing, the wafer surface may sustain some kind of contamination (oxide, fingerprints, etc.). Subsequently, at the end of the manufacturing process, the solar cells are produced with an undesirable interlayer between the busbar and the cell, which creates a higher contact resistance. The performance of a cell, however, may be good enough for it to be commercialized, and it therefore proceeds to module manufacturing. In this case, the adhesive failure occurs during the soldering process, where, although the adherence between the busbar and the tabbing ribbon is high, the peel test fails as a result of the complete detachment of the silver busbar from the cell. Thus, the area of the busbar turns dark in colour; this effect is commonly known as *black bus* or *dark bus*.

This problem has been detected by Aurinka in the solar cells of many suppliers. During module production, the 'black bus' effect appears as a failure in the peel test, where the adherence (peel force) exhibits very low values. Additionally, all the busbar's silver paste is removed, in a clear adhesive failure, in those areas where the dark colour appears. In the case of acceptable peel-test results, the peeled tabbing ribbon removes part of the busbar as a result of a cohesive 'failure' deliberately provoked by the peel force. Nevertheless, the cohesive 'failure' leaves a grey colour, and high adhesive values. A white colour appearance on the busbar surface means that no soldering has been performed and consequently the adhesion is also very low. Fig. 10 shows all the failure types described above, simultaneously in the same busbar, along with the adherence test results. The tabbing ribbon after the peel test is also presented. It is clearly shown that where a dark area appears, the peel force is very low, confirming the existence of an adhesive failure. One of the cells was inspected by optical microscope after the peel test. In the section view (Fig. 10, bottom right), it can be observed that no silver paste remains in the silicon where the black area appears (left arrow), whereas in the grey areas (where a cohesive 'failure' occurred), some silver remains (right arrow) and the peel force is much higher.

The lot of cells that exhibited this problem was electrically measured and compared with another lot from the same supplier having the same efficiency (Fig. 11). As can be deduced from the graph, the lot afflicted by the 'black bus' effect presents a very high scattering of R_s in its cells, with R_s values of up to 20mΩ, well above the standard 4–8mΩ. The inset in Fig. 11 shows, as final evidence of the existence of a contamination interlayer, a fingerprint on one of the affected cells after the peel test.

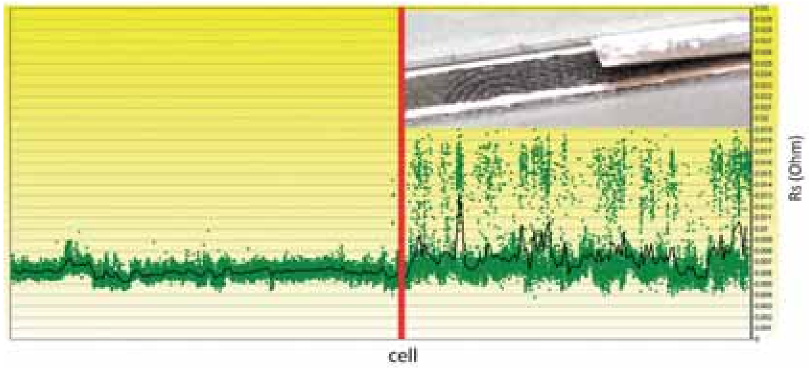

Figure 11. Series resistances of the cells suffering from the black bus effect (right) compared with cells without this failure from the same supplier and with the same efficiency (left).

(a) (b)

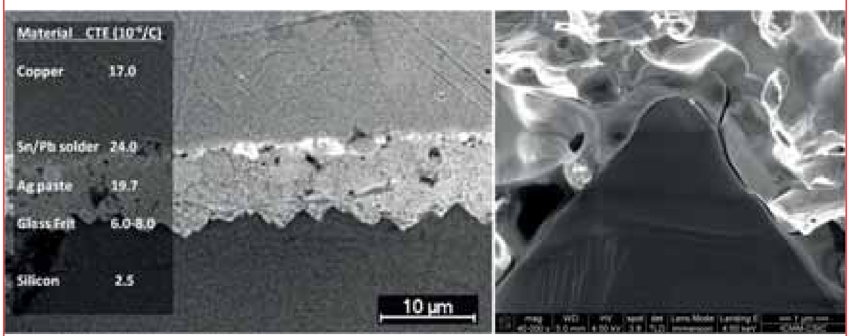

Figure 12. (a) SEM section view of one soldered solar cell: tabbing ribbon, front busbar and silicon are shown, and the CTEs are specified in the inset. (b) SEM section view of a fracture in the glass of a solar cell.

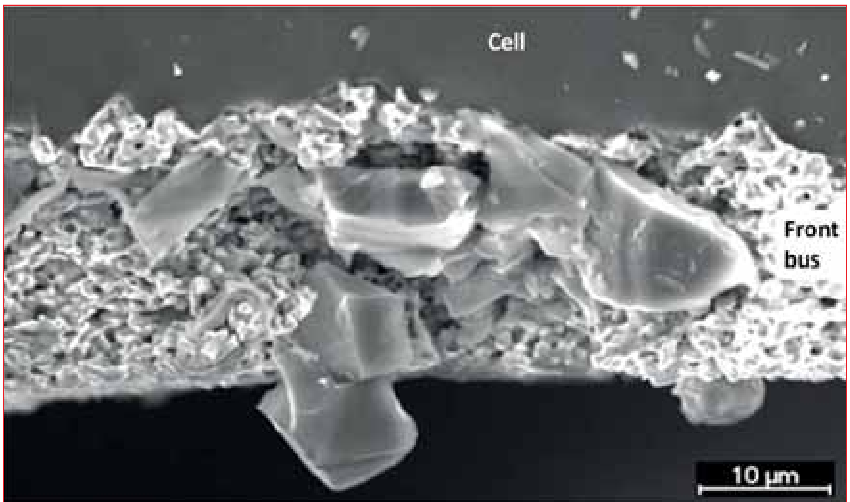

Figure 13. Example of bulk contamination of a front busbar.

"The average power of modules affected by the black bus effect was 3.8% lower than that of modules not exhibiting the failure."

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All the modules produced with both lots of cells were measured under standard test conditions (STC). The results show that the average power of modules affected by the black bus effect was 3.8% lower than that of modules not exhibiting the failure.

With regard to the nature of all the interfaces involved in solar cell interconnection, it is important to take into account the difference between the coefficients of thermal expansion (CTEs) of the different interfaces that participate in the soldering. Fig. 12(a) is an SEM photograph of a section view of a soldered solar cell. In this image all the interfaces are displayed and the CTE of each material is also indicated (CTEs were extracted from Moyer et al. [18]). From Fig. 12 it can be inferred that the solder strongly smears throughout the interface area because the thickness of the solder decreases from 15–20 microns down to a few microns. It is likely that a combination of temperature and the pressure of the tabber–stringer pins on the tabbing ribbon cause the thinning of the solder. An EDX analysis of the interface compositions confirms the composition shown in the inset of Fig. 12(a).

As reported by Moyer et al. [18], the largest change in CTEs takes place at the silicon–glass and glass–Ag interfaces, which means that, during thermal processes, the residual stress is concentrated mainly at those interfaces. As a consequence of silver paste components and the parameters of the firing process, a thick glass interface may be formed. When the solar cell is subjected to the thermal stress of the soldering process, the resulting shear stress can cause the glass to fracture. As a result, an adhesive failure of the silver busbar and the solar cell occurs and the known black bus effect may appear. Fig. 12(b) shows a fracture in the glass of a single-crystal solar cell after soldering.

Cohesive failure of the busbar due to silver paste

Leach resistance is strongly related to the cohesive properties of the busbar. The silver paste components can be separated into 1) inorganic – glass frit, Ag powder and oxides, and 2) organic – solvent, resin and organic additives. The inorganic components are responsible for adhesion and leach resistance [18], whereas unusual proportions of organic additives may be detrimental to these properties. Nevertheless, the organic components are responsible for the green strength of the silver paste, which, combined with the parameters of the drying and firing processes, may cause a loss of integrity of the busbar, translating into a lack of cohesion. On the other side, foreign microstructures formed by contaminants are also responsible for cohesive failure, as they replace the glass matrix and Ag particles that primarily constitute the busbars. Fig. 13 shows a readily apparent bulk contamination of the silver paste once it has been printed onto the solar cell.

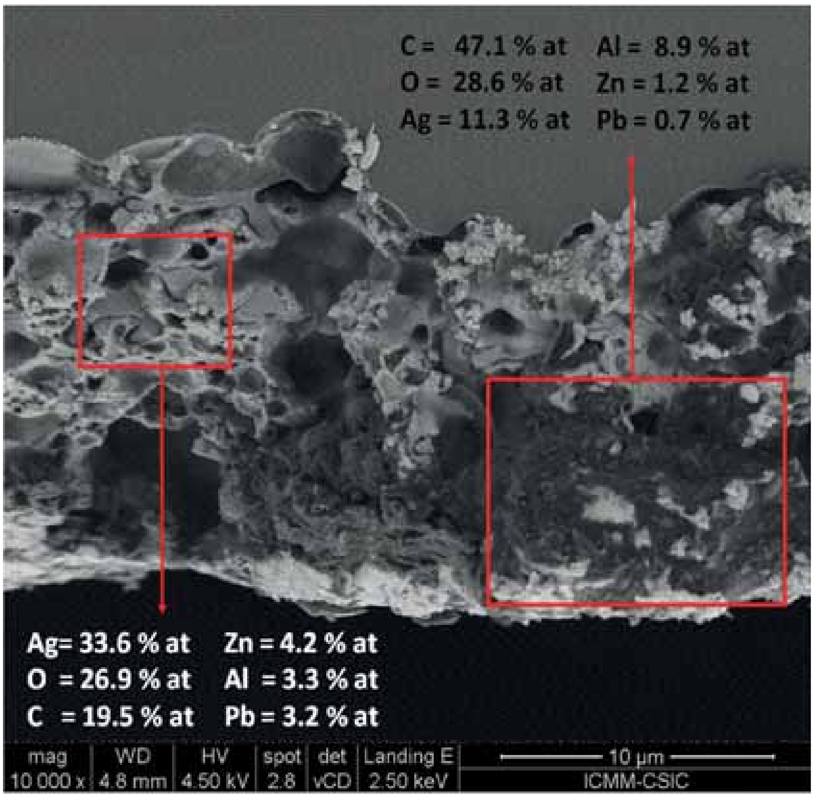

Figure 14. EDX analysis of two different areas of a front silver paste. In the dark areas, a prominent peak of Al is detected, while the bright areas correspond mainly to Ag.

In another sample investigation that took place in an industrial environment, a massive cohesive failure was observed in solar cells where the front busbars presented high concentrations of C and O, as well as Al as a contaminant; the latter is extremely rare and potentially harmful as a possible origin of shunt formations due to Al spiking. As usual, after the peel-test failure the cells were inspected in the laboratory. An SEM and EDX analysis was carried out on the solar cells, and Al was found in the bulk of the silver paste (Fig. 14).

Optical gains/losses

Once solar cells have been encapsulated, there are losses related to optical principles. Before the radiation reaches the cell, reflections at the air–glass and glass–encapsulant interfaces occur as well as absorption by the glass and encapsulant [2]. As the refraction index of encapsulant (typically EVA) is fairly similar to that of glass, the losses due to the glass–encapsulant interface will be considered negligible. Haedrich et al. [1] have estimated the other optical losses described above to be 1.1% abs.; in the same study the influence of the shadow projected by the tabbing ribbon onto the solar cell was also calculated, yielding a power loss of 0.32%. The radiation finally reaches the EVA–cell interface.

In order to minimize losses from reflection, the ARC layer possesses an intermediate index of refraction, the value of which lies between the indexes of glass and silicon. In particular, a silicon nitride ARC has a refractive index that varies between 1.985 and 2.167. As the cell is characterized in an air environment (with a refractive index of 1), the ARC contributes to reducing the index gap at the ARC and encapsulant interfaces, leading to a gain in power. This power gain results mainly from an increase in I_{sc}, which has been measured to be up to 5% compared with a bare cell (multicrystalline cell with a SiN_x coating [1])

Besides the optical gain due to refractive index coupling, as a result of encapsulation there are other optical considerations which contribute to an increase in module power [1,3,4,19]. For example, some PV glass producers have developed an ARC that is able to enhance the module power by approximately 2%; the self-cleaning properties of these coatings, however, are usually inadequate once the modules are installed outdoors, offsetting the gain in power.

With some module producers another practice has been identified: in this case the PV modules are produced with the PV glass patterned surface facing the sun. The main purpose of the glass pattern, when it is oriented to the inner side of the module, is to achieve a good contact adherence between the glass and the encapsulant. When the patterned side of the glass is oriented outwards, there is a decrease in reflectance because of multiple reflections on its surface. To quantify the gain in power that is related exclusively to the 'misorientation' of the glass, several modules were produced with the same cells and materials; 50% of them were produced with the glass patterned side facing out, and then all the modules were measured at STC. An average of 2% power gain was measured for the modules with the patterned surface facing the sun. However, although this power gain is real, once the modules are installed outdoors there is a power decrease due to the self-cleaning difficulties of the sun-facing textured surface: this equates to a net loss of power for the final customer, who has indeed paid for that additional 2% of power increase.

> "Once the modules are installed outdoors there is a power decrease due to the self-cleaning difficulties of the sun-facing textured surface."

Other gains are mainly derived from reflections on the tabbing ribbon and on the exposed backsheet where the cells are not present (i.e. cell spacing areas – see Fig. 15). The light reflected is directed to the glass–air interface and partially reflected back onto the cells.

In an attempt to quantify the power gain related exclusively to the cell spacing, two designs (A and B) of commercial modules were manufactured; the materials and processes were exactly the same. The modules were then measured at STC in a commercial solar simulator. The power gain derived from the back-reflected light has previously been calculated and measured, as reported in the literature [1,3,4]; in the current study, however, the power gain was found to be slightly better than the best results obtained by those researchers. Besides the backsheet reflection, other factors may be involved that explain an average power gain of 1% with a spacing increase of 1mm vertically and 0.5mm horizontally. From Fig. 16(b) it is seen that the increase in power is accompanied by a proportional increase in I_{sc}.

In addition to the benefit of a 1% power gain, there is another benefit, which is related to heat exchange with the environment. It is known that not all the irradiance absorbed by the PV module is convertible into electricity, but some of it is transformed into heat. The losses due to temperature are determined by the maximum

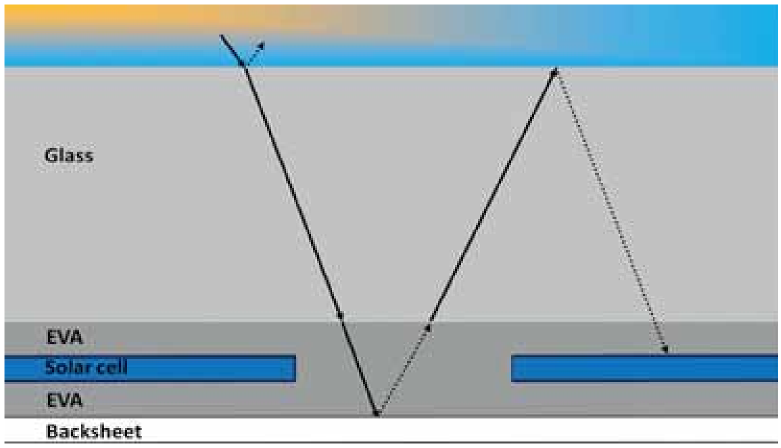

Figure 15. Sketch of the optical path related to backsheet reflections into the module.

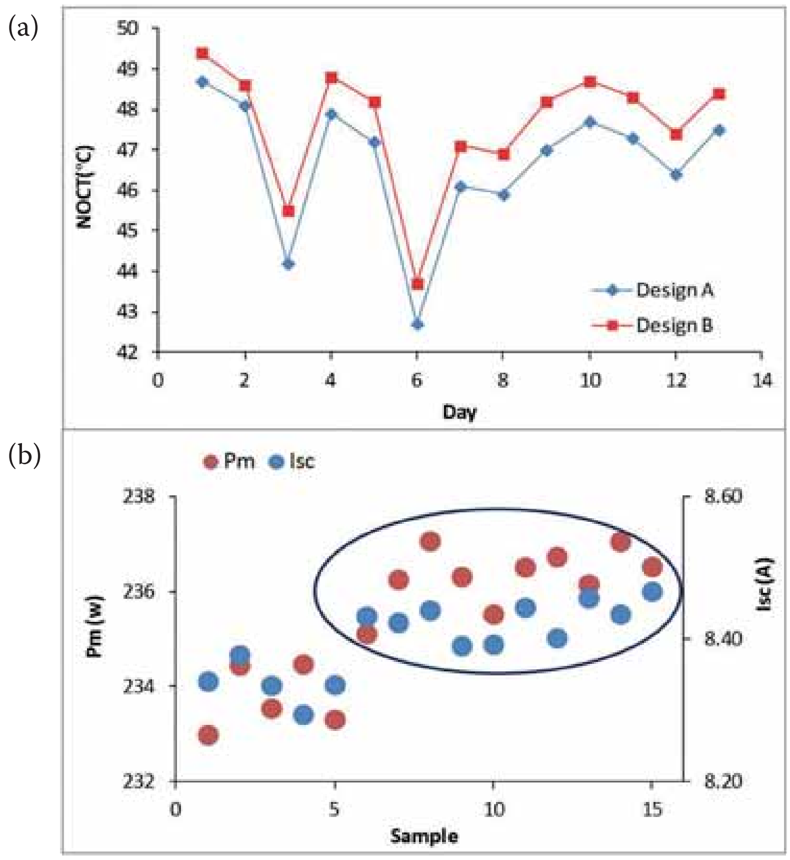

Figure 16. (a) NOCT results on different days for modules manufactured with two different designs. (b) Power and I_{sc} measurements for the two designs.

temperature coefficient γ, the approximate value of which for modules of crystalline silicon is –0.45%/°C. For example, for a PV module of 180Wp and an area of 1.3m^2 (nominal efficiency η_{STC} = 13.8%), encapsulated with glass (3.2mm) and an EVA backsheet, working at its maximum power point under an irradiance of 1,000W/m^2, thermal models [20] suggest a working temperature estimated at 48.7°C. This means, assuming the temperature coefficient given above, an actual efficiency given by $\eta_{48.7°C}$ = 13.8% × (1 – 23.7 × 0.0045) = 12.3%.

In actual operation, the temperature of the cell is determined by a balance of incoming and outgoing heat. On the one hand, it involves that portion of the irradiance which is not transformed into electricity but into heat in the interior of the cell. In this respect, it must be considered that a PV module with higher efficiency cells will transform a greater quantity of irradiance into electricity and less into heat; thus, if equality of all other construction features is assumed, the module's operating temperature will be lower. On the other hand, the dissipation of heat from the cell is limited by the encapsulation materials and module design. To investigate the second consideration, two modules, with designs A and B, were subjected to IEC 61215-10.6 [21] tests to determine the normal operation cell temperature (NOCT) on the CIEMAT electricity distribution network (Fig. 16(a)). Both modules were tested at the same time and together in the same rack. There is clear evidence that the NOCT of design A is around 1°C lower than that of design B.

Conclusions

This paper has presented an overview of all the various CTM losses. The sources of some of these losses have been investigated in an industrial environment; this may help the industry to avoid the losses, thus leading to a more efficient production of PV energy and a reduction in its cost. Finally, a different module design, aimed at increasing the output power, yielded a lower NOCT, with a consequent increase in the module's annual energy output.

Acknowledgements

The authors thank Aurinka PV Group for its support and materials in all the experiments carried out.

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Reliability and durability impact of high UV transmission EVA for PV modules

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ABSTRACT

Newly developed high UV light transmission ethylene vinyl acetate (EVA) has recently been extensively introduced for use in PV modules. It has been proved that this type of EVA can result in potential power gain because of the better blue light response of the solar cell, which in turn can further reduce the cost per watt of the PV module. However, if only high UV transmission EVA is used as an encapsulant, too much UV light irradiates the backsheet, which can cause the backsheet to yellow. In order to improve the reliability and durability of the modules, SUNTECH, as a module manufacturer, therefore uses combined EVA, i.e. high UV transmission EVA as the front encapsulant and conventional UV cut-off EVA as the rear encapsulant, to protect the UV-sensitive backsheet. This paper presents the results of an investigation of the reliability and durability of high UV transmission EVA in PV modules, through an enhanced UV test which exceeds IEC standards.

Introduction

A number of solar cell manufacturers have recently introduced high-efficiency products with improved quantum efficiency at short wavelengths. Conventional ethylene vinyl acetate (EVA) encapsulant, however, has a short wavelength cut-off at ~380nm and therefore cancels out the benefit of the potential power gain from cells with better blue light response. This cut-off is due to UV absorbers and stabilizers present in the EVA, which block the UV light and thus protect the backsheet. Newly developed high UV light transmission EVA, which can capture the UV light through reducing or removing UV absorbers and stabilizers, has therefore been extensively implemented in PV modules with better blue-light response cells; a power gain of at least 1% has in fact been demonstrated compared with conventional EVA [1].

"If only high UV transmission EVA is used as the encapsulant, too much UV light irradiates the backsheet, which can cause the backsheet to yellow."

In actual applications, if only high UV transmission EVA is used as the encapsulant, too much UV light irradiates the backsheet, which can cause the backsheet to yellow. The majority of module manufacturers therefore use combined EVA – i.e. high UV transmission EVA as the front encapsulant and conventional UV cut-off EVA as the rear encapsulant, to protect the UV-sensitive backsheet. As is well known, however, the UV absorber and stabilizer additives can prevent backsheet degradation in sunlight but can also decay over time. Whether the combined EVA can really provide the desired long-term durability for modules therefore needs to be proved.

This paper present the results of a study carried out by SUNTECH of the reliability and durability of high UV light transmission EVA as the front encapsulant in PV modules, by the use of enhanced UV tests which exceed IEC standards. At the material level, high UV light transmission EVA as the front encapsulant has been found to be more stable than conventional EVA during long-term UV exposure. The light transmission of high UV light transmission EVA does not show any change, and also no yellowing phenomenon can be observed. Conventional EVA, on the other hand, exhibits an obvious degradation of light transmission and slight yellowing.

The use of high UV light transmission EVA as both front and rear encapsulant, however, will fail to protect the UV-sensitive backsheet as a result of too much UV light irradiating the backsheet; this can cause the backsheet to yellow, with the yellowing index (YI) potentially rising to a value of 50.

The issues above can be addressed by the use of combined EVA. Although the UV light transmission can increase from 20% to 45% (which is quite close to the value for high UV transmission EVA) after 300kWh/m^2 UV exposure, no yellowing of the UV-sensitive backsheet can be observed, and the YI

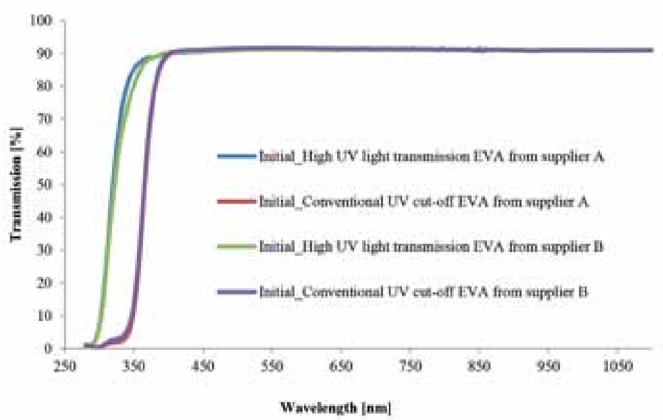

Figure 1. Light transmission curves of conventional UV cut-off EVA and high UV light transmission EVA from two different suppliers.

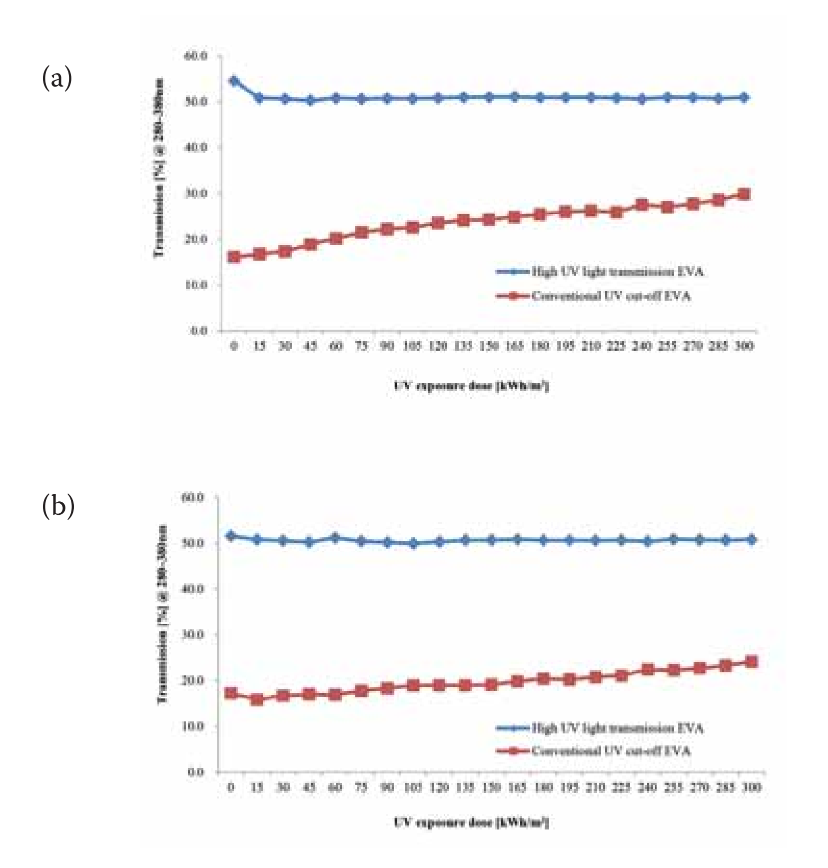

Figure 2. Transmission change at short wavelengths with UV exposure: EVA from supplier A; (b) EVA from supplier B.

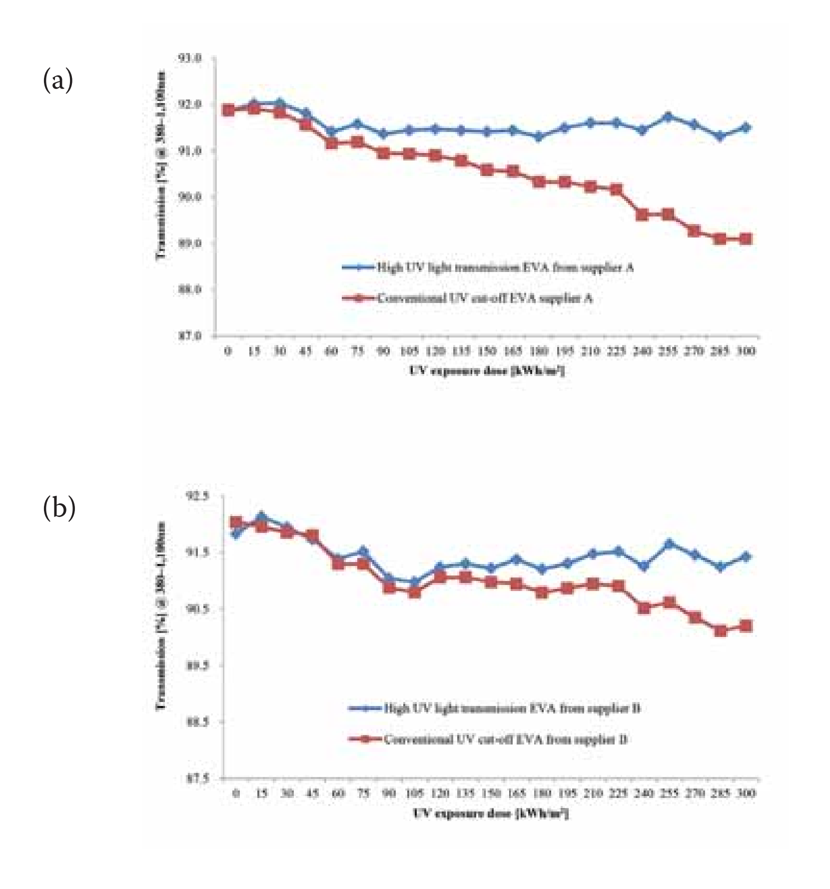

Figure 3. Transmission change at visible light wavelengths with UV exposure: EVA from supplier A; (b) EVA from supplier B.

of the UV-sensitive backsheet increases only slightly, implying that combined EVA serves as protection for the sensitive backsheet.

At the module level, the long-term impact on power was also investigated in the study. Suntech PV modules encapsulated with combined EVA were subjected to UV extended testing with UV doses of up to 330kWh/m^2. Test results reveal that the output power loss is less than 2.1% and that there are no visual defects.

Materials and procedure

High UV light transmission EVA and conventional UV cut-off EVA from two EVA suppliers are used for this study; the light transmission is shown in Fig. 1. Two backsheets with a fluoroplastic/polyester/tie layer structure are used, with one UV sensitive and the other UV non-sensitive. The UV exposure tests of the materials and modules are carried out in accordance with IEC 61215:2005 (Ed. 2.0) [2].

Results

Light transmission change

The change in light transmission via the front EVA to the cells not only affects module power output but also reveals the ageing of the materials. In order to evaluate the long-term performance of the high UV light transmission EVA and conventional UV cut-off EVA as front encapsulants, two such EVAs were laminated in a glass/EVA/glass arrangement and received long-term UV exposure up to 300kWh/m^2. Light transmission was measured at each 15kWh/m^2 UV exposure.

The results indicate that there was no change in light transmission at short wavelengths for the high UV light transmission EVA, while there was an obvious increase (of up to 10%) for the conventional UV cut-off EVA, as shown in Fig. 2. This indicates that the UV absorber and stabilizer additives in the conventional UV cut-off EVA decay with UV exposure.

Fig. 3 shows the light transmission change at visible light wavelengths. It can be observed that the light transmission clearly decreases by ~2–3% with UV exposure for the conventional UV cut-off EVA; however, there is a decrease of only ~0.5–1% in light transmission for the high UV light transmission EVA. The light transmission decrease in both cases is mainly caused by ageing of the materials.

The changes in the transmission curves from 280nm to 1,100nm before and after UV exposure are shown

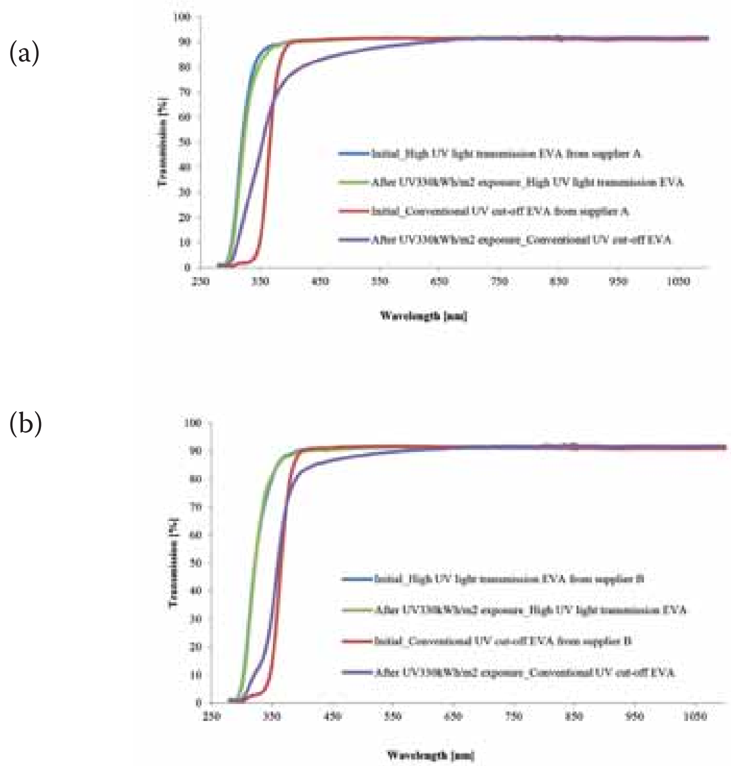

Figure 4. Transmission curve before and after 300kWh/m² UV exposure: (a) EVA from supplier A; (b) EVA from supplier B.

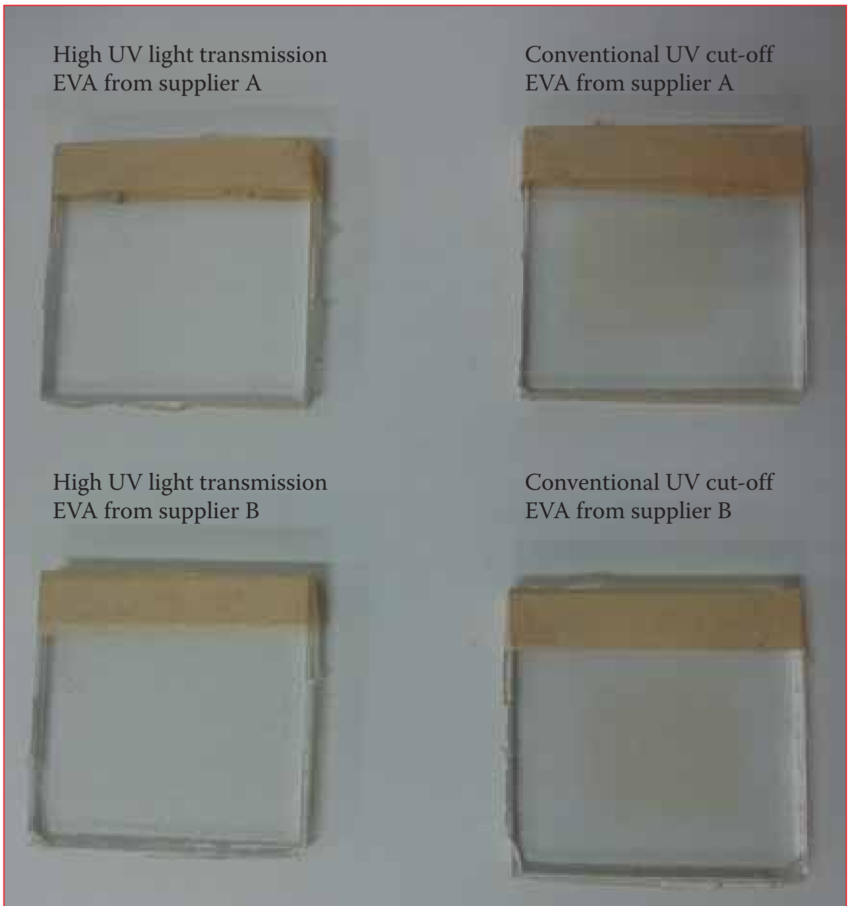

Figure 5. Visual changes in the conventional UV cut-off EVA and the high UV light transmission EVA after 300kWh/m² UV exposure.

in Fig. 4 for the two types of EVA. Again, the curve change clearly shows practically no change in the case of the high UV light transmission EVA. The conventional UV cut-off EVA, however, has degraded after 300kWh/m² UV exposure, which will affect module power output. This implies that high UV light transmission EVA is more stable than conventional UV cut-off EVA during long-term UV exposure.

In addition, the conventional UV cut-off EVA was observed to begin to yellow after 300kWh/m² UV exposure; however, the high UV light transmission EVA exhibited no visual defects, as shown in Fig. 5. It is speculated that the UV absorber and stabilizer additives can block UV light transmission but can also accelerate the material ageing, which will cause the light transmission to degrade and the EVA to yellow.

UV light transmission impact on the backsheet

UV light irradiation of the backsheet can cause yellowing. In order to reduce UV light damage to the backsheet, in actual applications, combined EVA – high UV transmission EVA as the front encapsulant and conventional UV cut-off EVA as the rear encapsulant – is used. However, the amount of UV light that can be blocked by combined EVA, and whether or not its use offers protection to the backsheet, need to be evaluated.

> “Compared with high UV transmission EVA, combined EVA can block more UV light.”

Fig. 6 shows the change in light transmission at short wavelengths of such combined EVA with UV exposure; compared with high UV transmission EVA, combined EVA can block more UV light. However, UV absorber and stabilizer additives in combined EVA decay faster than in conventional UV cut-off EVA: after 300kWh/m² UV exposure, the light transmission at short wavelengths increases from 20% to 45%, which is quite close to the value for high UV transmission EVA. The implication is that more UV light irradiation reaches the backsheet with combined EVA than with conventional UV cut-off EVA.

The UV light transmission impact on a UV-sensitive backsheet is shown in Fig. 7. It can be observed that the use of high UV light transmission EVA as both

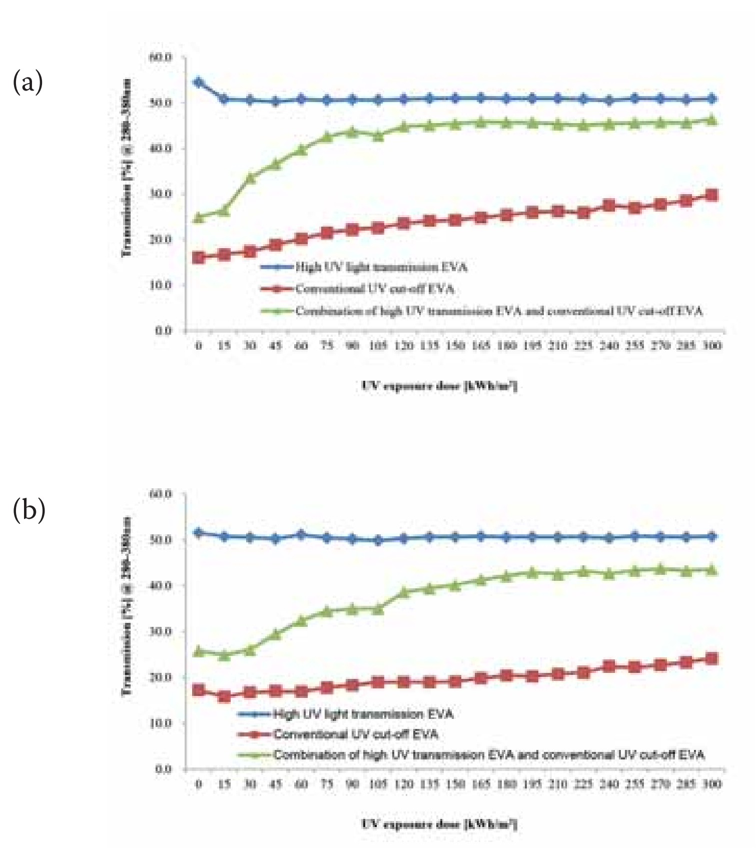

Figure 6. Differences in light transmission at short wavelengths between high UV light transmission EVA, conventional UV cut-off EVA and combined EVA: (a) EVA from supplier A; (b) EVA from supplier B.

front and rear encapsulant can result, after only 15kWh/m^2 UV exposure, in slight yellowing of the UV-sensitive backsheet, which becomes more and more severe with increasing UV exposure. The YI also confirms that the yellowing of the backsheet intensifies with greater UV exposure, reaching over 50 after 300kWh/m^2 UV exposure, as shown in Fig. 8.

The combined EVA, however, offers protection to the UV-sensitive backsheet, as in the case of conventional EVA: only slight yellowing along the edge of a dummy sample could be detected after 300kWh/m^2 UV exposure and the YI showed just a slight increase. The use of the combined EVA can therefore provide long-term durability of the module, even if the backsheet of the module is UV sensitive.

In the case of a UV-non-sensitive backsheet, UV light will not damage it; hence, the use of high UV light transmission EVA as both front and rear encapsulant also can provide long-term durability. Fig. 9 shows the visual changes in the UV-non-sensitive backsheet, and Fig. 10 shows the corresponding changes in the YI: backsheet yellowing cannot be observed, and there is almost no change in YI. This means that when the anti-UV performance of the backsheet is sufficiently effective, any of the EVAs can be used as encapsulant.

	After 15kWh/m^2 UV exposure	After 30kWh/m^2 UV exposure	After 45kWh/m^2 UV exposure	After 300kWh/m^2 UV exposure
Sample 1 High UV light transmission EVA + UV-sensitive backsheet				
Sample 2 Conventional UV cut-off EVA + UV-sensitive backsheet				
Sample 3 Combined EVA + UV-sensitive backsheet				

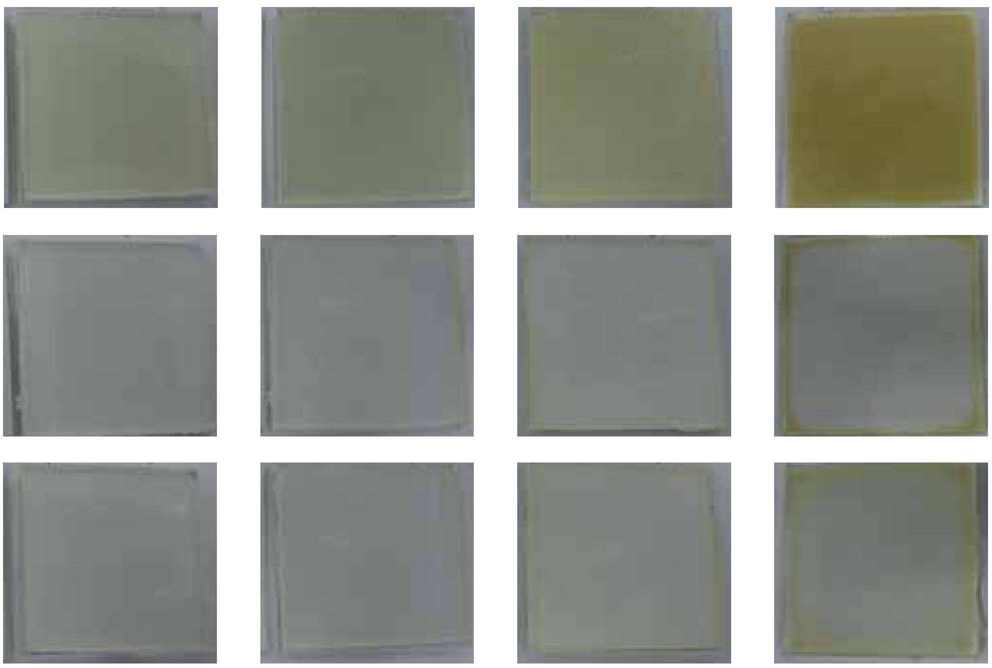

Figure 7. UV light transmission impact on the UV-sensitive backsheet.

Long-term power impact at the module level

The long-term impact on power at the module level was evaluated. Three Suntech PV modules encapsulated with combined EVA were subjected to UV extended testing: one module received up to 330kWh/m² UV exposure and other two received 165kWh/m² UV exposure. The results show an output power loss of less than 2.1% for Suntech modules after long-term exposure, as depicted in Fig. 11. The results at the module level also revealed that the use of combined EVA as encapsulant can provide long-term durability of the module.

> "Combined EVA provides long-term durability and an output power loss of less than 2.1% for Suntech modules after 330kWh/m² UV exposure."

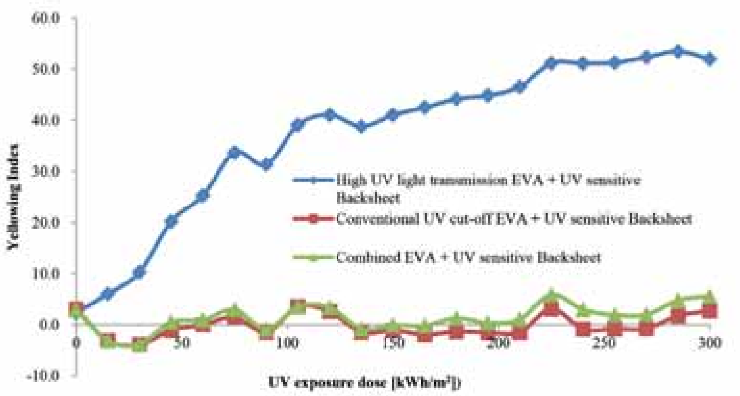

Figure 8. Changes in YI for the UV-sensitive backsheet.

Conclusions

High UV light transmission EVA has the benefit of better blue light response for solar cells; it is also more stable than conventional UV cut-off EVA under long-term UV exposure. At short and visible light wavelengths there is virtually no change in light transmission after 300kWh/m² UV exposure. Conventional EVA, however, exhibits a noticeable decrease and yellowing as a result of the decay of the UV absorber and UV stabilizer.

In actual applications, if high UV light transmission EVA is used as both front and rear encapsulant, the long-term effect on the UV-sensitive backsheet could negate the benefits because of too much UV light irradiating the backsheet, causing it to yellow. However, the use of a combination of high UV light transmission EVA and conventional UV cut-off EVA can not only benefit module power output, but also provide the same protection to the UV-sensitive backsheet as conventional EVA. Enhanced UV tests show that only a slight yellowing occurs along the edges of the dummy samples after 300kWh/m² UV exposure, and that there is a marginal increase in YI.

The results at the module level also reveal that the combined EVA provides long-term durability and an output power loss of less than 2.1% for Suntech modules after 330kWh/m² UV exposure.

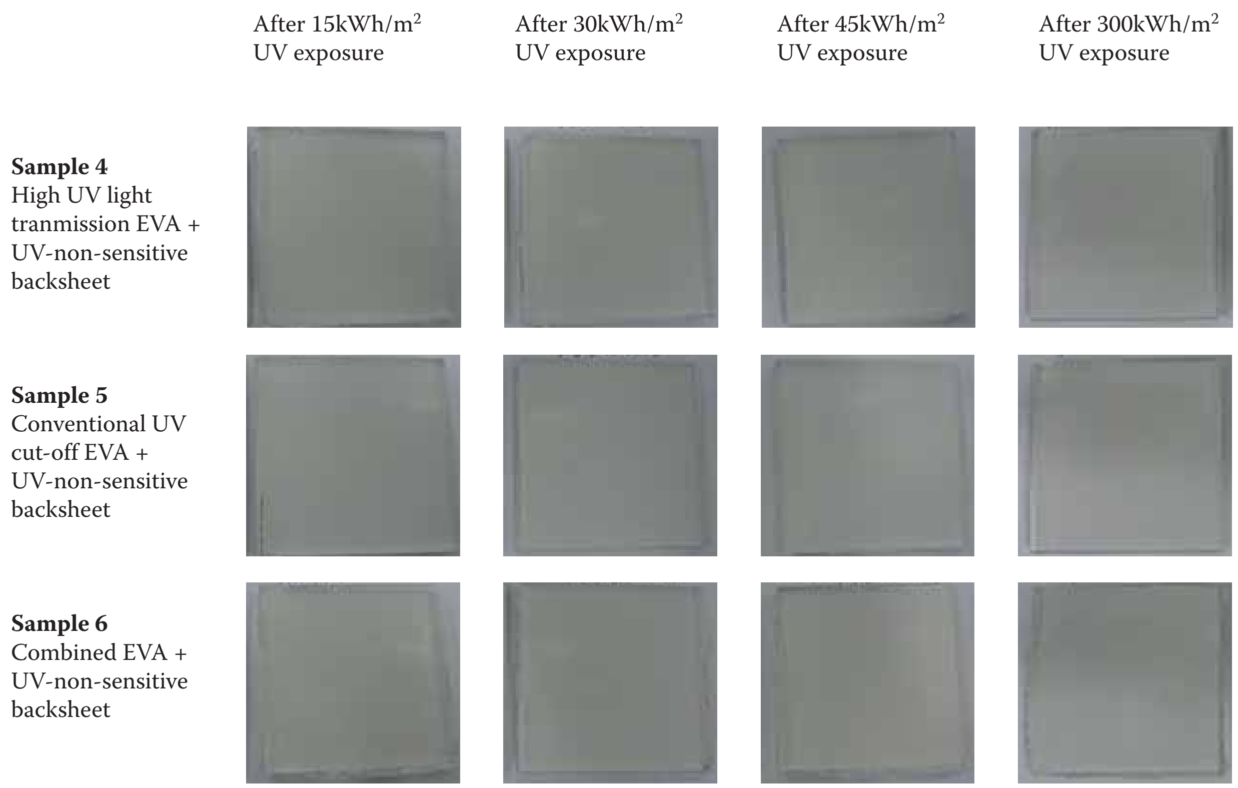

Figure 9. UV light transmission impact on the UV-non-sensitive backsheet.

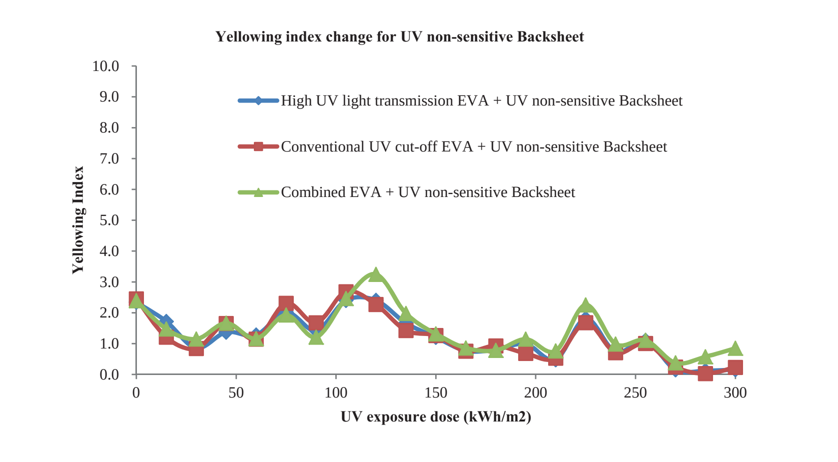

Figure 10. Changes in YI for the UV-non-sensitive backsheet.

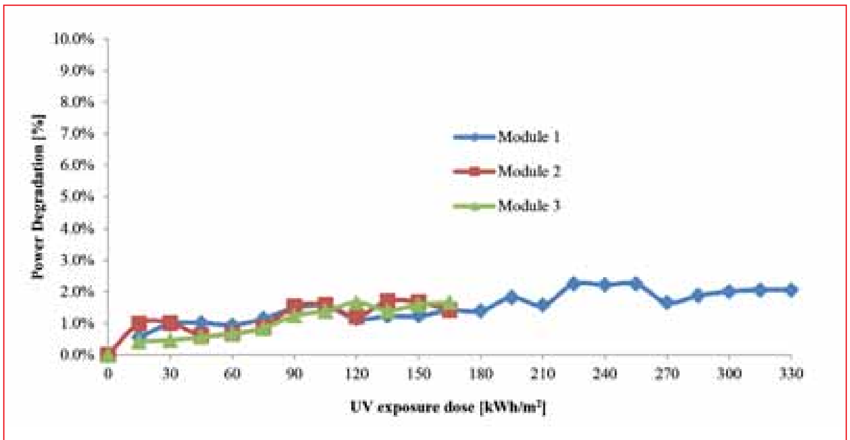

Figure 11. Long-term impact of UV exposure on module power.

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Market Watch

News

Global PV market to grow 36% with 55GW in 2015

The global solar market is expected to grow 36% this year with 55GW of PV installed within 2015, according to GTM Research's latest report. This is a strong increase given that last year the solar market only grew 2%.

The cumulative global market for solar PV is expected to triple by 2020 to almost 700GW, with annual demand reaching more than 100GW in 2019. GTM found that the Asia-Pacific region will account for more than half of the installations this year, meanwhile Europe will start an upswing, with North America continuing to grow. China, Japan and the US lead the rankings.

Meanwhile Mercom Capital Group forecast that global PV installations will reach 57.4GW within 2015. It cited China increasing its PV installation target by 20% to 17.8GW.

Source: ReneSola

China is expected to lead the way towards 55GW of new PV capacity this year.

National PV market updates

Key role for solar in 'seismic' shifts for global power - BNEF

A multi-trillion dollar investment surge in solar is set to play a central role in a "seismic" shift in the global electricity system between now and 2040, according to BNEF.

PV's falling costs and growing adoption by homeowners and businesses as a distributed generation source were two of the five dominant trends that will shape the global power system over the next 25 years.

BNEF foresees a US$3.7 trillion investment boom in solar at all scales as further declines in the cost of PV technology propel it forward. Of this some US$2.2 trillion will be channelled into distributed PV systems as consumers seize the opportunity to generate their own power, in combination with battery storage systems.

Chinese PV manufacturers targeting shipments to Japan, US and India - EnergyTrend

Chinese PV manufacturers were estimated to have shipped over 6GW of PV modules to three key markets in the first half of 2015, according to Taiwan-based market research firm EnergyTrend, a division of TrendForce.

EnergyTrend said that Japan was the largest module shipment destination for Chinese PV producers in the first half of the year with shipments topping 3.9GW.

The US was estimated to have topped 1.5GW of shipments from Chinese producers in the same period, while shipments to India reached around 900MW. This exceeded the estimated 700MW shipped to the largest market in Europe, the UK.

According to analysis by Photovoltaics International's sister website PV Tech of US shipments by from tier-one suppliers so far reporting first-half-year results, Trina Solar shipped around 525MW, compared to JinkoSolar's 284.5MW. Both companies have established manufacturing plants in South East Asia to meet growing US demand.

EnergyTrend also noted that Chinese PV manufacturers exported 12GW of modules during the first half of 2015.

Hilary Clinton targets 500 million US solar panels by 2020

Hilary Clinton said she wants the US to install 500 million panels within four years of her taking office, as the US presidential candidate outlined details about her energy and climate plan at a rally in Ames, Iowa.

Clinton wants to expand on the rollout of utility-scale solar witnessed under current president Barack Obama's tenure and increase the country's installed solar capacity to 140GW by 2020, stating her ambition of producing enough electricity from renewable energy sources to power every US home within a decade of her taking office.

She also said she intended to extend federal clean energy tax incentives should she win next year's election with the aim of making them more "cost-effective" for companies producing renewable energy.

US reviews 2012 China trade tariffs

The US Department of Commerce has reviewed its final anti-dumping (AD) and anti-subsidy (AS) rates on Chinese solar firms with most tier-one firms having their rates cut.

Yingli Green had its AD rate reduced from 24.48% to 0.79%. Wuxi Suntech had its rate increased from 29.14% to 33.08%. A swathe of companies including Canadian Solar, ReneSola, Trina Solar and JinkoSolar were cut to 9.67% in the AD case from rates between ~18-24% announced in December 2012.

The AD rate for firms not named on the list of companies has decreased from 249.96% to 238.95%.

Anti-subsidy rates have increased roughly 5% across the board.

SolarWorld Americas, the complainant in both cases, welcomed the results of the review, despite the fact that most of its tier-one rivals have had their rates cut.

France doubles solar tender size as prices catch up with wind

The French government has doubled the size of a solar tender from 400 to 800MW, claiming that bid prices for solar had now fallen to a similar level as wind power.

The tender for ground- or roof-mounted systems over 250kW had originally been set at 400MW, but as with a recent tender for mid-sized systems between 100-250kW arrays, it was doubled due to high demand and increased ambition as new French energy laws were passed.

The additional 400MW will be awarded to projects that submitted their bid before the June deadline. The energy and environment ministry revealed that for the first time, prices for solar electricity fell to the same level as onshore wind. Results will be revealed in the next few weeks.

According to a government statement offers for 2,000MW of capacity were submitted for 200MW of ground-mounted solar, with generally low prices offered by bidders.

Source: Welspun Energy

Solar is catching up with coal in attracting investors in India, according to Deutsche Bank.

Emerging markets

China-style solar ramp up 'just as feasible' in India

India is capable of a sharp ramp up of solar deployment on a level with China's solar spike in recent years, according to the Institute for Energy Economics and Financial Analysis (IEEFA). As of June this year, India had 4GW of installed projects and it now has just seven years to hit its 100GW by 2022 solar target.

This deployment trajectory had been met with some scepticism, "even by key proponents for solar". However, India could replicate China, which had an impressive ramp up of solar installations from 2GW in 2011, to 13GW in 2013, to a targeted 17.8GW in 2015.

IEEFA also forecast that India would install 75GW by 2021-22.

GTM Research: 363MW of PV capacity for Latin America in Q2 2015

GTM Research found that 363MW of new operational capacity for utility-scale PV came online in Latin America during the second quarter of 2015. The new total stands as an 80% improvement year over year, and is the largest quarter for growth in the history of the Latin America market.

En route to bringing several PV projects online, Honduras accounted for 307MW of the region's quarter totals, with the country's solar production receiving a boost thanks to a bonus tariff of 10% over the marginal grid cost for installations completed by the end of July.

With 29MW installed, Chile ranked second amongst Latin American markets, followed by Panama (12MW) and Brazil (11MW).

India solar power investment could surpass coal by 2019-20 – Deutsche Bank

Investment in solar power in India could surpass investment in coal by 2019-20, with US$35 billion already committed by global players, according to a Deutsche Bank report. The focus on solar would be driven by prime minister Narendra Modi's ambitious target of deploying 100GW of solar capacity in the country by 2022.

The report stated: "Private sector interest is decisively moving towards solar from coal power, and we foresee numerous opportunities of fund-raising, yieldco structuring and M&A activity."

Deutsche Bank raised its forecasts for solar capacity additions to 34GW by 2020, up 240% from its previous 14GW projection. Therefore, by 2020 annual solar power capacity additions could also surpass those in coal power projects, which are slowing down.

Egypt announces new tenders for 500MW of solar and wind capacity

Egyptian authorities have announced three new tenders for 500MW of new solar and wind capacity for the West Nile area of the country.

The first solar tender – totalling 200MW of installed PV capacity – will be offered to developers that boast experience in establishing three PV projects with a minimum capacity of 50MW each. Any potential bid must also include a bid bond for EUR4 million (US$4.46 million).

In Egypt's previous solar tender, bids for solar projects were twice oversubscribed – including 2GW of large-scale solar and 300MW of PV projects under 500kW.

Finance

Revised BNEF figures show flat growth in global clean energy investment

Investment in green energy resources globally during Q2 of 2015 was US$73.5 billion, down just 0.2% compared to Q2 2014 (US$73.6 billion), according to revised Bloomberg New Energy Finance (BNEF) figures. This takes the total for the first half of 2015 to US$127.9 billion, down just 3% on H1 2014.

Solar overall saw the highest investment of the different technologies at US$41.9 billion in Q2 2015, up 23% on the second quarter of 2014. Investment in small-scale solar during Q2 was US$20.4 billion, up 29% on the previous year, rising above the flat clean energy investments globally.

China contributed the most investment in clean energy at US$27.9 billion, which was 15% higher than the previous year.

Navigant: PV will be cost-competitive by 2020 in 'significant' portions of the globe

By 2020, solar PV will be "cost-competitive with retail electricity prices in a significant portion of the world", clean technology market consulting and research firm Navigant Research found.

Solar will make more than US$151 billion in annual revenues by 2024. Distributed PV is continuing on its path of becoming a cost-competitive form of energy, and is less often seen now as a premium product deployed for environmentally conscious or feed-in-tariff driven motives. From being a high-cost subsidy-dependent technology, the growing PV market has the "potential to displace other energy technologies".

Buffett project's record low cost part of pricing 'trend', says First Solar

Solar developer First Solar has agreed to sell power at US$0.0387/kWh, thought to be the lowest electricity price for solar ever, according to a filing with the Public Utilities Commission of Nevada.

First Solar's Playa Solar 2 project, located in the Solar Energy Zone in Clark County, Nevada, is expected to be fully operational by December 2016.

First Solar said it believes this level of pricing is reflective of a trend in the US and other parts of the world where lower costs are driving greater demand for solar. The firm said it expected to see more PPAs pricing out at comparable levels.

News

PV market evolution until 2020: The long quest for competitive PV

Gaëtan Masson, Becquerel Institute, Brussels, Belgium

ABSTRACT
The global PV capacity reached 177GW at the end of 2014, and by 2020 the PV Market Alliance forecasts that 630GW of PV could be installed. The entire value chain of the PV industry needs accurate data and a clear vision of how markets could develop in the future in order to avoid repeating past mistakes, and especially the damaging price war that led to a dramatic industry consolidation. The question of PV market evolution will be acute in 2015 and 2017, which will represent the next two important milestones for PV development: for the first time in years, the PV industry could approach its production capacity limits.

Introduction

In January 2015 the PV Market Alliance announced that the global PV market reached close to 40GW in 2014. That figure was later confirmed by the International Energy Agency, while several observers of the PV market continued to bet on a 45GW market, which was never confirmed. This optimistic trend in the PV industry has a tendency to hide the truth and to drive investments in the wrong direction. In the last five years, many decisions have been taken on the basis of the false idea that the PV market could experience a double-digit (or triple-digit) growth every year: Chinese investments which dramatically increased production capacity until 2012 were a clear example of market overestimation that led to dramatic consequences for the entire PV industry.

> "Forecasting an industry that is policy dependent will clearly always involve uncertainties."

In order to avoid repeating the mistakes of the past, the entire value chain of the PV industry needs accurate data and a clear vision of how markets could develop in the future. Forecasting an industry that is policy dependent will clearly always involve uncertainties. Political decisions have always driven the energy sector and will continue to frame it; the rise of prosumers will not transform a strategic industry into a simple consumer's playing field.

An incentives-driven market

If the policy influence on PV market development is looked at more closely, it will be noticed that in 2014 more than 85% of the global PV market was still driven by feed-in tariffs, tax breaks and similar schemes. On the assumption that incentivized self-consumption schemes (including net-metering ones) are also policy dependent, this figure rises to more than 95%. Projects that are popping up everywhere in the world these days rely on political acceptance of

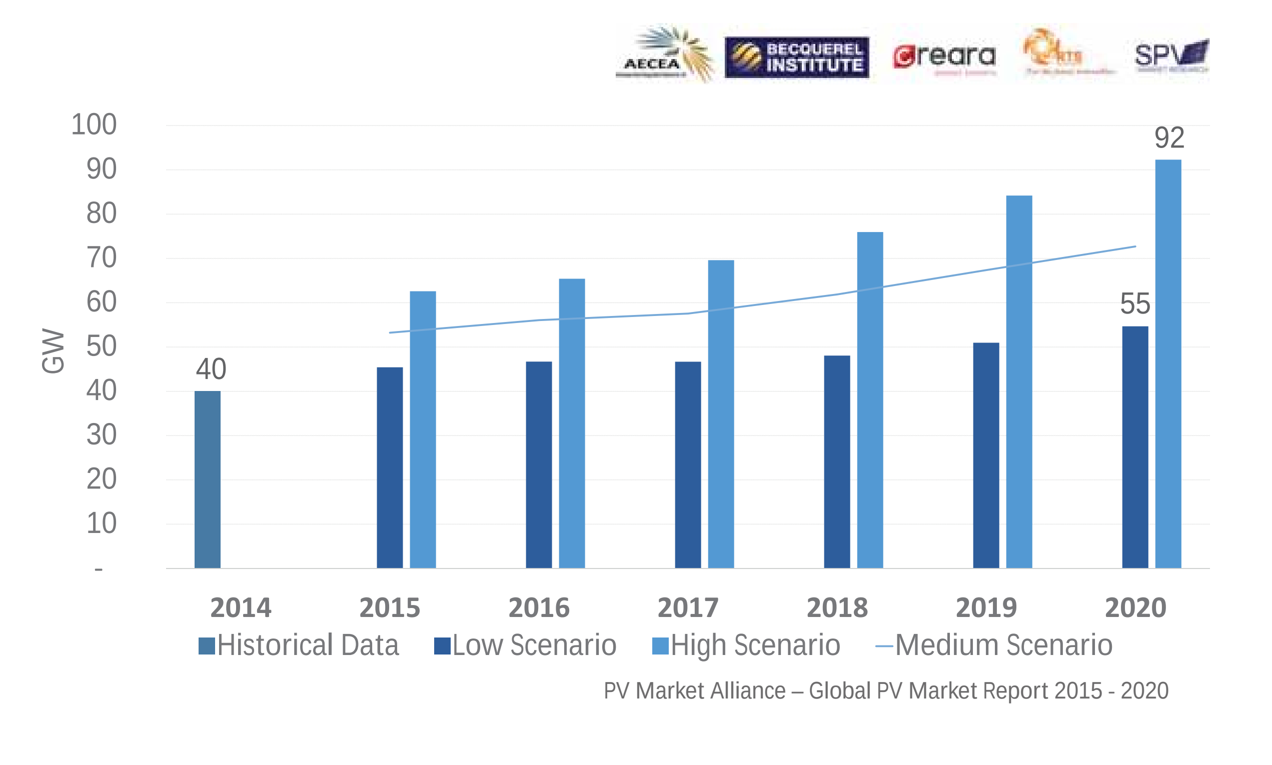

Figure 1. Global PV market evolution 2014–2020.

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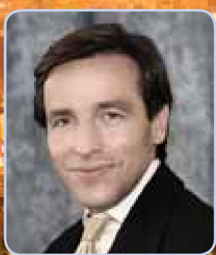

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PV development and, in many cases, on politically organized PV development through tenders or similar regulations.

These aspects of PV development should make all of us extremely humble when we try to forecast the future development of PV. In 2014 three countries where PV development is highly policy dependent achieved two-thirds of all installations: China, Japan and the USA. The deployment of PV in these three countries is the simple consequence of policy decisions that can be modified any time. Of course, we can put money on the increasing awareness of policymakers regarding the need to transition to a low-carbon economy. History has shown us, however, that nothing is ever guaranteed.

In that respect the forecasts for the coming years can vary significantly one way or another depending on the probability associated with negative policy decisions affecting the PV sector. The PV market should reach at least 50GW in 2015 in a reasonable scenario, and could reach 70 to 90GW in 2020 under conditions of positive development in all major regions, including the long-awaited Indian market (Fig. 1).

Six blocks

The global PV market can be split into six groups of countries, with different evolutions and challenges: China, Japan (and similar countries), North America, Europe, India and the remaining emerging PV markets. These six groups should be individually scrutinized and studied using various tools and from different points of view; how these countries influence market development will be seen below.

Perspectives for development

The year 2015 started with the recognition of an expected growth globally. The probability of seeing the market climb up to 50GW is rather high, and exceeding this level will depend mainly on the ability of China to fulfil expectations. With Europe stabilizing, or at best slightly growing, the potential for growth is globally important, since most large markets are expected to progress, and in some cases significantly.

But will we see a market above 50GW in 2015? Starting from around 40GW in 2014, this means we are looking for an additional 10GW. Some of these gigawatts could be expected from the US market, while a large part of additional installations could come from India and, of course, China. The latter installed close to 8GW of PV plants in H1 2015, according to the official figures, and would have to install 10GW in H2 in order to reach 17.8GW. But how would it be possible to achieve much more than 50GW in 2015?

The answer lies in the ability of emerging markets (especially India) to contribute significantly to market growth in 2015. In 2014 the contribution from emerging PV markets – including South Africa, Chile, Thailand, Malaysia, Mexico and Turkey – amounted to less than 3GW. One must recognize that adding 10GW represents a tremendous effort, given the relatively low speed at which emerging markets are growing.

After 2015 the next important milestone for the PV sector will be 2017. The uncertainties remain high from 2017 onwards because of high expectations from emerging markets, including India. Moreover, established markets – such as the USA, Japan and China – could be difficult to forecast after 2017 because of expected or possible policy changes. The fate of the US market, of course, will depend on how the transition from the current ITC programme will stabilize, decrease or push the market to boom. Since the US market is now completely dependent on the ITC (rightly or wrongly), forecasting its development from 2017 consists in assessing the chances of all candidates in the next presidential election – something markedly different from the PV market. However, it can be simply estimated that in the *medium* term, the conditions for a long-term uptake of PV in *some* US states will be met, and the market will find a way to continue developing, most probably driven initially by prosumers. In addition, according to the RTS Corporation estimates, the Japanese market should start to decline from 2017 onwards, which could make 2017 a really challenging year.

During their best year (2011), European markets contributed 23GW of PV installations. Since then, the market has declined 75%, and less than 7GW were installed in 2014. The European markets are expected to stagnate and possibly grow again before the end of the decade, powered by lowered prices and new business models. So far, however, the market has been kept relatively low by the stagnation of electricity consumption, the opposition to renewables in many countries from incumbent players, and the lack of appetite from policymakers for innovative regulations that could unlock PV deployment. Several markets in Europe nevertheless present conditions conducive to renewed growth, but neither investors nor potential prosumers are responding positively. It is expected that it will take years to overcome the negative image that the PV industry acquired in some countries following the bubbles of previous years. In addition, the recognition of the complexity of integrating PV electricity into PV markets is not helping to secure a stable long-term perspective of revenues while the European Commission and several states are pushing for more market integration. The situation can be summarized quite easily: in a policy-dependent sector, the lack of political support at the crucial moment is clearly not helping PV leap into a new development phase in Europe. In that respect, the future of PV in many European countries remains uncertain: many markets that once boomed out of control now have to cope with the disastrous image created by the PV bubble. On account of this, most are not announcing short-term generalized redevelopment.

Solving the competitiveness equation

The super-competitive bids seen in several countries in 2014 and 2015 have highlighted the rapid decline in PV system prices and the subsequent decline in electricity generation cost (LCOE). For PV, the competitiveness battle, however, is far from being won. A few years ago, I used to be the first to criticize the European association of conventional utilities (Eurelectric), which was claiming that PV would become competitive once it could be competitive with the wholesale price of electricity on the market – or, in other words, demonstrate an LCOE below 4 eurocents/kWh. Several years later, we are forced to accept that neither the grid parity (or 'socket parity') nor the more elaborate 'dynamic grid parity' (considering the present value of increasing retail prices) concept has unlocked a post-FiT PV market. On the contrary, most markets that are transitioning from a FiT-driven PV economy (such as Germany or Italy) to a competitiveness-driven PV market are experiencing huge difficulties in keeping themselves afloat. Furthermore, the prospect of adding electricity storage cost to already uncompetitive PV systems appears as an additional threat to that quest for competitiveness.

> "Neither the grid parity nor the more elaborate 'dynamic grid parity' concept has unlocked a post-FiT PV market."

The assessment of competitiveness is relatively easy and depends on several straightforward factors, including the level of solar irradiation, the system cost, the expected OPEX costs, the cost of capital, and finally the reference to which the PV LCOE will be compared.

For prosumers, the road to competitiveness starts with the grid

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parity concept; however, the question of the fair remuneration of the excess PV electricity quickly comes to the table. By definition, net-metering systems are a disguised way of granting feed-in tariffs at the retail electricity price level. The competitiveness for prosumers will therefore depend on their ability to valorize PV electricity in the face of retail electricity prices (minus fixed grid costs and some taxes) and to obtain a fair remuneration. That fair remuneration can be estimated as the value of solar PV electricity on electricity markets, taking into consideration all services provided by PV, from the energy-only value to the additional value of some ancillary services. Such a value can be hard to estimate, but it is certain that PV will have to compete with the market value either at the time of PV production or when the PV plus its storage unit can be sold on the market. In the first case, the value will be quite low, and is expected to decline with additional PV capacities producing at the same time. In the second case, the sale of electricity will occur when the market price is the highest, but the LCOE of the combined PV and storage unit will be much higher than that of a PV plant considered on its own. Looking at countries where PV penetration has significantly increased in recent years, one must admit the target price considered is very low and in no case higher than 5 eurocents/kWh.

In this regard, the competitiveness of PV for prosumers will hardly be reached by selling electricity on the market, but rather by increasing the self-consumption ratio of the installation, provided the complete retail price can be recompensed (which is far from being guaranteed). The countries where the price of retail electricity is quite high – for example, Germany, Denmark, Belgium, Italy and islands powered by GENSED – could be considered the low-hanging fruits of prosumers' competitiveness.

For utility-scale PV, the situation is similar: the sale of electricity to a local company is almost identical to the case of self-consumption by prosumers. Without self-consumption, the remuneration of the electricity that is injected into the grid will depend on either the price on the local electricity market or the average price of alternative electricity sources. The first countries where utility-scale plants could be competitive will therefore be those with a rather costly electricity mix at the time of PV production. In a nutshell, the upshot is that utility-scale PV will only develop without incentives in these countries, and will require incentives and guaranteed long-term PPA in others.

Who bears the risks?

If we accept the fact that 95% of the PV market to date remains policy dependent, and that the *real* competitiveness of PV has not yet been reached, forecasting the PV market consists in analysing the ability of the PV industry to offer products and services that will cope with existing regulatory frameworks and the limited competitiveness of PV solutions in today's energy world.

One element should be mentioned: the most competitive winning bids seen for tenders in 2014 and 2015 were achieved because of an extremely low cost of capital and often a high debt ratio. One must therefore admit that these projects will be risk free and that investors will be remunerated at a very low level. But any observer of the recent developments in the PV industry knows that PV is far from being a risk-free investment these days. Uncertainties linked to quality or to behaviour in hot and humid climates, or simply political uncertainties, should be associated with some risk premiums that are not reflected in these tenders. In this respect, the question of the real competitiveness of PV solutions in *normal* cases (and not emblematic tenders) remains more complex than it appears. The perspectives of non-incentivized market development should therefore be carefully assessed.

Industry evolution

The question of market evolution in the future is rather an important one, because for the first time in years, the PV industry could approach its production capacity limits. According to official numbers published by several observers of the PV industry, the production capacities could be as low as 40GW or higher than 60GW. Of course, such a wide estimate does not help much in taking the right investment decisions. In that respect, a future expected market increase should (or should not) trigger investments in new production capacities. As we have seen in the past, in several countries the uncertainties remain high for years to come; moreover, while the PV industry generally loves optimistic forecasts, this should not hide the challenges it is currently facing, and will face in the future

> "Forecasting the future of the PV market will be crucial in the coming years."

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One of these challenges is the question of the evolution of existing production lines in order to move to higher efficiencies. The announcements in recent months of upgrades towards PERC or similar concepts show that the heaviest part of the consolidation is coming to an end, and companies are returning to profitability and envisaging the future. In that respect, correctly forecasting the future of the PV market will be crucial in the coming years, so that the right investments in the PV value chain can be identified. The quest for higher efficiencies, as well as improving the reliability of all components, will be extremely important.

Forecasts

When all these points are considered, if the most optimistic scenario is uncertain, the most pessimistic one would imply a market stagnation in the coming years at a level of around 50GW. This scenario assumes that the development of PV in an established market would decrease, while the growth of emerging markets would take longer than expected.

The most probable scenario, however, given the global economic situation, consists in a moderate growth that would bring the global PV market from the 40GW attained in 2014 to 50GW in 2015, and to 70GW in 2020. PV could, of course, grow more rapidly than this anywhere in the world under the right incentives and framework conditions, and this is what we would all like to see. The conditions are complex, however, and competitiveness requires complex conditions as well; these intricacies, coupled with the fact that countries where PV is beginning to develop experience different economic and social conditions from those in the pioneering countries, could delay the expected PV deployment.

About the Author

Gaëtan Masson is the director of the Becquerel Institute, the operating agent of the IEA-PVPS Task 1 research programme and the vice-president of the EU PV technology Platform. The PV Market Alliance, publisher of the Global PV Market Report, is a partnership between Becquerel Institute, Creara, AECEA, RTS Corporation and SPV Market Research.

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The PV-Tech Blog
By Tom Kenning

Solar accounts for 1% of global electricity, how long will the next 1% take?

Solar energy's vital role in the global energy mix has been secured after recent figures showed it now accounts for 1% of all global electricity demand. This is the equivalent of 33 large, coal-fired power plants of 1GW. The 1% milestone has been a long time coming, but it finally puts to bed the question of whether solar is a mainstream renewable energy source. With the lure of solar power generation spreading worldwide, how long will it be until it reaches the next landmark of 2%?

Solar Power Europe's 'Global Market Outlook for Solar Power 2015-2019' report, which announced the 1% milestone, found that global solar capacity is now 178GW, which is 100 times more than it was 14 years ago.

GTM Research solar analyst Adam James told PV Tech that he expects global installed capacity to double by 2017. Thus, while it took 14 years to reach the 1% figure, solar will take just two years to reach close to 2%. However, James admitted that, in this case, GTM's forecasts are more optimistic than others.

Josefin Berg, senior analyst solar power at IHS Technology told PV Tech that she also expects global installed capacity to double in 2017/18, however, in the same period, overall power generation will increase worldwide. Furthermore, large-scale solar deployment in areas with poor solar irradiation won't make a huge difference in reaching that 2% mark. As a result, IHS forecasts that solar will account for 2% of global electricity demand sometime before 2021.

China, Japan and the US are consistently cited as the main drivers of solar installations in 2015, and analysts agree that plenty is riding on China to keep the market growing. For example GTM's latest report said that the Asia Pacific region will install 50% of all solar capacity in 2015 with China accounting for half of that. Clearly any change in policies that support solar in China is the biggest risks facing PV growth.

On the other hand, while there is a big rush to install PV in the US before the ITC tax credit expires, Berg said that any prolongation of this tax credit or an introduction of a grace period for certain projects could significantly help accelerate the PV market.

Meanwhile, in the background, developing countries are increasingly being earmarked as potentially major solar players. The key question with all of these emerging markets is when?

Finlay Colville, head of market intelligence at Solar Media's new Solar Intelligence Group, said: "Reaching the 1% figure may seem rather small, but solar has barely touched most countries and regions globally. Until now, it is mostly contributions from a few individual countries that has driven deployment to this mark. Getting to 2% will likely see a much broader spread of countries adopting solar, in particular across the Middle-East, Africa and Latin America."

James said that when you aggregate all of the smaller developing markets together, they will go from accounting for 1% of solar today to 17% over the next five years, marking a significant shift in the spread of the market.

India, with its enormous 100GW by 2022 target, could surprise all the doubters and contribute to a fast-approaching 2%, buoyed by the latest US$20 billion investment in the country's renewable energy market by Japanese telecoms provider-turned solar developer Softbank. On the other hand, it could stall, hampered by the classic barriers of poor grid infrastructure, land availability and financing.

Source: BHE Renewables

For solar to reach 2% of global electricity demand will be about more than just installing new capacity.

Berg said Chile is installing 1GW this year but is likely to calm down as a relatively small power market, while Brazil will only start impacting the global market in 2018.

More importantly, James highlighted that it is not yet known how fast solar can grow, with markets in Latin America having grown far faster in the early stages than Europe or Asia Pacific ever managed to. He added: "Looking at historical installation figures does not give you any kind of guidance for the future."

Clearly continued price declines in solar equipment and installation will play a major part in the transition, but in order to see the forecast levels of growth, James said companies must shift from the subsidised model to a customer focus.

In the old business model, mostly driven by feed-in tariffs, companies were largely insulated from market forces and they did not have to be particularly customer focused. Nowadays, however, without being able to rely on governments as an off-taker, firms must go out and find clients while competing with other energy sources and solar providers.

The result is the introduction of new financing vehicles such as yieldcos and securitization in order to bring in capital, keep projects moving, and make prices more competitive.

Meanwhile, new regulatory structures that are designed for more than one type of energy resource will be key to help integrate the intermittency of solar power generation.

James said: "What worked in the past isn't necessarily going to work in the future." He added that this is why Europe, which may no longer be the largest solar market in the world, will still be critical as a pioneer of these developments in the solar model.

Reaching 2% of global electricity demand, is not simply a case of installing enough solar capacity, for with the rise of energy storage technologies, optimising the use of solar within grids could become a key accelerator.

Colville said: "The shift will be from installed capacity to energy supply, and this may see solar's overall contribution being even more important than the 1% figure of today suggests."

Tom Kenning is a reporter for solar Media, publisher of Photovoltaics International

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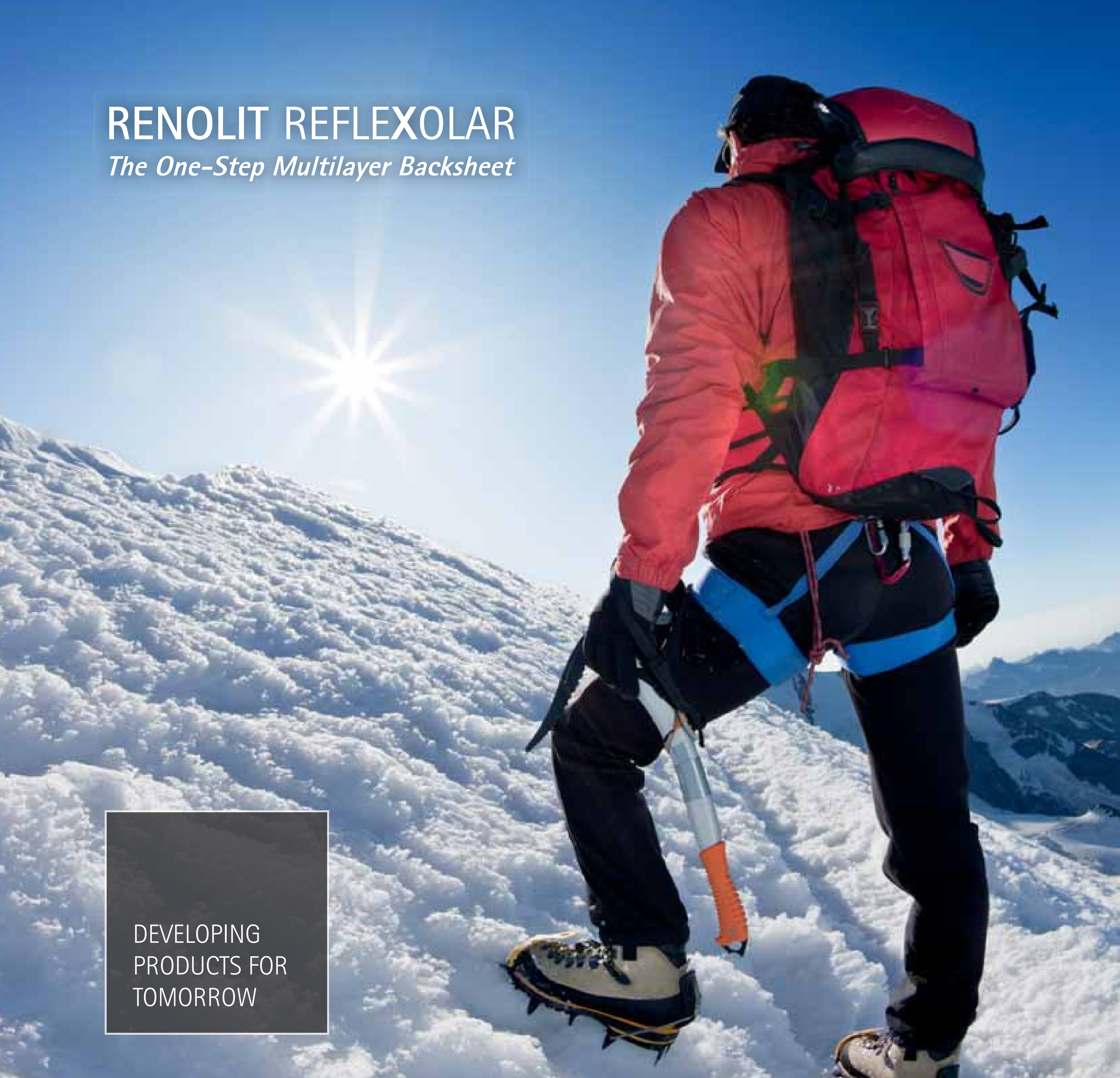

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