Technologies for mass production of PERC and MWT solar cells

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ABSTRACT

Over the last few years several technologies have been investigated with the aim of reducing recombination in emitters and at passivated surfaces. Because of its high efficiency potential, the passivated emitter and rear cell (PERC) design is of interest to both cell manufacturers and R&D institutes all over the world. Another cell design of interest is the metal wrap-through (MWT) solar cell, where the absence of front busbars leads to reduced shading. The MWT technology, especially when combined with rear-surface passivation, has the potential to significantly decrease the cost of ownership of today's solar cells. This paper gives an overview of the current status of the production technology for the fabrication of PERC and MWT-PERC solar cells, as well as a summary of recently published papers in this field.

Introduction

Since the initial work of Blakers in 1989 [1], many research institutes, universities and R&D departments have reported on progress in surface passivation, simplified process sequences and novel technologies targeted at an industrial fabrication of high-efficiency p-type passivated emitter and rear cell (PERC) structures [2,3]. Whereas the front side of PERC-type cells, and of standard H-pattern silicon solar cells with an aluminium back-surface field (Al-BSF), is identical, the former feature a dielectrically passivated rear surface with local contacts. A different solar cell structure that addresses changes in the front contact layout is the metal wrap-through (MWT) concept [4], in which the external busbar contacts are moved from the front to the rear, resulting in reduced shading. To benefit from reduced shading, only one additional process step – namely via drilling – is necessary for combining MWT with PERC [5] to yield high-efficiency MWT-PERC structures.

Since both MWT and PERC structures attract increased market attention owing to their high conversion efficiencies, this offers the possibility for increased €/Wp module prices and yet potentially reduced system cost with these premium products.

In recent years solar cell and equipment manufacturers have suffered from massive overcapacity in the PV market. The resulting decrease in the cost of solar modules wiped out margins and led to several companies leaving the PV business. The dramatic fall in price of solar modules has only recently slowed, let alone stopped. An increasing book-to-bill ratio of equipment vendors indicates that there might be some light at the end of the tunnel. Some forecasts anticipate increased equipment orders in 2014 for new production lines or for the retrofitting of existing ones.

This paper presents a brief overview of the different equipment that might be included in these lines for the fabrication of PERC and MWT-PERC solar cells; an update of recently published papers is also given. The scope of the paper is limited to solar cells fabricated from p-type silicon wafers; for an overview of n-type technology, the reader is referred to a recent article by Kopecek and Libal [6].

Solar cell structures

Fig. 1(a) shows a schematic cross section of a standard p-type Al-BSF solar cell with a full-area aluminium rear contact; an industrial p-type PERC solar cell with a passivated rear side and local contacts is shown in Fig. 1(b). The front side – namely the texture, emitter, anti-reflective coating (ARC) and front grid – of both solar cell structures is identical and may feature a selective emitter (SE).

Fig. 2 (top) shows the most prominent MWT structures without and with rear-surface passivation. In an attempt to further streamline the process sequences and reduce cost, new structures that omit the emitter on the rear and/or in the via have been developed (Fig. 2, middle and bottom): these have been proposed for BSF solar cells by Weiwei [7], and

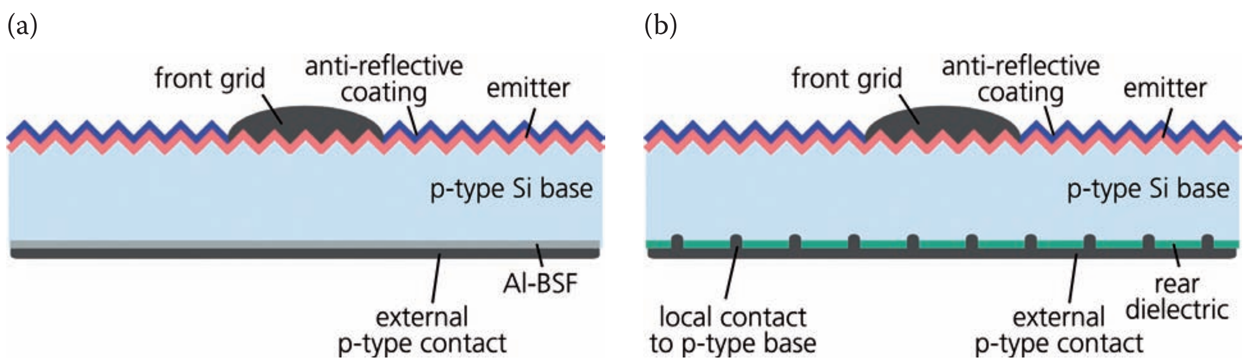

Figure 1. Schematic cross section of (a) a standard p-type Al-BSF solar cell, and (b) an industrial p-type PERC solar cell with local contacts.

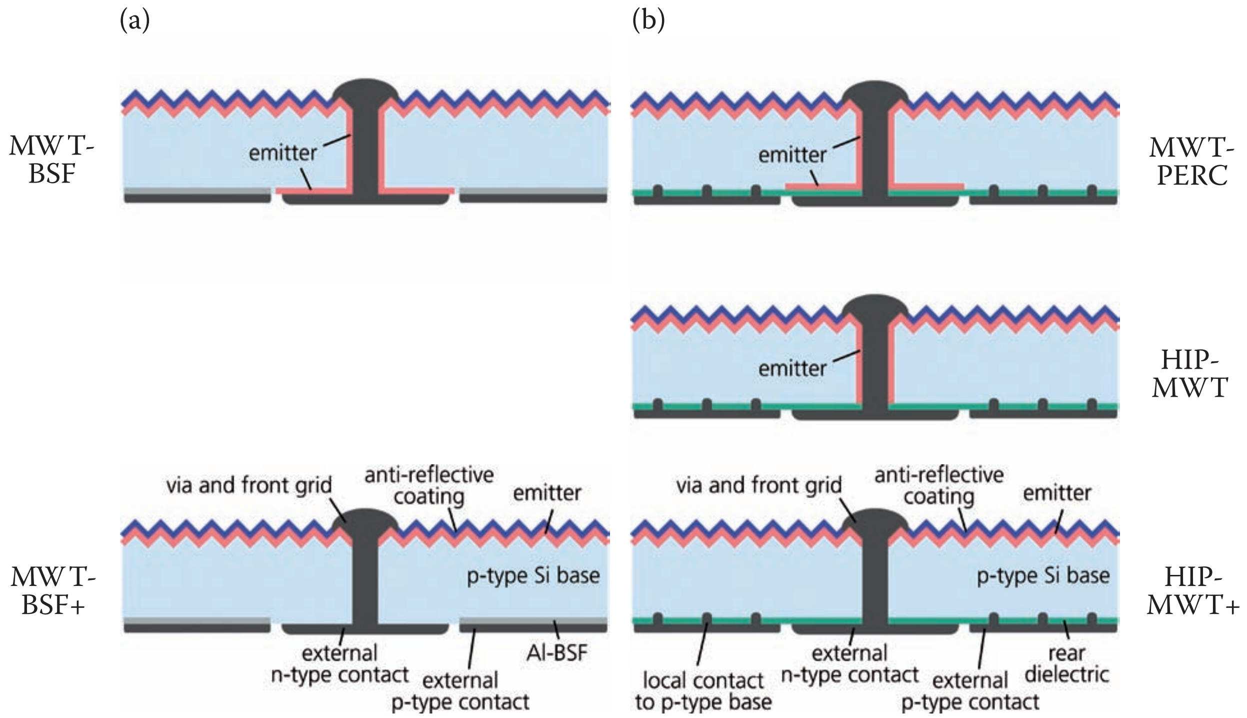

Figure 2. Overview of various MWT structures for p-type silicon wafers (a) without and (b) with rear-surface passivation. MWT-BSF+ denotes a simplified MWT-BSF structure without via and rear emitter, as proposed by Weiwei [7]. The high-performance MWT (HIP-MWT) approach [8] is a simplified version of the conventional MWT-PERC structure without rear emitter. A further simplified structure, without even a via emitter, is referred to as HIP-MWT+ [9].

for MWT solar cells with rear-surface passivation (MWT-PERC) [10] by Thaidigsmann (HIP-MWT+) [9,11]. Apart from the adapted contact layout, all other technologies known from Al-BSF or PERC fabrication sequences – for example emitter diffusion, selective emitter formation or surface passivation – can also be applied to MWT solar cells.

> "In principle, it is straightforward to integrate MWT cell fabrication into existing p-type Al-BSF or PERC production lines."

In principle, it is straightforward to integrate MWT cell fabrication into existing p-type Al-BSF or PERC production lines. The only additional process step is the drilling of vias [5], typically by a laser process, for example after surface passivation. Via metallization is then performed during the printing of the rear solder pads, using an adequately formulated via paste. As a result, retrofitting of production lines for conventional H-pattern solar cells is becoming more and more attractive – the front-end process sequence is the same as for H-pattern solar cells. It has recently been shown that some issues arising from the rear n-type contact might be overcome by omitting the via and rear emitter in these structures [9,11], which has been corroborated by the work of other authors [7,12]. The most important topic for future investigations is the long-term reverse-bias stability. Preliminary results indicate the existence of via pastes which do not show increasing leakage current after reverse loading [13,14]. Regarding reverse-bias stability, MWT solar cells without a rear emitter even offer the promising possibility of an integrated bypass diode functionality at no extra cost – its implementation only requires a specially adapted via paste composition [15]. From the point of view of the authors, solutions to all MWT-technology-related issues exist. An overview of the status of MWT solar cells and module technology can be found in the literature [9,16].

Several technologies that may be implemented for the fabrication of high-efficiency PERC or MWT devices will be discussed next.

Technologies

Emitter formation

As both p-type Al-BSF and PERC solar cells feature a phosphorus-doped emitter, advances in emitter formation are not solely limited to PERC solar cells. However, as rear-surface passivation leads to a lower overall recombination rate than for Al-BSF solar cells (and thus a higher open-circuit voltage), PERC solar cells especially benefit from low-recombination emitters. Furthermore, calculations show that, for industrial-type high-efficiency PERC solar cells, the recombination in the emitter region forms the largest contribution to the total [17], which highlights the necessity for process improvements in this field.

Because of its robustness and simplicity, atmospheric pressure diffusion of $POCl_3$ in tube furnaces is still the workhorse for emitter formation in the silicon solar industry. One quartz boat typically holds 200 to 250 wafers; back-to-back loading or the use of half-pitch boats is known to further increase throughput. An evolution of this process is low-pressure $POCl_3$ diffusion [18], which is considered to yield improved homogeneity over the wafer and boat, with boat capacities of 500 to 1000 wafers.

Recently, ion-implanted emitters have also come into the spotlight [19,20] owing to their precise junction control and low dark saturation current densities. The latter characteristic also results from thin thermal-oxide passivation layers that are grown during the required high-temperature step for crystal damage annealing and dopant activation. Another advantage of ion implantation is the elimination from the process chain of the phosphosilicate glass (PSG) layer removal and edge-isolation steps. Both atmospheric and low pressure diffusion, as well as ion implantation, are already up and running in production.

Methods for selective emitter formation include laser doping from PSG [21], the application of a dopant paste [22], and etch-backs of highly doped emitters, either by the activation of an etching paste [23] or in a liquid [24] or a gas phase [25]. Selective emitters, however, have lost some of their attraction, owing to the ability of the newest silver paste generations to also contact lightly doped emitters, with phosphorus surface concentration of $1{\bullet}10^{20}$ to $2{\bullet}10^{20}cm^{-3}$. If, in the race for the highest efficiencies, phosphorus surface concentrations below $10^{20}cm^{-3}$ and high-quality surface passivation layers are used, selective emitters can still demonstrate notable advantages over homogeneous emitters [17] because of improved shielding of contact recombination, which results in a higher open-circuit voltage.

> "Selective emitters can still demonstrate notable advantages over homogeneous emitters."

For further information on phosphorus emitters, the reader is referred to the article by Dullweber et al. [26].

Rear-surface passivation

A major difference between Al-BSF and PERC solar cells is the existence of a dielectrically passivated rear side, as indicated in Fig. 1. For decades the thermal oxidation of silicon has been the standard technology in the semiconductor industry for the passivation of n- or p-doped surfaces; it was also used in the first PERC cell by Blakers et al. [1]. The very good passivation quality of the thermal oxide layers results from the growing of the dielectric in the wafer at high temperatures (700°C < T < 1050°C) in an atmosphere containing O_2 or H_2O gas; this yields very low interface trap densities and a low density of fixed *positive* charge at the Si/SiO_2 interface ($Q_f < 5{\bullet}10^{11}cm^{-2}$). The positive charge depletes or weakly inverts the p-type surface. Recently, several institutes have applied thin thermal oxide layers grown at 800°C < T < 900°C for rear-surface passivation [27,28]. A promising synergic approach is the combination of ion implantation and thermal oxidation for rear-surface passivation into a single process sequence [29,30].

Nevertheless, most institutes and companies currently report on the use of Al_2O_3 passivation layers for achieving low surface recombination velocities on lightly doped p-type surfaces. The excellent passivation quality results from a high density of fixed *negative* charge at the Si/Al_2O_3 interface ($|Q_f| > 3{\bullet}10^{12}cm^{-2}$), which leads to an accumulation of majority carriers at the interface. High-throughput production equipment for these layers is available from several manufacturers: it mainly relies on atomic layer deposition (ALD) [31], plasma-enhanced chemical vapour deposition (PECVD) [3,32] or atmospheric pressure CVD (APCVD) [33]. Since very low surface recombination velocities have been reported with all technologies [34–36], the technology of choice might be a question of cost, material consumption, homogeneity, throughput and uptime rather than conversion efficiency.

In contrast to this, SiN_x layers with a refractive index $n > 2.4$

Company/Institute	Cell type	Front side	Rear side passivation	η [%]	V_{oc} [mV]	j_{sc} [mA/cm^2]	FF [%]
Hyundai (2013, [2])	LCO, Cz-Si		ALD Al_2O_3	20.1	650	39.0	79.2
Sunrise (2013, [3])	LCO, Cz-Si		PECVD Al_2O_3	20.3*	658	39.0	79.2
imec (2013, [27])	LCO, Cz-Si	Thermal SiO_2	Thermal SiO_2	20.1*	650	38.8	79.8
ISFH (2013, [19])	LCO, Cz-Si	Ion-implanted emitter + thermal SiO_2	ALD Al_2O_3	20.0	659	38.7	78.3
ISFH (2013, [25])	LCO, Cz-Si	Gas phase etched-back emitter	ALD Al_2O_3	20.3*	660	38.3	80.3
Q-Cells (2011, [51])	LFC, mc-Si			19.5*	652	38.9	76.7
Q-Cells (2011, [51])	LFC, Cz-Si			20.2*	652	38.9	79.9
ISE (2013, [52])	LFC, cast-mono	Thermal SiO_2	Thermal SiO_2	19.8*	654	39.0	77.6
Schott (2012, [53])	LCO, Cz-Si		MW-PECVD	21.0*	664	39.9	79.2

* Independently confirmed by Fraunhofer ISE CalLab PV Cells.

Table 1. Published results for 156mm p-type PERC solar cells with screen-printed contacts.

and SiO_xN_y passivation layers [37] make use of a high density of fixed *positive* charge at the interface ($Q_f > 2 \bullet 10^{12} cm^{-2}$). These layers drive the surface into a state of strong inversion, which leads to surface recombination velocities similar to those for Al_2O_3 layers. SiN_x layers are typically deposited at intermediate temperatures using PECVD technology in a direct or remote plasma configuration; however, when these layers are applied for rear-surface passivation in p-type PERC solar cells, inversion layer shunting [38] must be prevented.

In general, all rear passivation layers are formed with a thickness of around 5 to 20nm, followed by the deposition of other dielectric capping layers for improved optics and surface passivation, as well as for preventing alloying of the screen-printed aluminium layers through the passivation layers [2,39]. In some approaches, the deposition of the passivation and capping layer takes place in the same system, with the aim of reducing cost.

It should be added that a rear-surface conditioning process is typically carried out before surface passivation, to prevent the formation of a rear texture [19] or, at least, to partly remove it [12,28,29]. In some process flows, rear polishing is implemented in the wet chemical edge-isolation step [25,31].

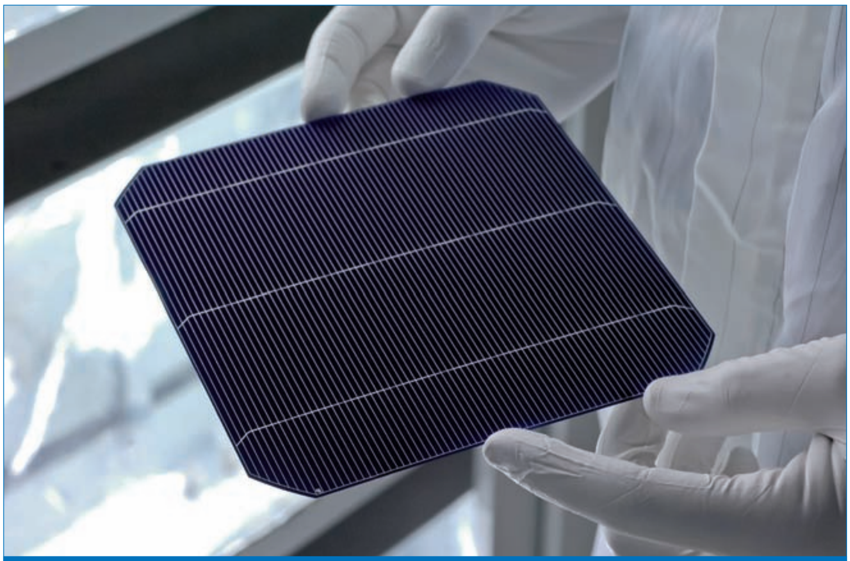

Figure 3. Photograph of a 156mm Cz-Si HIP-MWT solar cell fabricated at Fraunhofer ISE.

Contact formation

A second difference between Al-BSF and PERC solar cells is the metallization fraction of the rear side. Whereas Al-BSF solar cells feature a fully metallized and contacted rear surface, PERC solar cells feature only local contacts. To the authors' knowledge, only two approaches for local contacting are currently in production. The first approach makes use of laser-fired contact (LFC) technology, in which a laser locally alloys the rear point contacts through the passivation layer after contact firing [40]. The second approach is the local contact opening (LCO) concept [41], in which the rear passivation layers are locally opened by laser ablation or etching pastes before aluminium metallization and local contact alloying during contact firing. Several contact layouts have been reported, for example point, line or dash contacts.

The large majority of silicon solar cells fabricated throughout the world feature screen-printed contacts; however, in the race to achieve reduced shading, lower series resistance values and reduced silver consumption, other approaches are under investigation. To the authors' knowledge, print-on-print and dual print (printing of silver fingers and non-contacting busbars in two process steps using different silver pastes) are already up and running in production lines, whereas stencil printing, inkjet printing [42] and flexographic printing [43] of a metal paste have not yet been implemented in industrial manufacturing.

Two other approaches aim at eliminating the front busbars, similarly to the MWT approach. Both the 'SmartWire' [44] and the 'Multi Busbar' [45] approaches use a metal net applied perpendicularly to the silver finger grid in order to directly contact each silver finger. Compared with the MWT approach, the drawbacks are higher shading values and the necessity to still guide the interconnector from the front of a solar cell to the rear of the adjacent cell, which makes module assembly more complex.

Company/Institute	Cell type	Cell area [cm²]	Comment	η [%]	j_{sc} [mA/cm²]	V_{oc} [mV]	FF [%]	j_{-12V} [mA/cm²]
Kyocera (2008, [56])	MWT-BSF, mc-Si	233	RIE texture	18.3*	37.2	626	78.5	
ECN (2012, [57])	MWT-BSF, mc-Si	243		17.9	36.4	632	77.8	
Bosch (2011, [58])	MWT-BSF, Cz-Si	-	Selective emitter (SE)	19.4				
Canadian Solar (2013, [7])	MWT-BSF+, cast-mono Si	243	SE	19.6	39.0	639	78.7	2.45
Fraunhofer ISE (2011, [5])	HIP-MWT, mc-Si	243	PECVD-Al_2O_3	18.2*	36.9	637	77.3	2.55
Fraunhofer ISE (2011, [59])	MWT-PERC, FZ-Si	149	SE, thermal SiO_2, dispensed front grid	20.6*	39.9	661	78.3	4.65
Fraunhofer ISE (2012, [60])	HIP-MWT, mCz-Si	239	SE, thermal SiO_2, stencil-printed front grid	20.2*	39.2	661	78.0	2.75
Fraunhofer ISE (2012, [61])	HIP-MWT+, FZ-Si	149	SE, thermal SiO_2	20.3*	39.2	664	78.1	4.71
Canadian Solar (2013, [12])	Sim. HIP-MWT+, Cz-Si	239	Average values, SE, ALD Al_2O_3	20.6	40.0	661	77.9	

* Independently confirmed

Table 2. Published MWT solar cell results for p-type silicon wafers (mCz denotes magnetic-field-assisted Cz growth).

For MWT solar cells there is no stress on the front contacts during soldering: this promotes the use of very thin silver fingers with reduced contact adhesion requirements, formed (for example) by dispensing [46] or direct plating technology. Industrial solutions for the in-line annealing of contacts are already available [47].

Solar cell results

The implementation of a dielectrically passivated rear side with local contacts leads to an increase in conversion efficiency of 0.5 to 1.0% abs. compared with solar cells with a full-area Al-BSF rear contact, as reported by several authors [48–50]. Table 1 lists a selection of recently published results for large-area p-type PERC solar cell results with screen-printed contacts. From this table it is evident that, on Cz-Si, conversion efficiencies exceeding 20% have been achieved using several approaches. High-quality surface passivation layers and emitters yield open-circuit voltages of 660mV and short-circuit current densities close to 39mA/cm². Moreover, Table 1 indicates the remarkable progress achieved in the fabrication of high-quality multicrystalline and cast-mono wafers, which demonstrate open-circuit voltages above 650mV and conversion efficiencies approaching 20%.

The highest conversion efficiencies of PERC solar cells have in the past been reported by R&D groups at universities and research institutes. In the last few years, with solar cell manufacturing growing into a multi-billion dollar market, most companies have established their

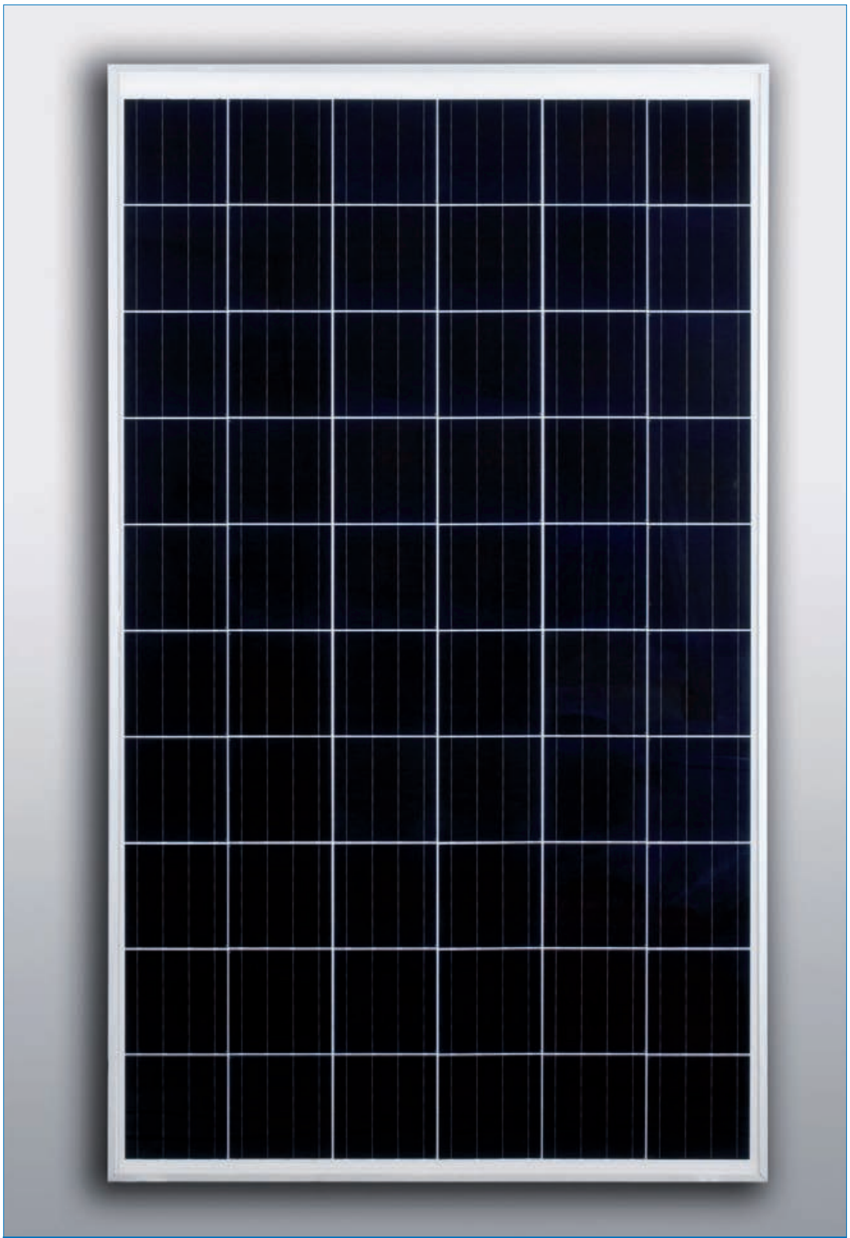

Figure 4. Photograph of a 60-cell HIP-MWT module with an output power of 277Wp (independently confirmed by Fraunhofer ISE CalLab PV Modules).

own R&D departments alongside their conventional production line business. Supported by the process fine-tuning that is possible when processing thousands of wafers per hour, industrial manufacturers now seem to have achieved at least the same conversion efficiency level for industrial-type PERC solar cells: indeed, at the EU PVSEC conference in Paris in 2013, several cell and production equipment manufacturers reported pilot-line and production conversion efficiencies of above 20% on Cz-Si.

"MWT technology allows an efficiency gain of up to 0.5% abs. compared with H-pattern solar cells."

Fig. 3 shows a photograph of a 156mm-size p-type Cz-Si HIP-MWT solar cell from Fraunhofer ISE. As reported by several authors, MWT technology allows an efficiency gain $\Delta\eta$ of up to 0.5% abs. compared with H-pattern solar cells [5,54,55]. A selection of recently published representative MWT results, both from industry and institutional research, is listed in Table 2. Very high conversion efficiencies of up to 19.6% [7] without and 20.6% [59] with rear-surface passivation have been reported. A calculation based on realistic assumptions of specific process improvements reveals that stable conversion efficiencies beyond 21% on p-type monocrystalline silicon wafers are possible with MWT-PERC-type structures [62].

Although several companies have been working on MWT technology [63,64], the concept has not yet been brought into mass production; this shortcoming is attributed to the lack of an economically feasible module interconnection technology in the past. Foil-based approaches [65] have been commercialized [66], but it has not been until now that competitive prices have been announced by producers of suitable structured backsheets. Owing to its reliability, cost effectiveness and similarities to conventional module interconnection, ribbon-based interconnection [67] is also the centre of interest for equipment manufacturers [68]. Together with industry partners [68], ISE has successfully demonstrated the ribbon-based module integration of HIP-MWT+ solar cells into a 60-cell demo module with an output power of 277Wp (see Fig. 4).

"MWT solar modules are expected to be widely available within the next few years."

Conclusions

This paper has summarized the current status of p-type PERC and MWT-PERC technology and solar cells. Several technologies were discussed that might be included in the newest generation of production lines for manufacturing high-efficiency PERC and/or MWT-PERC solar cells; the latest published cell results for both of these structures were summarized. Whereas solar modules fabricated from PERC solar cells are already commercially available, which underlines the maturity of this product, MWT – and particularly MWT-PERC – solar cells have not yet made the transition to high-volume production, although only one additional process – the drilling of vias – is required to make the benefits of reduced shading accessible. This is attributed to the lack of an economically feasible module interconnection technology in the past. Since all cell-related issues seem to have been resolved and production equipment is currently ready for use, MWT solar modules are expected to be widely available within the next few years.

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