Industrial implementation of bifacial PERC+ solar cells and modules: Present status and future opportunities

Thorsten Dullweber, Henning Schulte-Huxel, Susanne Blankemeyer, Helge Hannebauer, Sabrina Schimanke, Ulrike Baumann, Robert Witteck, Robby Peibst, Marc Köntges & Rolf Brendel, Institute for Solar Energy Research Hamelin (ISFH), Emmerthal, Germany, & Yu Yao, Meyer Burger Technology AG, Gwatt (Thun), Switzerland

Abstract

Since its first publication in 2015, the PERC+ cell concept, which is based on a passivated emitter and rear cell (PERC) design with a screen-printed Al finger grid on the rear, has been rapidly adopted by several solar cell manufacturers worldwide. The rapid industrial implementation of bifacial PERC+ cells is facilitated by the very similar process technology to that of mainstream monofacial PERC cells. Conversion efficiencies of industrial PERC+ solar cells of up to 22.1% (ISFH) with front-side illumination, and of 17.3% (LONGi) with rear-side illumination, have been reported. Meanwhile, four companies offer commercial bifacial PERC+ modules with a maximum rated power of around 300Wp when illuminated from the front side only. These modules incorporate 60 PERC+ cells with four or five busbars, which are interconnected by conventional stringing and tabbing technology. The first small-scale outdoor installations have confirmed an increase in energy yield relative to monofacial PERC modules of between 13 and 22%. Two large-scale outdoor installations with peak capacities of 2MWp and 20MWp are currently under construction in Taiwan and China respectively. A novel bifacial PERC+ prototype module that uses Smart Wire Connection Technology (SWCT) is reported in this paper: a set of 18 halved PERC+ solar cells are interconnected by soldering 18 wires directly to the Ag front and Al rear fingers. The resulting prototype module exhibits independently confirmed front- and rear-side efficiencies of 19.8% and 16.4% respectively. Additionally, Meyer Burger has certified a full-size PERC+ SWCT module in accordance with the IEC 61215 norm, thereby demonstrating the long-term reliability of this novel module technology.

Introduction

The PV industry is currently undergoing a conversion of its production capacity from silicon solar cells with a full-area aluminium rear contact to passivated emitter and rear cells (PERCs) [1,2]. Accordingly, the PV technology roadmap ITRPV [3] forecasts an increased market share of PERC solar cells from the current 15% to 60% by 2027. These industrial PERC cells employ p-type wafers and a full-area screen-printed aluminium (Al) rear layer which only locally contacts the silicon wafer in areas where the rear passivation has been removed by laser contact opening (LCO) [2]. The full-area aluminium layer prevents any transmission of sunlight from the rear side into the silicon wafer and hence precludes any bifacial applications of these industrial PERC cells. This is unfortunate because there is a growing interest in bifacial solar cell concepts for several applications, such as in PV power plants, where the produced electricity can be increased by up to 20% using bifacial solar modules instead of monofacial ones [4,5]. Accordingly, the PV technology roadmap ITRPV predicts a market share of bifacial solar modules of 30% by 2026 [3].

"PERC+ cells can increase energy yield by up to 25% because of their bifacial nature when integrated in glass–glass modules."

At the moment, industrial bifacial solar cell concepts mainly utilize n-type wafers, such as passivated emitter and rear totally diffused (PERT) solar cells [6–9]. However, a challenge for these bifacial PERT cells is that they typically require screen-printed silver (Ag) finger grids on both sides of the wafer, and hence consume a significant amount of expensive Ag paste. Moreover, the n-PERT cells use single-sided boron and phosphorus doping, which requires additional or alternative process steps compared with those involved in p-type PERC cell processing; as a result, manufacturing costs may be higher.

In 2015 ISFH, in parallel with SolarWorld, introduced a bifacial PERC solar cell called *PERC+* [10], which employs a screen-printed Al finger grid on the rear side, enabling front-side efficiencies of up to 21.5% and rear-side efficiencies of up to 16.7% [11]. Depending on the specific installation conditions at a PV power plant, PERC+ cells can increase energy yield by up to 25% because of their bifacial nature when integrated in glass–glass modules [10,12]. Another potential application is building-integrated PV, where bifacial PERC+ cells could provide a more aesthetically pleasing appearance than solar cells with a full-area Al layer [13]. SolarWorld has pioneered the mass production of bifacial PERC+ cells [14]. Meanwhile, several other solar cell manufacturers have introduced bifacial PERC+ into large-volume production and are now offering commercial bifacial glass–glass modules incorporating PERC+ solar cells.

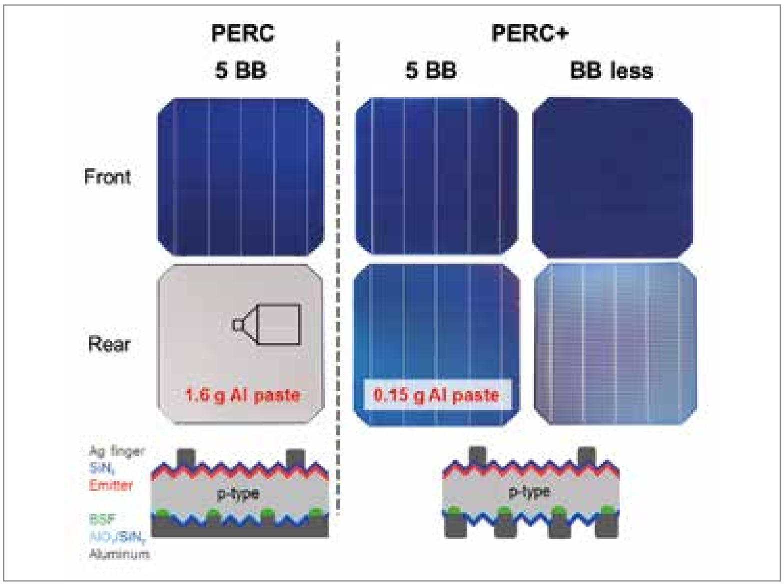

Figure 1. Photographs of the front and rear sides, as well as schematic cross-section drawings, of industrial PERC and PERC+ solar cells. PERC+ cells enable bifacial application and reduce the Al paste consumption, while using the same processing sequence as industrial PERC solar cells.

This paper provides an overview of the status of the implementation of the PERC+ solar cell concept in industrial solar cell and bifacial module production. The first section explains the process technology of PERC+ solar cells, summarizes the published front- and rear-side efficiencies of industrial PERC+ solar cells, and highlights the implications of the Al finger print for the Al-Si alloying process and Al contact formation.

The next section, on commercial PERC+ modules and field installations, outlines the status of commercial bifacial PERC+ glass–glass modules applying conventional tabbing and stringing interconnection technology, which have just recently been made available by several solar cell manufacturers. In addition, that section presents examples of the first outdoor field installations of bifacial PERC+ modules on rooftops or in PV power plants, along with their bifacial gains compared with monofacial PERC reference modules.

In the final section, a novel prototype module is demonstrated. Here, the Smart Wire Connection Technology (SWCT) [15] from Meyer Burger AG is applied to busbarless PERC+ solar cells by soldering 18 wires directly to the front Ag fingers and rear Al fingers, without the use of Ag pads. As a consequence, the Ag paste consumption is reduced to 55mg per PERC+ cell in the printing of the front-side Ag fingers [16]. The resulting PERC+ SWCT prototype module exhibits independently confirmed conversion efficiencies of 19.8% and 16.7% when illuminated from the front and the rear respectively [16].

Industrial PERC+ solar cells

ISFH and SolarWorld, initially independently and

Year	Efficiency [%] front/rear	Organization	Source	Comments
2015	21.5/16.7	ISFH	[11]	Industrial process flow. No rear Ag pads
2015	20.3/n.p.	Trina Solar	[13]	Optimized for optical appearance in BIPV
2016	20.7/13.9	Big Sun Energy Technology Inc	[17]	
2017	21.5/16.1	JinkoSolar	Pers. comm.	
2017	21.4/n.p.	Neo Solar Power	[18]	
2017	21.6/17.3	LONGi Solar	H. Li, pers. comm.	
2017	21.6*/n.p.	ISFH	[16]	Rear side optimized for monofacial applications
2017	22.1*/n.p.	ISFH	**	Busbarless Ag front-grid design

**Independently confirmed; ** This paper.*

Table 1. Published efficiencies of industrial PERC+ solar cells when illuminated from the front or rear side. Several leading solar cell manufacturers, such as SolarWorld and Trina Solar, are currently producing bifacial PERC+ cells and modules (see Table 2), but have not reported any, or recent, PERC+ cell efficiencies. (n.p. = not published.)

later jointly, embarked upon the development of a bifacial PERC solar cell design in 2015, by applying a screen-printed rear Al finger grid instead of the conventional full-area aluminium (Al) rear layer (see Fig. 1). This venture was accomplished by the use of the same PERC manufacturing sequence, with only minimal recipe modifications for rear passivation, LCO and Al screen printing [10]. Hence, it was possible for a monofacial PERC cell production line to be switched to producing bifacial PERC solar cells, without requiring any investment in new or different production tools.

The novel cell concept has been named *PERC+*, several advantages of which have been demonstrated in initial publications [10,11]. In particular, the Al finger grid has enabled bifacial application of PERC+ cells, with front-side efficiencies of up to 21.2%, and rear-side efficiencies of up to 16.7%, measured with a black chuck [11]. The corresponding bifaciality (the ratio of rear and front conversion efficiencies) was around 80.0%. When measured with a reflective brass chuck, PERC+ cells demonstrated front-side efficiencies of up to 21.5%, compared with 21.1% efficiencies achieved by conventional PERC cells [11]. The Al paste consumption of the PERC+ cells was drastically reduced to 0.15g instead of 1.6g for conventional PERC cells [10]. PERC+ solar cells are therefore attractive for both bifacial and monofacial module applications [10], which is why the naming convention *PERC+* has been chosen, rather than (for example) biPERC or bifiPERC.

In 2015 two additional publications addressed the concept of bifacial PERC+ cells. Trina Solar reported bifacial glass–glass modules that incorporated bifacial PERC+ solar cells designed for aesthetic optical appearance in building-integrated PV applications [13]. In contrast, Fraunhofer ISE assessed the concept of bifacial PERC+ cells mainly by numerical simulations of the potential front and rear conversion efficiencies and corresponding bifacial gains [12]. Several solar cell manufacturers have since introduced PERC+ solar cells into pilot production or mass production.

Table 1 summarizes the published conversion efficiencies of PERC+ cells when illuminated from the front or rear side. Whereas ISFH set the benchmark in 2015 for high PERC+ front- and rear-side efficiencies as outlined above, the first published PERC+ conversion efficiencies achieved by solar cell manufacturers were 20.3% [13] in 2015 and 20.7% [17] in 2016; these values have continually improved, to 21.6% in 2017, as reported by LONGi Solar (H. Li, pers. comm.) and by ISFH [16]. The 21.6% efficiency obtained by ISFH has been independently confirmed by ISFH CalTeC.

In addition, a busbarless PERC+ solar cell has recently been developed at ISFH by screen printing just the Ag fingers on the front side, without printing the Ag busbars. As shown in Fig. 1, the Al rear grid still in fact employs a five-busbar layout, since the specific Al finger layout was designed with a five-busbar configuration. However, it is expected that the same efficiency will be obtained with a busbarless Al finger grid.

The busbarless PERC+ cell was measured by Fraunhofer ISE CalLab by contacting the front side with 30 wires and the rear side with a full-area brass chuck. As shown in the last line of Table 1, the

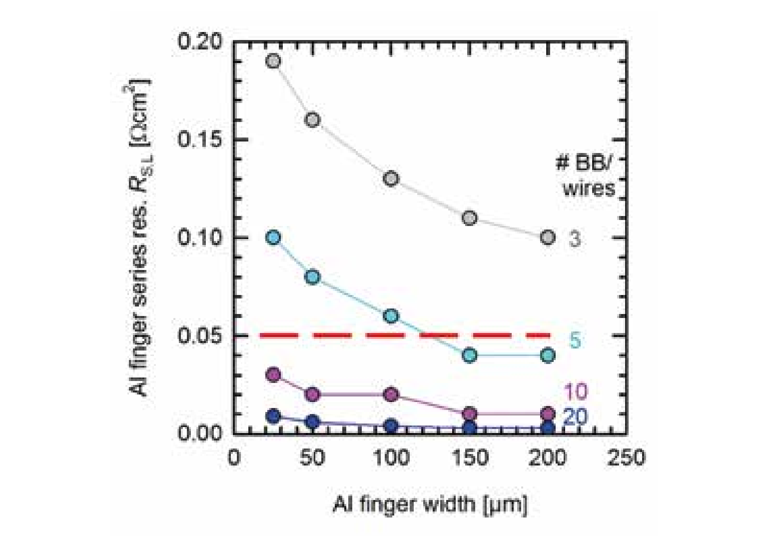

Figure 2. Calculated series resistance contribution $R_{s,L}$ of the Al finger grid as a function of the number of busbars/wires and the Al finger width.

"A key issue with the development of bifacial PERC+ cells is the very high specific resistivity of 20μΩcm."

busbarless PERC+ cell exhibits an independently confirmed conversion efficiency of 22.1% when illuminated from the front side. The other solar cell parameters are: open-circuit voltage V_{oc} = 669mV, short-circuit current density J_{sc} = 40.4mA/cm^2 and fill factor FF = 81.5%. The V_{oc} and FF values correspond very well to the five-busbar reference PERC+ solar cell. The high J_{sc} value of the busbarless PERC+ cell is explained by the absence of busbar shadowing, which increases the J_{sc} by 0.7mA/cm^2 compared with the five-busbar PERC+ cell.

Benefiting from continuous improvements to industrial PERC solar cells, with a current record efficiency of 22.6% [19], it is very likely that even higher PERC+ front-side efficiencies will soon be demonstrated. At the same time, the conversion efficiency of PERC+ cells with rear-side illumination and produced by cell manufacturers has improved from 13.9% [17] in 2016 to 17.3% (pers. comm. H. Li, LONGi Solar) in 2017. For the 21.6%- and 22.1%-efficiency PERC+ cells fabricated by ISFH in 2017, the rear-side efficiency was not measured, as the rear Al finger grid had been optimized for monofacial applications rather than for high bifaciality. Unfortunately, several leading solar cell manufacturers, such as SolarWorld and Trina Solar, who are producing bifacial PERC+ cells and modules (see Table 2) have not published recent (or any) PERC+ cell efficiencies, and hence are absent from Table 1 or only appear there with preliminary results.

If we look at the rapid development and implementation of bifacial PERC+ cells, as demonstrated in Table 1, the question remains as to why it has taken almost 10 years of industrial monofacial PERC cell R&D for the concept of bifacial PERC+ cells to be proved and published. A key issue with the development of bifacial PERC+ cells is the very high specific resistivity of 20μΩcm [10] of screen-printed Al fingers, which is approximately six times higher than that of screen-printed Ag fingers. In consequence, the rear Al finger grid has to be designed in such a way that series resistance losses caused by the Al finger lines are minimized.

The series resistance contribution $R_{s,L}$ of the Al finger grid is calculated as a function of the number of busbars/wires and the Al finger width, as shown in Fig. 2. In order not to significantly reduce the front-side efficiency when switching from PERC to PERC+, as a rule of thumb the series resistance increase caused by the Al finger grid should remain below 0.05Ωcm^2. As this is not possible with a three-busbar configuration because of the large Al finger length between the busbars, the five-busbar design can be regarded as an enabling technology of bifacial PERC+ cells when wide Al fingers of around 150μm are used. When moving to narrow Al fingers below

100μm width, smart wire module interconnection technologies with, for example, 20 wires per PERC+ cell drastically minimize resistive losses of the Al fingers to under 0.01Ωcm². It is challenging, however, to print very narrow Al fingers because of the spreading nature of Al pastes during screen printing.

When research on PERC+ began at ISFH at the end of 2014, the initial Al finger print tests with a 100μm screen-opening width and conventional full-area PERC Al pastes resulted in around 200μm-wide Al fingers. Since then, paste vendors have optimized PERC Al pastes for line-print capability, which now results in the achievement of Al fingers of widths approximately 100–150μm when utilizing a 100μm screen opening. In order to further increase the rear-side efficiency and bifaciality of PERC+ cells in the future, further development of Al pastes with even better fine-line printing capabilities is necessary.

Another challenge with PERC+ is the precise alignment of the Al finger print on top of the LCOs. In the case of extreme misalignment, when the Al finger does not overlap the LCO area, the open silicon surface of the LCO area leads to very high surface recombination of minority-charge carriers, and hence to significantly reduced open-circuit voltages. Accordingly, the alignment tolerances between Al finger print and LCO are in the range ±30μm depending on the detailed Al finger and LCO geometries. This requires high-precision laser processes and Al screens, as well as camera-based alignment schemes between LCO and Al screen print.

An interesting effect is that the limited Al volume of the Al fingers changes the alloying process with the silicon wafer during furnace firing, resulting in deeper Al-BSFs [10,22] compared with PERC cells with a full-area Al layer. The limited Al volume of the Al fingers leads to a higher silicon concentration in the screen-printed aluminium during furnace firing, which causes thicker Al-BSFs during the epitaxial regrowth in the cool-down phase [20]. This effect becomes more pronounced for narrow LCO widths of around 50μm, which are preferred, from a commercial perspective, in order to increase the throughput of the LCO tool.

Whereas with PERC cells a considerable number of voided contacts can be found, especially for narrow LCOs, in the case of PERC+ cells no fully voided contacts are present. Further analysis reveals that voids occur in particular for Al contacts where the Al-Si eutectic extends to a depth of more than 20μm into the Si wafer [21]. To explain this finding, an analytical model has been proposed, which calculates the surface energies of the liquid Al-Si melt, the Si wafer surface and the screen-printed Al particle surface [21]. According to this model, voids form for deep contacts, since in this situation during furnace firing a sufficient amount of Al-Si melt is available in order to wet the large surface area of Al particles, rather than the small surface area of the Si wafer. The Al fingers reduce the Al contact depth by about 7μm, which is the reason why PERC+ cells do not exhibit voids [21]. The increased Al-BSF thickness and the

Figure 3. Photographs of the front and rear sides of a commercial Bisun module from SolarWorld, incorporating PERC+ solar cells (image taken from Dullweber et al. [10]). Whereas this photograph still shows a three-busbar design, the more recent Bisun modules, as well as other bifacial PERC+ modules, use a four- or five-busbar design, as summarized in Table 2.

reduced number of voids of PERC+ cells compared with conventional PERC cells result in up to 3mV higher open-circuit voltages, because of reduced rear-contact recombination [10,21]. This is one reason why PERC+ cells are attractive for both monofacial and bifacial applications.

Commercial PERC+ modules and field installations

SolarWorld pioneered the mass production of bifacial PERC+ solar cells and the fabrication of novel PERC+ glass–glass bifacial modules named Bisun, which were launched at the Intersolar 2015 conference [14,22] (see Fig. 3). Since then, Neo Solar Power, Trina Solar and LONGi Solar have followed this technology route and are now also offering commercial bifacial glass–glass modules incorporating PERC+ solar cells [23–25], as summarized in Table 2. All the manufacturers concerned implement four- or five-busbar designs and obtain maximum power ratings of between 290Wp and 305Wp with 60 PERC+ cells per module [22–25]. These power ratings are stated for front-side illumination only. When additional rear-side illumination is employed, the output power increases accordingly: for example, with 10% additional rear-side illumination, the output power will increase by approximately 8%, to a total output power of close to 330Wp.

A larger number of busbars, such as four or five, is preferred for PERC+ modules, since the specific resistivity of Al fingers is six times higher than that of Ag front fingers [10]. The use of more busbars allows shorter Al finger lengths, thereby lowering the Al finger line resistance and the related resistive power losses. Since the first publication of a PERC

Company/Product	Maximum power rating [Wp]	Busbars/Cells	Source
SolarWorld/Bisun	290	5/60	[22]
Neo Solar Power/Glory BiFi	300	4/60	[23]
Trina Solar/DUOMAX	300	5/60	[24]
LONGi Solar/LR6 -60PD	305	4/60	[25]

Table 2. Commercially available bifacial modules incorporating PERC+ solar cells. The maximum power rating is stated for front-side illumination under standard test conditions (STC: AM1.5, 25°C) and with no rear-side illumination.

Company	Installation	Increased energy yield	Source
SolarWorld, ISFH, ISE	Theoretical calculation	Up to 25% (80% albedo, 0.5m mounting height)	[10]
SolarWorld	3.2kW, Bisun modules, roof installation, Germany	13% measured, 13.3% calculated (74% albedo, 0.28m mounting height)	[27]
SolarWorld	13kW, Bisun modules, single-axis tracker, Germany	22% measured (17% albedo, 0.9m mounting height)	[27]
Trina Solar	20MWp, DUOMAX modules, solar power plant, China	Under construction on sandy ground with high diffuse reflection	[28]
Neo Solar Power	2MWp, Glory BiFi modules, roof installation, Taiwan	Under construction on a Taiwan government building	[29]

Table 3. Examples of field installations of bifacial modules incorporating PERC+ solar cells. When available, simulated and measured outdoor performance values have been provided. The increase in energy yield refers to the additional energy yield generated by bifacial PERC+ modules relative to monofacial reference PERC modules.

(a)

(b)

Figure 4. Field installations of bifacial modules using PERC+ solar cells: (a) 13kWp Bisun modules from SolarWorld mounted on a single-axis tracker system [27]; (b) 2MWp rooftop installation currently under construction by Neo Solar Power, implementing their Glory BiFi modules [29].

cell using a five-busbar design [26], the PV industry has migrated from three busbars to four (or even five), which is beneficial to the industrial adoption of PERC+ cells as explained above. The interconnection of PERC+ cells in strings is accomplished using conventional tabbing–stringing technology, whereby the Cu ribbons are soldered to the Ag front busbars and to Ag pads on the PERC+ rear side.

In the application of bifacial PERC+ modules to outdoor field installations, the albedo of the ground and the mounting height of the module are particularly important parameters for maximizing the additional diffuse illumination of the module rear side, and hence for maximizing the additional energy yield of a bifacial PERC+ module compared with a monofacial PERC module. Numerical simulations predict that the energy yield of PERC+ modules could increase by up to 25% when mounted at a height of 0.5m above ground that has an albedo of 80% [10].

SolarWorld has made efforts to measure the energy yield of Bisun modules at two different small-scale outdoor test installations, as summarized in Table 3. A 3.2kWp installation on top of a flat roof with a high albedo of 74% as a result of white ballast stones demonstrated an increased energy yield of 13% compared with a monofacial PERC reference module; this compared well with the calculated energy yield of 13.3% [27]. When mounted on a single-axis tracker system, the Bisun modules produced 22% additional energy yield, despite the relatively low albedo of 17% of the sandy ground (Fig. 4(a)) [27].

At present, two large-scale bifacial PERC+ field installations are under construction, as listed in Table 3. Trina Solar is supplying its bifacial DUOMAX modules to a 20MWp power plant in China installed on sandy ground with a high albedo [28]. At the same time, Neo Solar Power is constructing a 2MWp rooftop installation on a Taiwanese government building, which uses its bifacial Glory BiFi modules (Fig. 4(b)) [29]. Both installations will be important for verifying the predicted energy yield increase of bifacial PERC+ modules in actual large-scale outdoor field installations.

Novel PERC+ prototype module employing SWCT

As shown in Fig. 2, one step further in terms of reducing resistive losses caused by PERC+ rear Al fingers is to move from four- or five-busbar designs to PERC+ solar cells without any busbars. In this case, the module interconnection is accomplished by 18 wires which are soldered directly to the Ag front and Al rear fingers by implementing the SWCT developed by Meyer Burger [15]. This novel PERC+ SWCT module concept was presented at the EU PVSEC conference in 2017 [16].

The PERC+ cells of the PERC+ SWCT prototype module were fabricated at ISFH using a process sequence described in detail in Dullweber et al. [10]. In the reference split group 1, a five-busbar Ag front-grid design was employed. These conventional five-busbar PERC+ cells were used later to calibrate the *I–V* tester which measures the busbarless PERC+ cells. The PERC+ cells of split group 2, which are later used for the SWCT module, are not furnished with Ag busbars on the front; instead, just the Ag fingers are printed, and hence the resulting PERC+ cells of split group 2 are busbarless, as shown in Fig. 1.

For the Al screen printing, the five-busbar reference PERC+ cells of group 1 are printed using an Al screen design with a five-busbar H-pattern, whereas the PERC+ cells of split group 2 are printed using a different screen without Al busbars, but which prints only the Al fingers. Both of these aluminium screens have a finger opening width of 100μm and a pitch *p* that is identical to the LCO pitch. The Al fingers are printed in alignment with the LCOs. Since the busbarless PERC cells receive only a Ag finger print and no Ag front busbars or Ag rear pads, the Ag paste consumption is reduced to 55mg per busbarless PERC+ cell.

The Ag front and Al rear contacts are fired in a conventional belt furnace, during which the Al paste locally alloys with the silicon wafer in areas where the rear passivation has been removed by laser ablation. A schematic drawing of the resulting bifacial PERC+ solar cell can be seen in Fig. 1. Finally, 18 busbarless PERC+ cells are laser cut into half cells, which are later used for the PERC+ SWCT module fabrication.

The *I–V* characteristics of the five-busbar reference PERC+ cells are measured using a conventional *I–V* tester, which contacts the rear-side full area with a brass chuck, and the front-side busbars with contact bars. The busbarless PERC+ cells are measured using a grid touch *I–V* tester from PASAN, which contacts the front Ag fingers with 30 wires and the rear Al fingers with 20 wires. The PASAN *I–V* tester is calibrated with a five-busbar reference PERC+ cell which has been measured using the conventional *I–V* tester.

A set of 18 halved busbarless PERC+ solar cells are used to fabricate a bifacial prototype module; a Meyer Burger SWCT system installed at the ISFH SolarTeC technology centre is also employed in the module fabrication process. The foil-wire assembly (FWA) tool from Meyer Burger is used to embed 18 wires (with a diameter of 200μm coated with InSn as a low-temperature solder) in a transparent foil.

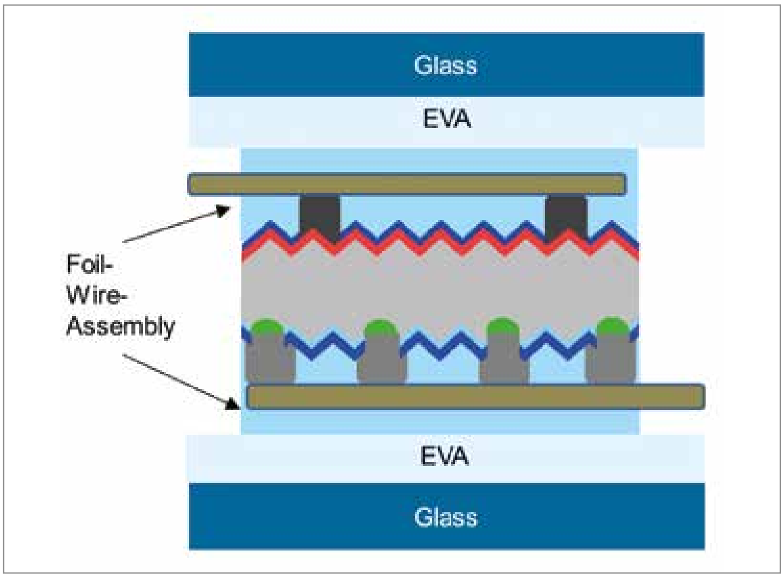

Figure 5. Schematic drawing of the interconnection of PERC+ cells by applying SWCT. During the lamination process, 18 InSn-coated wires are soldered directly to the Ag front and Al rear fingers.

Subsequently, the PERC+ SWCT prototype module is assembled as shown schematically in Fig. 5. The wires contact the Ag front and Al rear fingers directly, without the use of Ag busbars or Ag pads.

The PERC+ cells, including the FWA, are encapsulated by ethylene-vinyl acetate (EVA) foils with enhanced UV transmission [30] on both sides in a glass–glass module configuration. Both glasses are coated with an anti-reflection layer in order to reduce optical losses. Light-reflective films (LRF) produced by the company 3M are placed between neighbouring PERC+ cells; these films guide the incident light towards the cells, thereby increasing the light absorption in the module [31].

"One step further in terms of reducing resistive losses caused by PERC+ rear Al fingers is to move from four- or five-busbar designs to PERC+ solar cells without any busbars."

The module is laminated using a conventional lamination tool. During lamination, the InSn-coated wires are soldered to the Ag front fingers and Al rear fingers. Photographs of the front and rear sides of the resulting PERC+ SWCT prototype module are shown in Fig. 6(a) and (b) respectively. The *I–V* parameters of the PERC+ SWCT prototype module were measured independently by TÜV Rheinland, Germany, for both front- and rear-side illumination conditions.

When illuminated from the front, the five-busbar reference PERC+ cells exhibit efficiencies η_{front} of up to 21.1% with a very narrow distribution, whereas the front-side efficiency of the busbarless PERC+ cells ranges from 20.0 to 20.8%. This reduced efficiency is caused by a decrease in *FF* from 80.8% for the five-busbar PERC+ cells to between 76 and 78% for the busbarless PERC+ cells. Part of this drop in *FF* is caused by Ag finger interruptions which occurred as

	V_{oc} [V]	I_{sc} [A]	FF [%]	η [%]
PERC+ SWCT module, front	11.8	4.80	78.7	19.8[a]
PERC+ SWCT module, back	11.8	3.94	78.8	16.4[a]
18 busbarless PERC+ cells, front	11.9[b]	4.91[c]	77.3[c]	20.5[c]

[a]Independently confirmed by TÜV Rheinland; [b]Sum; [c]Average.

Table 4. Measured *I–V* parameters of the PERC+ SWCT prototype module, as well as those measured independently by TÜV Rheinland, for both front- and rear-side illumination conditions. Additionally, for the 18 PERC+ cells that were used for the module fabrication the sum of the V_{oc} values, along with the average I_{sc}, *FF* and η values, are given.

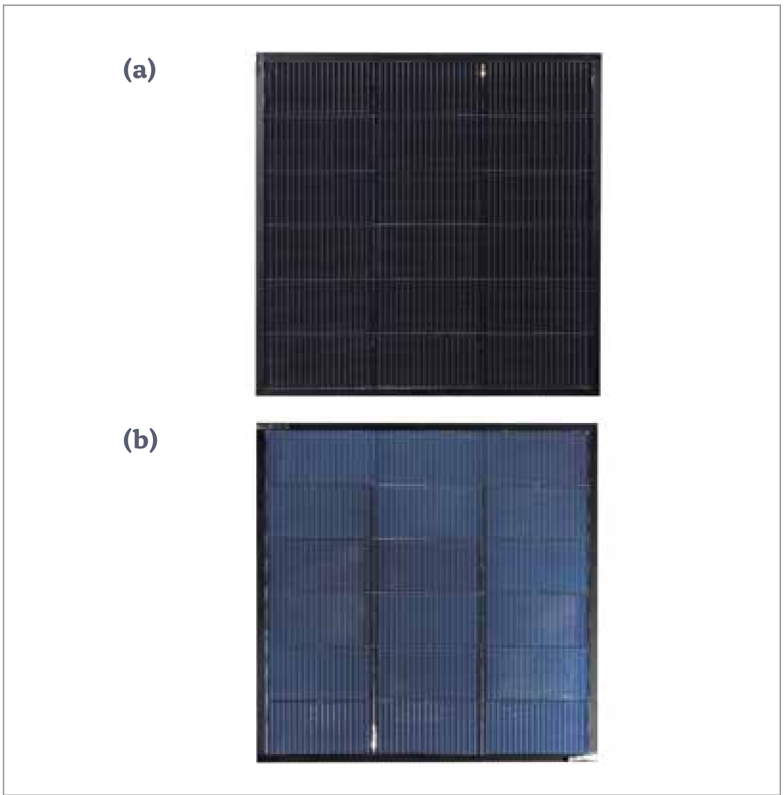

Figure 6. Photographs of the front (a) and rear (b) sides of the PERC+ SWCT prototype module, which incorporates 18 halved busbarless PERC+ cells.

a result of a non-optimized screen-printing process for the busbarless PERC+ cells.

With regard to V_{oc}, this ranges from 657 to 663mV for both five-busbar and busbarless PERC+ cells. The busbarless PERC+ cells yield the highest J_{sc} values of up to 40.4mA/cm² because of the absence of busbar shadowing, whereas the five-busbar PERC+ cells produce values of up to 39.7mA/cm². Whereas the busbarless PERC+ cells described above were used to process the PERC+ SWCT prototype module, in a later PERC+ cell batch the Ag screen-printing issue was fixed and the Al finger grid design was optimized for monofacial PERC+ applications; this then resulted in a 22.1%-efficient PERC+ solar cell, as shown in Fig. 1 and described earlier in the industrial PERC+ solar cells section.

"A full-size PERC+ SWCT module in compliance with the IEC 61215 norm has been certified by Meyer Burger, thereby demonstrating the long-term reliability of this novel module technology."

When illuminated from the rear, the busbarless PERC+ cells exhibit conversion efficiencies η_{rear} of between 15.8 and 16.5%. This relatively low rear-side efficiency is primarily due to a low J_{sc} of around 32mA/cm². As analysed and explained in detail in Dullweber et al. [10], the low J_{sc} values are caused by a high reflectance of the PERC+ rear side. The high reflectance is due to 1) the relatively wide Al fingers, accounting for approximately 10% of the metallized area; and 2) the non-ideal anti-reflection properties of the AlO_x/SiN_y rear passivation between the Al fingers. The bifaciality of the busbarless PERC+ cells is defined as η_{rear} divided by η_{front} and reaches values of up to 79%. As a figure of merit of bifaciality, the equivalent bifacial efficiency is defined as:

$$\eta_{eq,0.1} = \eta_{front} + 0.1\times \eta_{rear} \tag{1}$$

The factor '0.1' describes the additional stray light intensity irradiating the rear of the PERC+ cells relative to the AM1.5g front-side illumination. In practice, this factor can vary between 0 and 0.25 depending on, for example, the albedo of the ground and the detailed mounting geometries of the bifacial modules [10]. Inserting the measured front- and rear-side efficiency values (see above) in Equation 1 reveals an equivalent bifacial efficiency $\eta_{eq,0.1}$ of up to 22.4% for the busbarless PERC+ cells.

The *I–V* parameters of the PERC+ SWCT prototype module were independently measured by TÜV Rheinland, Germany, and are summarized in Table 4. When illuminated from the front side, the module exhibits an aperture conversion efficiency η_{front} of 19.8%, a V_{oc} of 11.8V, a short-circuit current I_{sc} of 4.8A and a *FF* of 78.7%. The module V_{oc} corresponds well to the sum of the V_{oc} values (11.9V) of the 18 busbarless PERC+ solar cells, as indicated in line 3 of Table 4. Moreover, the average I_{sc} of 4.91A of the 18 PERC+ cells corresponds well to the module I_{sc} when account is taken of the optical losses due to, for example, the higher reflectance of the module glass compared with the PERC+ cell. However, the module *FF* is 1.4% higher than the average *FF* of the 18 PERC+ cells, which is an indication that the PASAN *I–V* tester might be underestimating the PERC+ cell *FF*, since the calibration procedure was not yet optimized.

When illuminated from the rear side, the module I_{sc} decreases to 3.94A, resulting in a rear-side module efficiency η_{rear} of 16.4%; this corresponds well to the respective PERC+ cell rear-side efficiencies (not shown in the table). Accordingly, the module bifaciality

η_{rear}/η_{front} is 83%. Applying Equation 1 results in an equivalent bifacial efficiency $\eta_{eq,0.1}$ of 21.4% of the PERC+ SWCT prototype module. For comparison purposes, the highest monofacial PERC module efficiency reported so far is 20.2% [33], which demonstrates the additional energy yield to be expected from the novel bifacial PERC+ SWCT module when used in suitable outdoor field installations.

In addition to high conversion efficiencies, another important criterion for a new module technology is its reliability in terms of guaranteeing 20 or 25 years of module operation without significant degradation of the nominal output power. For the novel PERC+ SWCT module technology, the reliability of the interconnection between the Al fingers and the wires in particular has to be demonstrated, in addition to other reliability tests. To this end, Meyer Burger recently fabricated a PERC+ SWCT module utilizing 60 full-size PERC+ solar cells that were interconnected using SWCT module technology with 18 wires per PERC+ cell [32]. The wires had a diameter of 300μm and were coated with an In-free low-temperature solder material. The PERC+ SWCT module was externally certified [32] at Certisolis, France, in accordance with the IEC 61215 norm, which tests all reliability-relevant issues, such as module performance under temperature cycling and mechanical loading. In addition, the PERC+ SWCT module passed the IEC 61730 norm [32], which tests product safety, for example in terms of fire-protection standards.

Conclusions

Since its first publication by ISFH and SolarWorld in 2015, the PERC+ cell concept has been rapidly adopted by several solar cell manufacturers worldwide. The rapid industrial implementation of bifacial PERC+ cells is facilitated by the very similar process technology to that of monofacial PERC cells, which are becoming mainstream in the PV industry.

A novel bifacial PERC+ prototype module which implements SWCT technology has been presented. A batch of 18 halved PERC+ solar cells were interconnected by soldering 18 wires directly to the Ag front and Al rear fingers without the use of Ag busbars or Ag pads. The resulting prototype module exhibited independently confirmed front- and rear-side efficiencies of 19.8% and 16.4% respectively. These values correspond to an equivalent bifacial efficiency of 21.4%, which exceeds the world-record monofacial PERC module efficiency by more than $1\%_{abs}$. Additionally, a full-size PERC+ SWCT module in compliance with the IEC 61215 norm has been certified by Meyer Burger, thereby demonstrating the long-term reliability of this novel module technology.

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References

[1] Blakers, A.W. et al. 1989, *Appl. Phys. Lett.,* Vol. 55, p. 1363.
[2] Dullweber, T. & Schmidt, J. 2016, *IEEE J. Photovolt.,* Vol. 6, No. 5, p. 1366.
[3] ITRPV 2017, "International technology roadmap for photovoltaic (ITRPV): 2016 results", 8th edn (Mar.) [http://www.itrpv.net/Reports/Downloads/].
[4] Comparotto, C. et al. 2014, *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, p. 3248.
[5] Janssen, G.J.M. et al. 2015, *Energy Procedia*, Vol. 77, p. 364.
[6] Romijn, I.G. et al. 2013, *Proc. 28th EU PVSEC*, Paris, France, p. 736.
[7] Song, D. et al. 2012, *Proc. 38th IEEE PVSC*, Austin, Texas, USA, p. 3004.
[8] Mihailetchi, V.D. et al. 2010, *Proc. 25th EU PVSEC*, Valencia, Spain, p. 1446.
[9] Dullweber, T. et al. 2016, *physica status solidi (a)*, Vol. 213, No. 11, p. 3046.
[10] Dullweber, T. et al. 2016, *Prog. Photovolt: Res. Appl.,* Vol. 24, p. 1487.
[11] Dullweber, T. et al. 2015, *Proc. 31st EU PVSEC*, Hamburg, Germany, p. 341.
[12] Krauß, K. et al. 2016, *physica status solidi (a)*, Vol. 213, p. 68.
[13] Liu, B. et al. 2015, *Proc. 31st EU PVSEC*, Hamburg, Germany, p. 659.
[14] SolarWorld 2015, Press release [http://www.pv-tech.org/news/intersolar_europe_solarworld_to_launch_glass_glass_bifacial_modules].
[15] Faes, A. et al. 2014, *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, p. 2555.
[16] Dullweber, T. et al. 2017, *Proc. 33rd EU PVSEC,* Amsterdam, The Netherlands [in press].
[17] Chen, S.-Y. et al. 2016, *Proc. 32nd EU PVSEC*, Munich, Germany, p. 772.
[18] NSP 2017 [https://www.nsp.com/nspsolarcells?lang=en].
[19] Deng, W.W. et al. 2017, *Proc. 44th IEEE PVSC*, Washington DC, USA [in press].
[20] Kranz, C. et al. 2016, *IEEE J. Photovolt.*, Vol. 6, No. 4, p. 830
[21] Kranz, C. et al. 2016, *Sol. Energy Mater. Sol. Cells*, Vol. 158, p. 11.
[22] SolarWorld 2017 [https://www.solarworld.de/en/products/sunmodule-bisun-protect/].
[23] NSP 2017 [https://www.nsp.com/nspsolarmodules?lang=en].
[24] Trinasolar 2017 [http://www.trinasolar.com/en-uk/product/duomax4060/duomax-twin-deg5c07ii].
[25] LONGi Solar 2016 [http://en.longi-solar.com/Home/Products/module/id/12_.html].
[26] Hannebauer, H. et al. 2014, *physica status solidi*

(RRL), Vol. 8, p. 675.
[27] Neuhaus, H. (SolarWorld) 2017, Presentation at PV CellTech Conf., Penang, Malaysia.
[28] Trina Solar 2017 [http://www.trinasolar.com/en-uk/resources/newsroom/mon-05012017-1500].
[29] PV-Tech 2017 [https://www.pv-tech.org/news/nsp-to-construct-first-commercial-rooftop-system-using-its-bifacial-solar-m].
[30] Vogt, M.R. et al. 2016, *Energy Procedia*, Vol. 92, p. 523.
[31] Schulte-Huxel, H. et al. 2016, *IEEE J. Photovolt.*, Vol. 7, No. 1, p. 25.
[32] Yao, Y. et al. 2017, Presentation at 11th SNEC Int. PV Power Gen. & Smart Energy Conf. & Exhib., Shanghai, China.

About the Authors

Dr. Thorsten Dullweber leads the industrial solar cells R&D group at ISFH. His research focuses on high-efficiency industrial-type PERC and PERC+ silicon solar cells and ultrafine-line screen-printed Ag front contacts. Before joining ISFH in 2009, he worked for nine years in the microelectronics industry as a project leader at Siemens AG and then at Infineon Technologies AG.

Henning Schulte-Huxel studied physics in Leipzig and Bucharest, and laser technology in Jena, Germany. Between 2009 and 2010 he worked on laser ablation of CuInSe2. In 2010 he joined ISFH, and received his Ph.D. in physics in 2015 from the Leibniz University of Hanover. His research focuses are novel concepts for module integration and the analysis and reduction of cell-to-module losses.

Susanne Blankemeyer trained as an optician at Krane-Optik in Rheda-Wiedenbrück, Germany, and worked there until 1986. Between 1999 and 2007 she was a laboratory assistant in the R&D department at Orbotech, a manufacturer of automated optical inspection systems, in Bad Pyrmont, Germany. In 2007 she joined the module and interconnection technology group at ISFH, where she is currently involved in the development of novel interconnection techniques and optimization of module concepts.

Dr. Helge Hannebauer studied technical physics at the Leibniz University of Hanover from 2005 till 2009. His diploma thesis at ISFH involved the optimization of screen-printed solar cells. In 2016 he completed his Ph.D. thesis, also at ISFH, on advanced screen printing and selective emitters.

Sabrina Schimanke joined ISFH in 2008 as a technical assistant. She is responsible for an industrial wet chemical polishing tool at ISFH, including the development of improved chemical polishing processes. She is also in charge of processing PERC and PERC+ solar cells for different R&D projects at ISFH.

Ulrike Baumann graduated in 2011 as a laboratory technical assistant in chemistry. She then joined the industrial solar cells R&D group at ISFH, where she is in charge of processing industrial PERC and PERC+ solar cells. In addition, she is responsible for the optimization and maintenance of a production-type wet-chemical batch-processing tool.

Dr. Robby Peibst received his diploma degree in technical physics in 2005. In 2010 he received his Ph.D. from the Leibniz University of Hanover, with a thesis on germanium-nanocrystal-based memory devices. He joined ISFH in 2010 and has been in charge of the emerging solar technologies group since 2013. His research focuses on the development of enabling techniques for producing high-efficiency silicon solar cells.

Dr. Marc Köntges received his Ph.D. in physics in 2002 from the University of Oldenburg, for his research into thin-film solar cells. From 2002 he was in charge of the thin-film technology group at ISFH, and then became head of the module and interconnection technology group in 2005. He currently develops characterization and production methods for PV modules.

Rolf Brendel is the scientific director of ISFH. He received his Ph.D. in materials science from the University of Erlangen, for which he researched infrared spectroscopy. In 2004 he joined the Institute of Solid State Physics at the Leibniz University of Hanover as a full professor. His main research focuses on the physics and technology of crystalline silicon solar cells.

Enquiries

Thorsten Dullweber
Industrial Solar Cells Group
Institute for Solar Energy Research Hamelin (ISFH)
Am Ohrberg 1, D-31860 Emmerthal, Germany

Yu Yao
Meyer Burger Technology AG
Schorenstrasse 39, CH-3645 Gwatt (Thun), Switzerland