Five-busbar PERC solar cells with a record 21.2% conversion efficiency

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ABSTRACT

The PV industry is intensively evaluating technologies for further increasing conversion efficiency while maintaining, or even further reducing, production costs. Two promising technologies that meet these objectives are 1) the passivated emitter and rear cell (PERC), which reduces optical and recombination losses of the solar cell's rear side; and 2) multi-busbar/multi-wire module interconnection, which reduces optical and resistive losses of the front grid. This paper evaluates a combination of these two technologies, in particular industrial PERC solar cells with printed metal contacts employing a five-busbar (5BB) front grid instead of the typical three-busbar (3BB) design. The resulting 5BB PERC solar cells demonstrate an independently confirmed conversion efficiency of 21.2%, compared with the 20.6% efficiency for 3BB PERC cells. To the authors' knowledge, a value of 21.2% is the highest reported so far for typical industrial silicon solar cells with printed metal front and rear contacts. The higher conversion efficiency is primarily due to an increased short-circuit current, resulting from the reduced shadowing loss of the 5BB front-grid design, in combination with stencil-printed finger widths of only 46µm.

Introduction

Passivated emitter and rear cells (PERCs) are considered by many solar cell manufacturers and R&D institutes to be the next technology generation for industrial production. Fig. 1 shows the evolution of record conversion efficiencies obtained with industrial PERC solar cells (large area > 148cm^2 p-type monocrystalline silicon wafers, printed metal front and rear contacts) [1–11]. Starting with an efficiency of 19.2% [1] reported by Centrotherm in 2010, the benchmark for almost two years now has been 21.0% [6,7], demonstrated by Schott Solar in 2012.

According to the information available, many of the record PERC cells in Fig. 1 utilize AlO_x/SiN_y as the rear-surface passivation layer stack [3,4,7,9,11], in addition to laser contact opening (LCO) to form local Al rear contacts [1,2,4,7,8,9,11]. Only two papers report laser-fired contacts as the rear-contact formation method [3,5].

Regarding the emitter technology, several record efficiencies were obtained using a homogeneously diffused emitter instead of a selective emitter. The record 21.0%-efficiency PERC cell of Schott Solar [7] used a homogeneously diffused emitter as well, which was optimized by etching back the dead layer of the front surface and subsequently oxidizing the emitter, thereby reducing emitter recombination and increasing voltage and efficiency. In comparison, the PERC solar cells reported in this paper employ an AlO_x/SiN_y rear-surface passivation, LCO and a homogeneously diffused 70Ω/sq. emitter [11].

Besides PERC, another attractive technology is to increase the number of busbars (BB), as implemented, for example, in multi-wire module interconnection technologies [12–14] or multi-busbar approaches [15]. The printed Ag finger-line resistance contribution to the series resistance depends on the finger length between two busbars [16]: a greater number of BBs, therefore, reduces the finger length and hence the series resistance losses of the front finger grid. At the same time, in order to reduce the shadowing loss and Ag paste consumption, a larger finger pitch or a reduced finger width can be utilized without significantly increasing the series resistance [16].

In the work presented in this paper, a 5BB Ag-printed front-grid layout is applied to state-of-the-art

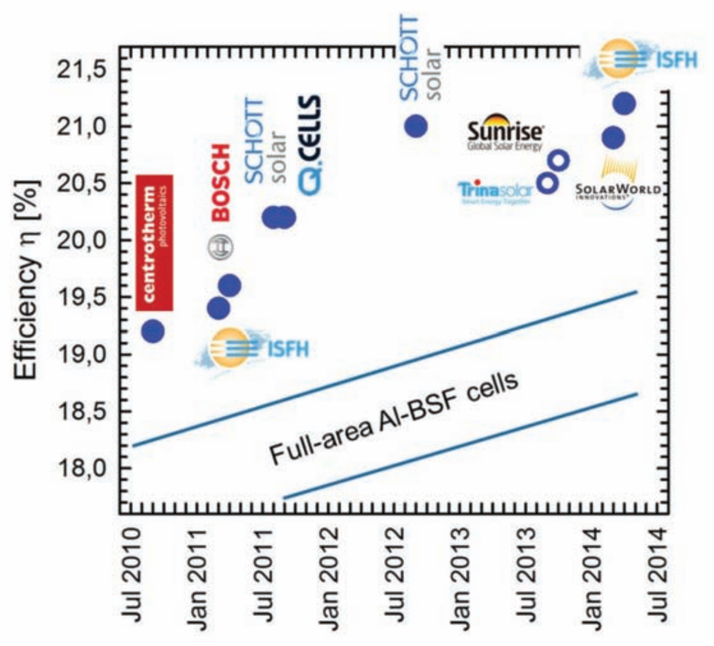

Figure 1. Record conversion efficiencies of PERC solar cells with printed metal contacts, using monocrystalline large-area p-type silicon wafers [1–11]. Solid blue circles refer to independently confirmed efficiencies, and open blue circles to in-house measurements. Typical efficiencies of full-area Al-BSF solar cells are also indicated.

industrial PERC solar cells, resulting in a record conversion efficiency of 21.2% [11]. Print-on-print (PoP) and stencil print (dual print) methods are evaluated for the fine-line Ag finger print. Each BB has a width of 0.5mm, which is very challenging for today's module interconnection technology. Nevertheless, Cu ribbons with a width of only 0.8mm are already under development [15], and, in combination with other technological advances, a 0.5mm-thick 5BB design is quite likely to be industrially feasible within the next few years.

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Fine-line printed fingers with 5BB front grid

Three different split groups are evaluated for the silver front-side grid: the groups differ in the number of busbars (BB) and the printing process, as shown in Table 1. In the conventional 3BB design, each BB has a width of 1.3mm, which equates to a total BB width of 3.9mm. The 5BB design has a width of 0.5mm per BB, and therefore a 2.5mm BB width in total. The finger grid spacing has been optimized for each BB design and print process.

PoP means the fingers are printed twice in two consecutive printing steps, with 40 and 50µm screen openings; in the second print, the busbars are also printed. Both prints use the same Ag paste. *Dual print* means that first the busbars are screen printed with a non-firing-through Ag paste; in a second print step the fingers are printed using a stencil with a 40µm finger opening. For the finger stencil print, the same Ag paste as for PoP is used.

Table 1 summarizes several properties of the resulting front grids. The BB width of 1.3mm of the conventional 3BB design corresponds to a metal fraction (shadowing loss) of 2.5%. The 5BB design, with a BB width of just 0.5mm, leads to a lower BB metal fraction of 1.6%. The finger width on the final solar cells is measured using an optical light microscope: the images are shown in Fig. 2(a) and (b), and the resulting average values are given in Table 1. While the PoP process results in finger widths between 62 and 66µm, the stencil print leads to a smaller finger width of 46µm, which significantly decreases the finger metal fraction to 2.4%. In total, the metal fraction of busbars and fingers has been reduced from 5.8% for the conventional 3BB layout using PoP, to 4.0% for the 5BB layout using dual print.

Five-busbar PERC solar cells

For this study 156mm × 156mm, 2–3Ωcm, boron-doped Cz silicon wafers were used. The process flow is described in detail in Hannebauer et al. [11] and Dullweber et al. [17], but only the most important process steps will be highlighted here. After cleaning, the rear side is coated with a protection layer which acts as an etching and diffusion barrier in the subsequent alkaline texturing and $POCl_3$ diffusion, with a resulting emitter sheet resistance of 70Ω/sq. Following the texturing and diffusion, the protection layer is removed by wet chemistry, and the rear side is passivated using a stack of ALD Al_2O_3 and PECVD SiN_x, whereas the front side is passivated with PECVD SiN_x. Line-shaped LCOs are formed on the rear side using a picosecond laser; the width and pitch of the line-shaped rear contacts has been optimized in

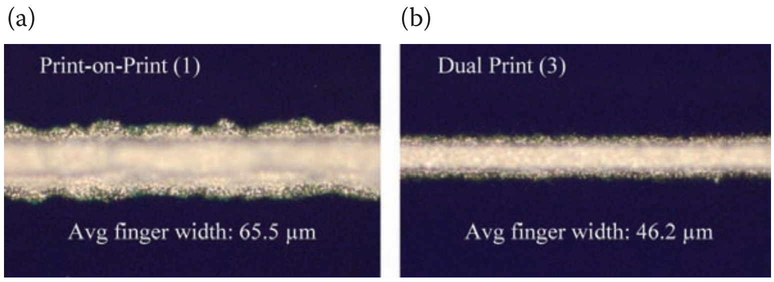

Figure 2. Optical light microscope images of fine-line printed Ag fingers, taken after firing on fully processed PERC solar cells in Tables 1 and 2: (a) PoP (group 1); (b) dual print (group 3). The extracted finger widths based on these measurements are summarized in Table 1.

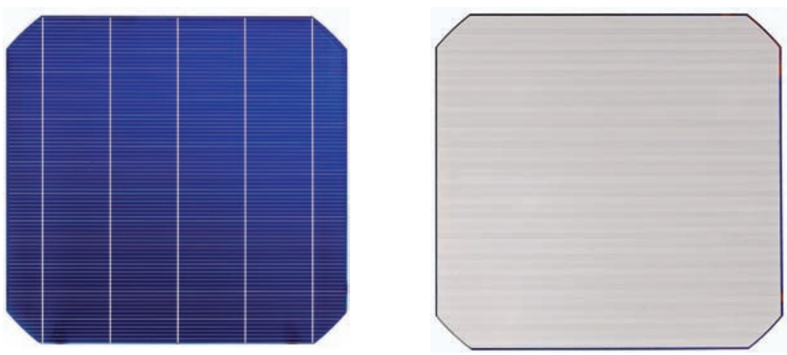

Figure 3. Photographs of the front and rear sides of the 5BB PERC solar cell.

Group	No. of BBs	Print technology	BB width [mm]	BB metal fraction [%]	Finger width [µm]	Finger metal fraction [%]
1	3	PoP	1.3	2.5	66	3.3
2	5	PoP	0.5	1.6	62	2.9
3	5	Dual print	0.5	1.6	46	2.4

Table 1. Summary of front-grid parameters for the three split groups. Whereas the conventional 3BB design (group 1) has a total (BB + fingers) metal fraction of 5.8%, for the best 5BB front grid (group 3) the total metal fraction is significantly reduced, to 4.0%.

order to obtain the best compromise between recombination losses and resistive losses.

After printing the front grid using the fine-line printing techniques and busbar designs as described in the previous section, the rear side of the PERC cell is full-area screen printed with an Al paste that has been specifically developed for PERC cell applications. The front and rear contacts are fired in a conventional belt furnace; during this process the Al paste locally alloys with the silicon wafer in areas where the rear passivation has been removed by laser ablation. Photographs of the front and rear sides of the resulting 5BB PERC solar cell are presented in Fig. 3.

The results of the best PERC solar cells for each BB design and front-grid printing process are summarized in Table 2. The 5BB PERC cells demonstrate an independently confirmed conversion efficiency of 21.2%, which to the authors' knowledge is the highest reported so far for a silicon solar cell with printed metal contacts. In comparison, the conventional 3BB PERC cell metallized with PoP achieves an independently confirmed efficiency of 20.6% – a typical value for the ISFH PERC baseline process. The efficiency increase of 0.6% abs. for the best 5BB PERC cells versus the conventional 3BB PERC cells is mainly due to the large increase in short-circuit current density J_{sc}, from 38.9mA/cm^2 to 39.8mA/cm^2.

> "The efficiency increase for the best 5BB PERC cells is mainly due to the large increase in short-circuit current density J_{sc}."

Fig. 4 shows the measured short-circuit current densities of the 3BB and 5BB PERC cells as a function of the calculated total shadowing loss of the front grid (BB and finger metallization fractions in Table 1). The J_{sc} error bars have been chosen in accordance with ISE CalLab specifications. The dashed line models the J_{sc} dependence on the shadowing loss.

The J_{sc} improvement for the 5BB PERC cells originates from the reduced shadowing loss of 1.8%, where 0.9% is due to the reduced BB width, and the other 0.9% to the reduced finger width (see Table 1). The open-circuit voltage V_{oc}, as shown in Table 2, increases from 658mV for the 3BB design to 662mV for the 5BB design because of the reduced front-contact area. In addition, because of the non-firing-through BB Ag paste, the front-contact area is further reduced for the dual-print group, leading to the highest V_{oc} value of 662mV.

The 5BB design yields an increase in *FF* from 80.5% to 80.9% as a result of reduced resistive losses. However, the root cause of the slightly lower fill factor *FF* of the dual-printed 5BB PERC cells still needs to be analysed.

Conclusions and outlook

This paper demonstrates a record high efficiency of 21.2% for industrial PERC solar cells which implement a 5BB front-grid design using either PoP or dual print as fine-line metallization processes. With the dual-print process, the finger width is reduced to 46µm, in contrast with 62–66µm when PoP is employed; the decreased finger width leads to a lower finger metal fraction of 2.4% for dual print. The front-grid metal fraction is further reduced by decreasing the width of each busbar from 1.3mm (3BB design) to 0.5mm (5BB design). Hence, the 5BB front grid with the best dual-print process reduces the total shadowing loss of the front grid to 4.0%, in contrast with 5.8% for a conventional 3BB front grid printed using PoP.

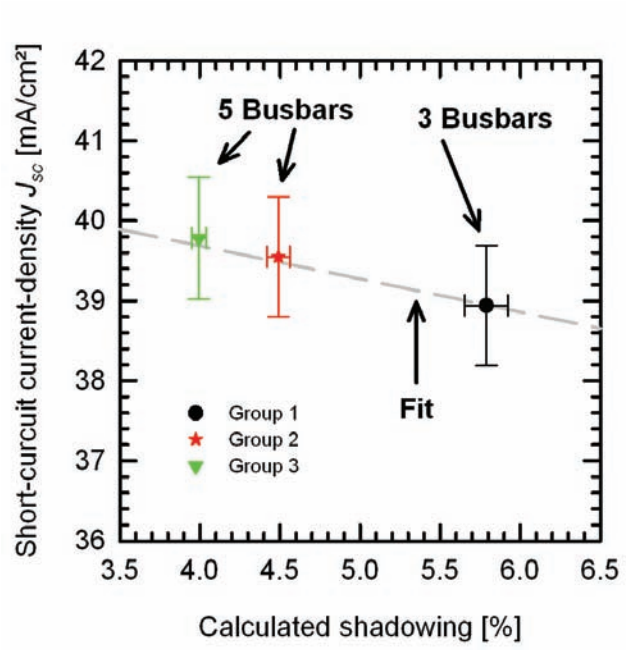

Figure 4. Measured short-circuit current density J_{sc} for the 3BB and 5BB PERC solar cells in Table 2 as a function of the calculated shadowing loss based on the front-grid layout and the measured finger widths in Table 1. The dashed line models the expected J_{sc} vs. shadowing loss dependence. The 5BB design with dual print (group 3) yields the lowest shadowing loss of 4.0% and the highest J_{sc} value of 39.8mA/cm^2.

Group	No. of BBs	Print technology	Efficiency [%]	J_{sc} [mA/cm^2]	V_{oc} [mV]	*FF* [%]
1	3	PoP	20.6*	38.9	658	80.5
2	5	PoP	21.2*	39.6	661	80.9
3	5	Dual print	21.2*	39.8	662	80.6

* Independently confirmed by Fraunhofer ISE CalLab.

Table 2. Solar cell parameters for the best PERC solar cells for each of the front-grid layout and printing processes, obtained from *I–V* measurements performed at standard testing conditions (25°C, AM1.5G spectrum).

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The resulting 5BB PERC solar cells demonstrate an independently confirmed conversion efficiency of 21.2%, compared with 20.6% efficiency for the 3BB PERC cells. The increased conversion efficiency is primarily due to an increase of 0.9mA/cm^2 in short-circuit current resulting from the reduced shadowing loss. Additionally, the 5BB PERC cells yield the highest V_{oc} values of up to 662mV because of the reduced metal contact area, as well as the highest *FF* of up to 80.9% because of lower resistance losses of the finger grid. Even though the 5BB design used in this work is quite challenging with today's module interconnection technology, it is expected that 5BB designs with a BB width of only 0.5mm will be manufacturable using advanced interconnection technologies within the next few years.

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Thorsten Dullweber received his Ph.D. from the University of Stuttgart in 2002. From 2001 to 2009 he worked as a microelectronics project leader at Siemens, Infineon and Qimonda. Since 2009 he has led the ISFH R&D solar cell production processes group, focusing on process and efficiency improvements in industrial-type screen-printed silicon solar cells.

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Tom Falcon has been with DEK since 2001, initially specializing in process development for DEK's semiconductor packaging technologies team, before moving to DEK Solar in 2008. He is currently responsible for developing metallization processes for silicon solar cells. Prior to joining DEK he held senior engineering positions with IBM, Nortel and Cookson Electronics.

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 of the Leibniz University of Hanover as a full professor. His main research focuses on the physics and technology of crystalline silicon solar cells.

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