Emitter technology options for industrial PERC solar cells with up to 20.3% conversion efficiency

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ABSTRACT

Passivated emitter and rear cells (PERC) are considered to be a next generation of industrial solar cells, and several companies have already started pilot production. The much-reduced rear-surface recombination in PERC cells requires improvements to the front side, for example the emitter, in order to further increase the conversion efficiency in the future. This paper presents an evaluation of the emitter technologies of three industrially applicable PERC cell concepts: 1) with an ion-implanted emitter, 2) with a chemically polished rear surface, and 3) with a selective emitter formed by gas phase etch-back (GEB). The results are compared with a reference high-efficiency $POCl_3$-diffused PERC cell. The three industrial PERC concepts utilize lean industrially applicable process flows which reduce the phosphorus concentration at the wafer surface. Accordingly, when compared with the $POCl_3$-diffused emitter, the ion-implanted and GEB emitters obtain significantly lower emitter saturation current densities of 40 to 60fA/cm² for emitter sheet resistances of 90 to 130Ω/sq. When applied to large-area PERC cells with screen-printed metal contacts, the ion-implanted and GEB emitter cells demonstrate up to 10mV higher open-circuit voltages than the $POCl_3$-diffused reference PERC cell, and achieve conversion efficiencies of 20.0 and 20.3%, respectively. The next steps in further increasing the efficiency are outlined.

Introduction

The passivated emitter and rear cell (PERC) concept was first published in 1989 [1] as a high-efficiency laboratory-type solar cell. PERC solar cells have since been intensively evaluated and optimized by industry and research institutes as a next-generation silicon solar cell concept for mass production. Several companies have already announced the pilot production of PERC solar cells [2–5], and efficiencies of up to 21.0% have been demonstrated for large-area PERC cells with screen-printed contacts [6]. Excellent rear-surface recombination velocities below 150cm/s have been reported, demonstrating the high-efficiency potential of industrial PERC cells [7,8].

Because of the much-reduced carrier recombination at the rear side of PERC cells, the phosphorus emitter now requires further optimization for conversion efficiencies beyond 21.0% to be achieved in the future. To keep production costs low, however, improvements in emitter technology have to be realized using a very lean process flow and as few extra process steps as possible. In recent years, a lot of effort has already been dedicated

to optimizing the phosphorus emitter, in particular with respect to selective emitters [9–14], which are applicable to PERC cells as well.

> "The phosphorus emitter now requires further optimization for conversion efficiencies beyond 21.0% to be achieved in the future."

Four different PERC process flows which yield almost identical rear sides, but result in four different phosphorus emitters, are investigated and compared in this paper:

1. **Ref. PERC:** ISFH reference PERC process flow employing a homogeneously $POCl_3$-diffused 70Ω/sq. emitter and a planar rear side obtained by a protection layer.

2. **I²-PERC:** PERC process flow where the emitter is formed by phosphorus **i**on **i**mplantation (I²) and subsequent annealing.

3. **Polished PERC:** PERC process flow where the rear side is chemically polished after texturing and $POCl_3$-diffusion. The rear polish and subsequent wet cleaning slightly etch back the emitter.

4. **GEB PERC:** PERC process flow where the very reactive gas phase of a modified polishing process is used to form a selective emitter via **g**as phase **e**tch-**b**ack (GEB).

Whereas the reference PERC process serves as a high-efficiency baseline process, the other three PERC process flows are designed to reduce the front-surface phosphorus concentration and hence potentially reduce the emitter saturation current density, allowing higher conversion efficiencies. At the same time, these three industrial PERC process flows incorporate very lean process sequences with the aim of targeting industrial mass production. The emitter doping profiles and saturation current densities, as well as the *I-V* parameters and quantum efficiencies of the resulting PERC solar cells, are reported in this paper.

The PERC process flows and emitter technologies investigated

Boron-doped Cz wafers of size $156 \times 156mm^2$ with a resistivity of $2-3\Omega cm$ and a starting thickness of $190\mu m$ are used for all PERC process flows. The four process flows, shown in Table 1, differ in their emitter formation and rear-surface preparation. Process steps which impact the emitter formation are highlighted in green. All four PERC process flows, however, apply the same initial wafer cleaning, alkaline texturing, SiN_x front-surface passivation, AlO_x/SiN_y rear-surface passivation, laser contact opening (LCO), screen printing of Ag front (print-on-print) and Al rear metal contacts, and firing profile, as indicated by the process steps highlighted in blue in Table 1. The resulting PERC cell structures are shown schematically in Fig. 1. An overview of each of the four different PERC process flows of Table 1 and Fig. 1, with an emphasis on the emitter formation, is given next.

A) Ref. PERC: reference PERC cells with rear protection layer

The process flow for the reference PERC solar cells is described in detail by Dullweber et al. [7]. Before texturing and $POCl_3$ diffusion, a dielectric protection layer is deposited on the rear side of the wafer, resulting in a planar and non-diffused rear side. A homogeneously doped emitter with a sheet resistance of about $60\Omega/sq.$ measured after diffusion is applied. Because of the subsequent wet cleaning (PSG and dielectric etch, cleaning before rear passivation), the emitter is etched back slightly, which increases the emitter sheet resistance to a final value of around $70\Omega/sq.$ A 10nm-thick atomic layer deposited (ALD) AlO_x layer is applied to the rear side. A plasma-enhanced chemical vapour deposition (PECVD) SiN_y capping layer is then deposited on top of the AlO_x passivation layer at the rear in order to improve both the optical reflectivity and the surface passivation quality.

The emitter is covered with a PECVD SiN_x anti-reflective coating. To form local line openings, the dielectric layer stack at the rear is locally ablated by LCO [7,15]. Line contacts were chosen instead of point contacts, since the former facilitate the formation of a deep and uniform local Al-BSF [16]. The Ag front contacts are deposited by a print-on-print (PoP) screen-printing process, resulting in a finger width of around $60\mu m$ [17]. The Al rear contact is formed by full-area Al screen printing of a commercially available Al paste designed for local rear contacts. In total, 11 process steps are necessary for this reference PERC process flow, resulting in the PERC solar cell shown schematically in Fig. 1 (left).

B) I^2-PERC: PERC solar cells with ion-implanted phosphorus emitter

As an alternative to $POCl_3$ diffusion, emitter formation by ion implantation is evaluated; see Dullweber et al. [18] for a detailed description of the I^2-PERC process flow. A single-

A: Ref. PERC	B: I^2-PERC	C: Polished PERC	D: GEB PERC
Wafer cleaning	Wafer cleaning	Wafer cleaning	Wafer cleaning
Rear protection layer	*Rear protection layer*		
Texturing	Texturing	Texturing	Texturing
Phosphorus diffusion	Ion implantation	Phosphorus diffusion	Phosphorus diffusion
PSG + dielectric etch	Anneal		Front: etch barrier
	Front: SiN_x	Rear: Polish	Polish + GEB
Rear: AlO_x/SiN_y	*Rear: dielectric etch*	Rear: AlO_x/SiN_y	Rear: AlO_x/SiN_y
Front: SiN_x	Rear: AlO_x/SiN_y	Front: SiN_x	Front: SiN_x
Rear: laser ablation	Rear: laser ablation	Rear: laser ablation	Rear: laser ablation
Ag screen printing	Ag screen printing	Ag screen printing	Ag screen printing
Al screen printing	Al screen printing	Al screen printing	Al screen printing
Co-firing	Co-firing	Co-firing	Co-firing
11 steps	12 (10) steps	10 steps	11 steps

Table 1. Process flows of the reference PERC cell (A), as well as the three industrially applicable PERC cell concepts with ion-implanted emitter (B), chemically polished rear surface (C) and selective emitter by gas phase etch-back (GEB) (D). The 'green' process steps impact the emitter formation, whereas the 'blue' process steps are identical for all four PERC process flows.
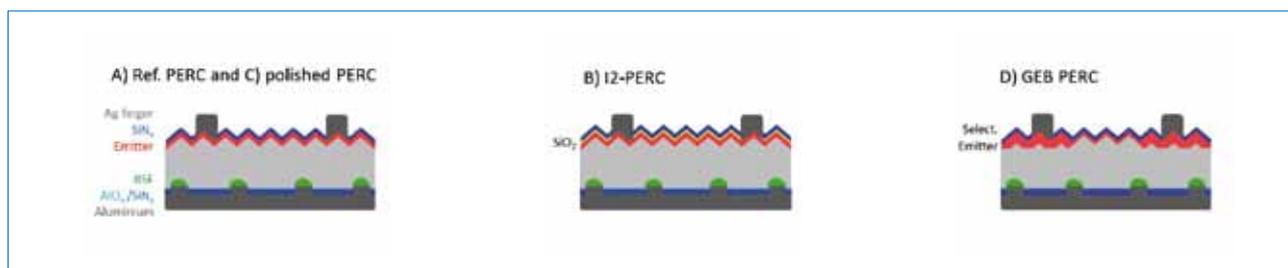
Figure 1. Schematic cross sections of the four PERC cells resulting from the different process flows in Table 1.

sided texturing of the front side is obtained by using a rear protection layer, which is later removed in the process flow. The phosphorus emitter is ion implanted using an implanter similar to the Applied Materials Solion tool [13]. Afterwards, the crystal damage caused by the ion implantation is annealed in a high-temperature step, which activates the phosphorus doping, resulting in an emitter sheet resistance of around $65\Omega/sq$. A thin thermal oxide is then grown in the furnace as part of the anneal, providing surface passivation of the emitter. A SiN_x anti-reflective coating is deposited on the front side, and the dielectric layer on the wafer rear side is then removed. Next, the AlO_x/SiN_y passivation stack is deposited on the wafer rear side. The LCO and the screen printing of the front and rear contacts is performed as described above for the reference PERC process flow.

The resulting PERC solar cell is shown schematically in Fig. 1 (centre); this cell differs from the reference PERC cell in its emitter doping profile and SiO_2/SiN_y front-surface passivation. A future option for a very lean process flow with industrial manufacturing in mind is to skip the rear protection layer and apply a single-sided alkaline texturing or a chemical rear polish after double-sided texturing as in the polished PERC cell (described in the next section). This would allow the dielectric etch (later in the process flow) to also be skipped, so that only 10 steps in total would be required for the PERC cell processing.

C) Polished PERC: PERC solar cells with polished rear side

The process flow for the polished PERC cell is described in detail by Kranz et al. [19]. After double-sided alkaline texturing, the emitter is formed by $POCl_3$ diffusion, resulting in an emitter sheet resistance of $45\Omega/sq$. after diffusion. The RENA InPilot tool is then used to take off about $5\mu m$ of silicon from the rear surface by single-sided wet chemical polishing; this removes the rear-side emitter and smooths the rear surface. After the polishing step, a cleaning sequence is carried out prior to depositing the AlO_x/SiN_y rear passivation layer. The polishing process, and even more so the subsequent wet cleaning, slightly etch back the emitter, which increases the emitter sheet resistance from the initial $45\Omega/sq$. to around $65\Omega/sq$. The passivation of the rear and front surfaces, the LCO and the screen printing of the front and rear contacts are performed as described
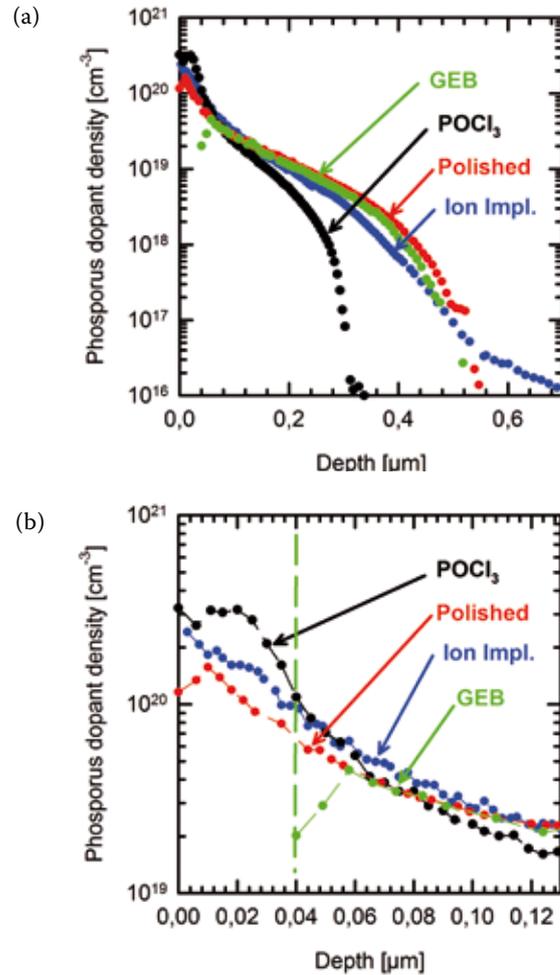

Figure 2. (a) Doping profiles of the ion-implanted phosphorus emitter ($65\Omega/$sq.), the emitter after polishing ($65\Omega/sq$.) and the gas phase etch-back (GEB) emitter ($90\Omega/sq$., shifted by 40nm) measured by ECV profiling. The doping profile of the $POCl_3$-diffused emitter ($70\Omega/sq$.) is included as a reference. **(b)** Close-up of the front surface in Fig. 2(a). The dashed green line denotes the removal of around 40nm of silicon by the GEB process. The lower concentration of surface phosphorus of the GEB, polished and implanted emitters compared with the $POCl_3$ emitter is the main reason why the J_{0e} (see Fig. 3) values are lower and the V_{oc} values are higher (see Table 2).
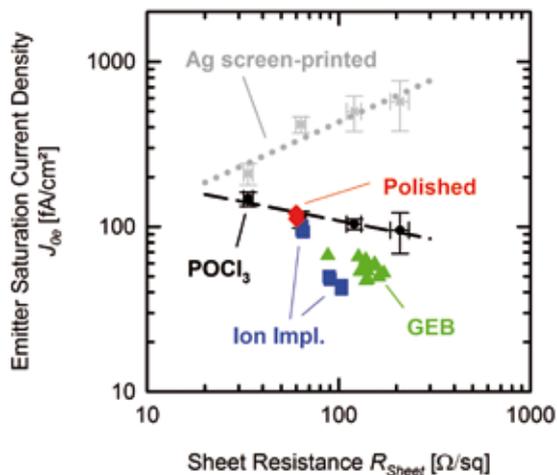

Figure 3. Emitter saturation current density of homogeneously $POCl_3$-diffused emitters with Ag screen-printed contacts (grey), as well as a SiN_x surface passivation (black) [21]. The emitter saturation current densities of the GEB (green) and ion-implanted (blue) emitters are significantly lower than for $POCl_3$-diffused emitters with the same sheet resistance.

earlier for the reference PERC process.

This very lean PERC process flow requires just 10 process steps. The schematic cross section of the resulting PERC solar cell is basically identical to the reference PERC cell in Fig. 1 (left). However, the rear surface of the polished PERC cell is slightly rougher, and the doping profile of the emitter is different from that of the reference PERC cell.

D) GEB PERC: PERC solar cells with selective emitter formed by gas phase etch-back

See Hannebauer et al. [20] for an in-depth description of the novel selective emitter process for GEB PERC cells. The wafers are double-sided textured and double-sided $POCl_3$ diffused, with an emitter sheet resistance of 45Ω/sq. Using an inkjet printer, an etch barrier (barrier material provided by Merck) is printed on the front side of the wafer in areas where the front Ag fingers will later also be screen printed. The printed etch barrier width is around 600μm, which is subject to further reduction and optimization.

The rear side is then polished using the RENA InPilot tool, and the emitter is thereby simultaneously etched back on the front side in between the etch barrier fingers by the reactive gas phase of the polish bath. In contrast with the previously described polished PERC process, the polish recipe is adjusted in order to obtain a much more reactive gas phase which removes about 30 to 40nm of the phosphorus emitter on the front side while wet chemically polishing and removing about 8μm of silicon on the rear side. The cleaning after the polish removes the etch barrier.

The final emitter sheet resistances are about 90Ω/sq. in between the etch barrier fingers (later SiN_x passivated), and about 45Ω/sq. below the etch barrier (later Ag screen printed). The passivation of the rear and front surfaces, the LCO and the screen printing of the front and rear contacts are carried out as described earlier for the reference PERC process. Compared

with the polished PERC cells, the GEB PERC process flow requires just one additional process step (etch barrier deposition) to form a selective emitter instead of a homogeneously doped emitter. Fig. 1 (right) shows a schematic drawing of the GEB PERC solar cell with selective emitter.

Emitter doping profiles and saturation currents

The doping profiles are obtained by electrochemical capacitance-voltage (ECV) measurements of planar test wafers which have been processed in a very similar way to that of the corresponding PERC solar cells. Fig. 2(a) shows the resulting doping profiles; the 70Ω/sq. $POCl_3$ emitter of the reference PERC cell is shown in black and serves as a reference. The doping profile of the 90Ω/sq. GEB emitter is almost identical to that of the polished PERC cell, since in both cases a 45Ω/sq. $POCl_3$ diffusion is applied. However, around 40nm of the front surface of the emitter has been removed by the GEB; accordingly, the ECV profile of the GEB emitter is shifted by 40nm in Figs. 2(a) and (b). The doping profile of the 65Ω/sq. ion-implanted emitter after annealing has a depth of around 0.55μm, which is comparable to that for the GEB and polished PERC emitters.

Fig. 2(b) shows a close-up of the first 0.1μm in Fig. 2(a) so that the significantly different phosphorus concentrations at the front surface can be observed. As can be seen, the GEB 90Ω/sq. emitter is etched back by approximately 40nm, resulting in the lowest phosphorus surface concentrations of $5\times10^{19}cm^{-3}$. The doping profile of the polished PERC emitter shows a front phosphorus concentration of around $1.5\times10^{20}cm^{-3}$, despite the strong 45Ω/sq. $POCl_3$ diffusion. This is achieved by the aggressive wet cleaning after the rear polishing, which partly etches the emitter front surface. The ion-implanted emitter indicates a low

phosphorus concentration of around $2\times10^{20}cm^{-3}$ of the front as well, which is achieved by a suitable combination of implant and annealing parameters. In this case, the diffusion mechanism follows a 'limited source behaviour' according to Fick's laws of diffusion, which allows a reduction in the surface concentration of phosphorus, as opposed to the typically 'unlimited source behaviour' of $POCl_3$ diffusion, which maintains the concentration at the surface.

To assess the electrical performance of the different emitters, the emitter saturation current density J_{0e} is measured by quasi-steady-state photoconductance (QSSPC) of suitable test structures using float zone wafers with resistivities of about 200Ωcm. The GEB, polished and ion-implanted emitters are processed in the same way as the corresponding PERC cells, including a textured surface passivated by SiN_x.

"The superior performance of the ion-implanted and GEB emitters is due to the significantly lower front-surface phosphorus concentration."

Measurements taken after firing are shown in Fig. 3. The black data points represent the reference $POCl_3$ emitter for different sheet resistances and are taken from Hannebauer et al. [21]. The grey data points, labelled 'Ag screen-printed', refer to J_{0e} measurements by dynamic infrared lifetime mapping (DILM) of Ag screen-printed contacts on $POCl_3$-diffused emitters with different sheet resistances, as published in Hannebauer et al. [21]. For sheet resistances of 90 to 130Ω/sq. in particular, the ion-implanted and GEB emitters yield significantly lower J_{0e}

PERC type	Emitter technology	Emitter doping	η [%]	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]
Ref. PERC	$POCl_3$	H, 70Ω/sq.	20.0	649	38.1	80.9
I^2-PERC	Ion implantation	H, 65Ω/sq.	20.0	659	38.7	78.3
Polished PERC	$POCl_3$	H, 65Ω/sq.	20.2	655	38.0	81.0
GEB PERC	GEB	SE, 90/45Ω/sq.	20.3*	660	38.3	80.3

*Independently confirmed by ISE CalLab

Table 2. Solar cell parameters of the best PERC solar cell of each process flow, measured under standard testing conditions (H = homogeneously doped; SE = selective emitter).

values of 40 to 60fA/cm^2, compared with 90fA/cm^2 for the POCl$_3$-diffused emitter. The superior performance of the ion-implanted and GEB emitters is due to the significantly lower front-surface phosphorus concentration, as shown in Fig. 2(b), resulting in fewer inactive phosphorus atoms which could act as recombination centres. For the polished PERC cells, however, the J_{0e} values of around 110fA/cm^2 are comparable to the current densities for POCl$_3$-diffused emitters of the same sheet resistance.

PERC solar cells

Table 2 shows the *I-V* parameters of the best performing PERC cells of the four PERC cell process flows described earlier. The reference PERC cell demonstrates a conversion efficiency η of 20.0%, whereas the polished and GEB PERC cells yield conversion efficiencies of 20.2% and 20.3% respectively. The benefit of the selective emitter of the GEB PERC cell can be seen in the high open-circuit voltage V_{oc} of 660mV and good short-circuit density J_{sc} of 38.3mA/cm^2. The I^2-PERC cell achieves 20.0% conversion efficiency and high V_{oc} and J_{sc} values; the fill factor *FF*, however, is significantly lower than for the other PERC cells. It has to be considered, though, that the I^2-PERC cell has been produced using an older process, with respect to the rear-surface passivation and front-side metallization, than in the case of the other three PERC cells, which have been created using the latest process at ISFH. If the latest process is applied to the I^2-PERC cells, the conversion efficiency is expected to be around 20.2%.

Another option for further increasing the conversion efficiency of I^2-PERC cells is to apply a selective emitter by putting a shadow mask in the ion beam, a technique which requires no additional process step [12]. Moreover, it should be mentioned that the GEB PERC cells stem from only the fourth batch ever of cells processed using this novel selective emitter concept. The etch barrier still has improvement potential with respect to the barrier width and the etch resistance. Efficiencies higher by at least 0.2% abs. are therefore expected with an optimized GEB PERC cell process in the future.

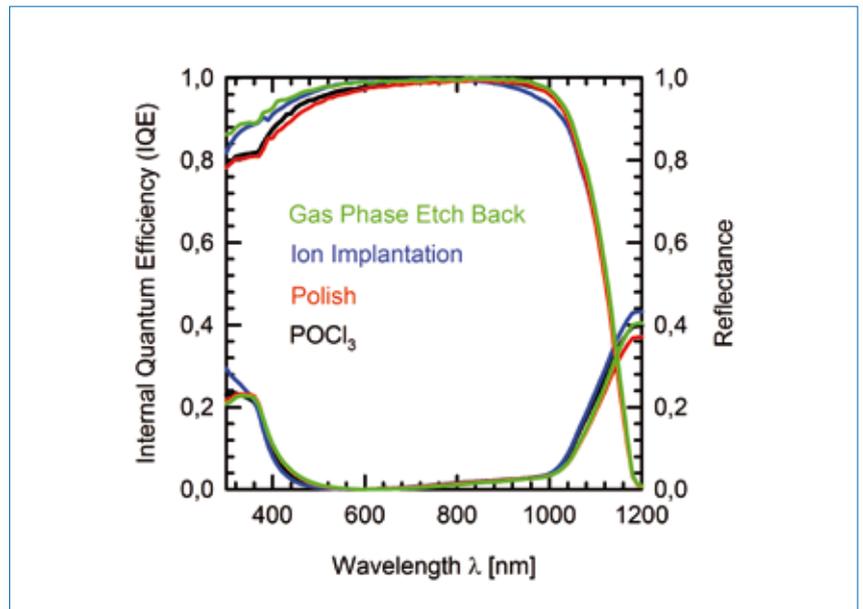"Efficiencies higher by at least 0.2% abs. are expected with an optimized GEB PERC cell process in the future."

Figure 4. IQE (top) and reflectance (bottom) measurements of the GEB PERC cell, the I^2-PERC cell, the polished PERC cell and the reference PERC cell (POCl$_3$) in Table 2. The improved IQE in the blue-wavelength regime of the GEB and I^2-PERC cells compared with the reference PERC cell is in accordance with the lower J_{0e} values shown in Fig. 3. The slightly lower IQE of the I^2-PERC cell in the infrared-wavelength regime is due to the older rear-passivation process.

To compare the performance of the different phosphorus emitters, the internal quantum efficiency (IQE) and reflectance of the four PERC cells of Table 2 were measured. As can be seen in Fig. 4, the GEB PERC and the I^2-PERC cells show a significantly improved blue-wavelength IQE compared with the reference PERC cell. Accordingly, the lower J_{0e} values of the ion-implanted emitter and the GEB emitter compared with the POCl$_3$ emitter in Fig. 3 translate into a higher blue-wavelength IQE, and hence into higher V_{oc} and J_{sc} values, as shown in Table 2.

Fig. 4 also indicates that the IQE of the I^2-PERC cell is slightly lower in the infrared regime around 1000nm wavelength; this is caused by the older rear-passivation process and is not related to the emitter formation. The IQE of the polished PERC cell is almost identical to that of the reference PERC cell, despite the different types of POCl$_3$ diffusion used in the process flows. The wet chemical etch-back of the emitter of the polished PERC cell therefore compensates for the stronger POCl$_3$ diffusion. Furthermore, in the red-wavelength regime the IQEs of the GEB and polished PERC cells are comparable to the IQE of the reference PERC cell, which proves that the rear polish is sufficient to allow an excellent rear-surface passivation.

Conclusions

Emitter technologies of three industrially applicable PERC cell concepts have been evaluated, including ion-implanted emitter, chemically polished rear surface, and selective emitter by GEB. The results were compared with a high-efficiency reference PERC cell. The three industrial PERC concepts employ lean industrially applicable process sequences which reduce the phosphorus concentration at the wafer surface.

"When applied to PERC cells, the ion-implanted and GEB emitters achieve conversion efficiencies of up to 20.3%."

The ion-implanted and GEB emitters consequently obtain significantly reduced emitter saturation current densities of 40 to 60fA/cm^2 for emitter sheet resistances of 90 to 130Ω/sq. When applied to PERC cells, the ion-implanted and GEB emitters demonstrate up to 10mV higher open-circuit voltages than the POCl$_3$-diffused reference PERC cell and achieve conversion efficiencies of up to 20.3%. The potential for further increases in efficiency has been discussed.

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

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Prof. 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.

Franck Delahaye studied process technology. In 1999 he started PV activities at RENA. He worked on various PV technologies and invented wet processing applications like single side etching. At present he is product manager in the solar division of RENA.

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