Abstract

Bifacial solar cell n-PERT concept involves boron and phosphorus doped regions requiring both proper surface passivation. In order to reduce n-PERT technology related €/W, one way considered is to simplify cell process-flow. In order to do so, we developed passivating/anti-reflective/doping SiO$_x$N$_y$:B and SiN$_x$:P layers. The co-anneal of these multifunctional layers allows for (1) emitter & BSF formation, (2) subsequent doped regions passivation, (3) providing satisfying optical properties. The features of our multifunctional PECVD-deposited layers are detailed. By exploiting the passivating properties of our multifunctional layers we eventually present our so-called “SOLENNA(3)” technology. This ultimately simplified technology provides large area (243cm$^2$) LID-free 19.8% efficient n-PERT cells with only 7 processing steps. This is to the authors’ knowledge the simplest n-PERT process ever introduced with such a high level of performance. Finally, the cost calculation based on a 100MW line capacity and confronting SOLENNA(3) to referent technologies was completed. Due to its simplicity, it was shown that SOLENNA(3) technology can compete with the classical Al-BSF technology in terms of cost per watt at the module level.

Keywords: silicon; passivated emitter rear totally diffused; solar cell; co-diffusion; boron silicate glass; passivation; doped silicon nitride

1. Introduction

Since c-Si photovoltaics (PV) industry scaled up to mass production, it is dominated by the conventional full Al-BSF cell architecture, applied to p-type silicon. Al-BSF device performance has been indeed steadily improved (with up to 19.5%-efficient p-type solar cells [1] and remains today the most suitable option in terms of €/Wp. Bifacial photovoltaics (bifi-PV) market is soaring, with a PERT (Passivated Emitter Rear Totally diffused) architecture providing 20%-efficient n-type devices showing no light induced degradation (LID). The PV community is more and more convinced that the use of bifaciality for future generation of PV systems will allow a
significant reduction of the levelized cost of electricity (LCOE). Nevertheless, bifi-PV deployment is still infringed by the additional cost related to the production of bifacial module, related to additional processing steps at the cell level. Indeed, the fabrication of PERT architecture, implies single-side p+ and n+ diffusion, B-emitter specific passivation and double-side SiN coating. Over the last years, academics and industrials accomplished significant R&D efforts to find ways of simplifying the process flow [2-7]. Most of these concepts have led in the recent years to solar cells with conversion efficiencies of above 20.0%. Nevertheless, the growth in the production of bifacial cells remains limited, mostly because the economic interest only occurs at the system level (LCOE) when the bifacial gain is considered. A faster growth of bifacial PV requires an even more simplified cell process to reduce the initial CAPEX investments and thus, the cost per Wp. In order to do so, we have developed PECV-deposited boron-doped silicon oxynitride (SiOxNy:B) and phosphorus-doped silicon nitride (SiNx:P). These layers were firstly integrated into a moderately simplified n-PERT process-flow (referred to as SOLENNAs2), as sacrificial doping sources. After further tuning of their passivating and optical properties, the layers could be kept in the final device, leading to an ultra-simplified n-PERT process-flow (referred to as SOLENNAs3). The doping layers features, and resulting solar cell results are presented in this paper, as well as a cost calculation of SOLENNAs3 technology, based on the assumption of a 100MW annual production.

2. Experimental

2.1. SiOxNy:B and SiNx:P elaboration and doping properties

Among the alternative doping techniques considered to simplify the fabrication of the p+/n/n+ structure, dielectric doped layers are of prime interest since they open the door to co-diffusion (the formation of emitter and BSF in one step). In the recent years, the annealing of boron silicate glass (BSG) during POCl3 diffusion led to co-diffused n-PERT devices with 20% efficiency [8]. In the present case, the boron doped layer we developed is a silicon ox-nitride based material (SiOxNy), in which boron is incorporated through the use of diborane (B2H6) precursor. The resulting SiOxNy:B layer was deposited on 180μm thick Cz(n) wafers (1-4 Ohm.cm) thanks to a direct low-frequency PECVD furnace, using a mixture of silane (SiH4), nitrogen oxide (N2O), and H2-diluted diborane. Various thicknesses of this material were considered in the [10nm-70nm] range. After annealing the coated samples (940°C; <1h) under neutral ambient, the resulting B-emitter sheet resistance (Rsheet) was measured by the 4PP method (see Fig.1.a).

![Figure 1](image)

Fig. 1.(a) (left) B-emitter Rsheet, as a function of SiOxNy:B layer thickness and (b) (right) n+-BSF Rsheet as a function of SiNx:P layer thickness after a common anneal (940°C; <1h).
We notice:

- A minimal thickness (here 19nm) is required to meet decent $R_{\text{sheet}} (<100 \text{ Ohm/sq})$ and uniformity (<5%) targets
- A further thickening of SiO$_x$N$_y$:B improves doping uniformity exclusively, with no impact on $R_{\text{sheet}}$ value.

The phosphorus doped layers were also deposited in a LF-PECVD furnace, using this time a mixture of silane (SiH$_4$), ammoniac (NH$_3$), nitrogen (N$_2$) and H$_2$-diluted phosphine (PH$_3$) as dopant precursor. The resulting SiN$_x$:P layers were coated on 180µm thick Cz p-type (2 Ohm.cm) wafers. Figure 1.b plots the BSF $R_{\text{sheet}}$ variation: resistance decreases steadily in the 60-20 Ohm/sq range, as SiN$_x$:P thickness increases, which corresponds to an expected finite source behaviour. In any case, the doping uniformity remains acceptable (<8%, even on <20nm thick SiN$_x$:P layer).

2.2. SiO$_x$N$_y$:B and SiN$_x$:P passivating properties

Satisfying passivation was reported with BSG layers [9]. In the present study, the PECVD layers were developed promoting a high doping property even for thin layers: 20nm thick SiO$_x$N$_y$:B and SiN$_x$:P layers are sufficient to reach decent doping targets ($p^+$-emitter < 80 Ohm/sq; n$^+$-BSF < 50 Ohm/sq). From an optical point of view, the integration of our layers on both front and rear sides of solar devices is thus facilitated. For which concern BSF passivation, the choice was made to develop an hydrogenated nitride layer (SiN$_x$:P) to boost intrinsic passivating properties of the layer.

![Fig. 2. Evolution of SiO$_x$N$_y$:B passivated emitter (left) and SiN$_x$:P passivated BSF (right) in terms of $J_0$ and implied $V_{oc}$ at 1sun.](image)

Our layers passivating properties were evaluated by means of QSSPC $J_0$ measurements after firing at 800°C of textured symmetrical samples ($p^+/n/p^+$ and $n^+/n/n^+$). The thermal budget for the annealing of the layers and related diffusion of the dopants is 940°C, less than 1 hour. These samples were elaborated from Cz(n) 4 Ohm.cm wafers that had been previously alkaline textured, RCA cleaned, and double-side coated with the layers of concern. SiO$_x$N$_y$:B layer exhibited initially poor passivation properties after annealing: indeed, the $p^+$ emitter saturation density was estimated to be greater than 1400fA/cm². No significant passivation enhancement was offered by capping the B-doped layer by an ARC SiN layer. For BSF concern, the $J_0$ offered by SiN$_x$:P layer was also quite high (near 400fA/cm²). Nevertheless, in that case, integrating a SiN capping allowed reducing it down to 337fA/cm². Further passivation improvement was achieved (see Fig. 2) by:

- Tuning PECVD conditions and SiO$_x$N$_y$:B & SiN$_x$:P stoichiometry. By doing so, the $J_0$ values curb down to 120fA/cm² for the emitter, and <250fA/cm² for the BSF.
Modifying co-anneal thermal budget and sample configuration in order to tune doping profiles and improve passivation homogeneity (as illustrated Fig. 3). We were able to reduce the $J_0$ values (85fA/cm² for the emitter; 180fA/cm² for the BSF).

Fig. 3. Solar cell PL images involving SiO$_x$N$_y$:B front passivation and SiN$_x$:P rear passivation. Evolution of PL signal homogeneity: before (top) and after (bottom) co-anneal optimization (thermal budget (940°C) & sample configuration during the annealing).

Corresponding cell precursors ($p^+$/n/n$^+$) integrating our optimized layers show decent implied $V_{oc}$ values of 665mV at 1 sun. Solar cells involving these multifunctional layers (as a replacement of conventional BBr$_3$ and POCl$_3$ diffusion techniques, and also as passivating layers) have been processed on 200μm thick Cz(n) 243cm² wafers. The next section details their processing and electrical parameters.

2.3. Solar cell processing and results

A first batch of solar devices using SiO$_x$N$_y$:B and SiN$_x$:P as sacrificial doping layers was elaborated. (1) After alkaline texturing and RCA cleaning of the wafer, (2) SiO$_x$N$_y$:B and (3) SiN$_x$:P layers are deposited on front and rear side. Samples are (4) co-annealed (940°C; <1h), leading to 65 Ohm/sq B-emitter and 30 Ohm/sq P-BSF. (5) Samples are HF-dipped to remove the doped layers and (6) RCA cleaned. (7) Thermal oxidation is followed by PECVD SiN coating for (8) front and (9) rear side passivation. Front and rear silver-based grid contacts are (10) screen-printed then (11) co-fired. The cell I-V parameters (class A solar simulator; reflective chuck) are listed Table 1. This batch provides 20%-efficient co-diffused solar cells with a fully dielectric-diffused route referred to as SOLENN(2).

Table 1. 243cm² SOLENN(2) solar cell I-V parameters measured under STC (25°C; AM1.5G; 1000W/m²);

<table>
<thead>
<tr>
<th>Batch of 13 devices</th>
<th>Voc (mV)</th>
<th>Jsc (mA/cm²)</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>646.9</td>
<td>38.7</td>
<td>79.4</td>
<td>19.9</td>
</tr>
<tr>
<td>Best cell</td>
<td>647.0</td>
<td>38.6</td>
<td>80.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>
A second batch of wafers was processed with an ultra-simplified n-PERT process, in which doped layers are maintained. The front & rear passivation being here granted by SiO$_x$Ny:B/SiN & SiN$_x$:P$\text{SiN}$ respectively, thermal oxidation was avoided, as well as doped-layer removal and surface clean. Rear PECVD SiN deposition was integrated in the SiN$_x$:P recipe for both passivation and barrier regarding phosphorus out-diffusion. The process-flow (see Figure 4) competes thus Al-BSF simplicity since reduced to the 7 following steps: (1) Alkaline texturing and RCA cleaning, (2) SiO$_x$Ny:B layer and (3) SiN$_x$:P$\text{SiN}$ stack deposition. (4) Co-annealing (940°C; <1h), (5) SiN front deposition on top of SiO$_x$Ny:B. (6) Front & rear grid screen-printing and (7) co-firing. The resulting cell structure - referred to as SOLENNA(3) - is depicted Fig. 5 while I-V parameters are listed Table 2. The $J_{sc}$ limitation (<38.7mA/cm$^2$) observed on both SOLENNA(2) and SOLENNA(3) batches is due to a degraded (-4.5% rel. compare to our n-PERT baseline) high-wavelength (>950nm) spectral response attributed to (1) heavy BSF doping, (2) rear SiN$_x$:P$\text{SiN}$ absorption. Nevertheless, this batch provides 19.8%-efficient /LID-free/ co-diffused solar cells, with only 7 processing steps: to our knowledge the simplest n-PERT approach with such a high level of performance.

![Image](image.png)

**Fig. 4.** Our ultra-simplified n-PERT process-flow (left) and final SOLENNA(3) cell structure (right)

**Table 2.** 243cm$^2$ SOLENNA(3) solar cell I-V parameters measured under STC (25°C; AM1.5G; 1000W/m$^2$):

<table>
<thead>
<tr>
<th>Batch of 11 devices</th>
<th>Voc (mV)</th>
<th>Jsc (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>644.1</td>
<td>38.6</td>
<td>79.1</td>
<td>19.7</td>
</tr>
<tr>
<td>Best cell</td>
<td>645.0</td>
<td>38.5</td>
<td>79.6</td>
<td>19.8</td>
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**3. Cost calculation**

A cost study was performed to assess the economic relevancy of SOLENNA(3) technology. The calculation addresses the cell process cost (CAPEX and OPEX), as well as the total CoO (in €/W$_p$) including wafer and module contributions. The scenario of a plant in Europe, with an annual capacity of 100MW annual capacity was taken, considering the following cell architectures and related process-flows:

- Al-BSF (5 steps) and PERC (8 to 9 steps) on p-type Cz (1$/wafer): efficiencies were assumed to be stabilized respectively at 19% and 20%, with no further LID.
- PERT (7 steps) and SOLENNA(3) (8-11 steps) on n-type Cz (1.1$/wafer), with a given efficiency of 20%.

A depreciation of 5 years for the equipment, 10 years for the facilities and 20 years for the building was assumed. Parameters such as yield, uptime, manpower, building and facilities were adjusted with the number of process steps of the different technologies. The CAPEX and OPEX of high efficiency architectures (PERC, PERT and SOLENNA(3)) have been confronted to a standard Al-BSF production (see Fig 5). All the investigated processes were based on two scenarii, respectively optimistic (blue bar chart in Fig. 5) and pessimistic (red). This variation
depends on process complexity (number of steps) and characteristics of the equipments considered (throughput and cost). A 20%-efficient SOLENNA(3) technology would outperform PERC technology in terms of CAPEX, and even would show an OPEX cost comparable to Al-BSF. As a result, the calculated “Cell CoO” range (sum of CAPEX and OPEX) from optimistic to pessimistic version of SOLENNA(3) is [15.5-16.5]€/Wp, against [14.8-15.4]€/Wp for Al-BSF, [18.5-19.8]€/Wp for PERC and eventually [17.8-21.5]€/Wp for PERT.

Nevertheless, the “total CoO” of the complete SOLENNA(3) PV panel, including wafer and module contributions, would still be slightly higher (63.5(+/-0.5)€/Wp) than standard Al-BSF PV panel (62.5 (+/-0.3) c€/Wp). This is mainly explained by the additional cost (+10%) considered for n-type wafers. It was then calculated that an extra wafer cost reduced to +4% over p-type would be required for SOLENNA(3) to compete Al-BSF technology also at module level, in terms of €/Wp. Of course, the additional output linked to the bifaciality of SOLENNA(3) was not considered here.

4. Conclusion and outlook

The use of our doping PECVD layers for B-emitter & P-BSF formation led to 20%-efficient co-diffused n-PERT large area Cz solar cell (SOLENNA(2)). Tuning our layers passivating properties opened the door to an ultra-simplified (7 steps) way to produce 19.8% n-PERT bifacial devices (SOLENNA(3)). By tuning stack optics (n,k), and BSF doping, we are confident to reach soon 20% with this technology. All the devices presented here have already proven stable efficiency after >120h light exposure (0.3sun; 50°C). First cost calculations show the high potential of SOLENNA(3) as an industrial-friendly solution for n-PERT mass production.

References
