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journal homepage: [www.elsevier.com/locate/solmat](http://www.elsevier.com/locate/solmat)21.0%-efficient screen-printed *n*-PERT back-junction silicon solar cell with plasma-deposited boron diffusion sourceNadine Wehmeier<sup>a,\*</sup>, Anja Nowack<sup>a</sup>, Bianca Lim<sup>a,1</sup>, Till Brendemühl<sup>a</sup>, Sarah Kajari-Schröder<sup>a</sup>, Jan Schmidt<sup>a,b</sup>, Rolf Brendel<sup>a,b</sup>, Thorsten Dullweber<sup>a</sup><sup>a</sup> Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany<sup>b</sup> Department Solar Energy, Institute of Solid-State Physics, Leibniz University Hanover, Appel Str. 2, 30167 Hanover, Germany

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## ABSTRACT

The manufacturing process of Passivated Emitter and Rear Totally diffused (PERT) solar cells on *n*-type crystalline silicon is significantly simplified by applying multifunctional layer stacks acting as diffusion source, etching and diffusion barrier. We apply boron silicate glasses (BSG) capped with silicon nitride ( $\text{SiN}_2$ ) layers that are deposited by means of plasma enhanced chemical vapor deposition (PECVD). Optimum PECVD deposition parameters for the BSG layer such as the gas flow ratio of the precursor gases silane and diborane  $\text{SiH}_4/\text{B}_2\text{H}_6=8\%$  and the layer thickness of 40 nm result in a boron diffusion with saturation current density  $J_{0,B}$  below  $10 \text{ fA/cm}^2$  applying an  $\text{AlO}_x/\text{SiN}_y$  passivation and firing. The PECVD BSG diffusion source is integrated into the *n*-type PERT back junction (BJ) solar cell process with screen-printed front and rear contacts. The only high temperature step is a  $\text{POCl}_3$  co-diffusion for the formation of the boron emitter from the PECVD BSG layer and for the formation of the phosphorus-doped front surface field (FSF). An independently confirmed energy conversion efficiency of 21.0% is achieved for a  $156 \times 156 \text{ mm}^2$  large *n*-PERT BJ cell with this simplified process flow. This is the highest efficiency reported for a large-area co-diffused *n*-type PERT BJ solar cell using a PECVD BSG as diffusion source. For comparison, reference *n*-type PERT BJ cells with separate  $\text{POCl}_3$  and  $\text{BBr}_3$  diffusions reach an efficiency of 21.2% in our lab. A synergistic efficiency gain analysis (SEGA) for the co-diffused *n*-PERT BJ cell shows that the main possible efficiency gain of 1.1%<sub>abs.</sub> originates from recombination in the phosphorus-diffused front surface field while the PECVD BSG boron-doped emitter accounts for only 0.1%<sub>abs.</sub> efficiency gain. We evaluate the use of the PECVD BSG/ $\text{SiN}_2$  stack as a rear side passivation as a replacement of the  $\text{AlO}_x/\text{SiN}_y$  stack in order to further simplify the process flow. We obtain  $J_{0,B}$  values of  $40 \text{ fA/cm}^2$ , an implied open-circuit voltage of 682 mV and a simulated *n*-PERT BJ cell efficiency of 21.1%.

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## 1. Introduction

The Passivated Emitter and Rear Cell (PERC) concept on *p*-type silicon wafers is expected to become a major industrial solar cell technology [1]. With a lean process flow, efficiencies of up to 22.1% [2] were recently demonstrated. However, the efficiency of PERC solar cells typically decreases around 0.5%<sub>abs.</sub> due to light-induced degradation (LID) of the boron-doped *p*-type Czochralski-grown (Cz) silicon used as base material [3,4].

Fig. 1 shows an *n*-type silicon PERT (*n*-PERT) BJ cell. This is an attractive cell concept which combines the advantages of *n*-type

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silicon (no LID, high bulk lifetime [5]) and of a process flow that is very similar to industrial *p*-type PERC (*p*-PERC) cells. The PERT BJ fabrication has the potential to be further simplified and to be implemented in existing PERC production lines. Until now, *n*-PERT BJ cells applying  $\text{BBr}_3$  and  $\text{POCl}_3$  furnace diffusions have demonstrated conversion efficiencies up to 22.5% using Ni/Cu/Ag plating on the front side and AlSi sputtering on the rear side for metallization [6] and with screen-printed contacts up to 21.4% [7] and very recently of 21.8% [8]. In this work, we apply plasma enhanced chemical vapor deposition (PECVD) of boron silicate glass (BSG). Combined with a co-diffusion process, this is an alternative approach to introduce the rear side  $p^+$ -emitter and the  $n^+$ -front surface field (FSF) of the *n*-PERT BJ cells. As an approach for process simplification, CVD BSG layers combined with a  $\text{POCl}_3$  co-diffusion have already been applied to *n*-PERT solar cells (front and back junction) [9–11] reaching conversion efficiencies up to 19.9%

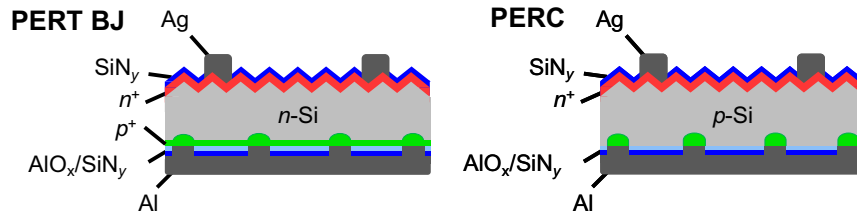


Fig. 1. Schematic diagram of the  $n$ -PERT BJ cell compared to the  $p$ -PERC cell.

[9] and 20.1% for bifacial devices [11].

We demonstrate monofacial  $n$ -PERT BJ cells with a record-high conversion efficiency of 21.0% with a co-diffused boron emitter from a PECVD BSG/SiN<sub>z</sub> stack that has already been presented in [12]. In this paper, we show a SEGA for the best  $n$ -PERT BJ cell that proves the high quality of the PECVD BSG diffusion source and shows the highest potential for synergistic cell improvements of up to 4.1%<sub>abs</sub>, by eliminating recombination, especially in the P FSF.

To further simplify the process, the multifunctional use of PECVD stacks as diffusion source and also as rear side passivation instead of AlO<sub>x</sub>/SiN<sub>y</sub> has been proposed and  $J_0$  values down to 50 fA/cm<sup>2</sup> have been demonstrated for a BSG/SiN<sub>x</sub> passivation by Engelhardt et al. [13]. In this work, we investigate the passivation quality of BSG/SiN<sub>z</sub> and BSG/SiO<sub>x</sub>N<sub>y</sub> stacks reaching lowest published  $J_0$  results of 40 fA/cm<sup>2</sup> and evaluate the implementation in  $n$ -PERT BJ cell processing by device simulations.

## 2. Material and methods

### 2.1. PECVD layer stack and co-diffusion

The PECVD BSG deposition is performed in a cluster system (CS 400P, von Ardenne) with an inductively coupled plasma (ICP) source. For the deposition of a 20–120 nm thin BSG layer, we use the precursor gases silane (SiH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and diborane (3% B<sub>2</sub>H<sub>6</sub>, diluted in 97% H<sub>2</sub>). The ratio SiH<sub>4</sub>/B<sub>2</sub>H<sub>6</sub> is varied from 4% to 8%. For this calculation the B<sub>2</sub>H<sub>6</sub> gas flow including the 97% H<sub>2</sub> dilution is used.

As a capping layer, we apply either a silicon nitride (SiN<sub>z</sub>) (SiNA, Meyer Burger) with a thickness of 120–180 nm or a silicon oxynitride (SiO<sub>x</sub>N<sub>y</sub>) with a thickness of 200–300 nm. The SiO<sub>x</sub>N<sub>y</sub> layer is deposited in the same ICP deposition chamber as the BSG layer without breaking the vacuum. It has a higher etching rate in HF compared to SiN<sub>z</sub>.

For the boron drive-in from the BSG layer, we apply a two-stage co-diffusion process in a POCl<sub>3</sub> furnace as described in [14] and as shown in Fig. 2: In one high-temperature process, the B drive-in from the PECVD BSG is performed first in an N<sub>2</sub> ambient at 950 °C for 60 min, and then a POCl<sub>3</sub> diffusion is applied at 829 °C. During the co-diffusion, the capping layer functions as a diffusion barrier against phosphorus. When an uncapped PECVD BSG layer is exposed to co-diffusion, a P in-diffusion disturbs the boron emitter formation as reported in [15].

### 2.2. Solar cell processing

For the processing of co-diffused  $n$ -PERT BJ cells as described in [12], 156 × 156 mm<sup>2</sup> phosphorus-doped  $n$ -type Cz silicon wafers with (100) orientation, a starting thickness of (180 ± 20) μm and a resistivity of 5–6 Ω cm after high-temperature treatment (T ≥ 950 °C) during the subsequent process flow are used. They are etched in KOH for saw damage removal and are subsequently RCA-cleaned. A 40 nm-thick PECVD BSG layer with a gas flow ratio of SiH<sub>4</sub>/B<sub>2</sub>H<sub>6</sub>=8% is deposited on the planar rear side and capped

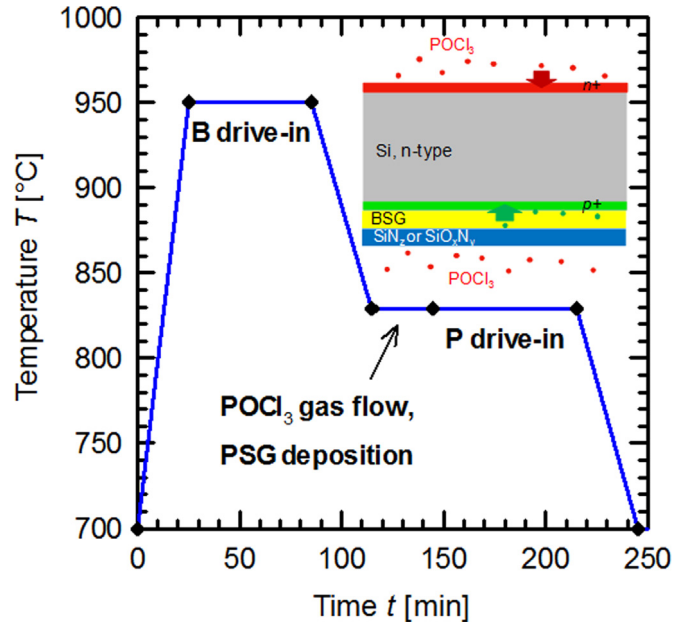


Fig. 2. Temperature profile of the two-stage co-diffusion [14]. The B drive-in from the PECVD BSG layer is performed at 950 °C in N<sub>2</sub> ambient. In the same high temperature process, a POCl<sub>3</sub> diffusion is performed at 829 °C. The BSG layer is capped with a PECVD SiN<sub>z</sub> or SiO<sub>x</sub>N<sub>y</sub> layer to prevent P in-diffusion.

with a 170 nm-thick PECVD SiN<sub>z</sub> layer (SiNA, Meyer Burger). The thickness of the SiN<sub>z</sub> layer is reduced during the following cleaning and etching steps, thus the higher thickness of 170 nm is chosen to ensure that the PECVD BSG/SiN<sub>z</sub> stack acts as an etch barrier during the following alkaline texturing and as a diffusion barrier during the POCl<sub>3</sub> co-diffusion. After removal of all dielectric layers in HF, the rear side is passivated by a stack of 5 nm AlO<sub>x</sub> deposited by spatial atomic layer deposition (ALD) (InPassion LAB tool, SoLayTec) and 100 nm SiN<sub>y</sub>. On the front side, a PECVD SiN<sub>y</sub> layer acts as passivation and as anti-reflecting coating (ARC). After laser contact opening on the rear side, the front side metallization is performed by Ag-screen printing applying a 5 busbar layout and a dual print process as described in [16]. Full-area Al-screen-printing on the rear side and co-firing finalize the cell as sketched in Fig. 1. For comparison,  $n$ -PERT BJ reference cells using sequential BBr<sub>3</sub> and POCl<sub>3</sub> diffusions are also fabricated as described in [17].

## 3. Results and discussion

### 3.1. Diffusion source and boron emitter

In order to characterize the boron emitter on planar  $n$ -type Cz-Si that is diffused from the PECVD BSG, we measure the boron sheet resistance  $R_{\text{sheet,B}}$  by means of four point probe (FPP) (Polytec, 4Dimensions) after removal of all dielectric layers. We perform lifetime measurements using a Sinton lifetime tester on symmetrically boron diffused test structures after AlO<sub>x</sub>/SiN<sub>y</sub>

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