

STATUS OF N-TYPE SOLAR CELLS FOR LOW-COST INDUSTRIAL PRODUCTION

Arthur Weeber*, Ronald Naber, Nicolas Guillevin, Paul Barton, Anna Carr, Desislava Saynova, Teun Burgers, Bart Geerligs
ECN Solar Energy, PO Box 1, NL 1755 ZG Petten, The Netherlands

*Corresponding author: Phone: +31 224 564113; Fax: +31 224 568214; Email: weeber@ecn.nl

ABSTRACT: We have reached 18.6% efficiency on large area (156 cm²) n-type crystalline silicon solar cells using conventional industrial processes like tube furnace diffusion and screen-printing. The 18.6% cell is a bifacial one with a boron emitter at the front side and a phosphorous back-surface-field (BSF). We have applied an industrially feasible boron/phosphorous co-diffusion process, and a simple wet-chemical oxidation process to passivate the highly-doped boron emitter. In this paper we will compare our results to those obtained by others. Another cell type discussed in the paper is an n-type cell with the junction at the rear. This cell has a screen-printed aluminium alloyed emitter, and the processing is comparable to conventional p-type cells. We have obtained an efficiency of 17.4% with this n-type cell. Possible improvements discussed in literature are presented as well.

Keywords: n-type, c-Si, high-efficiency

1 INTRODUCTION

Currently, more than 85% of the solar cells produced worldwide are based on crystalline silicon [1]. The fraction of crystalline silicon cells made from p-type material is close to 95%, and only somewhat more than 5% is made from n-type material. Although the total amount of n-type crystalline silicon solar cells is limited, two top-10 players, SunPower [2] and Sanyo [3], are using this material to manufacture high-efficiency solar cells. Both manufacturers apply advanced technologies and use high-quality monocrystalline base material. SunPower is manufacturing fully back-contacted cells (Interdigitated Back-Contacted, IBC) and Sanyo is producing so-called HIT (Heterojunction with Intrinsic Thin-layer) cells. On both cell types efficiencies of 23% have been reached. For the HIT cells both emitter and back-surface-field (BSF) are formed by the deposition of thin doped amorphous silicon layers. The surface passivation is accomplished by a layer of intrinsic amorphous silicon with a thickness of several nm.

The use of n-type material has several advantages over the use of p-type. Firstly, n-type material is less sensitive to most common metallic impurities, like Fe [4,5,6]. Because of this n-type material could have a higher tolerance for lower-quality feedstock [7,8]. Also after gettering and passivation higher minority carrier diffusion lengths have been observed for n-type material. Secondly, in n-type material boron-oxygen complexes are absent, and therefore it will not suffer from Light Induced Degradation [9,10]. Challenges encountered when processing n-type material into solar cells are the formation of p-type emitters by boron diffusion and the passivation of these highly-doped p-type emitter regions. Boron diffusion requires much higher temperatures than conventional phosphorous diffusion. This will make the simultaneous formation of the emitter and BSF a challenge. Furthermore, the passivation of highly-doped layers is not straightforward. Thermal oxidation is an option, but requires a long and high-temperature process step. A single-layer SiN_x coating will not result in good surface passivation because of the positive fixed charges in the layers. These fixed charges will result in an inversion layer that will enhance the effective recombination.

In this paper we will present a simple process for high-efficiency n-type crystalline silicon solar cells. We will show cell efficiencies up to 18.6% on large area

wafers using conventional equipment for wet-chemical processes, diffusion, passivation and metallization. Two cell concepts, one with an emitter at the rear, and one with an emitter at the front will be discussed in detail. Our results and possible improvements will be compared to results obtained by others.

2 SOLAR CELL CONCEPTS AND PROCESSING

2.1 Rear-side junction cell

A cross-section of the rear-side junction cell can be seen in Fig. 1. The design, and therefore the processing (Fig. 2) as well, are comparable to conventional p-type solar cells. The only difference is the use of other base material. Since the emitter is at rear, only high-quality base material can be applied. The use of lower quality material will result in much lower efficiencies because the diffusion length usually is less than several times the thickness of the cell. However, when very thin (130 μm) and larger (121 cm²) multicrystalline wafers are applied, efficiencies close to 16% are possible [11].

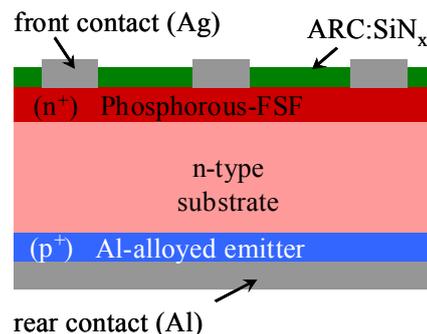


Figure 1: Cross section of rear-side junction n-type cell.

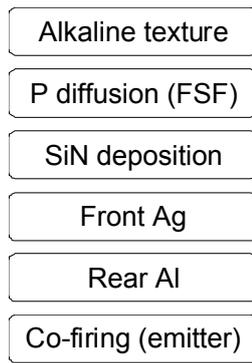


Figure 2: Process scheme of rear junction n-type cells.

We used high-quality (100) monocrystalline base material to make solar cells. First an alkaline texture was carried out to enhance light coupling. Then the front surface field was made by phosphorous diffusion to repel minority charge carriers. SiN_x deposition is carried out using a Roth&Rau inline MicroWave based PECVD system. The SiN_x layer acts as anti-reflection coating and improves the front surface passivation. The front side Ag and rear side Al metallization was applied by screen-printing. The emitter was formed during co-firing of the contacts. The alloying process results in a highly doped p-type layer. The remaining alloy at the rear acts as rear contact.

2.2 Front-side junction concept

A cross section of the front-side junction cell is presented in Fig. 3 and the processing scheme in Fig. 4. Since the emitter is at the front side, the concept can be applied to high-quality monocrystalline and lower quality multicrystalline base material.

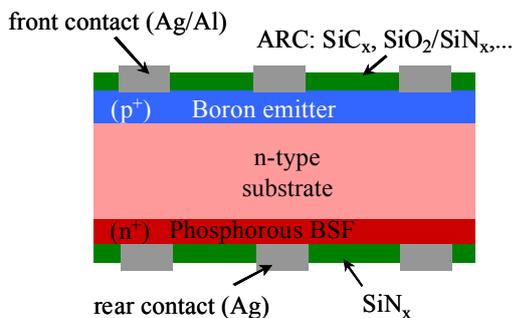


Figure 3: Cross section of front-side junction cell.

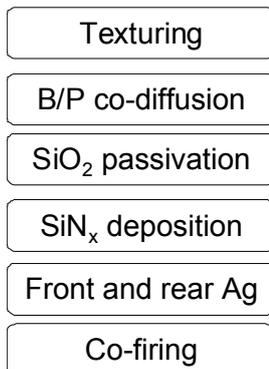


Figure 4: Process scheme of front-side junction cells.

The first step is a texturing process. For monocrystalline material we used alkaline texturing, and for multicrystalline material we applied acidic iso-texturing. The boron emitter and the phosphorous BSF were formed in a co-diffusion step using an industrial tube furnace [12] from Tempress. Surface passivation of the highly-doped boron emitter was performed using a simple and patented wet chemical oxidation process [13]. SiN_x layers for ARC and passivation purposes were deposited using our Roth&Rau PECVD system. Screen-printing was used to apply front and rear side Ag metallization. Contacts were formed during a co-firing step. An artist impression of the cells made according to this process sequence can be seen in Fig. 5.

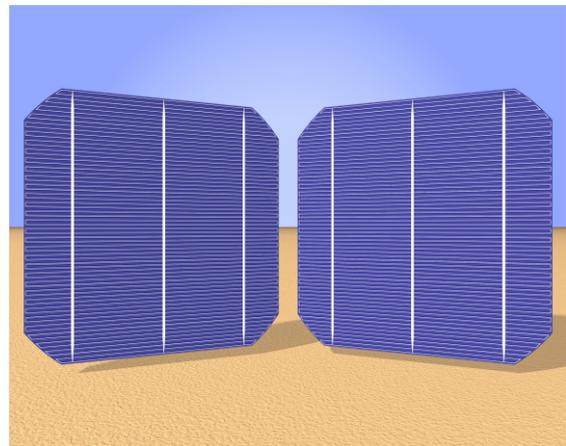


Figure 5: Artist impression of a bifacial front-side junction cell.

3 SOLAR CELL RESULTS

3.1 Results rear-side junction cell

Our best results on rear junction cells (Fig. 1) were obtained on 200 μm thin 140 cm^2 n-type FZ material [14]. 17.4% efficiency was independently confirmed by Fraunhofer ISE CalLab. The other cell parameters are depicted in Table I.

Table I: ECN's best cell results for rear junction cells

ρ (Ωcm)	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	η (%)
31	632	35.6	0.775	17.4*

* Confirmed by ISE CalLab

Detailed analysis of the cell showed that front and rear surface recombination velocities are limiting the efficiency. With excellent front surface passivation 18% should be feasible [14]. On small lab-scale cells with evaporated contacts at the front and an Al alloyed emitter at the rear, Gong et al. [15] demonstrated 17.7% cell efficiency (Cz n-type material), which is close to 18%. On 148.4 cm^2 large n-type substrates and applying aerosol printed and Ag plated front contacts 18.2% cell efficiency has been recently obtained by Schmiga et al. [16]. This 18.2% cell has a full Al doped emitter made during firing.

Improving the rear-side emitter passivation can further enhance the efficiency. On small lab-scale cells with evaporated contacts 20% cell efficiency has been observed. The passivation at the rear side has been

improved by removing the Si-Al alloy, etching several μm from the rear, and then applying dielectric layer (or stacks) passivation. Schmiga et al [17] applied an $\text{Al}_2\text{O}_3/\text{SiO}_x$ stack to passivate the rear emitter surface and obtained 20.1%. Bock et al. [18] used a similar process with amorphous Si passivation on the Al rear side emitter and has recently reached 20.0%. With a stack of amorphous Si and SiO_x 19.7% has been obtained.

3.2 Results front side junction cell

As was mentioned in the introduction, there are two key process steps in the manufacturing process of n-type front side junction cells (Fig. 2): 1) the co-diffusion of the boron emitter and phosphorous BSF and; 2) the surface passivation of the boron emitter. For the diffusion we are using an industrial tube furnace system of Tempress. A 60 Ω/sq emitter is made using BBr_3 . We are able to make boron emitters with a standard deviation in sheet resistivity of about 1.5 Ω/sq [12]. A sheet resistance scan can be seen in Fig. 6.

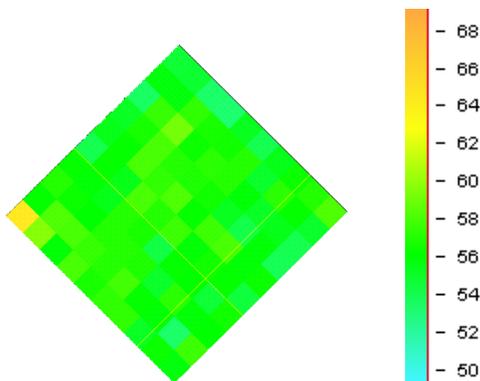


Figure 6: Sheet resistance mapping of a 60 Ω/sq boron emitter.

To passivate the highly doped emitter surface we developed a simple wet chemical oxidation process [13]. The effect of using an oxide layer with a PECVD SiN_x ARC layer can be seen in Fig. 7. It is clearly visible that the blue response of cells with a silicon oxide passivating layer is much better than that of cells without oxide and only a single SiN ARC layer. The lack of passivation for a single layer SiN coating can be explained by the fixed positive charges in that layer. These charges will create in an inversion layer which results in enhanced recombination. Recently, we have improved our wet oxide passivation process even further resulting in a gain in V_{oc} of about 10 mV [19]. The internal quantum efficiencies of both passivating oxide layers are presented in Fig. 8.

We processed n-type based solar cells using both multi and monocrystalline material. The cell size was about 156 or 243 cm^2 and our results are summarized in Table II. As far as we know these are the highest cell efficiencies reached using process equipment and processes that are commonly used in industry, or can be easily implemented in manufacturing lines.

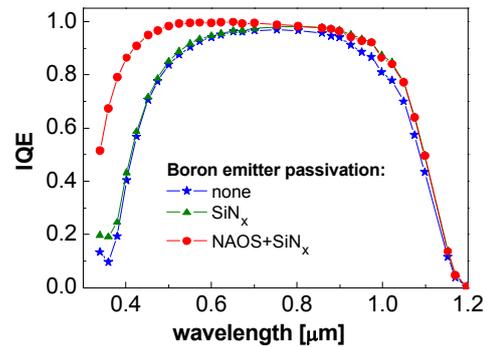


Figure 7: Internal quantum efficiency of cells with and without wet chemical oxide (NAOS).

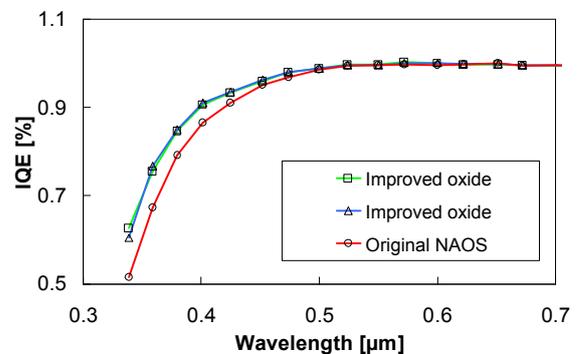


Figure 8: Internal quantum efficiency of cell with original NAOS oxide passivation and IQE of two cells with improved wet chemical oxidation.

Table II: ECN's best results on front side junction cells. In the texture column (text.): iso means isotexture, RP means random pyramids.

n-type	area (cm^2)	text.	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η (%)
mc	156	iso	617	35.3	76.8	16.7*
Cz	156	RP	634	37.5	77.9	18.5*
Cz	156	RP	640	37.5	77.6	18.6
Cz	243	RP	637	37.4	77.4	18.5

* confirmed by ISE CalLab (for a particular rear-side reflection surface).

Detailed analysis based on IV and IQE characteristics show that with an improved emitter (for example a selective emitter) and improved front side metallization (less shading losses) efficiencies above 19% should be possible in the near future.

A similar process based on large area wafers and screen-printed metallization is investigated by Buck et al. [20]. On 146 cm^2 n-type Cz they obtained 17.1% efficiency. Others working on this cell concept have applied high efficiency lab processing on small area cells and will be briefly discussed in the next section.

3.3 Results on n-type lab cells with front-side junction

One of the main research topics for n-type front-side junction cells is the passivation of the highly p-type doped emitter. Since a single layer, positively charged, SiN_x will not passivate well, alternative layers have been investigated. Especially, Al_2O_3 layers are of great interest because the negative fixed charges [21]. These fixed

charges will enhance the surface passivation and can result in very low emitter saturation currents (10 fA/cm^2) on unmetallized test structures [22]. The Al_2O_3 layers were deposited using plasma-assisted atomic layer deposition (ALD).

Benick et al. [23] applied these ALD Al_2O_3 with a thickness of 30 nm combined with a 40 nm thick SiN_x layer on small (4 cm^2) n-type Cz cells with a boron emitter. Using a thermal SiO_2 and local BSFs at the contacts at the rear they reached 23.2% efficiency. The contacts were evaporated. The very high V_{OC} (704 mV) demonstrates the excellent front surface passivation. Recently, Benick et al. [24] reached 21.8% efficiency applying an industrial type of boron emitter. This emitter had a depth of about $0.3 \mu\text{m}$ instead of the $> 1 \mu\text{m}$ deep one in [23].

3.4 Discussion n-type cells with front-side junction

Although the lab-scale processing described above is not industrially feasible, it demonstrates the efficiency potential of n-type solar cells with a boron emitter. With an industrial process efficiencies of about 19% could be reached on the short term by improving emitter and metallization processes. Even higher efficiencies seem to be possible by improved surface passivation. Further improvement of the front surface (emitter and passivation) and rear side passivation (di-electric layers with local BSFs) will make efficiencies of about 20% possible. Of course the shading losses should be minimized to reach this high efficiency.

4 BACK-CONTACTED CELLS

4.1 Recent cell results

A next step to improve the cell efficiency will be the development of back-contacted cells. These cells have the advantage that the cell concept will make the application of easy module manufacturing technologies possible [25]. Furthermore, the interconnection of back-contacted cells will reduce cell breakage.

As already mentioned in the introduction SunPower is manufacturing back-contacted solar cells. The best efficiency is above 23%. However, they are applying an advanced process.

Granek et al. [26] applied a process close to industrially feasible. Screen-printing and laser processing were applied for metallization and opening di-electric layers respectively. They obtained 21.3% efficiency on 4 cm^2 and $160 \mu\text{m}$ thin n-type FZ material. High FFs were obtained by tuning the sheet resistivity of the front surface field (FSF). Because of the higher lateral resistance in the base, the additional conductance in the FSF will reduce series resistance losses.

A back-contacted concept under development is the so-called Buried Emitter Back-junction Solar cell (BESC) [27]. Applying this cell design Mertens et al. has recently reached 21.8% cell efficiency. The cells were made using 4 cm^2 n-type Cz material and evaporated contacts.

4.2 Discussion back-contacted cells

Up to now only SunPower is successful in making high-efficiency back-contacted cells ($>20\%$) on industrial scale. Others can make cells with efficiencies above 21% using small area cells and/or lab-scale processing with evaporated contacts. The challenge would be to achieve efficiencies above 20% on back-contacted cells and using

low-cost technologies such as screen-printing. A first step has been made by Granek et al. [26].

5 CONCLUSIONS

Using n-type base material can lead to higher efficiencies thanks to its lower sensitivity to most common metallic impurities and the absence of boron-oxygen complexes. Up to now only SunPower and Sanyo are able to manufacture cells with efficiencies above 20% on industrial scale (using n-type material). They use, however, advanced processing.

Issues when processing n-type solar cells are boron diffusion and passivation of the highly doped boron emitter. We have developed an industrially feasible process using standard manufacturing equipment for boron-phosphorous co-diffusion and wet-chemical silicon oxide passivation. With these low-cost technologies we are able to make 18.5% (independently confirmed) efficient cells on large area (both 155 and 243 cm^2). The efficiency potential for this cell type is about 20%, which has been demonstrated on lab-scale using improved surface passivation on front and rear. With lab-scale processing 23.2% has been reached with ALD Al_2O_3 front side passivation and SiO_2 rear side passivation combined with local BSFs.

To reach even higher efficiencies back-contacted cells are needed. This cell concept is still under development at several research institutes. The challenge is to make very high efficiencies using screen-print processes. A first step with efficiencies above 21% has been already made.

6 ACKNOWLEDGEMENTS

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