# Advanced front-surface passivation schemes for industrial n-type silicon solar cells 

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#### Abstract

The n-Pasha n-type silicon solar cell currently achieves an average conversion efficiency of $20.2 \%$ using a relatively simple process flow. This bifacial cell concept developed by ECN is based on homogeneously doped $\mathrm{p}^{+}$front and $\mathrm{n}^{+}$back surfaces. To enhance the cell efficiency, it is important to reduce the carrier


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## Introduction

In 2010 ECN, Tempress and Yingli introduced the n-Pasha cell to the market as a novel bifacial cell concept based on n-type Czochralski-grown $(\mathrm{Cz})$ silicon with homogeneous diffusions, dielectric passivation and printed metallization (Fig. 1) [1]. Recently, Nexolon America selected
this cell concept for their production line, enabling the production of bifacial modules [2].
> "The bifacial cell concept allows higher power output per installed Wp."

One of the key benefits of a bifacial cell is the capturing of albedo light from the 'open' rear side. Recent field studies [3] have revealed a higher power generation with these bifacial cells than with monofacial cells during the morning and evening hours, which is when indirect light contributes most to the carrier generation. Even when


Figure 1. A schematic cross section of the bifacial n-Pasha cell concept, which enables the capture of albedo light.
positioned vertically, for example along roads, bifacial modules are able to generate electricity all day long while the sun moves from east to west. The bifacial cell concept therefore allows higher power output per installed Wp.

The current n -Pasha baseline process yields an average efficiency of $20.2 \%$, with a top efficiency of $20.4 \%$ on high-quality Cz material [4]. These cells, and other cells based on n-type Si wafers, compete with p-type PERC cells (rear passivated cells with local contacts) for a spot in the higher-efficiency segment. One of the main advantages of $n$-type cells as compared to PERC is the absence of light-induced degradation. On the other hand, there are a number of technological and scientific challenges for industrial n-type cells which have to be addressed in order to achieve high efficiencies while remaining cost-competitive:

- (Independent) control of diffused $\mathrm{n}^{+}$ and $\mathrm{p}^{+}$doping profiles.
- Excellent level of passivation of both front and rear surfaces.
- Reduced contact recombination on the $\mathrm{p}^{+}$side.
- Minimal consumption of silver paste to contact both sides.
- Insensitivity of cell efficiencies to variations in resistivity of the n-type base.

The last two issues in the list have been successfully addressed in previous articles in this journal [5,6]. After a general discussion on recombination, this paper will address the first two topics, currently the limiting factors of n-Pasha solar cells [7]: the optimization of the boron-doping profile and the passivation.

## Physics of carrier recombination in solar cells

The recombination of light-generated electron-hole pairs reduces the conversion efficiencies of solar cells. Although to a certain extent this recombination is inevitable because of intrinsic processes such as Auger and radiative recombination, the recombination can also be enhanced by lattice defects. These defects can form energy states within the silicon band gap, via which charge carriers can effectively recombine: this mechanism is known as Shockley Read Hall (SRH) recombination. Such defect states are omnipresent in solar cells as a result of (lattice) defects both in the silicon bulk and at the silicon surface.

Towards n-type silicon base material
Electronically active defects within the bulk of the silicon, such as defects at the grain boundaries and boron-oxygen complexes, can effectively be mitigated by using, respectively, monocrystalline silicon rather than multicrystalline silicon, and n-type silicon rather than (boron-doped) p-type silicon. Switching to n-type silicon is also beneficial, as this material is much less sensitive to transitional metal contaminants, such as Fe [8]. It is precisely these benefits in terms of bulk quality that were the incentive for many institutes and companies to develop solar cells based on n-type monocrystalline silicon base material, such as the $n$-Pasha cell concept.

## Surface recombination

Although a high-quality bulk material in principle allows for high conversion efficiencies, to achieve this potential at the cell level care must be taken to reduce carrier recombination near the surfaces of the cells (Fig. 2). More specifically, one can distinguish between recombination at the metallic contacts and recombination in the wellpassivated regions in between.
Since metallic contacts exhibit a very high density of states across the silicon band gap, the metalsilicon interface acts as a 'catalyst' for electron-hole pair recombination. If the silicon underneath the contacts (conventionally termed emitter and back-surface field) is heavily doped, the conductivity of one carrier type is
reduced, while it is drastically enhanced for the other. In this way, the metal contacts are effectively made selective for one carrier type (i.e. selective electron or hole contacts are formed [9]), and recombination is suppressed. A parameter governing both the carrier selectivity and the recombination is the recombination current parameter, or (thermal equilibrium) recombination current density [9] (formerly referred to as emitter saturation current density, which should ideally be as low as possible. Unfortunately, heavy doping leads to a trade-off, as it enhances Auger recombination, which varies as a function of the square of the majoritycarrier density. It is for these reasons that initiatives using (semi-conducting) passivated selective contacts without the necessity of heavy doping have emerged: very high efficiencies have been demonstrated [10]. A well-known example is the use of intrinsic and doped amorphous Si layers in silicon heterojunction solar cells.
Although for metallic contacts heavy doping is consequently required to ensure a low contact resistance and an adequate carrier selectivity, for the regions in between the metallic contacts the function of the doped regions is solely to conduct the carriers laterally. In homogeneously diffused solar cells, such as $n$-Pasha, the recombination in between the contacts consists of both Auger recombination due to the heavy doping, and surface recombination due to the presence of surface defects (where the interface defect density


Figure 2. A schematic band diagram of silicon, showing the generation of excess carriers by the absorption of light and the surface recombination of excess charge carriers via interface defect states.
is denoted by $D_{\mathrm{it}}$ ). In the following sections, improvements to the $\mathrm{p}^{+}$doped region and to the surface passivation, both aiming to reduce the front-surface recombination, will be addressed.

## Doping-profile optimization

For the n -Pasha cells, the boron and phosphorus diffusions are performed in a Tempress industrial tube furnace using $\mathrm{BBr}_{3}$ and $\mathrm{POCl}_{3}$ as precursors, respectively. The phosphorus $\mathrm{n}^{+}$ region at the rear provides additional lateral conductivity for electrons, which makes the $n$-Pasha concept less sensitive to changes in the n -type bulk resistivity and allows the use of a bulk material with a high resistivity of $10 \Omega \cdot \mathrm{~cm}$ [6]. The latter consideration is of importance for $n$-type solar cells, as the variation in base resistivity of n -type ingots is higher than for p -type ingots because phosphorus has a higher segregation coefficient than boron. The efficiency improvements of n-Pasha cells through using a shallower doped $\mathrm{n}^{+}$region, while maintaining the lateral transport properties, have recently been reported by the authors [5,6]. Here, however, the focus will be on improving the boron-doping profile.

Fig. 3(a) shows the electrochemical capacitance-voltage (ECV) profile of a standard boron diffusion of the n -Pasha cell with a sheet resistance $R_{\mathrm{s}}$ of $60 \Omega / \mathrm{sq}$. This standard profile (profile 1) exhibits a boron-depleted region within the first 10 to 30 nm ; the depleted region originates from the higher solubility of boron in $\mathrm{SiO}_{2}$ than in Si . $\mathrm{SiO}_{2}$ is intentionally formed after boron diffusion to reliably remove the boron-rich layer (BRL), a Si-B compound which is otherwise difficult to remove and is detrimental to surface passivation [11]. The boron-depleted region of profile 1 can, however, be etched back, resulting in doping profiles 2 and 3. Note that the application of dielectrics for surface passivation in the work reported in this paper does not reintroduce such a depletion region because of the synthesis at low temperatures.

To study the effect of the three different doping profiles of Fig. 3(a) on the recombination current density, the profiles served as input for 2-D Atlas simulations [12]. In Fig. 3(b) the simulated $J_{0}$ value of each profile is shown as a function of the surface recombination velocity (SRV). Removal of the boron-depleted region in profiles 2 and 3 yields a reduction in $J_{0}$, both for well-passivated surfaces with low SRVs and for surfaces without passivation, such as the contacted regions, having high SRVs. A recent study by Black et


Figure 3. (a) ECV profiles of a standard boron-doped surface (profile 1) and after etching (profiles 2 and 3 ); (b) $J_{0}$ as a function of the SRV of the borondoped surfaces, from Atlas simulations; (c) implied open-circuit voltage of symmetrically diffused $\mathrm{p}^{+} / \mathrm{n} / \mathrm{p}^{+}$samples passivated by $\mathrm{NAOS} / \mathrm{SiN}_{x^{0}}$, measured by QSS-PC.
al. [13] showed that the interface defect density $\left(D_{\mathrm{it}}\right)$ is independent of the boron-dopant concentration at the Si surface of the $\mathrm{Si} / \mathrm{SiO}_{2} / \mathrm{Al}_{2} \mathrm{O}_{3}$ interface. The benefits of etching the borondepleted region can therefore be fully explained by the decreased minoritycarrier (i.e. electron) concentration at the surface, which results in a lower surface recombination and hence in a lower $J_{0}$.

To experimentally determine $J_{0}$ of the different diffusion profiles, symmetrically diffused and textured $\mathrm{p}^{+} / \mathrm{n} / \mathrm{p}^{+}$samples were fabricated with the diffusion profiles in Fig. 3(a). The samples were passivated by the conventional $n$-Pasha front-passivation scheme: nitric acid oxidation (NAOS) [14] plus $70 n m$ hydrogenated amorphous silicon nitride $\left(a_{-S i N}^{x}: ~ H, ~ o r ~\right.$ in short, $\mathrm{SiN}_{\mathrm{x}}$ ), deposited by (remote) plasma-enhanced chemical vapour deposition (PECVD). This SiN $_{\mathrm{x}}$ layer also serves as an anti-reflection coating. The results from quasi-steadystate photoconductance (QSS-PC) measurements are shown in Fig. 3(c). Etching back the diffusion profile 1 to profile 2 leads to an improvement of $\sim 12 \mathrm{mV}$ in the implied opencircuit voltage i- $V_{\mathrm{oc}}$, corresponding to a significant reduction in $J_{0}$ of $50 \mathrm{fA} / \mathrm{cm}^{2}$ per side. The additional $\mathrm{i}-V_{\mathrm{oc}}$ gain obtained by extending the etch, however, is quite small (profile 3). Moreover, profile 3 results in a higher sheet resistance than for the other two profiles: $85 \Omega /$ sq. vs. $60 \Omega /$ sq. for profiles 1 and 2 . The higher sheet resistance reduces the lateral conduction of holes and may affect the fill factor of the cells. For diffusion profile 2, however, there is no significant increase in sheet resistance.
> "Etching back the $\mathrm{p}^{+}$region is both a simple and an effective approach for optimizing diffusion profiles."

The benefit of using doping profile 2 is also confirmed at the cell level. The $V_{\text {oc }}$ of the cells increases by 6 mV , resulting in an efficiency gain of $\sim 0.2 \%$ abs. (Table 1 ). Therefore, etching back the $\mathrm{p}^{+}$region is both a simple and an effective approach for optimizing diffusion profiles. The
next step is to improve the passivation of the $\mathrm{p}^{+}$surface.

## Surface passivation of n-Pasha cells

For a long time, no satisfactory solution existed for the passivation of borondoped $\mathrm{p}^{+}$surfaces. It is known that passivation by thermally grown silicon dioxide, although initially providing reasonable levels of passivation, is subject to significant light-induced degradation [15]. Moreover, the passivation of boron-doped surfaces by $\operatorname{SiN}_{x}$, which is the commonly used material for the passivation of $\mathrm{n}^{+}$surfaces, generally results in low passivation, or even none at all [14]. The poor passivation performance
on a $\mathrm{p}^{+}$surface can be explained by its large positive fixed charge density ( $Q_{\mathrm{f}}>2 \cdot 10^{12} \mathrm{~cm}^{-2}$ ), which increases the minority-carrier (i.e. electron) density near the surface.
In 2008 ECN reported the significant improvements in the passivation of $\mathrm{p}^{+}$ doped Si by adding a chemical oxide below the $\mathrm{SiN}_{x}$; the oxide is grown at room temperature by a nitric acid oxidation of silicon (NAOS) [14]. This breakthrough in the passivation of boron-doped surfaces enabled the industrial development of low-cost n-type Si solar cells. Around the same time, however, a superior passivation of $\mathrm{p}^{+}$surfaces was discovered: $\mathrm{Al}_{2} \mathrm{O}_{3}$ prepared by atomic layer deposition (ALD) [16]. The excellent level of passivation could be attributed to a

Figure 4. Recombination current density (a) and implied open-circuit voltage (b), as measured by quasi-steady-state photoconductance measurements of symmetrically boron-diffused $\mathrm{p}+/ \mathbf{n} / \mathrm{p}+$ samples with random-pyramid texture (Rs $=60 \Omega /$ sq.), passivated by different passivation schemes.

|  |  | $I_{\mathrm{sc}}[\mathrm{A}]$ | $J_{\mathrm{sc}}\left[\mathrm{mA} / \mathrm{cm}^{2}\right]$ | $\left.V_{\mathrm{oc}} \mathrm{V}\right]$ | FF | $\eta[\%]$ |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Boron profile 1 (standard) | avg | 9.31 | 39.0 | 0.647 | 0.784 | 19.7 |
| Boron profile 2 (etched back) | avg | 9.35 | 39.1 | 0.653 | 0.779 | 19.9 |

Table 1. I-V results for cells with the boron-doping profiles 1 and 2 , passivated by NAOS/SiN ${ }_{x}$.
very low interface defect density and a high negative fixed charge density $\left(Q_{\mathrm{f}} \approx-5 \cdot 10^{12} \mathrm{~cm}^{-2}\right.$ ) [17]. However, reactors with significant throughput were not available at the time. Since the discovery of passivation by $\mathrm{Al}_{2} \mathrm{O}_{3}$, industry has put a lot of effort into high-volume manufacturing by ALD, resulting in the development of, for example, spatial and batch ALD reactors for $\mathrm{Al}_{2} \mathrm{O}_{3}$. Although $\mathrm{Al}_{2} \mathrm{O}_{3}$ can also be deposited by PECVD, the requirement of very thin $(\sim 1-3 \mathrm{~nm}) \mathrm{Al}_{2} \mathrm{O}_{3}$ films for $\mathrm{p}^{+}$ passivation of cells makes ALD the ideal candidate. A comparison between ALD $\mathrm{Al}_{2} \mathrm{O}_{3}$ passivation and the conventional passivation scheme of the $\mathrm{p}^{+}$surface of n -Pasha is therefore highly relevant.

Several industrial passivation schemes for symmetrically diffused and textured $\mathrm{p}^{+} / \mathrm{n} / \mathrm{p}^{+}$samples were compared with the conventional boron profile of $n$-Pasha (profile 1 of Fig. 3(a)). First, the standard surface passivation of $n$-Pasha cells (NAOS/ $\mathrm{SiN}_{\mathrm{x}}$ ) was directly compared with the passivation by $\mathrm{Al}_{2} \mathrm{O}_{3}$ films on NAOS. The $\mathrm{Al}_{2} \mathrm{O}_{3}$ films were deposited in a batch ALD reactor from ASM or by spatial ALD in a Levitech reactor, and capped by 70nm PECVD $\operatorname{SiN}_{x}$. Generally, $\mathrm{Al}_{2} \mathrm{O}_{3}$ passivation is enhanced by annealing the films around the optimum temperature of $400^{\circ} \mathrm{C}$. In this case, however, the passivation was activated by the thermal budget of the PECVD $\operatorname{SiN}_{x}$ deposition process and a subsequent firing step $\left(\sim 800^{\circ} \mathrm{C}\right)$. The results are summarized in Fig. 4. The passivation schemes comprising $2 \mathrm{~nm} \mathrm{Al} \mathrm{O}_{3}$ yield a significant reduction in $J_{0}$, from $90 \mathrm{fA} / \mathrm{cm}^{2}$ to $66 \mathrm{fA} / \mathrm{cm}^{2}$, as compared to conventional passivation; this can be attributed to the very low interface defect density and the high negative fixed charge density associated with the $\mathrm{Al}_{2} \mathrm{O}_{3}$ films. The $\mathrm{Al}_{2} \mathrm{O}_{3}$ films prepared by the two ALD deposition systems performed similarly, indicating the robustness of the ALD process.

## "The passivation schemes comprising $2 \mathrm{~nm} \mathrm{Al}_{2} \mathrm{O}_{3}$ yield

 a significant reduction in $J_{o}$, as compared to conventional passivation."Second, it was found that the conventional $\mathrm{p}^{+}$surface passivation by $\mathrm{NAOS} / \mathrm{SiN}_{\mathrm{x}}$ can also be improved. A reduction in $J_{0}$ from $90 \mathrm{fA} / \mathrm{cm}^{2}$ to $75 \mathrm{fA} / \mathrm{cm}^{2}$ was achieved by tuning the a-SiN $\mathrm{S}_{\mathrm{x}}$ :H towards a more hydrogenrich composition. This improvement can be attributed to an increased level of chemical passivation induced by the additional hydrogenation of the $\mathrm{Si} / \mathrm{SiO}_{2}$ interface [18]. More details concerning the specific experiments on $\mathrm{p}^{+}$surface passivation can be found in the literature [19], in which the passivation of the $\mathrm{n}^{+}$surface is also addressed.

Interestingly, the high level of passivation of the $\mathrm{p}^{+}$surface by $\mathrm{Al}_{2} \mathrm{O}_{3}$ can be further enhanced by improving the surface pretreatment, which conventionally consists of a diluted hydrofluoric (HF-) dip. Fig. 5 shows the effect on the i- $V_{\text {oc }}$ of using a novel chemical pretreatment on a $\mathrm{p}^{+} / \mathrm{n} / \mathrm{n}^{+}$lifetime sample with boron-doping profile 1 , passivated by NAOS $/ \operatorname{SiN}_{x}$. The gain in $\mathrm{i}-V_{o c}$ is even higher when the new pretreatment is combined with $\mathrm{Al}_{2} \mathrm{O}_{3}$ passivation of the $\mathrm{p}^{+}$surface (i.e. NAOS $/ \mathrm{Al}_{2} \mathrm{O}_{3} /$ $\mathrm{SiN}_{\mathrm{x}}$ ), yielding i- $V_{\text {oc }}$ values of 676 mV . Table 2 shows the $I-V$ results for
cells having the new chemical pretreatment but using the standard passivation scheme. Improvements solely to the chemical pretreatment led to a gain in conversion efficiency of $0.3 \%$ abs., which is the result of a higher $V_{\text {oc }}$. It is expected that this efficiency will be increased even further by implementing $\mathrm{Al}_{2} \mathrm{O}_{3}$ surface passivation.

## Conclusions and outlook

The efficiency of $n$-Pasha solar cells is limited by the charge carrier recombination within the borondoped $\mathrm{p}^{+}$region and at its surface. In this paper several industrially feasible approaches have been identified for reducing the recombination at the front side. First, the borondepletion region can be reduced by etching the boron-doped surface; in combination with NAOS/ $\operatorname{SiN}_{\mathrm{x}}$ passivation, this results in a lower recombination current density and higher cell efficiencies. Second, the passivation of a standard $\mathrm{p}^{+}$diffusion profile can be improved by using $2 \mathrm{~nm} \mathrm{Al} \mathrm{I}_{2} \mathrm{O}_{3}$ deposited by batch or spatial ALD. Finally, a novel chemical pretreatment, in combination with


Figure 5. Implied open-circuit voltage for textured $\mathrm{p}^{+} / \mathrm{n} / \mathrm{n}^{+}$samples having different surface pretreatments and different $\mathrm{p}^{+}$surface passivation, with $\mathrm{NAOS} / \mathrm{SiN}_{\mathrm{x}}$ passivation of the $\mathrm{n}^{+}$surface.

|  |  | $\mathrm{I}_{\mathrm{sc}}[\mathrm{A}]$ | $\mathrm{J}_{\mathrm{sc}}\left[\mathrm{mA} / \mathrm{cm}^{2}\right]$ | $\mathrm{V}_{\mathrm{oc}}[\mathrm{V}]$ | FF | $\eta$ [\%] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Standard HF dip | avg | 9.31 | 39.0 | 0.649 | 0.785 | 19.8 |
| Improved oxide pretreatment | avg | 9.30 | 38.9 | 0.655 | 0.788 | 20.1 |



Figure 6. Schematic cross section of a potential new design of the front side of an $n$-Pasha cell, comprising $\mathrm{Al}_{2} \mathrm{O}_{3}$ surface passivation and selective $\mathrm{p}^{+}$regions which are highly doped under the metallic contacts.
standard passivation by $\mathrm{NAOS} / \mathrm{SiN}_{\mathrm{x}}$, also demonstrates improvements in $n$-Pasha efficiency of $0.3 \%$. Photoconductivity measurements indicate that further improvements in efficiency may be gained by combining the novel pretreatment with $\mathrm{Al}_{2} \mathrm{O}_{3}$ passivation.
"Further improvements in efficiency may be gained by combining the novel pretreatment with $\mathrm{Al}_{2} \mathrm{O}_{3}$ passivation."

The results presented in this paper will be implemented in $n$-Pasha cells in the next few months. These modifications pave the way for realizing conversion efficiencies of $21 \%$ on highquality Cz wafers.

As a next step to reducing $J_{0}$ of the front surface, an implementation of selective doping under the contacts

is being considered for n -Pasha cells (Fig. 6). This area selectivity allows a separate optimization of $J_{0, \text { contact }}$ and the contact resistance on the one hand, and of $J_{0, \text { surface }}$ and the lateral conduction of holes on the other. This helps to reduce the metal contact recombination associated with the $\mathrm{p}^{+}$ diffusion, which is an important loss factor for $n$-type Si cells.

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