Towards industrial n-type PERT silicon solar cells: rear passivation and metallization scheme

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Abstract

Recently, we presented an industrially feasible passivation and contacting scheme for the front side boron emitter of n-type silicon solar cells based on firing processes. On these cells, efficiencies up to 20.8% have been achieved on small areas. These cells feature a fully-metalized BSF on the rear side, which limits the $V_{OC}$ to about 655 mV. When changing to a PERT cell design with a passivated BSF, both the $V_{OC}$ as well as the $J_{SC}$ can be improved due to a reduced recombination at the rear and an improved optical confinement. In this work we studied different POCl$_3$ diffusions for their applicability to n-type PERT solar cells with respect to passivation and metallization. The achieved results have been used to fabricate a first batch of n-type PERT solar cells, on which $V_{OC}$ values up to 671 mV have been measured. The improved internal quantum efficiency above 900 nm confirms the improvement of the rear side of the cell. The boron emitter of this cell was passivated with a stack of 5 Å ALD Al$_2$O$_3$ (four ALD cycles) and 70 nm PECVD SiNx. Thus the $V_{OC}$ of 671 mV demonstrates furthermore, that the Al$_2$O$_3$ thickness of fired Al$_2$O$_3$/SiNx stacks for the passivation of boron emitters can be drastically reduced to four atomic layers of Al$_2$O$_3$.

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1. Introduction

Currently, the industrial crystalline silicon solar cell production is still dominated by p-type silicon solar cells. However, as the silicon PV industry tends to introduce advanced high-efficiency solar cell concepts, the quality of the base material is becoming more and more important [1]. n-type Cz silicon
does not suffer from light induced degradation, which is known to occur for $p$-type Cz silicon due to boron-oxygen pairs [2-4]. Furthermore, $n$-type silicon features a higher tolerance to common metal impurities compared to $p$-type silicon [5]. Thus, $n$-type Cz silicon offers a material quality allowing to fully benefit from efficiency potentials given by high-efficiency solar cell architectures. With conversion efficiencies above 23%, the potential of $n$-type silicon has been demonstrated at the device level for different cell structures in recent years [6-8].

In the case of standard silicon solar cells with a diffused front side junction, however, a change of the base material from $p$-type to $n$-type silicon requires an adaptation of several cell fabrication processes. Regarding the front side, one key challenge was the passivation of the boron-doped emitter, which has been overcome by the negatively charged dielectric aluminum oxide ($\text{Al}_2\text{O}_3$). This dielectric layer has been proven to feature an excellent surface passivation on $p^+$ surfaces [6, 9], even after a typical contact firing process [10-13]. Recently, we showed that the surface passivation by an $\text{Al}_2\text{O}_3/\text{SiN}_x$ stack can be combined with a contact formation to the boron emitter based on printing, firing and plating processes [14]. Applying those contacts on $p^+nn^+$ solar cells featuring a fully-metalized back surface field (BSF) without a dielectric rear passivation, we achieved efficiencies up to 20.8% on small areas and 19.6% on large areas [12].

However, the open-circuit voltage $V_{oc}$ of these cells is limited by the non-passivated, fully-metalized BSF to values of $\sim$655 mV. In Fig. 1 the internal quantum efficiency (IQE) of these cells is compared to the IQE of a high-efficiency $n$-type PERL cell (passivated emitter and rear locally diffused), which features a dielectric rear side passivation. From the higher IQE of the PERL cell in the long wavelength range, it is obvious that there is a considerable potential for improvement. Thus, the application of a dielectric layer on the fully-diffused rear side, i.e. a PERT cell design (passivated emitter and rear totally diffused, see Fig. 2), will allow to benefit from both an enhanced optical confinement as well as an improved rear side passivation. In the following the cells with a fully-diffused BSF passivated with a dielectric layer are referred to as “PERT cells”, while the cells with the fully-diffused and fully-metalized BSF (without dielectric layer passivation on the rear) are referred to as “cells with fully-metalized BSF”.

This contribution is focused on the rear side of such $n$-type PERT solar cells with printed, fired and plated front contacts and evaporated rear contacts, especially on the evaluation of different BSF diffusions with regard to passivation and metallization. Also, we will briefly refer to the passivation of the boron emitter by fired $\text{Al}_2\text{O}_3/\text{SiN}_x$ stacks, as recent results show that even one atomic layer of $\text{Al}_2\text{O}_3$ is enough to achieve a high level of surface passivation with such fired stacks [15].

![Fig. 1. IQE and reflectance R of the small area $p^+nn^+$ solar cell with fully-metalized BSF [12] compared to a high-efficiency $n$-type PERL solar cell [6].](image1)

![Fig. 2. Schematic cross-section of the $n$-type PERT solar cell structure with a totally-diffused and passivated rear side.](image2)
2. Influence of the BSF profile on the $V_{OC}$

To get a rough estimate of the ideal shape of the BSF profile for $n$-type PERT solar cells, we performed PC1D [16] simulations of $p^+n^+$ solar cells with either a fully-metalized or a fully-passivated BSF for different Gaussian-shaped doping profiles. The front side of the solar cell was modeled with the shallow boron emitter and a surface recombination velocity $S_{\text{front}} = 1000 \text{ cm/s}$, according to the fabricated $p^+n^+$ solar cells shown in an earlier publication [12]. The Gaussian-shaped BSF was varied as a function of the surface concentration $N_{\text{surf}}$ and the depth of the profile $d_{\text{BSF}}$. For the simulation of the fully-metalized BSFs, the surface recombination velocity of the rear $S_{\text{rear}}$ was assumed to be $10^7 \text{ cm/s}$, the thermal carrier velocity. For the passivated BSFs, $S_{\text{rear}}$ was adapted to $N_{\text{surf}}$ by applying the $S(N_{\text{surf}})$ model of ref. [17], which models $S$ for $n^+$ surfaces passivated with thermally grown SiO$_2$. Lateral current flow and increased recombination on the rear due to the local metal contacts at the rear were neglected, thus the simulated $V_{OC}$ values for the passivated BSFs are upper limits.

Fig. 3 shows the maximum $V_{OC}$ as a function of the phosphorous surface concentration as well as the depth of the profile. It can be seen that in the case of the fully-metalized BSF the $V_{OC}$ increases with increasing surface concentration $N_{\text{surf}}$ and increasing depth of the profile $d_{\text{BSF}}$, whereas in the case of the passivated BSF the $V_{OC}$ increases for decreasing $N_{\text{surf}}$ and $d_{\text{BSF}}$. Hence for PERT solar cells with a homogenously doped BSF, a trade-off is required between a weakly-doped BSF ideal for the passivated regions and a heavily-doped BSF ideal for the metalized regions. However, to achieve $V_{OC} > 670 \text{ mV}$, the surface concentration should be below $10^{20} \text{ cm}^{-3}$.

3. Experimental

Prior to the fabrication of $n$-type PERT solar cells, we first studied different BSF diffusions with respect to the surface passivation as well as the contact formation. For this purpose special test structures were prepared, featuring three different phosphorus diffusion profiles (see Fig. 4). The POCl$_3$ tube diffused profiles additionally were exposed to a high temperature process similar to the boron emitter diffusion, as this is also the case in the solar cell processing sequence.
To characterize the surface passivation of the BSF diffusions, symmetrical $n^+nn^+$ lifetime samples on 200 μm thick, shiny-etched $n$-type FZ Si wafers with a base resistivity of 10 Ω cm were fabricated. For the passivation of the BSF diffusions, two different dielectric passivation layers were applied: (i) a standard anti-reflection SiN$_x$ and (ii) a stack of silicon-rich oxynitride (SiriON) covered by SiN$_x$ [18]. Both layers were deposited in an in-line PECVD reactor (SINA XS, Roth & Rau). After the deposition of the passivation layers, the samples were fired at 800 °C, similar to the firing process required for contacting the boron emitter [14]. Quasi-steady-state photo-conductance decay (QSSPC) measurements [19] were performed for determining the effective excess carrier lifetime using the lifetime tester WCT120. The optical constants $f_{\text{opt}}$ required for the evaluation of the QSSPC measurements were determined by comparing the QSSPC measurements with photo-conductance decay (PCD) measurements in the transient mode. This was performed at high injection levels with intense light, where possible slow surface states should be saturated for transient PCD and QSSPC measurements, thus making the comparison valid [20]. The BSF saturation current densities $J_{0,\text{BSF}}$ were determined according to the high injection level method [21, 22] and were evaluated for a temperature of 25 °C with a corresponding intrinsic carrier concentration $n_i = 8.6 \times 10^{19} \text{cm}^{-3}$, and assuming an high-injection Auger recombination model according to [23].

To qualify the contact formation of evaporated aluminum on the different BSF diffusions, the specific contact resistance $\rho_C$ was measured. Therefore TLM measurements were performed applying the TLM structure proposed by Meier and Schroder [24].

A first batch of $n$-type PERT solar cells (as schematically shown in Fig. 2) was fabricated on 1 Ω cm $n$-type FZ Si wafers with a thickness of 250 μm. These solar cells feature an alkaline textured front side diffused with a shallow 90 Ω/sq boron emitter. The emitter was passivated using a stack of 5 Å Al$_2$O$_3$ and 70 nm of the anti-reflection SiN$_x$ (refractive index $n = 2$). The Al$_2$O$_3$ layer was deposited via plasma-assisted ALD, were only four ALD cycles were performed to deposit the 5 Å thick Al$_2$O$_3$ layer. Jet-printed, fired and plated front contacts were used for contacting the emitter [14]. The rear was diffused with the 120 Ω/sq BSF and passivated using the SiriON/SiN$_x$ stack. After the firing process required for the contact formation to the boron emitter, laser ablation was used to open the SiriON/SiN$_x$ stack on the rear for the local point contacts. A contact spacing of 0.75 μm was applied leading to metalized area fraction of 0.3%. Finally, the aluminum was evaporated on the rear.

![Fig. 4. Diffusion profiles of the shallow phosphorous-doped BSF diffusions. All diffusions were driven-in with a temperature process similar to the boron emitter diffusion.](image1)

![Fig. 5. BSF saturation current densities $J_{0,\text{BSF}}$ for the three BSF diffusions shown in Fig. 4 measured after firing. The $J_{0,\text{BSF}}$ values are shown for both the silicon-rich oxynitride (SiriON) / SiN$_x$ stacks and the SiN$_x$ layers.](image2)
4. Results and discussion

Fig. 5 shows the $J_{0,BSF}$ values of the three BSF diffusions passivated with the SiN$_x$ layer and the SiriON/SiN$_x$ stack after firing. With both passivation layers, very low $J_{0,BSF}$ values in a range of ~10 fA/cm$^2$ for the 260 Ω/sq BSF and ~30 fA/cm$^2$ for the 120 Ω/sq BSF could be achieved. However, the SiriON/SiN$_x$ stack showed a slightly enhanced performance on all BSF diffusions. From these $J_{0,BSF}$ values, an upper limit for the $V_{OC}$ can be calculated with the one-diode equation. To do so, an emitter saturation current density $J_0$ of 100 fA/cm$^2$ was assumed, which corresponds to the metalized boron emitter of the $p^+nn^+$ solar cells [12]. For the estimation of the $V_{OC}$, the dark saturation current density is calculated to $J_0 = J_{0e} + J_{0,BSF}$. In the case of the 260 and 120 Ω/sq BSF diffusions, the $V_{OC}$ is limited to values of ~683 mV and ~679 mV, respectively, and for the 60 Ω/sq BSF to about 665 mV. Thus, especially the 260 and 120 Ω/sq BSF diffusions are best suited for the $n$-type PERT solar cells with respect to surface passivation. For the 260 and 120 Ω/sq BSF, this $V_{OC}$ values, calculated from the $J_{0,BSF}$ values, are in good agreement with simulated $V_{OC}$ values of section 2 (right graph of Fig. 3).

From Fig. 4, it can be seen that the surface concentration $N_{surf}$, which is the most crucial value for the metal contact formation, varies over more than one order of magnitude for the different BSF diffusions. However, the measured specific contact resistance $\rho_C$ of evaporated aluminum contacts is below 1 mΩ cm$^2$ for all BSF diffusions. For the 120 and 260 Ω/sq BSF diffusions, both featuring surface concentrations below $10^{20}$ cm$^{-3}$, $\rho_C$ values of $(32\pm6) \mu\Omega$ cm$^2$ and $(470\pm70) \mu\Omega$ cm$^2$ have been measured respectively. These values are in good agreement with literature values for Al-Si contacts [25] and are well suited for the application to $n$-type PERT solar cells.

In Tab. I, the best $I$-$V$ parameters of our first $n$-type PERT solar cell batch are compared to the results of the fully-metalized BSF cells. Besides the $I$-$V$ parameters, the pseudo fill factor $PFF$, determined with the Suns-$V_{OC}$ technique [26], as well as the series resistance $R_{s,light}$, evaluated by comparing the one-sun with the dark $I$-$V$ curve [27], are also listed. Open-circuit voltages $V_{OC}$ up to 671 mV have been achieved on the $n$-type PERT cells with a size of 104 cm$^2$ (125×125 pseudo cm$^2$ wafer with a broken edge). This high $V_{OC}$ value demonstrates the improvement of the rear side by the SiriON/SiN$_x$ passivated 120 Ω/sq BSF diffusion compared to the fully-metalized BSF cells. From the one-diode equation a dark saturation

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<th>$A$ (cm$^2$)</th>
<th>$V_{OC}$ (mV)</th>
<th>$J_{SC}$ (mA/cm$^2$)</th>
<th>$FF$ (%)</th>
<th>$\eta$ (%)</th>
<th>$PFF$ (%)</th>
<th>$R_{s,light}$ (Ω cm$^2$)</th>
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* independently confirmed by Fraunhofer ISE CalLab
current density $J_0$ of 168 fA/cm$^2$ can be extracted for the 671 mV, whereas the 649 mV of the fully-metalized BSF cell results in a $J_0$ of 408 fA/cm$^2$. Thus, the application of the passivated 120 $\Omega$/sq BSF on $n$-type PERT cells results in a decrease of $J_{0,BSF}$ by more than 200 fA/cm$^2$.

However, the fabricated PERT cells suffer from an incomplete front side metallization, leading primarily to the strongly reduced fill factor of ~70%. A 21.6 cm$^2$ cell has been cut out from 106 cm$^2$ cell from a part, featuring a complete front side metallization. On this small-area cell the fill factor FF increased from 67 to 77% in combination with a decrease of $R_{s,light}$ from 2.3 to 1.1 $\Omega$ cm$^2$, proving the effect of the front side metallization. However, the $R_{s,light}$ of 1.1 $\Omega$ cm$^2$ is still a rather high compared to the 0.5 $\Omega$ cm$^2$ of the fully-metalized BSF cells. This can possibly originate from the non-optimized rear side metallization. Furthermore, the PERT cells have ~50% wider metal fingers at the front side, which caused mainly the reduction of the short-circuit current density $J_{SC}$ by 0.7 mA/cm$^2$ compared to the fully-metalized BSF cell. This is supported by the 3% higher reflectance observed on the PERT cells for wavelengths between 400 and 1000 nm (see Fig. 6).

Fig. 6 shows the internal quantum efficiencies IQE of the $n$-type PERT solar cell compared to the fully-metalized BSF cell. As can be seen, the PERT solar cell shows an improved IQE in the long wavelength range above 900 nm, mainly due to the superior passivation of the rear surface. Thus, even if there have been metallization problems on the front side, this is a proof of concept for $n$-type PERT solar cells and further work is necessary for optimizing the required fabrication processes, such as for the rear mirror or the rear metallization.

The 671 mV further demonstrates that the applied stack of 5 Å ALD Al$_2$O$_3$ (four atomic layers) and 70 nm PECVD SiN$_x$ shows a remarkably high surface passivation quality on the boron emitter. This indicates that the number of ALD cycles required for a surface passivation by an Al$_2$O$_3$/SiN$_x$ stack could be drastically reduced, in this case to four ALD cycles. A detailed study of the surface passivation of boron emitters by fired Al$_2$O$_3$/SiN$_x$ stacks revealed that even with one atomic layer of Al$_2$O$_3$ emitter saturation current densities $J_{0e}$ in the range of 50 fA/cm$^2$ can be achieved, allowing for $V_{OC}$ values in the range of 700 mV [15]. These are very encouraging results for an industrial realization of the ALD technology for PV applications, as throughput and cost-of-ownership could be drastically reduced.

5. Conclusions

In this work we studied experimentally different phosphorous-doped BSF diffusions for their applicability to $n$-type PERT solar cells, especially with respect to the surface passivation with different dielectric layers and the contact formation with evaporated aluminum. Very low BSF saturation current densities in the range of 30 fA/cm$^2$ have been achieved on lifetime samples. The specific contact resistance of evaporated aluminum to these BSF diffusions was measured to values < 1 m$\Omega$ cm$^2$. These results were used to fabricate a first batch of $n$-type PERT solar cells. Open-circuit voltages $V_{OC}$ up to 671 mV have been measured, which is an increase by more than 15 mV, compared to cells with a fully-metalized BSF. Furthermore, for the surface passivation of the boron emitter a stack of ALD Al$_2$O$_3$ and PECVD SiN$_x$ was applied with a remarkably thin Al$_2$O$_3$ layer of 5 Å (four ALD cycles). Thus, the high $V_{OC}$ of 671 mV achieved with this stack demonstrates that the Al$_2$O$_3$ thickness of fired Al$_2$O$_3$/SiN$_x$ stacks can be drastically reduced, in this case to four atomic layers.

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