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High efficiency n-type Si solar cells on Al₂O₃-passivated boron emitters

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In order to utilize the full potential of solar cells fabricated on n-type silicon, it is necessary to achieve an excellent passivation on B-doped emitters. Experimental studies on test structures and theoretical considerations have shown that a negatively charged dielectric layer would be ideally suited for this purpose. Thus, in this work the negative-charge dielectric Al₂O₃ was applied as surface passivation layer on high-efficiency n-type silicon solar cells. With this front surface passivation layer, a confirmed conversion efficiency of 23.2% was achieved. For the open-circuit voltage $V_{oc}$ of 703.6 mV, the upper limit for the emitter saturation current density $J_{0e}$, including the metalized area, has been evaluated to be 29 fA/cm². This clearly shows that an excellent passivation of highly doped p-type c-Si can be obtained at the device level by applying Al₂O₃.

For passivation of highly doped p-type c-Si, a dielectric containing a fixed negative-charge density without any absorption in the visible part of the solar spectrum would be ideal. One dielectric layer meeting these specifications is the negative-charge dielectric Al₂O₃, which can be fabricated in a low temperature process.

Hoex et al. measured emitter saturation currents below 10 fA/cm² on highly doped p-type c-Si surfaces of unmetallized lifetime samples coated with Al₂O₃ synthesized by atomic layer deposition (ALD).¹⁰ The high density of fixed negative charges (up to $\sim 10^{13}$ cm⁻²) within this layer provides an effective field effect passivation on highly p-type doped surfaces.¹¹ The excellent passivation of lightly doped p-type c-Si by Al₂O₃ has already been demonstrated at the rear of a diffused emitter p-type c-Si solar cell.¹² In this paper, it will be proven that the excellent surface passivation of highly doped p-type c-Si by Al₂O₃ can be accomplished at the device level by achieving very high energy conversion efficiencies.

The effect of built-in charges on the passivation quality for highly doped p- and n-type surfaces is shown in Fig. 1. For this experiment, symmetrical $p^+/n/n^*$ and $n^+/p/p^*$ lifetime samples (1 Ω cm n- or p-type c-Si) were passivated by a 105 nm thick thermal SiO₂ and subsequently a charge density in the range between $-4$ and $4 \times 10^{12}$ cm⁻² was applied on both sides of the samples by means of corona charging.⁹ The quasi-steady-state photoconductance (QSSPC) method¹⁸ is used to measure effective lifetime $\tau_{eff}$. The implied $V_{oc}$ was extracted from the QSSPC data as proposed by Sinton:¹⁹

$$V_{oc}^{implied} = \frac{kT}{q} \left( \frac{\Delta n + N_{dop}}{n_i^2} \right),$$

where $\Delta n$ is the excess carrier density, $k$ the Boltzmann constant, $T$ the temperature, $q$ the elementary charge, $N_{dop}$ the bulk doping concentration, and $n_i$ the intrinsic carrier density.

The observed detrimental effect of positive charge on the passivation of highly doped p-type surfaces can be explained by the surface depletion of the majority carriers (i.e., the holes) induced by these positive charges. The surface depletion

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n-type silicon has an enormous potential for wide-scale application in the photovoltaics industry. Its relative tolerance to common impurities (e.g., Fe)¹ potentially results in higher minority carrier diffusion lengths compared to p-type c-Si substrates with a similar impurity concentration. Furthermore n-type c-Si does not suffer from the boron-oxygen related light-induced degradation (LID), which is known to cause the LID for c-Si solar cells based on p-type Czochralski c-Si.²

In order to benefit from these advantages of the c-Si bulk material, a technology for adequate passivation of the B-doped emitters is essential. However, at the device level the excellent passivation quality as achieved for highly doped n-type emitters has not been realized so far for highly B-doped p-type c-Si. SiO₂, the most effective passivation for highly doped n-type surfaces, does not show the same performance on highly B-doped surfaces.⁴⁻⁷ The high boron solubility combined with the presence of a small fixed positive charge density contribute to this gap in performance. a-Si:H, the second standard passivation layer for n⁺-doped surfaces, does not passivate highly doped p-type surfaces effectively due to the high concentration of built-in positive charges.⁶,⁹,¹¹ Nevertheless, Chen et al. have shown a-SiNₓ:H passivation on highly doped p-type surfaces with $J_{0e}$ values below 10 fA/cm² for sheet resistivities above 100 Ω/sq.¹² However, no n-type cells have been fabricated using this approach which would demonstrate the potential of this technology at the device level. Alternative passivation layers under investigation for highly doped p-type surfaces are a-Si:H and a-SiCₓ:H. With a-Si:H $J_{0e}$ values below 30 fA/cm² have been reached for sheet resistivities above 100 Ω/sq.⁶,¹³ a-SiCₓ:H shows only poor passivation properties so far, with $J_{0e} > 400$ fA/cm² on highly doped p-type surfaces ($R_{sheet} = 100$ Ω/sq).¹⁴ Apart from SiO₂, all other layers, especially those rich in Si, show a considerable absorption for photons with a wavelength <600 nm which is undesirable for the application as antireflection coating.

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tion enhances the minority carrier (i.e., the electron) concentration at the surface, leading to an enhanced surface recombination. The opposite effect occurs when a negative-charge density is applied. In this case, an accumulation layer is induced, providing an effective field effect passivation at the p-type surface. By applying a negative-charge density of $-4 \times 10^{12} \text{cm}^{-2}$, the implied $V_{oc}$ is increased from below 650 mV (without surface charging) to approximately 690 mV. An analogous effect, but with opposite polarities, can be observed for highly n-type doped surfaces.

In order to investigate the excellent level of surface passivation of highly doped p-type c-Si surfaces by Al$_2$O$_3$ at the device level, n-type passivated emitter with rear locally diffused

(AM1.5G, 100 mW/cm$^2$, 25 °C).

<table>
<thead>
<tr>
<th>$V_{oc}$ (mV)</th>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (28 cells)</td>
<td>696.9±5.6</td>
<td>40.9±0.3</td>
<td>78.8±1.8</td>
</tr>
<tr>
<td>Best</td>
<td>703.6</td>
<td>41.2</td>
<td>80.2</td>
</tr>
</tbody>
</table>

$^a$Independently confirmed by Fraunhofer ISE CalLab.

followed by a drive-in oxidation at 1050 °C result in a homogeneous B emitter with a sheet resistance of 140 Ω/sq (6 × 10$^{18}$ cm$^{-3}$ surface doping concentration, 1.5 μm depth). This front side B emitter is passivated by a stack consisting of a 30 nm Al$_2$O$_3$ film followed by a 40 nm thick SiN$_x$. The deposition of the Al$_2$O$_3$ was performed by plasma-assisted ALD (on an Oxford Instruments FlexAL™ setup) at a temperature of 200 °C. The plasma-assisted chemical vapor deposition SiN$_x$ was deposited at 400 °C (SINA XS, Roth & Rau AG).

The one-sun parameters of the PERL solar cells featuring the Al$_2$O$_3$ front side passivation are summarized in Table I. The best cell exhibits a $V_{oc}$ of 703.6 mV, a $J_{sc}$ of 41.2 mA/cm$^2$, and a FF of 80.2% resulting in an independently certified solar cell efficiency of 23.2% (aperture area measurement). The exceptional high values for $V_{oc}$, despite the lack of a two-step emitter, prove the outstanding ability of Al$_2$O$_3$ for the passivation of highly doped p-type surfaces in the solar cell devices.

To gain a deeper insight into the front surface passivation, an upper limit of the emitter saturation current $J_{0e}$ can be determined from the open-circuit voltage $V_{oc}$ and the saturation current density $J_0 = J_{0b} + J_{0e}$ by employing the one-diode equation:

$$V_{oc} = \frac{kT}{q} \ln \left( \frac{J_{sc}}{J_{0b} + J_{0e}} + 1 \right).$$

The $V_{oc}$ is determined by the saturation current densities of both the emitter $J_{0e}$ and the base $J_{0b}$. Thus, to obtain an upper limit for $J_{0b}$, a reasonable $J_{0e}$ has to be derived. The saturation density of the base, which also includes recombination in the bulk and at the rear side, can be calculated by

$$J_{0b} = \frac{q n_i^2 D_p}{L N_D} \frac{S_{\text{rear,eff}} \cosh(W/L) + D_p/L \sinh(W/L)}{D_p/L \sinh(W/L) + S_{\text{rear,eff}} \sinh(W/L)}.$$  

The effective surface recombination velocity (SRV) of a point contacted rear is given by

$$S_{\text{rear,eff}} = \frac{D_p}{W} \left[ \frac{p}{2W \sqrt{\pi}} \arctan \left( \frac{2W}{p} \sqrt{\pi} \right) - \exp \left( - \frac{W}{p} \right) \right]^{-1} + \frac{D_p}{f W S_{\text{cont}}} \left[ 1 - \frac{f}{1 - f} \right].$$

where $D_p=11.6 \text{cm}^2/\text{s}$ is the hole diffusion coefficient, $W=250 \mu\text{m}$ the wafer thickness, $p=135 \mu\text{m}$ the contact pitch, $f=5\%$ the metallization fraction, and $S_{\text{cont}}$ and $S_{\text{pass}}$ the SRVs of the metalized and the passivated sections of the rear side, respectively. $S_{\text{cont}}$ has been calculated by numerical modeling in PC1D (Ref. 21) on an idealized cell structure with intrinsic bulk lifetime, assuming $S_{\text{front}}=0 \text{ cm/s}$. A strong P-type back surface field is present beneath the contacts. In this case, $S_{\text{cont}}$ is independent of the actual SRV of the metal-Si interface.
leading to $S_{\text{cont}} \approx 55 \text{ cm/s}$. Applying Eqs. (2) and (3), the upper limit for the total dark emitter saturation currents $J_{\text{0,cont}}$ are 45 $\text{FA/cm}^2$ for $S_{\text{pass}}=0 \text{ cm/s}$ ($J_{\text{0b}}=10 \text{ FA/cm}^2$) and 29 $\text{FA/cm}^2$ for a more realistic but still very good $S_{\text{pass}}=5 \text{ cm/s}$ ($J_{\text{0b}}=25 \text{ FA/cm}^2$), including the recombination in the contacted and passivated areas of the emitter. To estimate the impact of the contacted area on $J_{\text{0e,cont}}$, using PC1D and a $S_{\text{cont}}$ of 10$^8 \text{ cm/s}$, we have calculated the dark saturation current in the contacted region, $J_{\text{0e,cont}}$, to be 1800 $\text{FA/cm}^2$. This results in an area-weighted dark saturation current for this region, $f_{\text{cont}} \times J_{\text{0e,cont}}$, of 20.3 $\text{FA/cm}^2$ (contacted area $f_{\text{cont}}=1.1\%$). The area-weighted value for the passivated region has been calculated, $(1-f_{\text{cont}}) \times J_{\text{0e,pass}}=9.9 \text{ FA/cm}^2$, using the $J_{\text{0e}}$ value of $\sim 10 \text{ FA/cm}^2$ extracted by Hoex et al. on nonmetallized lifetime test structures with a comparable B emitter.\(^{15}\) This leads to a $J_{\text{0e,total}}$ of 30.2 $\text{FA/cm}^2$ which is in good agreement to our previous calculation of 29 $\text{FA/cm}^2$. A $V_{\text{oc}}$ of 702 mV agreeing very well with the measured $V_{\text{oc}}$ of the cells has been obtained, taking into account a $J_{\text{0b}}$ of 25 $\text{FA/cm}^2$ ($S_{\text{pass}}=5 \text{ cm/s}$) from Eq. (3). This calculation shows that about 66% of the recombination in the emitter is due to the contacted area.

The high internal quantum efficiency (IQE) in Fig. 3 also shows the effective front side passivation. These very high IQE values of $\sim 100\%$ in the 300–600 nm range clearly demonstrate that the negative-charge dielectric $\text{Al}_2\text{O}_3$ is an excellent front surface passivation layer on B-doped emitters. Not only an excellent passivation quality has been reached on highly $p$-doped $c$-Si by $\text{Al}_2\text{O}_3$ resulting in a $V_{\text{oc}}$ of 703.6 mV but moreover no additional detrimental effects such as optical absorption or inversion channel shunting are present, which would result in a poor performance at the device level.

In summary, an exceptionally high conversion efficiency of 23.2% for an $n$-type PERL solar cell with a front side B-doped emitter has been reported in this work. To date the highest reported efficiencies on $n$-type material were 22.7% (681 mV) on a backside-contact solar cell\(^{22}\) and also 22.7% (702 mV) on a rear emitter PERT solar cell.\(^{23}\) This study demonstrates the excellent performance of our $n$-type solar cells and the superior passivation of highly B-doped surfaces by the negative-charge dielectric $\text{Al}_2\text{O}_3$. The passivation of highly $d$-type $c$-Si has been obtained at the device level achieving the required technology for high-efficiency diffused emitter solar cells on $n$-type $c$-Si.

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