PROGRESS IN THE SURFACE PASSIVATION OF SILICON SOLAR CELLS

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ABSTRACT: In order to increase the efficiency of silicon-wafer-based solar cells in production well above 20%, it is indispensable to improve the currently applied level of surface passivation at the front as well as at the rear of the cells. This paper focuses on two main challenges: (i) the low-temperature passivation of lowly doped p-type silicon surfaces at the cell rear and (ii) the passivation of highly boron-doped p+ emitter surfaces as used at the front of solar cells on high-lifetime n-type silicon wafers. In the past, low surface recombination velocities (< 20 cm/s) have been achieved on low-resistivity (~1 Ωcm) p-type silicon using plasma-enhanced-vapour-deposited (PECVD) silicon nitride (SiNx) as well as amorphous silicon (a-Si). However, the high density of fixed positive charges within the PECVD-SiNx layer induces an inversion layer at the rear of p-type Si cells, producing a detrimental parasitic shunting, which reduces the short-circuit current density by up to 3 mA/cm². The passivation quality of a-Si on the other hand is very temperature sensitive. More recently it has been shown that atomic-layer-deposited (ALD) aluminium oxide (Al2O3) provides an outstanding level of surface passivation, which can be attributed to its extremely high negative fixed charge density in combination with the very gentle deposition technique ALD, leading to low interface state densities. The application of these ALD-Al2O3 layers to the rear of p-type solar cells shows that this passivation scheme is indeed suitable for high efficiencies and that due to the large negative fixed charge density no parasitic shunting occurs. We also demonstrate that ALD-Al2O3 seems to be the ideal passivation layer for boron-doped p+ emitter surfaces. In a direct comparison with other passivation schemes, it is found that Al2O3 even outperforms optimized thermally grown SiO2 and opens the possibility of achieving very large open-circuit voltages up to $V_{oc} = 740$ mV.

Keywords: Silicon, Surface Passivation, Al2O3

1 INTRODUCTION

In high-efficiency laboratory silicon solar cells, surface recombination is very effectively suppressed by means of silicon dioxide (SiO2) grown in a high-temperature (≥ 900 °C) oxidation process [1]. Very low surface recombination velocities (SRVs) are in particular realized at the lightly doped rear surface, where the combination of a thermally grown SiO2 layer with an evaporated film of Al give – after an additional annealing treatment at ~400°C (the so-called ‘alneal’) – SRVs below 20 cm/s on un-metallized low-resistivity (~1 Ωcm) p-type silicon wafers [2]. In addition, the SiO2/Al stack at the cell rear acts as an excellent reflector for near-bandgap photons, significantly improving the light trapping properties and hence the short-circuit current of the cell. One of the main reasons why high-temperature oxidation has not been implemented into the majority of industrial cell processes up to now is the high sensitivity of the silicon bulk lifetime to high-temperature processes. In particular in the case of multi-crystalline silicon wafers, significant degradation of the bulk lifetime has not been implemented into the majority of industrial cell processes up to now is the high sensitivity of the a-Si passivation to high-temperature processes. More recently it was shown that thin films of aluminium oxide (Al2O3) grown by atomic layer deposition (ALD) provide an excellent level of surface passivation on lowly doped (~1 Ωcm) p- and n-type silicon wafers [9,10,11] as well as on highly boron-doped p+ emitters [12].

In the first part of this contribution, we compare the passivation properties of SiNx, a-Si and ALD-Al2O3 regarding the application to the rear of high-efficiency p-type silicon solar cells. The second part of the paper addresses the issue of passivating highly boron-doped p+ emitters, which has been a main obstacle in the past for fabricating high-efficiency cells on high-lifetime n-type silicon wafers.
PASSIVATION OF UNDIFFUSED p-Si

Figure 1. Comparison of the injection-dependent effective SRVs $S_{\text{eff}}(\Delta n)$ measured on 1-2 Ωcm p-type float-zone silicon wafers passivated by (i) SiN$_x$, deposited by remote-PECVD [13], (ii) intrinsic a-Si deposited in a parallel-plate PECVD reactor [8] and (iii) Al$_2$O$_3$ deposited by means of plasma-assisted ALD [14]. The lines are guides to the eye.

Figure 2. Measured effective SRV $S_{\text{eff}}$ as a function of the Corona charge density $Q_C$ deposited onto dielectric passivation layers of SiN$_x$ and Al$_2$O$_3$. The lines are guides to the eye.

Figure 2 shows the measured effective SRV as a function of the Corona charge density deposited onto dielectric passivation layers of SiN$_x$ and Al$_2$O$_3$. In the flat-band case when the deposited Corona charge density equals the fixed charge density within the dielectric layer, the recombination rate shows a maximum. From this maximum the charge density within the layer can be deduced. As can be seen from Fig. 2, the fixed charge density within the SiN$_x$ layer is positive and amounts to $Q_f = +2 \times 10^{12}$ elementary charges/cm$^2$, whereas the fixed charge density within the Al$_2$O$_3$ layer is negative and amounts to $Q_f = -1.3 \times 10^{13}$ cm$^{-2}$. The fixed negative charge density within the Al$_2$O$_3$ layer induces an accumulation layer at the p-type silicon surface in contrast to the SiN$_x$ layer inducing and inversion layer. As a consequence, the Al$_2$O$_3$ provides a very effective field-effect passivation without the additional contribution of recombination in the space charge region, which is the dominant recombination channel in the case of the SiN$_x$ passivation of p-type silicon surfaces at low injection densities [5]. In addition, due to the formation of an accumulation layer instead of an inversion layer at the p-type silicon surface, the above-mentioned parasitic shunting effect at the solar cell rear is not expected for an Al$_2$O$_3$-rear-passivated cell. In combination with its very high transparency for near-bandgap photons, ALD-deposited Al$_2$O$_3$ should hence be an optimal choice for a dielectric layer at the silicon solar cell rear.

Note that on n-type silicon with a resistivity of ~2 Ωcm also very low SRVs of 4 cm/s have been measured over the entire relevant injection range [10,14]. Hence ALD-Al$_2$O$_3$ is also excellently suited for passivating the rear of n-type silicon solar cells. In Section 4 the potential of all-Al$_2$O$_3$ passivated n-type cells will be analysed in detail.
cleaning, an SiO$_2$ layer is grown on both wafer surfaces. The 20 µm of Aluminium is evaporated on the entire cell rear of 2 mm and a metallization fraction of 4% is used. A photolithography mask resulting in a point contact pitch in a wet oxidation process at 1000°C. Subsequently, 2×2 square cells of 0.5 cm$^2$ (FZ) silicon with a thickness of 310 µm and a resistivity of 0.5 Ω·cm is used to demonstrate the applicability of Al$_2$O$_3$ rear surface passivation. The remaining process steps are identical for all three cell batches. Using photolithography point contact openings are etched into the dielectric layers at the rear. A photolithography mask resulting in a point contact pitch of 2 mm and a metallization fraction of 4% is used. 20 µm of Aluminium is evaporated on the entire cell rear using electron-beam evaporation. A tunnel oxidation of the n'-emitter is performed at 500°C for 10 min, resulting in an ~1.5 nm thick oxide layer. The 20 µm thick Al front metal grid is then evaporated through a shadow mask onto the tunnel oxide. Finally, a surface-passivating Si$_3$N$_4$ antireflection coating is deposited onto the front of the PERC solar cell by remote-PECVD at 500°C. The aperture area of all solar cells is 4 cm$^2$ and the entire front metallization, including the busbar, is within the active cell area.

Table 1 summarizes the one-sun parameters of the processed PERC-type solar cells featuring different rear surface passivation schemes, as measured under standard testing conditions (25°C, 100 mW/cm$^2$, AM 1.5 G). The results marked with an asterisk were independently confirmed at Fraunhofer ISE CalLab. The best reference solar cell with alnealed SiO$_2$ rear surface passivation is characterized by an efficiency of η = 20.5%, an open-circuit voltage of $V_{oc} = 656$ mV and a short-circuit current density of $J_{sc} = 38.8$ mA/cm$^2$. The analysis of the internal quantum efficiency (IQE) shows that the $V_{oc}$ is limited by the front emitter. The average values of all 4 cells with SiO$_2$ rear passivation show only a very small scatter, demonstrating the high reproducibility of the process. The average parameters of the cells with Al$_2$O$_3$, Al$_2$O$_3$/SiO$_2$ and SiO$_2$ rear passivation agree within the scatter ranges. In particular it is noticeable that the $J_{sc}$ of the cells with Al$_2$O$_3$ and Al$_2$O$_3$/SiO$_2$ rear surface passivation is not reduced compared to the SiO$_2$-passivated cells. In the case of high-positive-charge dielectrics, such as Si$_3$N$_4$ with fixed positive charge densities >10$^{12}$ cm$^{-2}$, it was reported that $J_{sc}$ is reduced by 1-2 mA/cm$^2$ compared to the thermal SiO$_2$ reference, due to the above-described parasitic shunting effect. This effect is not expected in the case of Al$_2$O$_3$ as it is a negative-charge-dielectric inducing an accumulation layer. The cell results summarized in Table 1 confirm the expected non-existence of the parasitic shunting for Al$_2$O$_3$-passivated as well as for Al$_2$O$_3$/SiO$_2$-passivated rear surfaces. The best cell of the entire batch is obtained for the Al$_2$O$_3$/SiO$_2$-passivated cell, resulting in an independently confirmed efficiency of η = 20.6%, a $V_{oc}$ of 660 mV and a $J_{sc}$ of 39.0 mA/cm$^2$. It is not possible to quantify the exact rear surface passivation quality from comparison of the cell parameters given in Table 1, as these solar cells are largely limited by recombination losses in the front emitter. Hence, we analyze the IQE in the wavelength range 800-1200 nm to determine the rear SRVs of the different rear surface passivation schemes. The symbols in Fig. 4 show the IQE as a function of wavelength λ of PERC cells.

Table 1. One-sun parameters measured under standard testing conditions of 290 µm thick PERC-type silicon solar cells with three different rear surface passivations: (i) thermal SiO$_2$ (220 nm), (ii) ALD-Al$_2$O$_3$ (130 nm) and (iii) ALD-Al$_2$O$_3$/PECVD-SiO$_2$(200 nm). All cells were fabricated on 0.5±0.03 cm FZ p-Si wafers [11].

<table>
<thead>
<tr>
<th>Rear side</th>
<th>Cell ID</th>
<th>$V_{oc}$ [mV]</th>
<th>$J_{sc}$ [mA/cm$^2$]</th>
<th>$FF$ [%]</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal SiO$_2$ (220 nm)</td>
<td>7_1</td>
<td>656</td>
<td>38.9</td>
<td>80.3</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>Average of 4</td>
<td>655±1</td>
<td>38.4±0.5</td>
<td>80.3±1.3</td>
<td>20.2±0.3</td>
</tr>
<tr>
<td>ALD-Al$_2$O$_3$ (130 nm)</td>
<td>3_3</td>
<td>655</td>
<td>38.7</td>
<td>78.9</td>
<td>20.0*</td>
</tr>
<tr>
<td></td>
<td>Average of 4</td>
<td>656±2</td>
<td>38.6±0.1</td>
<td>79.4±1.4</td>
<td>20.0±0.4</td>
</tr>
<tr>
<td>ALD-Al$_2$O$_3$ (30 nm)/PECVD-SiO$_2$ (200 nm)</td>
<td>2_4</td>
<td>660</td>
<td>39.0</td>
<td>80.1</td>
<td>20.6*</td>
</tr>
<tr>
<td></td>
<td>Average of 8</td>
<td>657±2</td>
<td>38.6±0.3</td>
<td>80.4±1.1</td>
<td>20.4±0.4</td>
</tr>
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</table>

*Calibrated measurement at Fraunhofer ISE CalLab.
Al₂O₃/SiO₂. A further reduction in the bulk lifetime, the SRVs determined from the IQE analysis are upper limits as well. Table 2 summarizes the rear SRVs $S_r$ and the internal rear reflectances $R_r$ extracted from the IQE analysis. All three rear structures are equally effective reflectors for near-bandgap photons ($R_r = 91\%$). The rear SRV (including recombination at the metal contacts) of the reference cell with annealed SiO₂ amounts to $S_r = (90 \pm 20)$ cm/s. The extracted $S_r$ for the cell with single-layer Al₂O₃ rear passivation is the same as for the SiO₂-passivated reference cell, showing that ALD-deposited Al₂O₃ performs as good as aluminium-annealed high-temperature-grown SiO₂. A further reduction in the $S_r$ is obtained for the Al₂O₃/SiO₂ stack, resulting in an $S_r$ of only $(70 \pm 20)$ cm/s, which we attribute to the hydrogenation of interface states at the Al₂O₃/Si interface during deposition of the hydrogen-rich SiO₂ layer.

The effective SRV of a point-contacted rear is given by Fischer’s equation [17]

$$S_r = \frac{D_e}{W} \left[ \frac{p}{2W} \sqrt{\frac{\pi}{f}} \arctan \left( \frac{2W}{\pi f} \right) \right]^{-1} + \frac{S_{\text{ass}}}{1-f}, \quad (1)$$

where $D_e$ is the electron diffusion coefficient, $W$ the wafer thickness, $p$ the contact pitch, $f$ the metallization fraction and $S_{\text{ass}}$ are the SRVs on the metallized and on the passivated areas of the rear. According to Eqn. (1) the minimum SRV $S_{\text{min}}$, for a point-contact rear with perfect passivation in the non-metallized area (i.e., $S_{\text{pass}} = 0$) is given by the first summand on the right-hand side of Eqn. (1). For our cell structure we determine $S_{\text{min}} = 73$ cm/s ($D_e = 23$ cm²/s, $W = 290$ µm, $p = 2000$ µm, $f = 4\%$, $S_{\text{ass}} = 91\%$). As the $S_r$ of $(70 \pm 20)$ cm/s extracted from the IQE analysis is practically identical to the $S_{\text{min}}$ calculated using Eq. (1), we conclude that recombination in the passivated area of the cell rear can be completely neglected. Note that, although a slightly better passivation is obtained in the case of the Al₂O₃/SiO₂ stacks, the rear SRV of the single-layer Al₂O₃-passivated cells is also mainly determined by recombination at the metal contacts. The IQE results clearly prove that atomic-layer-deposited Al₂O₃ is a very effective new dielectric passivation layer for high-efficiency silicon solar cells.

### Table 2. Effective rear surface recombination velocity $S_r$ and internal rear reflectance $R_r$ extracted from the IQE measurements shown in Fig. 5.

<table>
<thead>
<tr>
<th>Rear side</th>
<th>Rear surface recombination velocity $S_r$ [cm/s]</th>
<th>Internal rear reflectance $R_r$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal SiO₂ (220 nm)</td>
<td>90 ± 20</td>
<td>91 ± 1</td>
</tr>
<tr>
<td>Al₂O₃ (130 nm)</td>
<td>90 ± 20</td>
<td>90 ± 1</td>
</tr>
<tr>
<td>Al₂O₃(30 nm)/SiO₂(200 nm)</td>
<td>70 ± 20</td>
<td>91 ± 1</td>
</tr>
</tbody>
</table>

with the three different rear passivation schemes, measured at a fixed bias light intensity of 0.3 suns. The solid lines in Fig. 4 show the fits to the measured data. To model the IQE$(\lambda)$ dependence we use the software LASSIE [16,17], which combines the extended IQE evaluation by Basore [18] with the improved optical model developed by Brendel [19]. The bulk lifetime is assumed to be limited by Auger recombination, resulting in a bulk diffusion length of $L_b = 1500$ µm for the 0.5 Ωcm $p$-type silicon material used in this work [20]. As we assume the intrinsic upper limit for the bulk lifetime, the SRVs determined from the IQE analysis are upper limits as well. Table 2 summarizes the rear SRVs $S_r$ and the internal rear reflectances $R_r$ extracted from the IQE analysis. All three rear structures are equally effective reflectors for near-bandgap photons ($R_r = 91\%$). The rear SRV (including recombination at the metal contacts) of the reference cell with annealed SiO₂ amounts to $S_r = (90 \pm 20)$ cm/s. The extracted $S_r$ for the cell with single-layer Al₂O₃ rear passivation is the same as for the SiO₂-passivated reference cell, showing that ALD-deposited Al₂O₃ performs as good as aluminium-annealed high-temperature-grown SiO₂. A further reduction in the $S_r$ is obtained for the Al₂O₃/SiO₂ stack, resulting in an $S_r$ of only $(70 \pm 20)$ cm/s, which we attribute to the hydrogenation of interface states at the Al₂O₃/Si interface during deposition of the hydrogen-rich SiO₂ layer.

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### 3 PASSIVATION OF B-DOPED $p$-EMITTERS

Emitter saturation current densities $J_{0e}$ of boron-doped $p$-emitters were extracted from QSSPC measurements of the effective lifetime as a function of the injection density using the method of Kane and Swanson [21,12]. High-resistivity (20-90 Ωcm) shiny-etched $n$-type silicon wafers with a thickness of ~260 µm were used as base material. BBBr, diffusions were performed on both sides of the wafers in the temperature range 895-1010°C [22]. After etching off the boron glass, the drive-in was performed by a thermal oxidation at 1050°C [22]. All oxide-passivated samples received a 40-min forming gas anneal at 400°C before the QSSPC measurements. The sheet resistance of the $p$-emitters was determined from four-point probe measurements [23].

Figure 5 shows the measured emitter saturation current densities $J_{0e}$ of the boron-diffused $p$-emitters as a function of their sheet resistance. After boron diffusion all samples were thermally oxidized and forming gas annealed. The open blue triangles in Fig. 5 show the result-

![Image](image-url)
measuring \(J_{0e}\) values ranging from 85 \(\text{fA/cm}^2\) at a sheet resistance of 30 \(\Omega/\text{sq}\) down to only 30 \(\text{fA/cm}^2\) at 100 \(\Omega/\text{sq}\). However, as has been shown in a recent study [24], this very good passivation quality is highly unstable and after approximately two years of storage in the dark the \(J_{0e}\) of the oxide-passivated p\textsuperscript{+} emitters degraded to ~300 \(\text{fA/cm}^2\) (filled blue triangles in Fig. 5). The fact that SiO\textsubscript{2}-passivated boron-doped p\textsuperscript{+} emitters are unstable has also been observed on high-efficiency n-type PERL silicon solar cells with p\textsuperscript{+} front emitter [25].

A very elegant method to improve the poor passivation quality of thermally grown SiO\textsubscript{2} on p\textsuperscript{+} emitters has recently been proposed [26,27]. This method makes use of the excellent passivation quality of SiO\textsubscript{2} on n\textsuperscript{+} surfaces by implementing an additional phosphorus diffusion at the surface of the p\textsuperscript{+} emitter. The resulting n\textsuperscript{+}/p\textsuperscript{+} junction at the surface can be well passivated as the excellent passivation properties of oxide on the n\textsuperscript{+} surface are exploited. The described new passivation method has already been applied in the “buried emitter solar cell” [26,28] currently under development at ISFH.

The black open squares in Fig. 5 show the \(J_{0e}\) values measured after stripping off the a-Si/SiN\textsubscript{x} stacks deposited by PECVD (open circles) [24] and (v) ALD-Al\textsubscript{2}O\textsubscript{3} [12]. The filled red triangles in Fig. 5 show the measured \(J_{0e}\) values after stripping off the a-Si/SiN\textsubscript{x} stacks, depositing Al\textsubscript{2}O\textsubscript{3} by plasma-assisted ALD at 200\(^\circ\)C and annealing the samples for 30 min at 425\(^\circ\)C [12]. The \(J_{0e}\) values of the Al\textsubscript{2}O\textsubscript{3}-passivated p\textsuperscript{+} emitters range from ~50 \(\text{fA/cm}^2\) measured at a sheet resistance of 30 \(\Omega/\text{sq}\) down to only 6 \(\text{fA/cm}^2\) at 150 \(\Omega/\text{sq}\) [12]. To our knowledge this is the best passivation realized so far on boron-doped p\textsuperscript{+} emitters. A very high open-circuit voltage of 704 mV and an efficiency of 23.2\% have in fact recently been realized using the above ALD-Al\textsubscript{2}O\textsubscript{3} passivation scheme on the front boron-doped p\textsuperscript{+} emitter of an n-type cell, whereas the rear was thermally oxidised [31]. As an additional advantage, Al\textsubscript{2}O\textsubscript{3} as a large-bandgap material (~9 eV) is perfectly transparent for solar radiation. Hence, double layers consisting of a 10 nm thick a-Si film deposited at 230\(^\circ\)C and a 60 nm thick SiN\textsubscript{x} film deposited at the same temperature. The a-Si/SiN\textsubscript{x} stacks were subsequently annealed at 350\(^\circ\)C for 5 min to improve their passivation quality [24]. Despite the remarkably low deposition temperature, the a-Si/SiN\textsubscript{x} stack passivates as effectively as the best high-temperature SiO\textsubscript{2} and is also perfectly stable, as has been shown in a recent study [24]. The main disadvantage of the a-Si/SiN\textsubscript{x} stack regarding the application to the front p\textsuperscript{+} emitter is the increased absorption within the a-Si layer, reducing the short-circuit density of the solar cell.

The filled red triangles in Fig. 5 show the measured \(J_{0e}\) values after stripping off the a-Si/SiN\textsubscript{x} stacks, depositing Al\textsubscript{2}O\textsubscript{3} by plasma-assisted ALD at 200\(^\circ\)C and annealing the samples for 30 min at 425\(^\circ\)C [12]. The \(J_{0e}\) values of the Al\textsubscript{2}O\textsubscript{3}-passivated p\textsuperscript{+} emitters range from ~50 \(\text{fA/cm}^2\) measured at a sheet resistance of 30 \(\Omega/\text{sq}\) down to only 6 \(\text{fA/cm}^2\) at 150 \(\Omega/\text{sq}\) [12]. To our knowledge this is the best passivation realized so far on boron-doped p\textsuperscript{+} emitters. A very high open-circuit voltage of 704 mV and an efficiency of 23.2\% have in fact recently been realized using the above ALD-Al\textsubscript{2}O\textsubscript{3} passivation scheme on the front boron-doped p\textsuperscript{+} emitter of an n-type cell, whereas the rear was thermally oxidised [31]. As an additional advantage, Al\textsubscript{2}O\textsubscript{3} as a large-bandgap material (~9 eV) is perfectly transparent for solar radiation. Hence, double layers of a thin (up to ~10 nm) Al\textsubscript{2}O\textsubscript{3} film and a SiN\textsubscript{x} antireflection layer on top are excellently suited for the application to high-efficiency cells on n-type silicon with a boron-doped p\textsuperscript{+} front emitter.

We have also studied the stability of the Al\textsubscript{2}O\textsubscript{3} passivation under UV illumination. The experiments mimic 2 years outdoor conditions.
outdoor conditions. The results of this experiment are shown in Fig. 6. The Al₂O₃ passivation is found to be perfectly stable and shows no degradation at all during UV exposure.

4 ALL-Al₂O₃ PASSIVATED CELLS

Figure 7. Calculated limiting (a) 1-sun efficiency η and (b) open-circuit voltage V_{oc} as a function of cell thickness W for a 1-Ωcm n-type silicon base assuming Lambertian light trapping. Black squares: only bulk recombination via Coulomb-enhanced Auger; red circles: additional surface recombination at the Al₂O₃-passivated p⁺ emitter and Al₂O₃-passivated n-Si base; blue triangles: additional contact recombination and front-grid shading.

Using the measured recombination parameters of Al₂O₃-passivated p⁺ emitters and on undiffused Al₂O₃-passivated n-type Si surfaces we calculate the 1-sun efficiency and V_{oc} limits for all-Al₂O₃ passivated n-type silicon solar cells. For these calculations we assume an n-type silicon wafer with a base resistivity of 1 Ωcm and Lambertian light trapping [32]. The I-V characteristics is calculated using the expression

\[ J = J_L - qW \frac{\Delta n}{\tau_b} - J_{0e} \left[ \exp \left( \frac{qV}{kT} \right) - 1 \right] - qS_{r} \Delta n, \]

where \( J_L \) is the light-generated current density, \( W \) the cell thickness, \( \tau_b \) the bulk lifetime, \( J_{0e} \) the emitter saturation current density and \( S_{r} \) the rear surface recombination velocity. In order to estimate the ultimate efficiency limit for a 1-sun silicon solar cell we assume a perfectly passivated emitter and rear surface, i.e. \( J_{0e} = 0 \) and \( S_{r} = 0 \) in Eq. (2). The cell thickness \( W \) is varied between 1 and 1000 µm. The bulk recombination lifetime \( \tau_b \) is assumed to be limited by Coulomb-enhanced Auger recombination, and we use a widely accepted parameterization as a function of the carrier densities [33].

Figure 8. The all-Al₂O₃ passivated n-type silicon solar cell has an efficiency limit of 26.1% including bulk, surface and contact recombination as well as shading losses.

Table 3. Calculated limiting 1-sun efficiency η and open-circuit voltage V_{oc} as a function of cell thickness W for a 1-Ωcm n-type silicon base assuming Lambertian light trapping.

<table>
<thead>
<tr>
<th>Losses</th>
<th>η_{max} (%)</th>
<th>V_{oc} (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bulk</td>
<td>28.5</td>
<td>770</td>
</tr>
<tr>
<td>bulk + Al₂O₃</td>
<td>27.5</td>
<td>740</td>
</tr>
<tr>
<td>bulk + Al₂O₃ + contacts</td>
<td>26.1</td>
<td>720</td>
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</tbody>
</table>

Figure 7 and Table 3 show the calculated efficiency limit and the corresponding V_{oc} for three different cases. The uppermost curve (black squares) shows that Coulomb-enhanced Auger recombination limits the efficiency of a silicon solar cell to an ultimate efficiency of 28.5% for a cell thickness of ~50 µm. The red curve (circles) includes recombination in the Al₂O₃-passivated boron-diffused p⁺ emitter as well as recombination at the undiffused Al₂O₃-passivated cell rear. For Al₂O₃-passivated p⁺ emitters we have measured a \( J_{0e} \) value of 6 fA/cm² and for undiffused n-type silicon a SRV of \( S_{r} = 4 \) cm/s. These additional recombination channels reduce the efficiency limit to 27.5% for a cell thickness between 100 and 300 µm. Moreover, the all-Al₂O₃ passivated cell permits open-circuit voltages of up to 755 mV for a cell thickness between 3 and 10 µm. The V_{oc} limit drops to 740 mV at a cell thickness of 100 µm, where the efficiency peaks. Adding contact recombination and contact shading in a realistic way reduces the efficiency limit further to 26.1% and the V_{oc} limit to 728 mV (blue triangles in Fig. 7). At a cell thickness of 200 µm our calculation gives a maximum efficiency of 26.1% at a V_{oc} of 720 mV. The latter case corresponds to the cell structure shown in Fig. 8. Under the contacts we assume that heavy diffusions reduce the contact recombination. The front p⁺ diffusion beneath the metal contacts has a sheet resistance of 5 Ω/sq, resulting in an emitter saturation current density of \( J_{0e,max} = 420 \) fA/cm² [34]. The n⁺ diffusion at the rear has a sheet resistance of 30 Ω/sq and a
Atomic layer deposition (ALD) of $\text{Al}_2\text{O}_3$ has been identified as an ideal new passivation scheme for passivating undiffused $p$- and $n$-type silicon surfaces as well as for the passivation of boron-doped $p^+$ regions. Our calculations of efficiency and $V_{oc}$ limits of $n$-type Si solar cells show that all-$\text{Al}_2\text{O}_3$ passivated cells have an efficiency limit of 27.5% at a $V_{oc}$ of 740 mV. Including contact recombination and optical shading with realistic assumptions the efficiency limit drops to 26.1% at a $V_{oc}$ of 720 mV.

In addition to the outstanding surface passivation provided by ALD-deposited $\text{Al}_2\text{O}_3$, the deposition process itself is also beneficial from an application point of view. In contrast to the conventionally applied PECVD, ALD consists of two self-limiting half-reactions, which implies several important advantages: (i) ALD gives highly conformal coatings, which allows to deposit and passivate e.g. deep trenches or even pores in silicon, (ii) pin-hole and particle-free deposition is achieved, (iii) as ALD is a self-limiting process uniform films can be deposited over large areas with mono-layer growth control and (iv) very low impurity concentrations of deposited films and hence very high film quality is achieved. The main disadvantage of ALD for photovoltaic applications is its relatively low deposition rate. However, this disadvantage can be overcome by depositing ultrathin (2-30 nm) ALD-$\text{Al}_2\text{O}_3$ films and capping them with a thicker film of e.g. PECVD-SiO$_2$, SiN$_x$, or SiC$_x$ [36]. Apart from the advantageous optical properties of these stacks, we have demonstrated that the passivation quality of such ALD/PECVD stacks can even be superior to that of single layers of $\text{Al}_2\text{O}_3$ [11], which we attribute to the hydrogenation of interface states at the $\text{Al}_2\text{O}_3$/Si interface during deposition of the hydrogen-rich PECVD layer. Combination of ALD and PECVD might hence be a key technology for future industrial high-efficiency solar cells.

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