Influence of wafer thickness on the performance of multicrystalline Si solar cells; an experimental study

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The influence of the thickness of silicon solar cells has been investigated using neighbouring multicrystalline silicon wafers with thickness ranging from 150 to 325 µm. For silicon solar cell structures with a high minority carrier diffusion length one expects that Jsc would decrease as the wafer becomes thinner due to a shorter optical path length. It was found experimentally that Jsc is nearly independent of the thickness of the solar cell, even when the minority carrier diffusion length is about 300 µm. This indicates that the Al rear metallisation acts as a good back surface reflector. A decrease in Jsc is observed only if the wafer thickness becomes less than about 200 µm.

The observed trend in Voc as a function of the wafer thickness has been explained with PC1D modelling by a minority carrier diffusion length in the Al-doped BSF which is small in relation to the thickness of the BSF. This effectively increases the recombination velocity at the rear of the cell.

We have shown that the efficiency of solar cells made with standard industrial processing is hardly reduced by reducing the wafer thickness. Solar cell efficiencies might be increased by better rear surface passivation.

Keywords: photovoltaics; wafer thickness; lifetime; BSF; multicrystalline silicon; PC1D modelling

Introduction

It is generally accepted that the cost of photovoltaic conversion has to diminish for PV to become of major importance as a renewable energy source. For crystalline silicon wafer technology, the silicon material is a major cost item. One option to make a more efficient use of the expensive silicon material is the use of thinner silicon wafers. The total amount of silicon used per Wp decreases by about 20 % when using 200 µm wafers instead of 300 µm wafers in spite of relatively increased kerf losses when process yield and cell efficiency are not affected.

Within the present investigation we studied the influence of the wafer thickness of both high quality and low quality base material on the electrical properties of the mc-Si solar cells. The material quality of the cells has been varied by using different processing schemes.

Thus far, experimental studies on the influence of wafer thickness on cell efficiency have been hampered by the absence of neighbour wafers with varying thickness. Interpretation of the results was thus complicated because of possible differences in (electronic) material quality of wafers with different thickness. Now experiments have been performed on multicrystalline silicon neighbour wafers with varying thickness.

The significance of the influence of the wafer thickness on the solar cell characteristics was investigated using statistical analysis. Solar cell results have been modelled with PC1D.
Experimental set-up

Sets of silicon wafers have been processed using standard processing sequences using industrial techniques (see Figure 1). Each set consisted initially of eight 10×10 cm² neighbour wafers. The thickness of the 8 wafers before the saw damage etch ranged from 150 µm to 325 µm with steps of 25 µm. Because of breakage of cells either during wafer fabrication, handling or cell processing, several sets consisted of less than 8 cells. Two different scenarios have been used to process the wafers into solar cells, the main difference being the emitter sheet resistance and the anti reflection coating (ARC). A thick emitter in combination with a TiO₂ ARC resulted in solar cells with a relatively short minority carrier diffusion length. A shallow emitter in combination with a passivation SiNₓ ARC should result in solar cells with a much longer minority carrier diffusion length due to passivation by the SiNₓ. Throughout this article, the TiO₂ scenario refers to the low material quality scenario, while the SiNₓ scenario refers to the high material quality scenario.

The SiNₓ ARC was applied with a remote microwave plasma enhanced CVD (R-MW-PECVD) system at ECN, the TiO₂ coating was applied with an industrial atmospheric pressure CVD (APCVD) system at Shell Solar Energy B.V.. A total of 22 neighbour sets has been processed; 10 with an SiNₓ ARC and 12 with a TiO₂ ARC (see Table 1).

![Diagram](image-url)

**Figure 1:** Applied process sequence; firing conditions used were different for the different scenarios and varied slightly with wafer thickness. The firing conditions were not fully optimised for each thickness.
Table 1: Variations in the neighbour sets used.

<table>
<thead>
<tr>
<th>group</th>
<th>wafer thickness</th>
<th>AR coating</th>
<th># neighbour sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>150 – 325 µm</td>
<td>SiN_x</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>150 – 325 µm</td>
<td>TiO_2</td>
<td>12</td>
</tr>
</tbody>
</table>

We assume that the improvement of the bulk material quality by SiN_x is independent of the wafer thickness. Only then the neighbour wafers still have comparable material quality after processing. A set of 330 µm neighbour wafers and a set of 200 µm neighbour wafers have been processed with both SiN_x and TiO_2 ARC to validate this assumption.

To determine the internal reflection at the aluminium rear metallisation, a measured reflection curve of a specially prepared sample was modelled using a stratified system with scattering surfaces. The scattering is modelled using the Phong model.

We measured the IV characteristics of all cells. The reflectance, the spectral response and the ECV-profile of the BSF of selected cells was measured. The statistical analysis to identify significant trends has been performed using the program Statgraphics version 5. The device modelling was done with PC1D version 4.5. Although this is a one-dimensional model, the observed trends of the various cell parameters are expected to be comparable to a more complicated two-dimensional model.

Method of statistical analysis

Weeber and Sinke have shown the importance of the use of a two factor analysis of variance to determine whether or not observed trends are significant, specially when neighbour wafers are used. In this work one of the factors is the thickness, the other factor is the neighbour type (statistical block). We want to investigate whether or not the cell results (J_sc, V_oc, FF) depend on the thickness of the cell.

The cell result of an individual cell can be represented by:

\[ y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \]

in which:
- \( i \) = thickness indicator (1, 2, ..., a) (i = 1 for 150 µm, i = 8 for 325 µm wafers)
- \( j \) = neighbour set (1, 2, ..., b) (b = 12 for TiO_2; b = 10 for SiN_x)
- \( y_{ij} \) = individual cell result (J_sc, V_oc, FF)
- \( \mu \) = the overall mean
- \( \tau_i \) = the effect of the thickness
- \( \beta_j \) = the effect of neighbour set \( j \)
- \( \varepsilon_{ij} \) = the usual random error term

The effect of the thickness and the effect of the neighbour set are defined as deviations from the overall mean. The sum of the squares SS can be split in a term of the thickness, a term of the neighbour set and an error term:

\[ SST = SS_{\text{thickness}} + SS_{\text{neighbour}} + SS_{\text{error}} \] (2)

The mean square of the thickness (MS_{thickness}) indicates the variability of the thickness and MS_{neighbour} indicates the variability within the neighbour solar cells. MS_{error} indicates the variability of the random error term. Table 2 shows the formulae to calculate the mean squares.
Table 2: Analysis of variance for a complete block design

<table>
<thead>
<tr>
<th>source of variation</th>
<th>degrees of freedom</th>
<th>mean square</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness</td>
<td>a-1</td>
<td>SS_{thickness} (\frac{a-1}{a-1})</td>
</tr>
<tr>
<td>neighbours</td>
<td>b-1</td>
<td>SS_{neighbour} (\frac{b-1}{b-1})</td>
</tr>
<tr>
<td>error</td>
<td>(a-1)(b-1)</td>
<td>SS_{error} (\frac{(a-1)(b-1)}{(a-1)(b-1)})</td>
</tr>
<tr>
<td>total</td>
<td>ab-1</td>
<td></td>
</tr>
</tbody>
</table>

The observed difference between two thicknesses is significant if the difference between the means of the two thicknesses is greater than the least significant difference LSD. In formula form:

\[ |y_i - y_k| > \text{LSD with } \text{LSD} = t_{\alpha/2, (a-1)(b-1)} \sqrt{\frac{2\text{MS}_{\text{error}}}{b}} \]

\(t_{\alpha/2, (a-1)(b-1)}\) is a statistical factor (t-statistics) and depends on the confidence limit (95% in our case) and the degrees of freedom. The value of \(t\) can be found in standard books on statistics. Note that \(\text{MS}_{\text{error}}\) not only depends on the variance of the solar cells with thickness \(i\) and \(k\), but also on the variance of all the solar cells. \(\text{MS}_{\text{error}}\) is also used to calculate the confidence limits in Table 3 to Table 5. The confidence limit is not the standard deviation within the group, but is calculated as \(\pm \frac{t_{\alpha/2,ab-1}}{\sqrt{\frac{2\text{MS}_{\text{error}}}{b}}}\).

A more detailed discussion of the statistical method is given by Montgomery. In our case the calculations are complicated because values are missing. During wafer production and cell processing wafers are broken; more breakage occurred for thinner wafers. The method to compensate for those missing values is described by Montgomery in chapter 5.

We used the computer program Statgraphics to perform the calculations.

Results

To investigate the significance of observed trends, the main electrical parameters have been analysed statistically. Throughout this discussion, the 95 % confidence limit is used to identify significant differences. In Table 3 and Table 4, the mean value of the main electrical parameters of the groups are given.

In Table 3, the mean values of the main electrical parameters of the solar cells processed according to the SiN\(_x\) scenario are given (group A). Within the 95 % confidence limit, both \(J_{sc}\) and \(V_{oc}\) are independent of the wafer thickness, as long as the wafer thickness is over 200 µm. If thinner wafers are used, the decrease in both \(V_{oc}\) and \(J_{sc}\) becomes statistically significant.
Table 3: Cell results of neighbour cells with varying thickness processed with an SiN\textsubscript{x} ARC (group A). Errors show 95 % confidence limit.

<table>
<thead>
<tr>
<th>thickness (µm)</th>
<th>J\textsubscript{sc} (mA/cm\textsuperscript{2})</th>
<th>V\textsubscript{oc} (mV)</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>325</td>
<td>30.2±0.2</td>
<td>601±2</td>
<td>74.4±0.9</td>
<td>13.5±0.2</td>
</tr>
<tr>
<td>300</td>
<td>29.8±0.2</td>
<td>601±2</td>
<td>74.1±0.9</td>
<td>13.3±0.2</td>
</tr>
<tr>
<td>275</td>
<td>30.2±0.2</td>
<td>602±2</td>
<td>73.4±0.8</td>
<td>13.3±0.2</td>
</tr>
<tr>
<td>250</td>
<td>30.0±0.2</td>
<td>601±2</td>
<td>74.2±0.9</td>
<td>13.4±0.2</td>
</tr>
<tr>
<td>225</td>
<td>29.9±0.2</td>
<td>602±2</td>
<td>74.6±0.8</td>
<td>13.4±0.2</td>
</tr>
<tr>
<td>200</td>
<td>29.7±0.2</td>
<td>600±2</td>
<td>74.7±0.8</td>
<td>13.3±0.2</td>
</tr>
<tr>
<td>175</td>
<td>29.3±0.2</td>
<td>599±2</td>
<td>73.4±1.0</td>
<td>12.9±0.2</td>
</tr>
<tr>
<td>150</td>
<td>29.1±0.2</td>
<td>597±3</td>
<td>71.4±1.3</td>
<td>12.4±0.2</td>
</tr>
</tbody>
</table>

In Table 4 the mean values of the main electrical parameters for the solar cells processed following the TiO\textsubscript{2} scenario are given (group B). The statistical analysis shows that both J\textsubscript{sc} and V\textsubscript{oc} are independent of the wafer thickness within the 95 % confidence limit.

Table 4: Cell results of neighbour cells with varying thickness processed with an TiO\textsubscript{2} ARC (group B). Errors show 95 % confidence limit.

<table>
<thead>
<tr>
<th>thickness (µm)</th>
<th>J\textsubscript{sc} (mA/cm\textsuperscript{2})</th>
<th>V\textsubscript{oc} (mV)</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>325</td>
<td>26.3±0.1</td>
<td>581±2</td>
<td>70.3±0.5</td>
<td>10.8±0.2</td>
</tr>
<tr>
<td>300</td>
<td>26.5±0.2</td>
<td>582±2</td>
<td>72.0±0.5</td>
<td>11.1±0.2</td>
</tr>
<tr>
<td>275</td>
<td>26.6±0.1</td>
<td>582±2</td>
<td>72.6±0.5</td>
<td>11.2±0.2</td>
</tr>
<tr>
<td>250</td>
<td>26.3±0.2</td>
<td>581±2</td>
<td>73.8±0.5</td>
<td>11.3±0.2</td>
</tr>
<tr>
<td>225</td>
<td>26.6±0.2</td>
<td>582±2</td>
<td>73.1±0.5</td>
<td>11.3±0.2</td>
</tr>
<tr>
<td>200</td>
<td>26.7±0.2</td>
<td>582±2</td>
<td>73.2±0.5</td>
<td>11.3±0.2</td>
</tr>
<tr>
<td>175</td>
<td>26.7±0.2</td>
<td>581±3</td>
<td>72.5±0.8</td>
<td>11.3±0.2</td>
</tr>
<tr>
<td>150</td>
<td>26.8±0.5</td>
<td>583±6</td>
<td>73.1±1.6</td>
<td>11.4±0.2</td>
</tr>
</tbody>
</table>

The results of the experiments to validate the assumption the bulk passivation is independent of the wafer thickness and the experiments to estimate the internal rear reflectivity do not directly contribute to the insight in the influence of the wafer thickness on the solar cell performance in relation to the material quality. For that reason the results are discussed in this section and not in the discussion section.

SiN\textsubscript{x}, bulk passivation in thick and thin wafers

In Table 5 the mean values of the main electrical parameters of neighbour cells processed according to the two different scenarios are given. For the 330 and 200 µm thick neighbours both V\textsubscript{oc} and J\textsubscript{sc} are significantly higher for the SiN\textsubscript{x} scenario compared to the TiO\textsubscript{2} scenario. This is in accordance with results reported by Duerinckx et al.\cite{9}.
Table 5: Cell results of neighbour cells with the same thickness processed using different scenarios. Errors show 95% confidence limit.

<table>
<thead>
<tr>
<th>scenario</th>
<th>thickness</th>
<th>$J_{sc}$</th>
<th>$V_{oc}$</th>
<th>FF</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO$_2$</td>
<td>330 µm</td>
<td>28.1 ± 0.2</td>
<td>598 ± 1</td>
<td>71 ± 1</td>
<td>11.9 ± 0.2</td>
</tr>
<tr>
<td>SiNx</td>
<td>330 µm</td>
<td>30.4 ± 0.2</td>
<td>609 ± 1</td>
<td>72 ± 1</td>
<td>13.3 ± 0.2</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>200 µm</td>
<td>27.2 ± 0.2</td>
<td>584 ± 2</td>
<td>73 ± 1</td>
<td>11.6 ± 0.1</td>
</tr>
<tr>
<td>SiNx</td>
<td>200 µm</td>
<td>29.9 ± 0.3</td>
<td>604 ± 3</td>
<td>73 ± 1</td>
<td>13.2 ± 0.2</td>
</tr>
</tbody>
</table>

In Figure 2 the IQE data for 330 µm thick cells processed using the SiN$_x$ and TiO$_2$ scenario respectively are shown. Neighbour wafers have been used for this experiment, so differences in materials properties of the starting wafers can be neglected. The IQE in the SiN$_x$ scenario is higher for all wavelengths.

The increase in blue response results from the shallower emitter in the SiN$_x$ scenario in combination with some surface passivation. The increase in red response results from the bulk passivating properties of the SiN$_x$ ARC reported before. Using PC1D modelling, the minority carrier diffusion length for the SiN$_x$ scenario and the TiO$_2$ scenario were estimated at 400 µm and 200 µm respectively (curve marked “calculated”).

In Figure 3 the measured and calculated IQE data for the 200 µm thick neighbour wafers are shown. Again, the differences can be attributed to differences in emitter profile and the surface and bulk passivation by the SiN$_x$ ARC. As for the 330 µm thick wafers, a large improvement in minority carrier diffusion length is observed for the SiN$_x$ scenario.

![Graph showing IQE comparison between SiN$_x$ and TiO$_2$ scenarios](image)

**Figure 2:** Internal Quantum Efficiency for 330 µm thick neighbour cells; SiN$_x$ and TiO$_2$ scenario respectively. Solid lines are calculated with PC1D using minority carrier diffusion lengths of 400 and 200 µm resp.
Figure 3: Internal Quantum Efficiency for 200 µm thick neighbour cells; SiNₓ and TiO₂ scenario resp. Solid lines are calculated with PC1D using minority carrier diffusion lengths of 350 and 150 µm resp.

For both wafer thicknesses the minority carrier diffusion length is increased by about 200 µm. This indicates that the increase in material quality by the SiNₓ ARC is independent of the wafer thickness. Neighbour wafers thus still have identical material quality after the SiNₓ processing sequence and the SiNₓ ARC is useable to investigate the influence of the wafer thickness on neighbour wafers with a (relatively) high (induced) material quality. The TiO₂ scenario is used to obtain results on (relatively) poor material quality.

N.B. note that the 330 µm wafers and the 200 µm wafers are not neighbours of each other.

Rear side reflectivity

In order to estimate the internal reflection coefficient of the rear side, screen printed aluminium BSF were made on 50 µm thick mono crystalline double polished wafers using different firing conditions. The reflection curves were measured and subsequently modelled using the Phong model. This model allows to adjust the scattering continuously from perfectly specular to perfectly Lambertian. Phong coefficient and reflection coefficient are intimately coupled. For instance if the rear surface is supposed to be specular, the reflection coefficient must be low, otherwise the modelled reflection will be too high. However, changing the Phong coefficient also changes the optical path length. So the correct pair of Phong coefficient and reflection coefficient can be found by comparison of the calculated and measured reflection in the region where silicon is semitransparent (950 to 1100 nm). This allows to pinpoint the optical properties of the BSF accurately. This model has been used by us in the past to model the optical properties of saw-damage etched multi-crystalline silicon wafers.

The Phong coefficient and the reflection coefficient of the Al rear were supposed to be wavelength independent over the wavelength region of interest. In Figure 4 the results of the modelling is shown. We observe that assuming a more scattering rear surface results in a shift of the sloping part of the calculated reflection curve to higher wavelengths (see insert). The difference between measured and the calculated reflection curve is minimal if an internal reflection coefficient at the rear Al surface of 78 % is assumed. The reflection is mainly diffuse.
with a Phong coefficient of about 2.0 (see Table 6). The rear side reflection was found to be nearly independent (± 1 %) of the firing conditions.

**Table 6: Phong and reflection pairs used in modelling.**

<table>
<thead>
<tr>
<th>Phong constant</th>
<th>reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>73 %</td>
</tr>
<tr>
<td>3.4</td>
<td>75 %</td>
</tr>
<tr>
<td>2.5</td>
<td>77 %</td>
</tr>
<tr>
<td>2</td>
<td>78 %</td>
</tr>
<tr>
<td>1.5</td>
<td>79 %</td>
</tr>
<tr>
<td>0.5</td>
<td>80 %</td>
</tr>
</tbody>
</table>

![Graph showing calculated and measured external reflection for various internal reflectances at the aluminium rear. Insert shows the shift to higher wavelengths if the internal rear reflection increases.](image)

**Figure 4:** Difference between calculated and measured external reflection for various internal reflectances at the aluminium rear. Insert shows the shift to higher wavelengths if the internal rear reflection increases.

**Discussion**

**Wafer thickness and material quality effect on short circuit current Jsc.**

We investigated for both high and low quality base material the influence of the wafer thickness on the solar cell characteristics. In both scenarios $V_{oc}$ and $J_{sc}$ are independent of the wafer thickness for most thicknesses. Only for wafer thickness less than 200 µm in the SiN$_x$ scenario a statistically significant decrease in the short circuit current is observed. The independence of $J_{sc}$ can be explained by the high reflectivity of the aluminium rear metallisation shown above (see Figure 4). For the thinnest wafers in the SiN$_x$ scenario, the reflectivity is too low to prevent some loss in $J_{sc}$.

In Figure 5 the measured and calculated short circuit current for both scenarios are shown. The statistical analysis for the TiO$_2$ scenario indicates that $J_{sc}$ is independent of the wafer thickness.
thickness. However, Figure 5 suggests that in this scenario the spreading in the short circuit current decreases with decreasing wafer thickness. Particularly the lower short circuit currents seem to disappear. This trend has been observed before in large scale experiments also (unpublished results). This can be qualitatively explained by the high internal reflectivity combined with a low effective bulk diffusion length. Due to the low bulk diffusion length, electrons generated near the rear side of the solar cell have a very low probability for collection. Due to the high internal rear reflection, the total generation is hardly reduced by thinning the wafer. But the generation takes place closer to the junction and that will increase the collection probability.

![Figure 5: Scatterplot of Jsc as a function of the wafer thickness for both scenarios. Solid curves calculated using PC1D; SiNx: L_bulk = 350 µm, L_BSF = 0.3 µm, S_front = 1.5·10^5 cm/s, TiO2: L_bulk = 100 µm, L_BSF = 0.35 µm, S_front = 10^7 cm/s.](image)

**Wafer thickness and material quality effect on open circuit voltage Voc.**

The independence of Voc on the wafer thickness results from the relative low quality of the aluminium BSF. Voc is a function of the temperature T, the light generated current J_L (ideally this is equal to Jsc) and the dark saturation current J_0:

\[
V_{oc} = \frac{kT}{q} \ln \left( \frac{J_L}{J_0} + 1 \right)
\]

(4)

The dark saturation current of a silicon device depends on the effective recombination velocities. The contribution of the base to the dark saturation current is given by:

\[
J_{0p} = \frac{qD_ph_i^2}{L_pN_a} * F_p
\]

(5)

With:

\[
F_p = \frac{S_p \cosh(\frac{w_p}{L_p}) + \frac{D_p}{L_p} \sinh(\frac{w_p}{L_p})}{\frac{D_p}{L_p} \cosh(\frac{w_p}{L_p}) + S_p \sinh(\frac{w_p}{L_p})}
\]

(6)
For devices having a BSF, the actual surface recombination velocity $S_p$ has to be replaced by the effective recombination velocity $S_{eff}$. Instead of using the well-known equation established by Godleski, we used $S_{eff}$ estimated by PC1D because of the limitations of the Godleski model. In equation (5), only $F_p$ depends on the wafer thickness. From equation (6) it can be concluded that the influence of the wafer thickness is cancelled out in $F_p$ and $V_{oc}$ is thus independent of the wafer thickness if either:

$$\cosh \left( \frac{W_p}{L_p} \right) = \sinh \left( \frac{W_p}{L_p} \right) \Rightarrow W_p \gg L_p$$  \hspace{1cm} (7)

or:

$$S_{eff} = \frac{D_p}{L_p}$$  \hspace{1cm} (8)

Equation (7) is a general case, equation (8) is a coincidental condition which holds for only 1 value of the minority carrier diffusion length.

To investigate whether the independence of $V_{oc}$ on the wafer thickness results from the bulk diffusion length (equation (7)) or the rear surface passivation (equation (8)), the experimental results have been modelled using PC1D. To obtain a starting point for the modelling of the neighbour solar cells, the minority carrier diffusion length in the bulk, the diffusion length in the BSF and the front surface recombination velocity has been modified by iteration until both the measured IQE, the $J_{sc}$ and the $V_{oc}$ are fitted well by PC1D for the 325 µm thick wafer. In this iteration process, some parameters were fixed on their measured experimental values (see Table 7).

**Table 7: Experimental values used in PC1D calculations.**

<table>
<thead>
<tr>
<th></th>
<th>SiNx scenario</th>
<th>TiO2 scenario</th>
<th>measured by</th>
</tr>
</thead>
<tbody>
<tr>
<td>front metal coverage</td>
<td>9 %</td>
<td>9 %</td>
<td>visual inspection</td>
</tr>
<tr>
<td>emitter peak $[P]$</td>
<td>$1.0 \times 10^{23}$ at $P$/cc</td>
<td>$1.6 \times 10^{23}$ at $P$/cc</td>
<td></td>
</tr>
<tr>
<td>emitter $R_{sheet}$</td>
<td>50 Ω</td>
<td>40 Ω</td>
<td></td>
</tr>
<tr>
<td>emitter profile</td>
<td>error function</td>
<td>error function</td>
<td></td>
</tr>
<tr>
<td>[B] base ($=N_a$)</td>
<td>$1 \times 10^{16}$ at $B$/cc</td>
<td>$1.2 \times 10^{16}$ at B/cc</td>
<td>ECV$^*$</td>
</tr>
<tr>
<td>[B] BSF ($=N_a^-$)</td>
<td>$5 \times 10^{18}$ at $B$/cc</td>
<td>$2 \times 10^{18}$ at B/cc</td>
<td>ECV</td>
</tr>
<tr>
<td>thickness BSF</td>
<td>9 µm</td>
<td>5 µm</td>
<td>ECV</td>
</tr>
<tr>
<td>rear reflection</td>
<td>78 %</td>
<td>78 %</td>
<td>modelling (Figure 4)</td>
</tr>
<tr>
<td>refractive index ARC</td>
<td>2.2</td>
<td>2.3</td>
<td>reflection</td>
</tr>
<tr>
<td>thickness ARC</td>
<td>71 nm</td>
<td>73 nm</td>
<td>reflection</td>
</tr>
<tr>
<td>$D_p$</td>
<td>28.6 cm$^2$/sec</td>
<td>28.0 cm$^2$/sec</td>
<td>calculated from $N_a$</td>
</tr>
</tbody>
</table>

$^*$: Electrochemical Capacitance/Voltage measurement. The base dopant concentration in the TiO2 scenario is based on PC1D modelling. Note that the wafers used in the two scenarios are no neighbours of each other. $D_p$ is used to calculate equation (8).

In Figure 6, the measured and calculated IQE curves for the 325 µm thick wafer processed with the SiNx scenario are shown. To obtain the best fit for this scenario, a minority carrier diffusion length of 350 µm had to be assumed. For the diffusion length in the BSF a value of 0.3 µm has been used and for the front surface recombination a velocity of $1.5 \times 10^7$ cm/s had to be assumed. From PC1D modelling, this is equivalent with an effective rear side recombination velocity of 3500 cm/s. According to equation (8), $V_{oc}$ would be independent of the thickness in this experiment if $S_{eff} = 820$ cm/s. For $S_{eff} < 820$ cm/s, $V_{oc}$ would increase with increasing wafer thickness, for $S_{eff} > 820$ cm/s $V_{oc}$ would decrease (see Figure 7). Also, $W_p < L_p$, so neither the
condition of equation (7) nor the condition of equation (8) is fulfilled. Because $S_{\text{eff}} > 820$ cm/s, the modelling predicts that $V_{oc}$ should decrease with decreasing wafer thickness.

In this work it is experimentally found that $V_{oc}$ is independent of the wafer thickness for wafers thicker than 200 µm. This results from the sensitivity of $V_{oc}$ to $S_{\text{eff}}$ and the wafer thickness in the range of interest. In Figure 7 the sensitivity of $V_{oc}$ to the effective rear surface recombination velocity in the SiN$_x$ scenario is shown. The curves are calculated with PC1D, using the input parameters as given in Table 7. Instead of modelling a BSF, the rear surface recombination velocity is set at the value given in the legend. The figure shows that for $S_{\text{eff}} = 3500$ cm/s, $V_{oc}$ decreases by about 6 mV for a 200 µm wafer compared to a 325 µm thick wafer. Due to the small amount of wafers the observed statistical variation in this experiment is no contradiction to the decrease predicted by the PC1D modelling. On large quantities a slight decrease in $V_{oc}$ should be observed.

![Figure 6](image_url)

**Figure 6:** Internal Quantum Efficiency for 325 µm wafer with SiN$_x$ scenario. Solid curve calculated using PC1D: $L_{\text{bulk}} = 350$ µm; $L_{\text{BSF}} = 0.3$ µm, $S_{\text{front}} = 1.5 \times 10^5$ cm/s.
In Figure 7 the calculated change in $V_{oc}$ as a function of the wafer thickness for various effective rear side recombination velocities. A 325 µm thick wafer is taken as reference.

In Figure 8 the measured and calculated $V_{oc}$ data for both scenarios are shown. For the high quality material (SiN$_x$) PC1D modelling predict a small decrease in $V_{oc}$ with decreasing wafer thickness. However, as can bee seen in the figure, the magnitude of the decrease is within the experimental variations. This confirms that the dependence is not statistically significant in this experiment.

The best fit for the low quality material (TiO$_2$) has been obtained using a minority carrier diffusion length of 100 µm for the bulk and 0.35 µm for the BSF. The front surface recombination velocity was found to be $10^7$ cm/s. In this scenario, the condition given by equation (7) ($L_p << W_p$) is fulfilled. The independence of the wafer thickness on the $V_{oc}$ results from the low material quality of the wafers.
Figure 8: $V_{oc}$ as a function of the wafer thickness for both scenarios. Error bars show 95% confidence limits. Solid curve calculated using PC1D; SiN$_x$: $L_{bulk} = 350$ µm, $L_{BSF} = 0.3$ µm, $S_{front} = 1.5 \cdot 10^5$ cm/s, TiO$_2$: $L_{bulk} = 100$ µm, $L_{BSF} = 0.35$ µm, $S_{front} = 10^5$ cm/s.

In Figure 9 the influence of the wafer thickness on $V_{oc}$ for various material qualities and two rear surface passivation schemes is shown. For Si solar cells with an average rear surface passivation ($S_{eff} = 3500$ cm/s), a decrease in the wafer thickness results in a decrease of the $V_{oc}$. This decrease is biggest for cells with a good bulk quality. Because these cells normally have a higher $V_{oc}$, the modelling predicts that the use of thinner wafers will result in a smaller $V_{oc}$ distribution.

For cells with a good rear surface passivation (e.g. $S_{eff} < 200$ cm/s) an increase in $V_{oc}$ is predicted. For cells with a low material quality which normally have the lowest $V_{oc}$, the increase is less than for cells with a moderate or good material quality. The use of thinner wafers in combination with a good rear surface passivation scheme will broaden the $V_{oc}$ distribution because the increase in $V_{oc}$ is smallest for the wafers with the lowest $V_{oc}$. 

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The reason for the dramatically low diffusion length in the BSF is not yet fully understood. It may result from the quality of the aluminium that is used; it is known that the Al paste contains Fe contamination. Whether this is the main reason, or if stresses induced by the alloy process induce (additional) materials degradation needs further investigation.

**Wafer thickness and material quality effect on efficiency.**

The results indicate that for the presently used Al BSF rear side passivation scheme $J_{sc}$ is independent of the wafer thickness for wafers thicker than 200 µm for both high and low quality material. The spreading in $J_{sc}$ will probably decrease due to an expected increase in $J_{sc}$ for very low quality material. Within experimental error a slight decrease in $V_{oc}$ can be expected for the high quality material on an industrial scale, resulting in a slight decreased variation of $V_{oc}$.

In this work we observed a significant influence of the wafer thickness on the fill factor. However, in our opinion this is because the firing conditions used were not fully optimised for the various wafer thickness. We have no indications that the fill factor is influenced by the thickness assuming optimum firing conditions are used. Therefore the decreased variation in both $J_{sc}$ and $V_{oc}$ result in a smaller efficiency distribution for thinner wafers in large scale experiments where optical firing conditions will be used.

In Figure 10 the efficiency is shown as a function of the wafer thickness for both scenarios together with some PC1D calculations. To extract the influence of the fill factor on the efficiencies, a FF of 0.75 is used in this figure to calculate the efficiencies. The high recombination velocity is a limiting factor to the solar cell efficiency. As an example, the efficiencies are calculated assuming a rear side recombination velocity of only 200 cm/s. Such recombination velocities can be obtained using a well passivating SiN$_x$ coating 14, 15, 16 or by using B-doped Al paste to increase the doping level of the alloy 17. This would increase the efficiency of the high quality wafers by about 1 to 1.5 % absolute, the increase for the poor quality wafers would be negligible for the thick wafers and...
increase to about 0.5 % for the 150 µm thin wafers. The efficiency distribution would thus increase dramatically. This will probably mean that such rear surface passivating processing sequences must be combined with bulk passivating or gettering processing sequences in a production environment.

To obtain the indicated efficiency gains the high internal reflectance of the device has to be maintained.

![Graph showing efficiency vs. thickness for various rear side passivation schemes on high (SiNx) and low (TiO2) quality material.](image)

**Figure 10:** Influence of thickness on efficiency for various rear side passivation schemes on high (SiNx) and low (TiO2) quality material.

**Conclusion**

For both the high and low quality material, the efficiency of mc-Si solar cells is practically independent of the thickness for wafer thickness larger than 200 µm. For thinner wafers, the efficiency of the cells with a high bulk quality decreases while it is still constant for the cells with a low bulk quality. On a large quantity of cells, it is expected that a small significant decrease in $V_{oc}$ will be observed. However, the $V_{oc}$ distribution might be somewhat narrower. The low minority carrier diffusion length in the Al-BSF results in a high effective surface recombination velocity which prohibits the expected increase in the $V_{oc}$ for thinner wafers.

The unexpected independence of $J_{sc}$ on the wafer thickness is attributed to a high internal reflection at the rear side Al for the cells with a high quality material. Because of the internal reflection the current loss is minimised. For cells with a poor bulk quality, an increase in $J_{sc}$ is expected, resulting in a narrower distribution in $J_{sc}$ as for $V_{oc}$. The experimental results indicate that the need for additional light trapping only becomes important for wafer thickness less that 200 µm.

From this work it can be concluded that for the used back surface passivation scheme, the use of thinner wafers will not reduce the average solar cell efficiency. The efficiency distribution will be narrowed. This shows that, providing that the overall production yield is not reduced, thinner wafers can assist in lowering the cost of PV. PC1D calculations indicate that major
Improvements in solar cell performance can be realised if other rear surface passivation schemes are applied, but these schemes may result in a broadening of the efficiency distribution.

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**References**
