EFFECT OF WAFER THICKNESS ON THE PERFORMANCE OF mc-Si SOLAR CELLS

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ABSTRACT: 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. It was found experimentally that η is nearly independent of the wafer thickness. J_{sc} is nearly independent of the thickness due to a high internal reflectivity of the Al rear metallisation. A decrease in J_{sc} is observed only if the wafer thickness becomes less than about 200 µm. The weak dependence of V_{oc} on the wafer thickness was well within experimental error in this investigation.
From PC1D modelling it is concluded that η is limited by the rear surface passivation of the commonly used Al-BSF. Alternative rear surface passivation schemes should increase the solar cell performance significantly, but this has not yet been confirmed experimentally.
Keywords: c-Si - 1: Si Wafer Thickness - 2: Back-Surface-Field - 3.

1. INTRODUCTION

It is generally accepted that in order for PV to become of major importance as a renewable energy source the cost of photovoltaic conversion has to be reduced [1]. For crystalline silicon wafer technology, the silicon material is a major cost item [2]. 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 when process yield and cell efficiency are not affected.

In this work we studied the influence of the wafer thickness on the electrical properties of the mc-Si solar cells. The number of wafers processed is too small to investigate the process yield.

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

The significance of the influence of the wafer thickness on the solar cell characteristics was investigated using statistical analysis. Results have been modelled with PC1D.

2. EXPERIMENTAL SET-UP

Sets of silicon wafers have been processed using standard industrial techniques. Each set consisted initially of eight 10×10 cm^2 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. During wafer fabrication, handling or cell processing, several wafers broke.

First the wafers were given an NaOH saw damage etch, which removed about 25 µm of the wafer. Then a 50 Ω/ emitter was made by phosphorus diffusion in a belt furnace. After removal of the phosphorus glass using HF, a SiN_x anti reflection coating (ARC) was applied with a remote microwave plasma enhanced CVD (R-MW-PECVD) system [3]. Finally the front side (Ag) and rear side (Al) metallisation was applied by screen printing and fired in a single step using an infra-red heated belt furnace. The firing conditions needed to be adjusted for the different wafer thickness. However, the firing conditions were not fully optimised. In Figure 1 the process sequence is shown.

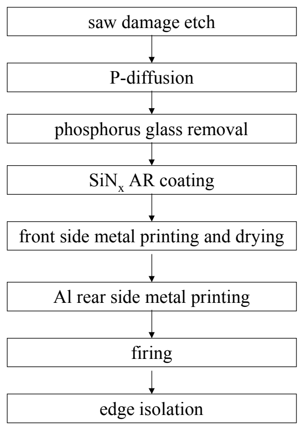

Figure 1: Applied process sequence; firing conditions varied slightly with wafer thickness.

We measured the IV characteristics of all cells, while the reflectance, the spectral response and the ECV-profile was measured on selected cells. The statistical analysis has been performed using the program Statgraphics Plus version 5 [4], while the device modelling was done with PC1D version 4.5 [5].

Weeber and Sinke [6] have shown the importance to use a two factor analysis of variance to determine the significance of observed trends. The influence of the thickness is significant if the difference in cell result *y* is greater then the *least significant difference* LSD. In formula from:

$$\left|\bar{y}_{i.} - \bar{y}_{k.}\right| > LSD;\; LSD = t_{\alpha/2,(a-1)(b-1)}\sqrt{2MS_{error}/b} \quad (1)$$

$t_{\alpha/2,((a-1)(b-1)}$ is a statistical factor (t-statistics) and depends on the confidence limit (95 % in this article) and the degrees of freedom. The value of t can be found in standard books on statistics. *a* and *b* are the number of groups and the number of wafers per group respectively. MS_{error} is the mean square of the overall random error term. It not only depends on the variance of the results of the solar cells with thickness *i* or *k*, but also on the variance of the results of the other solar cells. MS_{error} is also used to calculate the 95 % confidence limits in Table 1. The confidence limit is not the standard deviation within the group, but is calculated as $\pm t_{\alpha/2,ab-a}\sqrt{MS_{error}/b}$.

A more detailed discussion of the statistical method is given by Montgomery [7]. In our case the calculations are complicated because values are missing. During wafer production and cell processing wafers broke; for thinner wafers more breakage occurred. The method to compensate for those missing values is described by Montgomery [7].

3. 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 trends.

In Table 1 the mean values of the main electrical parameters of the solar cells are given. Within the 95 % confidence limit both J_{sc} and V_{oc} are independent of the thickness for wafers thicker than 200 µm. For thinner wafers the decrease in J_{sc} becomes statistically significant.

Table 1: Cell results of neighbour cells with varying thickness Errors show 95 % confidence limit.

W µm	J_{sc} mA/cm²	V_{oc} mV	FF %	η %
325	30.2 ± 0.2	601 ± 2	74 ± 1	13.5 ± 0.2
300	29.8 ± 0.2	601 ± 2	74 ± 1	13.3 ± 0.2
275	30.2 ± 0.2	602 ± 2	73 ± 1	13.3 ± 0.2
250	30.0 ± 0.2	601 ± 2	74 ± 1	13.4 ± 0.2
225	29.9 ± 0.2	602 ± 2	75 ± 1	13.4 ± 0.2
200	29.7 ± 0.2	600 ± 2	75 ± 1	13.3 ± 0.2
175	29.3 ± 0.2	599 ± 2	73 ± 1	12.9 ± 0.2
150	29.1 ± 02	597 ± 3	71 ± 1	12.4 ± 0.2

4. DISCUSSION

4.1 Effect of wafer thickness on J_{sc}.

For thin wafers light trapping is important to increase the optical path length. Therefore, the internal reflectance at the rear side of the solar cell is an important parameter. We experimentally determined that the internal reflectivity at the Al rear of the solar cell is approximately 80 % and nearly fully diffuse (see Figure 2 [8]).

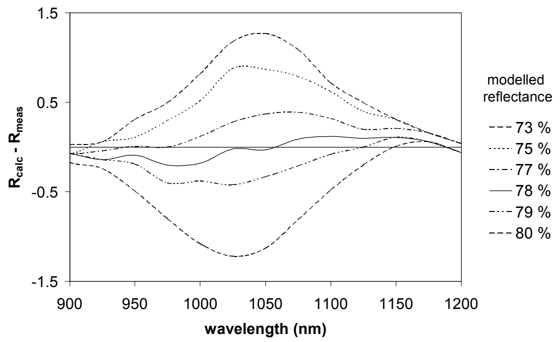

Figure 2: Difference between calculated and measured external front side reflection. Curves are given for various internal reflectance at the Al rear.

V_{oc} and J_{sc} are independent of the wafer thickness for most thicknesses. Only for wafer thickness less than 200 µm 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. For the thinnest wafers the reflectivity is too low to prevent some loss in J_{sc}.

Because of the high reflectivity the spreading in the short circuit current may decrease for thinner wafers. In cells with a low bulk diffusion length electrons generated near the rear side of the cell have a very low probability for collection. Due to the high internal rear reflection, the total generation is barely reduced in thinner wafers. The generation is closer to the junction, so the collection probability will increase. This trend, a smaller current distribution combined with a slight increase of the average current, is observed in large scale experiments.

4.2 Effect of wafer thickness on V_{oc}.

The independence of V_{oc} on the wafer thickness results from the relatively low quality of the aluminium BSF. V_{oc} is a function of the temperature T, the light generated current J_L (ideally this is equal to J_{sc}) and the dark saturation current J_0:

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{J_L}{J_0} + 1\right) \quad (2)$$

The dark saturation current of a silicon device depends on the effective recombination velocities of the BSF. The contribution of the base to the dark saturation current is [9]:

$$J_{0p} = \frac{qD_p n_i^2}{L_p N_a} * F_p \quad (3)$$

With:

$$F_p = \frac{S_p \cosh\left(\frac{W_p}{L_p}\right) + \frac{D_p}{L_p} \sinh\left(\frac{W_p}{L_p}\right)}{\frac{D_p}{L_p} \cosh\left(\frac{W_p}{L_p}\right) + S_p \sinh\left(\frac{W_p}{L_p}\right)} \quad (4)$$

For devices having a BSF, the actual surface recombination velocity S_p has to be replaced by the effective recombination velocity S_{eff}. We estimated S_{eff} using PC1D. In equation (3), only F_p depends on the wafer thickness. From equation (4) it can be concluded that the influence of the wafer thickness is cancelled out in F_p when

$$\cosh\left(\frac{W_p}{L_p}\right) = \sinh\left(\frac{W_p}{L_p}\right) \Rightarrow W_p >> L_p \quad (5)$$

or:

$$S_{eff} = \frac{D_p}{L_p} \quad (6)$$

In these two cases V_{oc} is independent of the thickness W.

Equation (5) is a general case, equation (6) is a coincidental condition which holds for only a single 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 (5)) or the rear surface passivation (equation (6)), the experimental results have been modelled using PC1D. To obtain a starting point for the modelling of the neighbouring solar cells, the minority carrier diffusion length in the bulk, the diffusion length in the BSF and the front surface recombination velocity have 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 2).

Table 2: Experimental values used in PC1D calculations.

	value	measured by
front metal coverage	9 %	visually
[B] base (=N_a)	$1\cdot10^{16}$ at B / cc	ECV*
[B] BSF (=N_a^+)	$5\cdot10^{18}$ at B / cc	ECV
thickness BSF	9 µm	ECV
rear reflection	78 %	modelling
refractive index ARC	2.2	reflection
thickness ARC	71 nm	reflection
D_p	28.6 cm^2 / sec	calculated

*: Electrochemical Capacitance/Voltage measurement
D_p is used to calculate equation (6)

In Figure 3 the measured and calculated IQE curves for the 325 µm thick wafer are shown. To obtain the best fit for this thickness a minority carrier diffusion length of 350 µm in the bulk and a minority carrier diffusion length of 0.3 µm in the BSF had to be assumed. Note that the minority carrier diffusion length in the BSF is much less than the thickness of the BSF. For the front surface recombination a velocity of $1.5.10^5$ cm/s had to be assumed. From PC1D modelling, the effect of the BSF is equivalent with an effective rear side recombination velocity of about 3500 cm/s. According to equation (6), 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 4). Also, $W_p < L_p$, so neither the condition of equation (5) nor the condition of equation (6) is fulfilled. Because S_{eff} > 820 cm/s, the modelling predicts that V_{oc} should decrease with decreasing the 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_{eff} and the wafer thickness in the range of interest. In Figure 4 the sensitivity of V_{oc} to the effective rear surface recombination velocity is shown. The curves are calculated with PC1D, using the input parameters as given in Table 2. Instead of modelling a BSF, the rear surface recombination velocity is set at the value given in the legend. Figure 4 shows that for S_{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 not in contradiction with the decrease predicted by the PC1D modelling. On large quantities a slight decrease in V_{oc} is expected.

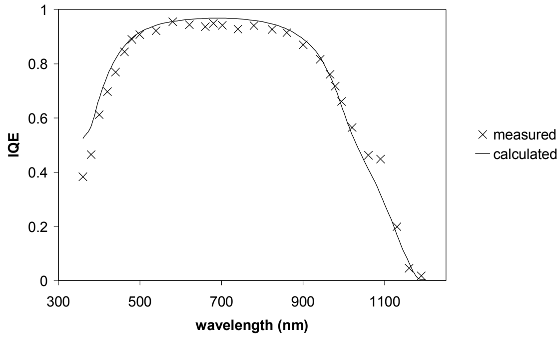

Figure 3: IQE data for 325 µm wafer. Solid curve calculated using PC1D: L_{bulk} = 350 µm; L_{BSF} = 0.3 µm, $S_{front} = 1.5.10^5$ cm/s.

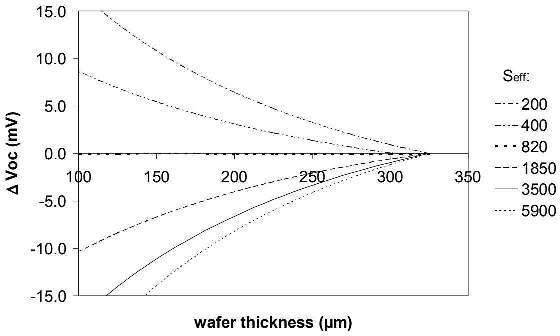

Figure 4: Calculated change in V_{oc} as a function of the wafer thickness for various effective rear side recombination velocities. 325 µm thick wafer is taken as reference.

In Figure 5 the measured and calculated J_{sc} and V_{oc} data are shown. The PC1D calculations predict a small decrease in V_{oc} with decreasing wafer thickness. However, as can be seen in the figure, the magnitude of the decrease is within the experimental error. This confirms that the dependence is not statistically significant in this experiment.

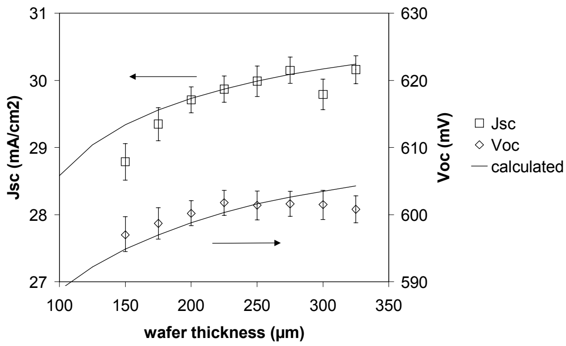

Figure 5: J_{sc} and V_{oc} as a function of the wafer thickness. Error bars show 95 % confidence limits. Solid curve calculated using PC1D: L_{bulk} = 350 µm, L_{BSF} = 0.3 µm, $S_{front} = 1.5.10^5$ cm/s.

To fit the measured data using PC1D a very short diffusion length in the BSF had to be assumed. The reason for this low diffusion length in the BSF is not yet fully understood. To investigate if the deterioration of the diffusion length in the BSF results from impurities in the Al-paste used, we made cells using high purity sputtered Al for the BSF. Here also we found a comparable decrease in the diffusion length of the BSF.

4.3 Effect of wafer thickness on efficiency.

In Figure 6 the efficiency is shown as a function of the wafer thickness together with some PC1D calculations. Due to small variations in the processing, the FF of the solar cell varies. To eliminate this influence a FF of 0.75 is used to calculate the efficiencies. The high recombination velocity at the rear side 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 [10, 11], a high quality highly doped Al BSF [12] or by using B-doped Al paste to increase the doping level of the alloy [13]. This would increase the efficiency by about 1.6 % absolute.

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

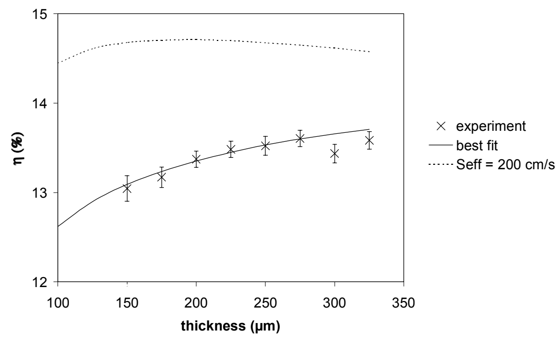

Figure 6: Influence of thickness on efficiency for various rear side passivation schemes.

To decrease the effective recombination velocity of the rear surface, we used boron doped Al paste to increase de dopant level of the BSF which decreas. ECV measurements reveal that the addition of a small amount of boron does increase the dopant concentration in the BSF without influencing the thickness of the BSF (see Figure 7). Despite this we observed a slight (but not significant) decrease in V_{oc} and thus we don't see an improvement of the BSF action. Surprisingly, we observed a significant 2 % decrease in the short circuit current. From PC1D modelling we assume that this results from a decrease in the rear side reflectivity.

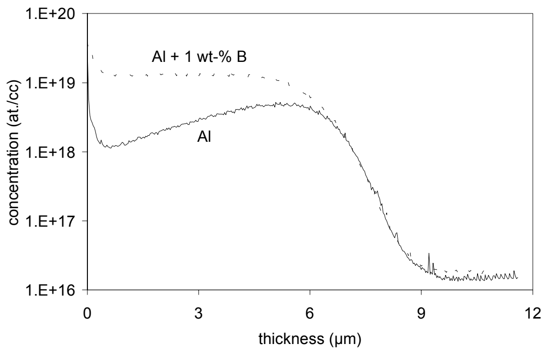

Figure 7: Dopant concentration of BSF made with and without boron addition to the Al-paste

5. CONCLUSION

The efficiency of mc-Si solar cells is nearly 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. On a large quantity of cells, it is expected that a small but significant decrease in V_{oc} will be observed. The low minority carrier diffusion length in the Al-BSF results in a high effective surface recombination velocity. This prevents 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 of the cells. Because of the internal reflection the current loss is minimised. Due to the high rear side internal reflectivity an increase in J_{sc} is expected for cells with a low material quality resulting in a narrowing of the distribution of both J_{sc} and V_{oc}. To prevent a decrease in J_{sc} improved rear reflectance is necessary for wafers thinner than 200 µm.

From this work it can be concluded that for the used rear 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 be an important contribution to lower the cost of PV. PC1D calculations indicate that major improvements in solar cell performance can be realised if better rear surface passivation schemes are applied, but these schemes may result in a broadening of the efficiency distribution.

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