

HIGH-QUALITY mc-Si WAFERS FOR HIGH-EFFICIENCY SOLAR CELLS

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ABSTRACT: High purity feedstock was used by ScanWafer to make high-quality mc-Si wafers. These wafers were characterized in detail by ECN and UKON. The initial lifetime of minority carriers over the ingot varied from about 10 to about 100 μ s. The interstitial oxygen and substitutional carbon concentrations are below 10 ppma and that low concentration will hardly affect the lifetime in the material and the solar cell output. Standard firing-through SiN_x:H cell processing resulted in efficiencies from 15 to 16%. Advanced in-line processing resulted in an maximum efficiency of 16.5%. The lifetime after cell processing was 75-150 μ s. Modelling shows that this lifetime hardly limits the efficiency and efficiencies above 17% are possible.

Keywords: multicrystalline Si, high-efficiency, lifetime

1. INTRODUCTION

Solar cell efficiencies need to be increased significantly to reach multicrystalline silicon (mc-Si) PV technology at 1 €/Wp costs. This can only be achieved if high-quality mc-Si wafers become available, and an appropriate high efficiency and industrially feasible processing sequence can be developed. In this study, a first batch of wafers produced from high-quality Si feedstock material is characterized in detail. Lifetime and impurity concentrations were measured and related to solar cell parameters. The results are quantified with respect to the cell results and improvements to make 17% solar cells are identified.

2. EXPERIMENTAL

The production of multicrystalline silicon wafers can be divided into two steps: casting and cutting. The process to make the special wafers started with placing highly pure silicon in special melting furnaces. The feedstock used for this ingot was virgin high-quality Si feedstock. The silicon was then gradually cooled through a controlled process and silicon crystals were formed. The result was a large block of crystallised silicon, also called an ingot. The ingot is cut into 125×125 mm² bricks by a band saw. An efficient wire saw, cut the bricks' hard material into wafers with a thickness of about 300 μ m.

Impurity concentrations were measured using selected wafers over the height of the ingot. The concentration of interstitial oxygen [O_i] and substitutional carbon [C_s] were measured with Fourier Transform Infrared (FTIR) spectroscopy. The concentrations were determined according to the method of Kirshnan et al. [1]. Lifetime measurements were carried out using the Quasi Steady State Photoconductivity (QSSPC) method [2] at an injection level of 10¹⁵ cm⁻³ where both surfaces of the wafers were passivated with SiN_x:H. The concentration of interstitial iron [Fe_i] can be determined from the lifetime before and after illumination according to McDonald et al. [3]. The specific resistivity was determined from the sheet resistivity of the wafers.

Solar cells were processed using a standard industrial firing through SiN_x:H process as presented in **Table 1** or an advanced in-line process as is shown in **Table 2**.

Current-voltage (IV) measurements were performed for characterization and PC-1D 5.5 [4] was used to model the obtained solar cells and to analyse the efficiency potential of the mc-Si material.

Light Beam Induced Current (LBIC) mapping with a wavelength of 980 nm was performed to determine the homogeneity of the cell quality.

The Internal Quantum Efficiency (IQE) was calculated from the spectral response and reflection.

To analyse the efficiency potential of the material PC-1D5.5 was used for modelling.

Table 1: Industrial baseline solar cell processing on 125×125 mm² multicrystalline wafers.

Industrial solar cell processing sequence	
1.	Alkaline saw damage removal
2.	45 Ω /sq POCl ₃ emitter
3.	SiN _x :H deposition with parallel plate PECVD system
4.	Screen-printing of the Ag front and Al rear side metallization
5.	Simultaneous firing of the front and rear side metallization using an infrared heated belt furnace
6.	Edge isolation

Table 2: Advanced inline solar cell processing on 125×125 mm² multicrystalline wafers.

Advanced in-line solar cell processing sequence	
1.	Acidic etch for saw damage removal and texturing
2.	60 Ω /sq spin-on emitter and infrared heated belt furnace diffusion
3.	SiN _x :H deposition with MicroWave PECVD system
4.	Screen-printing of the Ag front and Al rear side metallization
5.	Simultaneous firing of the front and rear side metallization using an infrared heated belt furnace
6.	Edge isolation
7.	Deposition of MgF ₂ coating

3. RESULTS

3.1 Material quality

The specific resistivity of wafers from bricks as a function of the height in the ingot can be seen in **Figure 1**. The specific resistivity varies from 1.6 Ωcm in the bottom to 1.0 Ωcm in the top of the ingot. These resistivities correspond to dopant concentrations of $9 \cdot 10^{15} \text{ B/cm}^3$ and $1.5 \cdot 10^{16} \text{ B/cm}^3$ respectively. B1, B2 and B3 are adjacent bricks in the ingot and it can be seen that the dopant concentration is constant over the width of the ingot.

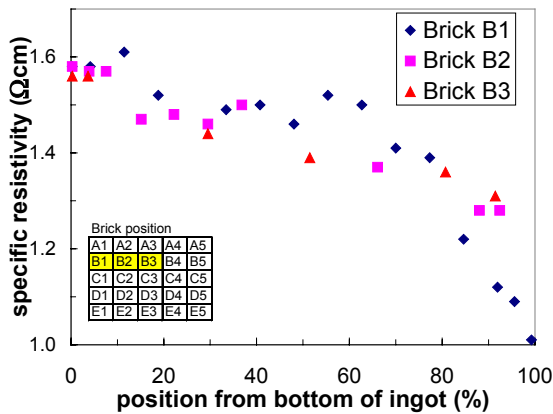


Figure 1: Position dependent bulk resistivity for 3 adjacent bricks in an ingot. The insert shows the position of the bricks in the ingot.

Figure 2 shows typical $[O_i]$ and $[C_s]$ related to the position in the ingot. It can be seen that $[O_i]$ decreases from about 7 ppma at the bottom to 1-2 ppma at the top. $[C_s]$ increases from 4-5 ppma at the bottom to 8-9 ppma at the top.

The interstitial iron concentration $[Fe_i]$ can be calculated from the lifetimes measured before and after 3 minutes illumination. During illumination FeB pairs dissociate and result in a higher lifetime because the dissociated iron is a less active recombination centre [5,6] at the used injection level. Both lifetimes and the interstitial iron concentration $[Fe_i]$, calculated from these lifetimes, are presented in **Figure 3**. The initial lifetime is above 40 μs for about 80% of the ingot, after illumination it is above 100 μs . $[Fe_i]$ is below $1 \cdot 10^{12} \text{ at./cm}^3$ for about 90% of the ingot.

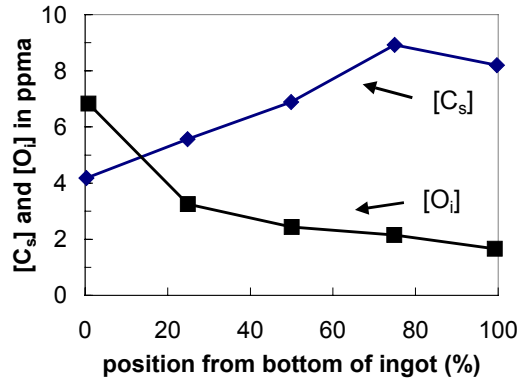


Figure 2: Typical concentrations of substitutional carbon and interstitial oxygen as a function of the position in the ingot.

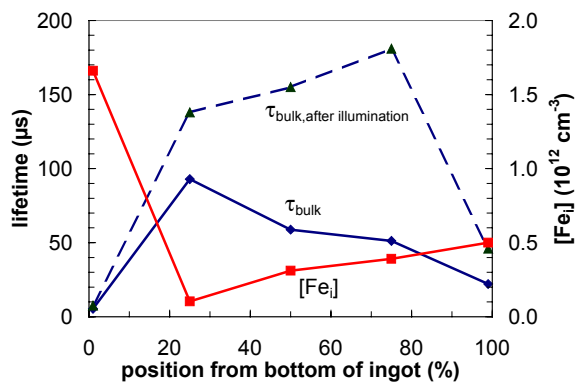


Figure 3: Position dependent bulk lifetime and interstitial iron concentration.

3.2 Solar cell results

In **Figure 4**, **Figure 5** and **Figure 6** short-circuit current J_{SC} , open-circuit voltage V_{OC} and efficiency η as a function of the height in the ingot is depicted. Standard processing was performed according to **Table 1**. The efficiency of the cells is more or less constant over the ingot and between 15 and 16%. Processing according to **Table 2** results in a 16.5% efficient solar cell ($V_{OC}=611 \text{ mV}$, $J_{SC}=35.2 \text{ mA/cm}^2$, $FF=77.2\%$).

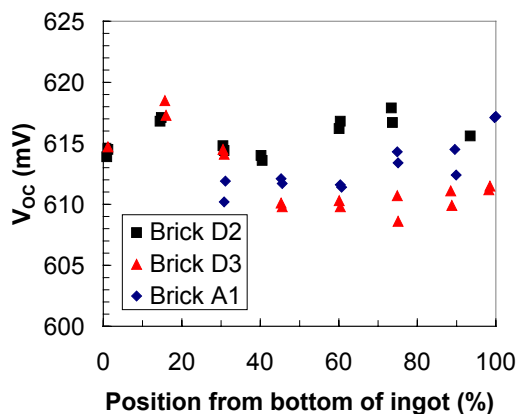
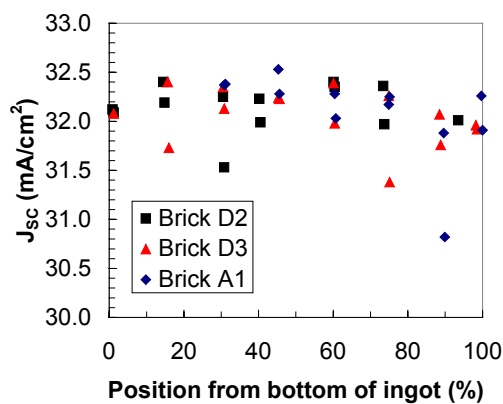
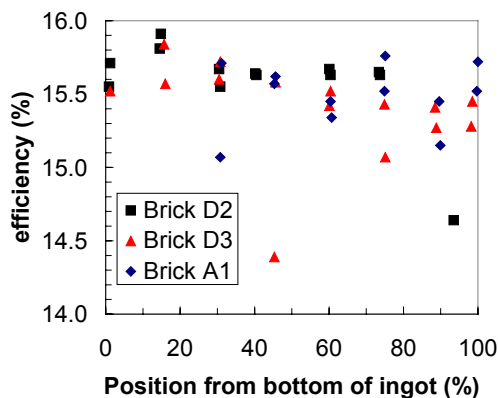
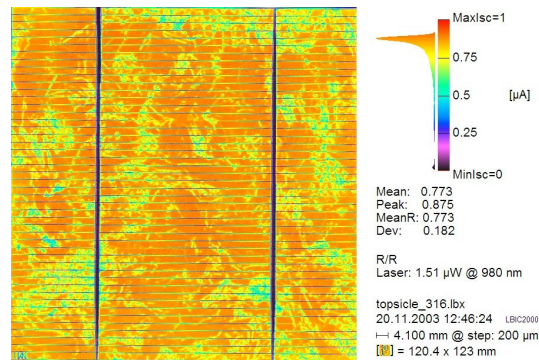

 Figure 4: V_{OC} dependent on the position in the ingot.

 Figure 5: J_{SC} dependent on the position in the ingot.


Figure 6: Efficiency dependent on the position in the ingot.

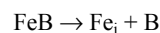
The homogeneity of the cell quality is determined with LBIC. It can be seen from **Figure 7** that the homogeneity is good. A clear peak in the histogram of IQEs at the yellow-red area is visible.


 Figure 7: LBIC map of a cell processed with a standard baseline process (**Table 1**). It is from brick D2 near the top of the ingot.

4. DISCUSSION

From the above results it can be seen that the material quality of the batch of high-quality material is good. The oxygen and carbon concentrations are low enough so that they hardly affect the cell output [7,8]. The initial lifetime τ is above $40 \mu\text{s}$, which corresponds to a diffusion length of more than $300 \mu\text{m}$. In the central part of the ingot τ varies from 50 to $90 \mu\text{s}$, which corresponds to diffusion lengths of 400 to $500 \mu\text{m}$.

The lifetime after illumination is higher than before because of the dissociation of FeB pairs:



where Fe_i represents a dissociated interstitial iron atom. This Fe_i is less active as a recombination centre at the used injection level for lifetime measurements [5,6]. After dissociation of the FeB pairs lifetimes of about $150 \mu\text{s}$ were measured in the centre of the ingot. This lifetime corresponds to a diffusion length of $700 \mu\text{m}$, more than twice the thickness of the cell.

During emitter diffusion Fe will be gettered [9,10] and the lifetime measured after illumination can be seen as an estimate for the lifetime after gettering. This means that for most of the ingot the lifetime is above $50 \mu\text{s}$. Only near the bottom the ingot the measured lifetime seems to be much lower. However, this lower measured lifetime does not correlate with the cell output, which is similar to the other cells from the ingot. Probably this is due to an artefact in measuring the lifetime after FeB dissociation for wafers with low lifetime.

To determine potential efficiency improvements the IV and IQE are 'fitted' using PC-1D. **Figure 8** shows the modelled and measured IQE of a cell processed according to **Table 2**, but then with a single layer antireflection coating. The IQEs between wavelengths 800 and 1000 nm are determined by bulk lifetime τ_{bulk} and rear side surface recombination velocity S_{rear} . These two parameters are highly correlated, and a better τ_{bulk} combined with a higher S_{rear} results in a comparable fit as a lower τ_{bulk} combined with a lower S_{rear} . The best fits were obtained with bulk lifetimes between 75 and $150 \mu\text{s}$ combined with a rear side surface recombination velocity S_{rear} between 300 and 600 cm/s respectively. The lifetimes correspond to values that

are measured. A lifetime of 150 μs does not really limit the efficiency. An infinite lifetime will only improve the efficiency with about 0.2% absolute.

IQEs around 1100 nm determine internal reflection at the rear R_{rear} . The fitted R_{rear} is 60% and is relatively low. In previous experiments [11] reflections of 76-78% were measured.

IQEs for wavelengths shorter than 500 nm are determined by the emitter quality and passivating properties of $\text{SiN}_x\text{:H}$. All effects dealing with a non-perfect emitter (like a dead layer) and with absorption in $\text{SiN}_x\text{:H}$ are included in the effective front surface recombination velocity S_{front} . This means that the presented value of $1.5 \cdot 10^5 \text{ cm/s}$ is an overestimate of the actual value.

Table 3 shows the parameters that were obtained from the PC-1D fit. Improved values for the parameters, which are achieved in other studies, are also presented and used as input for PC-1D simulations. It is shown that implementation of processes that result in the improved parameters will obtain 17% mc-Si solar cells.

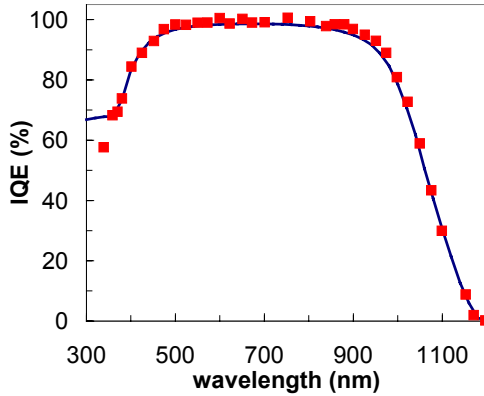


Figure 8: Measured and fitted IQE for a cell processed according to **Table 2**.

Table 3: Fitted cell parameters and foreseen improvements and the effect on the solar cell output parameters calculated with PC-1D.

	fitted	impr.		output	impr.
τ_{bulk} (μs)	75-150	150	Voc (mV)	610	622
R_{rear} (%)	60	75	Jsc (mA/cm^2)	34.4	35.6
S_{rear} (cm/s)	300-600	200	FF	0.761	0.770
S_{front} (cm/s)	$1.5 \cdot 10^5$	$1.0 \cdot 10^5$	η (%)	16.0	17.1
J_{02} (nA/cm^2)	100	60			

5. CONCLUSIONS

The batch of high-quality mc-Si material from ScanWafer is as good as the best commercially available. 16% solar cells can be made from that material. Furthermore the homogeneity in material quality is very good. There is hardly any variation in cell output over the ingot (both top to bottom and laterally). The homogeneity within a single wafer is also good.

The oxygen and carbon concentration are below 10 ppm and will hardly affect the cell parameters. The interstitial iron concentration is below 10^{12} cm^{-3} and should even improve after gettering. All these parameters result in a lifetime above 40-50 μs before processing. Cell processing results in efficiencies around 16% and a τ_{bulk} up to 150 μs , which does not limit the efficiency anymore. Further improvements on material quality that result in a stable 150 μs lifetime all over the ingot and improvements in processing, based on previous achieved results, should result in average cell efficiencies of more than 17%.

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