P-TYPE MULTICRYSTALLINE-SI SOLAR CELLS USING BLENDED SOLSILC SILICON

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ABSTRACT: Blends of polycrystalline and SOLSILC silicon in multicrystalline p-type ingots were tested by solar cell processing. By comparing IV-parameters and Internal Quantum Efficiency of cells from p-type multicrystalline cells it was concluded that a minor cell performance reduction can be attributed to impurities. This can be significantly improved by emitter optimization or an extra cleaning step. In this manner, a cell efficiency of 16.4% was obtained for both 25% blend and reference.

1 INTRODUCTION

Use of Upgraded Metallurgical Grade silicon (UMG) can lower the cost per Wp of silicon solar cells. Therefore, there is much interest in processing solar cells from UMG feedstock.

The development of "SOLSILC" silicon, the material discussed in this work, is an R&D collaboration of Fesil Sunergy, SINTEF, ScanArc and ECN. The "SOLSILC" route is a low cost route to produce solar grade silicon (SoG-Si), using a production route that resembles UMG-Si production. Here, a mixture of high purity quartz, carbon black and SiC pellets is converted to liquid silicon in an arc furnace. Dedicated quality control and optimization of the composition of the raw materials is of major importance, ensuring a high yield and high quality SoG-Si silion.

The first purpose of this work is to compare p-type multicrystalline cells produced from 2 different blends of SOLSILC and polysilicon feedstock to a clean polysilicon reference. Additionally, several options to diminish the differences between the two are explored.

2 EXPERIMENTAL

Directionally solidified cast multicrystalline silicon ingots were grown from two different blends of electronic-grade polysilicon and SOLSILC silicon, with blending ratio's of SOLSILC to poly of 10% and 25%, respectively. Wafers from the resulting ingots were processed into cells and compared to reference cells from identically grown ingots using 100% high-purity polysilicon.

All of the tested ingots, were grown in a labscale 12kg Crystalox furnace. For ingot growth on a larger scale, improvement of the crystal quality, and therefore a larger minority carrier lifetime in the resulting material, is expected.

Also, the material described in this paper, is from a SOLSILC run in June, 2007. Material from more recent runs in 2009 has already demonstrated large quality improvement by raw materials control, but this has not yet been tested in a solar cell device.

Dopants were added to arrive at 1-2 Ohm cm resistivity. However, due to a large underestimation of the dopant concentrations by the chemical analysis technique of the input material, slightly lower output resistivities (Fig. 1) than expected were obtained. The solar cells were made with processes that are representative for industrial production (Table I). Additionally, some possibilities of process optimizations were explored, using different emitter diffusion profiles and an extra cleaning step. In these optimizations, sets of neighboring wafers were selected from the same 4 ingot positions for all three ingots.

Two of the diffusion processes that are referred to in this paper are non-industrial processes including a few hrs. long drive-in step. These will be referred to as "emitter 1" and "emitter 2". "Emitter 3" refers to a close-to-industrial process with a short drive-in. In The cells were analyzed by I-V and internal quantum efficiency.

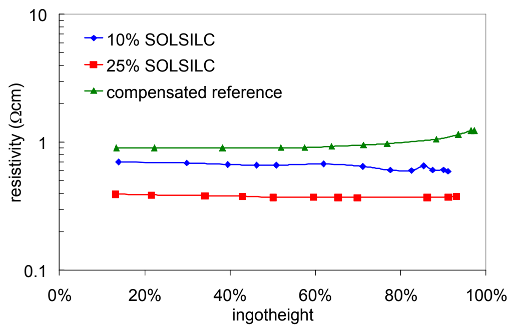


Figure 1: Resistivity profiles of the multicrystalline ingots measured by inductively coupled coil measurements.

3 RESULTS AND DISCUSSION

Solar cells were made from wafers with a lower bulk resistivity than the reference, 0.7, 0.4 and 1.0 Ohm cm for the 10% blend, 25% blend and reference, respectively. In general, low resistivity causes a decrease of J_{SC} and an increase of the V_{OC}, due to increased bulk recombination that is associated with a higher dopant density and a higher built-in voltage. These trends are also recognizable in the J_{SC} and V_{OC} plots in Figs. 3a and 3b. However on efficiency level, the positive effect in V_{OC} and the related increase in FF, almost cancel out the J_{SC} reduction. Most likely, the efficiency results of SOLSILC blended Si are limited by the impurities in the material.

The choice of emitter process can result in an increase in the J_{SC}. In Figs. 3 and 4, the red squares represent the results of the tests using the industrial process. Other data are results of process optimizations, using 3 different types of emitters, with and without an additional clean after the emitter step. One of the tested emitter profiles, emitter 3,

results in a less steep slope of the trendline through the dataset as compared to the other emitters. This is an indication of recombination reduction, possibly due to improved gettering. For the other emitters, the slope is steeper, but the total trend shifts up to higher values of J_{SC} for all three ingots. This is an indication that the cell process is improved, but that the cell performance relative to the reference did not improve, since it also increases the reference.
The extra cleans for emitters 1 and 2, also have a minor impact on the slope, but increase the J_{SC}. A potential disadvantage of the extra clean steps is that they will negatively influence the FF. For emitter 2, this leads to a lower efficiency than expected based on $J_{SC} \times V_{OC}$. Therefore, emitter 2 without clean gives the best results on SOLSILC material, 16.4% efficiency for all three ingots (Table III).

Table I: p-type solar cell process.

isotexture and pre-treatment
Emitter P-diffusion
P-glass removal (+ additional clean)
µw-PECVD SiN_x ARC front
Screen print of Ag front metal (H-pattern)
Screen print of Al rear metal (Full)
Cofiring

Table II: Sheet resistances of adapted process steps.

emitter diffusion process	sheet resistance (Ohm sq)
industrial emitter	58.6 ±1.7
emitter 1	78.8 ±1.3
emitter 2	87.2 ±1.8
emitter 3	66.7 ±1.2
emitter 1 + clean	92.7 ±2.4
emitter 2 + clean	105.0 ±3.3

In these graphs it is hard to separate the reduction of J_{SC} due to lower resistivity from that due to impurities in SOLSILC silicon. Nevertheless, there are some ways to gather information on the presence of impurities. A low resistivity cannot be reduced by gettering. Moreover, when the reduction of J_{SC} follows a segregation-like profile throughout the ingot, which means that it is nearly stable in the bottom and increases dramatically in the top, this trend cannot be explained by changes in resistivity, since the resistivity profile is relatively flat in these ingots.

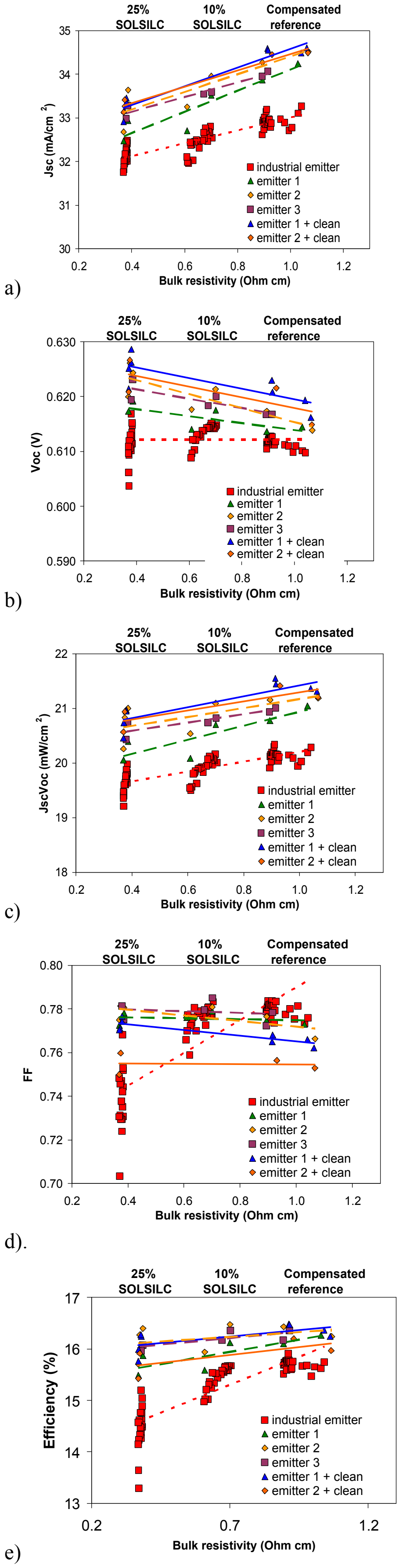


Figure 4: FF and efficiency for p-type multi crystalline cells. The lines are linear fits through the data.

Table III: Best cell results for emitter 2 in the bottom of the ingot.

	J_{SC} (mA/cm^2)	FF	Efficiency (%)	J_{SC}×V_{OC} (mW/cm^2)	V_{OC} (mV)
10% blend	34.0	0.78	16.5	21.1	621
25% blend	33.6	0.78	16.4	21.0	624
reference	34.3	0.78	16.4	21.2	617

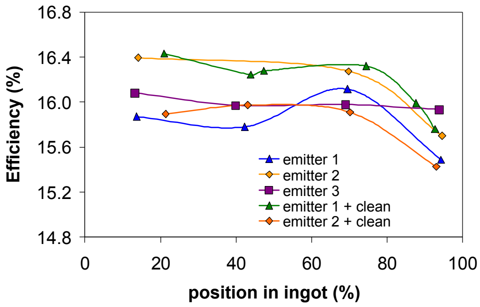


Figure 5: Conversion efficiency of the blended ingot with 25% SOLSILC Si against position in the ingot for all 5 optimized processes. The wafer positions refer to the full height of the ingot (including bottom and top pieces that are usually cut off).

In Fig. 5 it is demonstrated that for all of the optimized emitter processes, the efficiency decreases by about 4% relative in the top. This indicates that there are impurities present that segregate to the top. For emitter 3, the efficiency profile is constant over the ingot height, which suggests that this diffusion process causes efficient gettering. This segregation trend is also clearly visible for both blended ingots in the relative IQE vs. ingot height (Fig. 6) where the red response drops significantly towards the top. Such a drop cannot be explained by the resistivity profile which is about constant as a function of ingot height.

The relative IQE results from Fig. 6. are taken relative to reference cells that were processed with the same process and taken from comparable ingot heights. In this way, the effects from overall process improvements, due to the emitter choice, and effects from the casting, by in-diffusion of impurities from the crucible in the bottom and solid state back diffusion in the top, can be excluded from the interpretation.

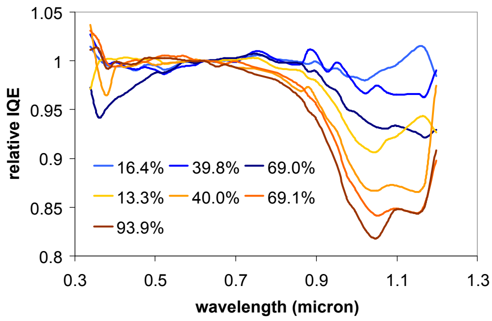
In Fig. 6b the relative IQE profiles for different emitters, with and without an additional clean, are presented. These IQE profiles were measured on neighboring cells, taken from ~90% ingot height of the 25% blend ingot. The gettering effectiveness of P-diffusion can be deduced from the decrease in long wavelength (>0.8 µm) response of the tested cell compared to a reference made from clean polysilicon. A less reduced red response for a certain emitter choice is an indication of more effective gettering of impurities, although also here other effects might play a role.

The results in Fig. 6b can be divided in 3 groups based on their reduction of red response. The industrial emitter and emitter process 3 give the best result, followed by emitters 1 and 2 in combination with an additional cleaning step. Emitter processes 1 and 2 are the least effective in gettering the impurities, their relative decrease in red response at 1.1 micron is about 10% larger than for emitter 3.

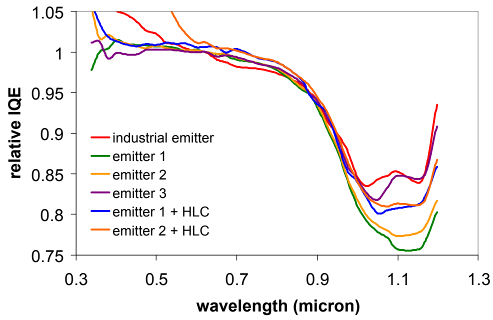
5 CONCLUSIONS

Blends of polycrystalline and SOLSILC silicon were tested in multicrystalline p-type ingots with two blending ratio's of 10% and 25% SOLSILC Si. By comparing IV- and IQE results of cells from different ingot positions and blends, it was concluded that there is a minor cell performance reduction due to impurities. However, for a large part of the ingot this can be minimized by optimization of the emitter step of the industrial type cell process.

The difference between the multicrystalline blends and the reference increases gradually towards the top of the ingot, which indicates segregation of impurities and leads to ~4% relative efficiency loss above 90% ingot height. However, by optimization of the emitter and/or adding an extra cleaning step, approximately equal, high cell efficiencies of 16.4%, 16.5% and 16.4% for the 25% blend, 10% blend and reference, respectively, could be achieved in the bottom of the ingot.



a)



b)

Figure 6: IQE profiles relative to cells from comparable heights of the reference ingot. a) ingot height dependence for the 10% (blue) and 25% (yellow/brown) SOLSILC blends, processed with emitter 3 (and no clean). b) different emitters with and without extra cleaning step.

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