

ANALYSIS OF MULTICRYSTALLINE SOLAR CELLS FROM SOLAR GRADE SILICON FEEDSTOCK

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ABSTRACT

The paper focuses on the analysis of solar cells from the newly developed solar grade silicon (SoG-Si) feedstock from a metallurgical process route. The emphasis of our experiments was to define an industrial solar cell process to achieve efficiencies higher than $\eta=16\%$ on multicrystalline wafers containing a significant amount of the SoG-Si. The material was prepared as multicrystalline ingots by directional solidification and wafered by conventional wire saw technique. We demonstrate efficiencies higher than 16% on several wafers of 156cm^2 size with an industrial process sequence from batches containing 25% and 65% Elkem SoG-Si feedstock. The new feedstock under investigation will enable the mass PV production and opens the route for cost reductions in the PV-industry.

INTRODUCTION

This work focuses on the analysis of solar cells from the newly developed solar grade silicon feedstock from a metallurgical process route, referred to as SoG-Si in this paper, which has been a long-term strategic goal for Elkem, the main supplier to the poly-Si industry. The new feedstock under investigation will enable the mass PV production and opens the route for cost reductions in the PV-industry, as the investment cost for an industrial scale feedstock production plant is expected to be significantly reduced compared to the investment for a comparable production plant based on silane or trichlorosilane technology. Likewise, the operating cost is expected to be comparably low. The energy payback period is dominated by the energy used to purify and crystallize the base silicon. Therefore the low energy consumption of the metallurgical process route is another favorable factor which will result in shorter energy recovery time for the resulting PV installations. Fig 1 illustrates the accumulated energy production of two hypothetical advanced silicon wafer solar modules with $\eta=16\%$ and $\eta=15,5\%$ efficiency respectively. The $\eta=16\%$ module is thought to be from electronic grade silicon (EG-Si) with an assumed energy recovery time of four years. The energy consumption for a future metallurgical refining plant is calculated to be in the range 25-30 kWh/kg and the energy payback time could accordingly be reduced to two years or

less, if minimum 65% SoG-Si feedstock is used for the production of the module. The example demonstrates that even with a 0,5% lower efficiency the SoG-Si module would produce about 7% more energy during his life (25 years). However, in this work we demonstrate, that solar cell performances on multicrystalline wafers from 65% SoG-Si feedstock close to those out of EG-Si are achievable. We show, that only slight process variations are necessary to adapt the industrial process steps to the material. We compare results on a 16% efficiency level achieved on multicrystalline wafers from 25% and 65% Elkem SoG-Si feedstock blended with EG-Si.

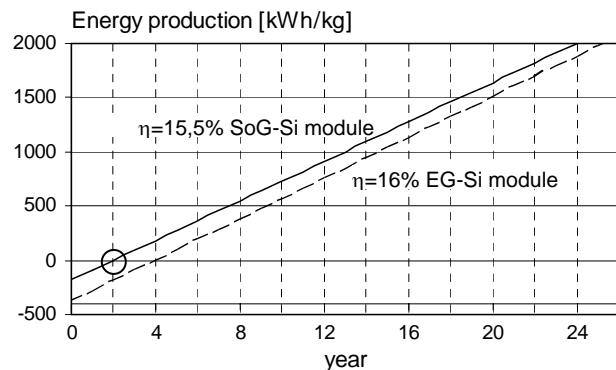


Fig 1: Accumulated energy production of two silicon wafer solar modules, one from EG-Si and one from 65% SoG-Si. The SoG-Si module would produce about 7% more energy during 25 years operation due to its shorter energy payback time of two years compared to four years in case of the EG-Si module. Further assumptions are: Wafer thickness including kerf loss: $450\mu\text{m}$; ingot yield: 80%; wafering, cell and module manufacturing yield: 80%; annual energy earning: $950\text{kWh}/\text{kW}_p$ (central Europe).

SoG-Si TECHNOLOGY

The SoG-Si technology has been reported in [1,2]. As illustrated in Fig 2, commercial metallurgical grade silicon melt from Elkem's electric arc furnace was treated with a special slag, casted, crushed and later leached with suitable leach liquors to remove impurities. The resulting solar grade silicon crystals are melted and further refined before crushing and sizing to suit ingot preparation in the following step.

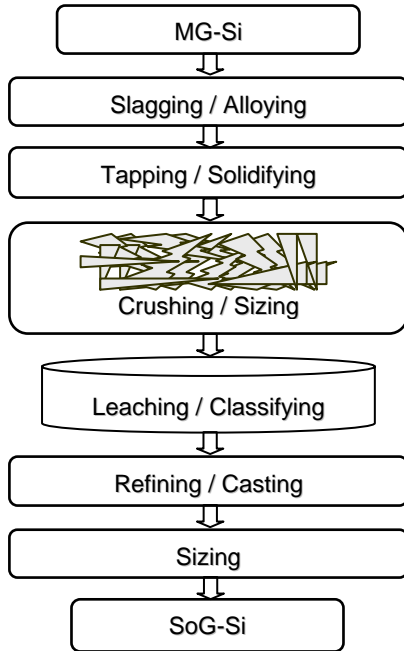


Fig 2. Process sequence from metallurgical to solar grade silicon

SOLAR CELL PROCESS

The applied solar cell process is shown in Fig 3. Two different batches of silicon feedstock have been analyzed: (a) 25% of Elkem's SoG-Si, blended with 75% EG-Si and (b) 65% Elkem SoG-Si with 35% EG-Si respectively.

All solar cells reported here were fabricated on 156cm² multicrystalline wafers of 250-300µm thickness. Process steps 2-4 were carried out at the University of Konstanz (UKN). The as-cut wafers were treated by chemical iso-texturisation (HNO₃, HF) for saw damage etch and light trapping. The porous layer was removed by KOH, followed by further cleaning in HCl, dionised water and HF-dip. This texturisation was carried out in a RENA pilot inline wet bench. The result was a funnel like texture of the silicon surface with an etch hole size of 1-10µm (Fig 4). The resulting light trapping is very effective for this material, having a bulk resistivity of 0.8-1 Ωcm. POCl₃ emitter diffusion resulted in 50-55 Ω/sq. In case of the 65% SoG-Si, the wafers stayed in the POCl₃ tube for an additional hour at moderate temperature to improve the phosphorous getter effect. Passivation and metallisation was carried out in a conventional way by PECVD-SiN_x deposition, full Al BSF and firing through in a belt furnace.

Further solar cells have been processed in a commercial cell line for ingot yield demonstration and for comparison with 100% EG-Si multicrystalline reference wafer material.

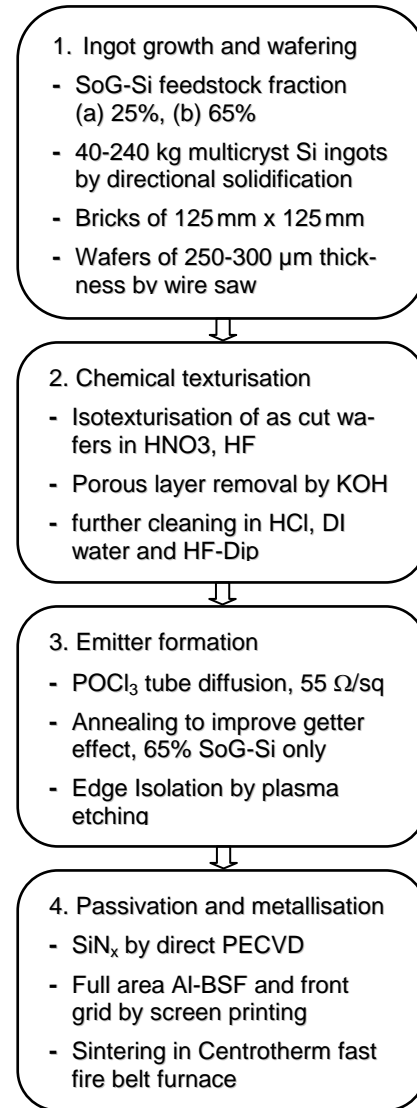


Fig 3. Flow chart of industrial like solar cell process

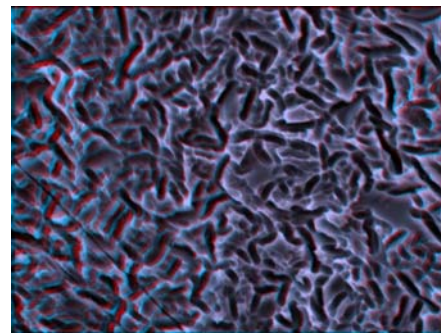


Fig 4. Surface of an iso-texturized multicrystalline SoG-Si wafer

RESULTS AND DISCUSSION

The multicrystalline Si blocks were characterized using wafers from bottom to top through the ingots. In the following we compare solar cell results reached on the 25% and the 65% SoG-Si materials and a 100% EG-Si ingot as a control.

Results on 25% SoG-Si

Initial results on feedstock with a weight fraction of 25% were achieved in a standard industry solar cell line. We used EG silicon wafers of same size and thickness as control and the data are presented in Fig 5. The efficiency distributions for both blocks were roughly comparable to each other, indicating that this SoG-Si material is suitable for PV and that the yield is as usual.

To investigate if higher efficiencies can be reached, the advanced cell process described above was applied to a few wafers from the centre region. The resulting efficiency increase is mainly due to the iso-texturisation, which works very effective on the 0,9 Ωcm wafer material under investigation. The efficiency results are included in Fig 5, whereas the other solar cell parameters are shown in Table 1. Both, the best cell and the average of 8 cells were over $\eta=16\%$ at standard conditions (AM1.5, 25°C).

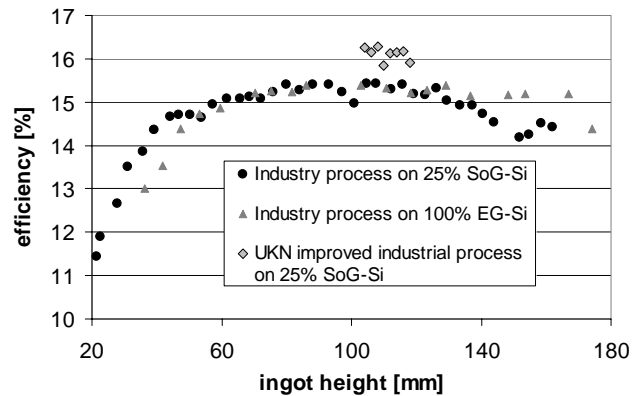


Fig 5. Cell efficiency distribution through a brick from bottom to top achieved on feedstock from 25% SoG-Si and a brick from 100% EG-Si as a control.

Table 1. Best and average cell results achieved on the 25% SoG-Si feedstock with a standard industry process and a more advanced industrial applicable process at the University of Konstanz (UKN). The wafer resistivity was about $\rho=0,9 \Omega\text{cm}$

Results 25% SoG-Si	J_{sc} [mA cm^{-2}]	V_{oc} [mV]	FF [%]	η [%]
	Standard industry process (39 cells)			
best cell	32.1	618.0	77.8	15.4
average	30.9	609.7	77.3	14.6
	UKN improved process (8 cells)			
best cell	33.7	622.3	77.6	16.3
average	33.4	621.4	77.6	16.1

Results on 65% SoG-Si

The next run aimed to reach the same efficiency level ($\eta=16\%$) on wafers containing a significant higher amount of Elkem's SoG-Si feedstock. We chose a weight fraction of 65% SoG-Si and 35% EG-Si respectively. The ingots resulted in a average bulk resistivity about 0,8 Ωcm and again the wafers were processed in a commercial solar cell line and compared with the wafers from EG-Si as shown in Fig 6.

Again our improved process revealed higher efficiencies and therefore demonstrates, that the material can be used for advanced solar cell concepts. This time the improvement was not only due to the iso-texturisation. The wafers were exposed to extended phosphorous gettering as described in the next chapter and the aluminium alloying process at the rear was optimized to achieve an optimal BSF and Al getter effect. As shown in Fig 6, wafers from different ingot positions between bottom and top were used in the advanced process and the efficiency improvement as compared to the standard process was most significant for the lower and central part of the ingot. Table 2 shows the average and best value parameters. The improved process revealed $\eta=16.3\%$ for the best cell while the average is limited to $\eta=15.6\%$ because cells from the lower and higher part are included.

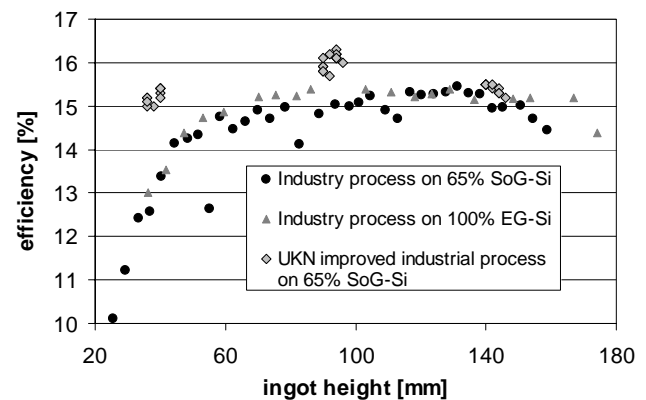


Fig 6. Cell efficiency distribution through a brick from bottom to top achieved on feedstock from 65% SoG-Si. The same controls from Fig 5, 100% EG-Si, are included.

Table 2. Best and average cell results achieved on the 65% SoG-Si feedstock with a standard industry process and a more advanced industrial applicable process at the University of Konstanz (UKN). The wafer resistivity was about $\rho=0,8 \Omega\text{cm}$

Results 65% SoG-Si	J_{sc} [mA cm^{-2}]	V_{oc} [mV]	FF [%]	η [%]
	Standard industry process (36 cells)			
best cell	32.0	620.6	77.1	15.3
average	30.9	612.9	75.5	14.3
	UKN improved process (35 cells)			
best cell	33.7	626.7	77.0	16.3
average	33.1	620.8	75.9	15.6

A phosphorous getter analysis

The wafers from 65% SoG-Si were exposed to extended phosphorous gettering after POCl_3 emitter diffusion. Before unloading they remained in the process tube for additional 60 minutes at N_2 atmosphere and 700°C . The influence of this treatment on the minority carrier lifetime was measured by microwave induced photoconductive decay measurements ($\mu\text{-PCD}$). For this investigation two sister wafers from a center ingot position were undertaken the POCl_3 diffusion one with and one without the additional gettering step. We mapped two regions of $40\text{ mm} \times 40\text{ mm}$ on the wafers, whereas region 1 was in the middle and region 2 close to the edge of the wafers. The mapping resolution was 1 mm and the average lifetime results are illustrated in Fig 7. The wafer exposed to the longer getter time shows a clear lifetime improvement in both regions.

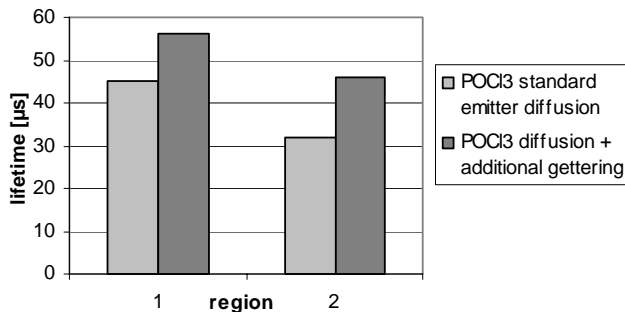


Fig 7. Phosphorous getter analysis quantified with $\mu\text{-PCD}$ lifetime measurement technique. Region 1 is located in the middle of the investigated sister wafers whereas region 2 lies closer to the ingot edge.

Internal quantum efficiency

As described above we reached the same efficiency levels on the 25% and the 65% SoG-Si wafers. Here in addition we demonstrate, that the spectral response is equivalent in both cases. Fig 8 shows the measured internal quantum efficiency on two solar cells with about $\eta=16\%$. The fitted effective diffusion lengths around $400\text{ }\mu\text{m}$ are in the range of those from commercial high quality multi-crystalline silicon wafers.

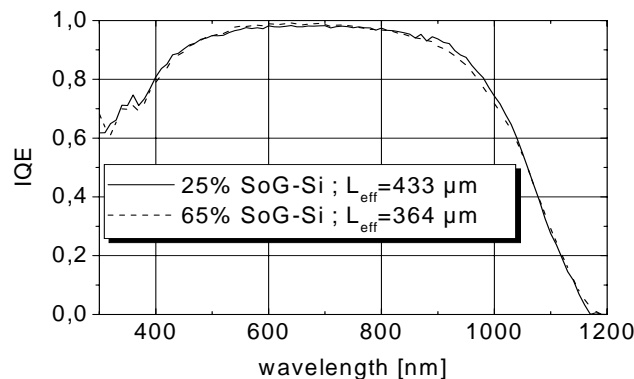


Fig 8. Internal quantum efficiency of two $\eta=16\%$ cells from 25% and 65% SoG-Si feedstock

CONCLUSIONS

It is demonstrated that in case of 65% SoG-Si the same efficiency level is achievable as for the 25% SoG-Si wafers, if the solar cell process parameters are carefully adapted to the material. Efficiencies higher than 16% have been reached in both cases on several wafers with industrial process steps. It is confirmed that the SoG-Si from metallurgical route is clearly competitive to other PV grade silicon sources.

The chemical isotropic texturisation is of high relevance for the investigated SoG-Si. The method is already implemented in advanced cell lines and other cell manufactures will follow. The longer POCl_3 diffusion time could create higher cost (max $0.05\text{ US\$/Wp}$), but it is still not investigated, if a shorter getter time will lead to the same results. SiN_x deposition by direct PECVD needs only slight deposition time adaptation, depending on wafer resistivity. Optimal Al alloying and gettering is achievable by process parameter adaptations without additional cost.

Elkem intends to produce the SoG-Si feedstock in pilot scale and will have the possibility to produce an annual amount of several thousand tons in full scale at a later stage.

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