

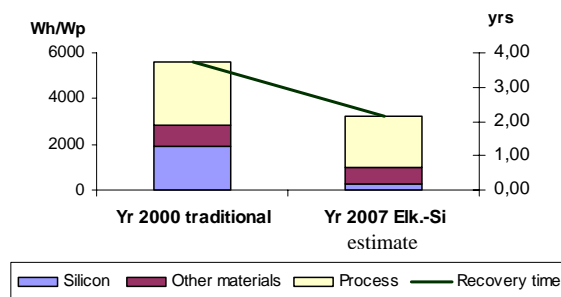
## INVESTIGATION OF MULTICRYSTALLINE SILICON SOLAR CELLS FROM SOLAR GRADE SILICON FEEDSTOCK

K. Peter<sup>1</sup>, E. Enebakk<sup>2</sup>, K. Friestad<sup>2</sup>, R. Tronstad<sup>2</sup>, C. Dethloff<sup>2</sup>  
<sup>1</sup>University of Konstanz, Department of Physics, D-78457, Germany  
 email: kristian.peter@uni-konstanz.de  
<sup>2</sup>Elkem Solar AS, Fiskaaveien 100, N-4675 Kristiansand, Norway

**ABSTRACT:** The paper focuses on the analysis of solar cells from the newly developed solar grade silicon feedstock (Elkem-Si) 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 multi-crystalline wafers containing a significant amount of the Elkem-Si. The material was prepared as multi-crystalline ingots by directional solidification and wafered by conventional wire saw technique. We demonstrate efficiencies higher than 16% on several wafers of 156cm<sup>2</sup> size with an industrial process sequence from batches containing 25% to 100% Elkem-Si feedstock. The new feedstock under investigation will enable the mass PV production and opens the route for cost reductions in the PV-industry.  
**Keywords:** Silicon, Solar Grade, Multi-Crystalline

### 1 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 Elkem-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 dedicated feedstock volumes for PV-industry and opens the route for cost reductions and mass production of PV-modules. 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 an additional favorable factor which will result in shorter energy recovery time for the resulting PV installations. Figure 1 illustrates the energy consumption and energy recovery time for the production of a multi-crystalline silicon solar cell module of 15% efficiency.



Source: K. Knapp, T. Jester 2000 [1] / Elkem Solar analysis


**Figure 1:** Energy consumption (Wh/Wp) and energy recovery time (yrs) for the production of a multi-crystalline silicon solar cell module of 15% efficiency in year 2000 and estimate for year 2007 with 100% Elkem-Si. Assumptions are 1700 kWh/m<sup>2</sup>/yr, Wafer thickness reduced from 330  $\mu\text{m}$  to 230  $\mu\text{m}$ , other materials and process energy consumption reduced by 20%.

The energy consumption for a future metallurgical refining plant is calculated to be in the range of 25 kWh/kg and the energy payback time could accordingly be reduced to two years or less, if 100% Elkem feedstock is used for the production of the module. A module from Elkem-Si will produce at least 5% more energy during its life (25 years) as compared to the modules out of electronic grade silicon (EG-Si).

In this work we demonstrate, 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 multi-crystalline wafers from 25%, 65%, 75% Elkem-Si feedstock blended with EG-Si and 100% Elkem-Si feedstock.

### 2 ELKEM SOLAR SILICON TECHNOLOGY

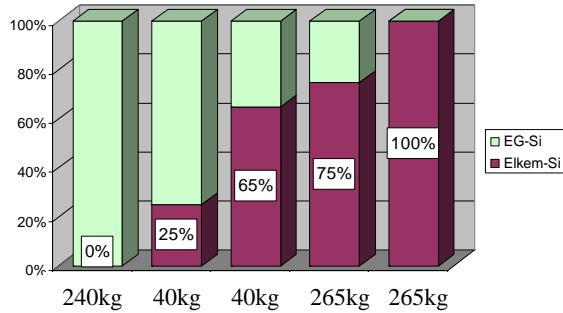
The SoG-Si technology has been reported in [2-4]. As illustrated in Figure 2, commercial metallurgical grade silicon melt from Elkem's electric arc furnace was treated with pyro- and hydro-metallurgical refining processes including slag treatment, alloying and leaching. The resulting solar grade silicon crystals are melted and further refined before crushing and sizing to suit ingot preparation in the following step.

Process step	Description
<b>Elkem Silicon Metal</b>	- Elkem Silicon Globally largest supplier
<b>Pyro-metallurgical refining</b>	- Energy efficient refining
<b>Hydro-metallurgical refining</b>	- Run in industrial scale today (Silgrain <sup>®</sup> )
<b>Final polishing</b>	- Adapting material to customer specific.
	- Process exclusively designed for PV Solar manufacturers

**Figure 2:** Metallurgical refining process

### 3 SOLAR CELL PROCESS

Multi-crystalline ingots, bricks and wafers have been manufactured at industrial partner. Five different batches of silicon feedstock were analyzed, which contained different amounts of Elkem-Si, up to 100%, blended with EG-Si accordingly. The ingot weights and compositions are illustrated in Figure 3.



**Figure 3:** Ingot compositions used for this investigation

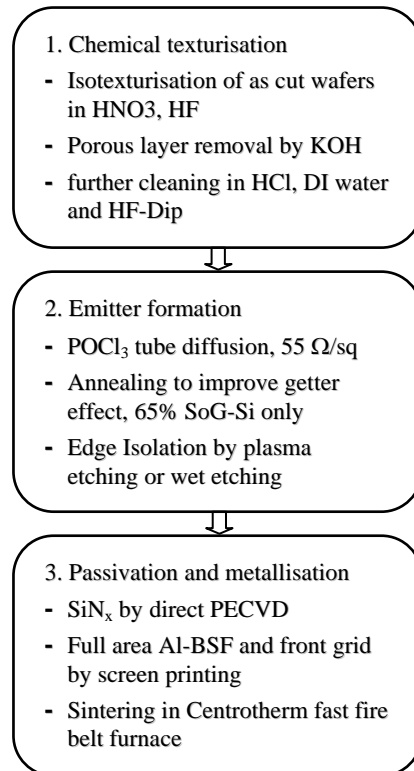
The applied solar cell process is shown in Figure 4. All solar cells reported here were fabricated on 156cm<sup>2</sup> multi-crystalline wafers of 220-280μm thickness. The cell process steps 1-3 were carried out at the University of Konstanz. The as-cut wafers were treated by chemical iso-texturisation (HNO<sub>3</sub>, HF) for saw damage etch and light trapping. The porous layer was removed by KOH, followed by further cleaning in HCl, deionized water and HF-dip. This texturization 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 (Figure 5). The resulting light trapping is very effective for this material, having a bulk resistivity of about 0.8 Ω-cm. POCl<sub>3</sub> emitter diffusion resulted in 50-60 Ω/sq. In the case of the 65% Elkem-Si, the wafers stayed in the POCl<sub>3</sub> tube for an additional hour at moderate temperature to improve the phosphorous getter effect.

To separate the emitter from the rear, edge isolation was achieved either by plasma etching (25% and 65% ingots) or removal of the n<sup>+</sup> layer by single sided etching in the inline wet etch bench (75%, 100%, and Ref. ingots). Passivation and metallization was carried out in a conventional way by PECVD-SiN<sub>x</sub> deposition, full Al BSF and firing through in a belt furnace.

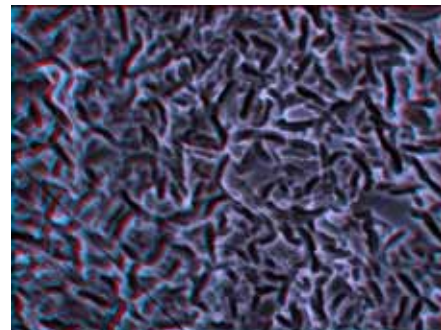
Further solar cells have been processed in a commercial cell line for ingot yield demonstration and for comparison with 100% EG-Si multi-crystalline reference wafer material. The results will be published separately.

### 3 RESULTS AND DISCUSSION

The multi-crystalline 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%, the 65%, the 75% and the 100% Elkem-Si feedstock and a 100% EG-Si ingot as a control.



**Figure 4:** Flow chart of industrial like solar cell process



**Figure 5:** Surface of an iso-texturized multicrystalline Elkem-Si wafer. The result was a funnel like texture of the silicon surface with an etch hole size of 1-10μm.

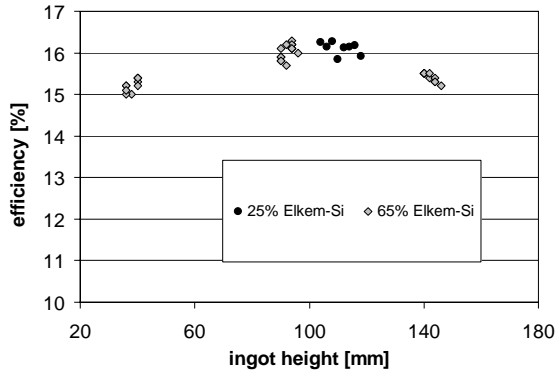
#### 3.1 Results on 25% Elkem-Si

Initial results on Elkem-Si with a weight fraction of 25% were achieved in a standard industry solar cell line. The results ( $\eta \sim 15\%$ ) are presented in [3]. To investigate if higher efficiencies can be reached, the advanced cell process described above was applied to a few wafers of 280 μm thickness from the centre region. The resulting efficiency increase is mainly due to the iso-texturisation, which works very effective on the 0.9 Ω-cm wafer material of this ingot under investigation. The achieved solar cell parameters are shown in Fig. 6 and Table I. Both, the best cell and the average of 8 cells were over  $\eta = 16\%$  at standard conditions (AM1.5, 25°C).

### 3.2 Results on 65% Elkem-Si

The next run aimed to reach the same efficiency level ( $\eta=16\%$ ) on wafers containing a significantly higher amount of Elkem-Si feedstock. We chose a weight fraction of 65% Elkem-Si and 35% EG-Si respectively. The ingots resulted in an average bulk resistivity of about  $0.8 \Omega\text{-cm}$ . Wafers of about  $280 \mu\text{m}$  thickness were used.

Again, our improved process revealed high 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 isotexturisation. The wafers were exposed to extended phosphorous gettering as described in the next chapter and the aluminum 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. Table I 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.



**Figure 6:** Solar cell efficiencies dependent on wafer position in the brick from bottom to top achieved on feedstock from 25% and 65% Elkem-Si respectively.

Results Elk.-Si	$J_{sc}$ [ $\text{mA cm}^{-2}$ ]	$V_{oc}$ [mV]	FF [%]	$\eta$ [%]
<b>25% Elkem-Si (8 cells, 270<math>\mu\text{m}</math>)</b>				
best cell	33.7	622.3	77.6	<b>16.3</b>
average	33.4	621.4	77.6	16.1
<b>65% Elkem-Si (35 cells, 270<math>\mu\text{m}</math>)</b>				
best cell	33.7	626.7	77.0	<b>16.3</b>
average	33.1	620.8	75.9	15.6
<b>75% Elkem-Si (10 cells, 225<math>\mu\text{m}</math>)</b>				
best cell	33.8	624.4	77.6	<b>16.4</b>
average	34.0	622.2	75.1	15.9
<b>100% Elkem-Si (10 cells, 225<math>\mu\text{m}</math>)</b>				
best cell	33.4	623.7	77.1	<b>16.1</b>
average	33.7	623.4	74.8	15.7

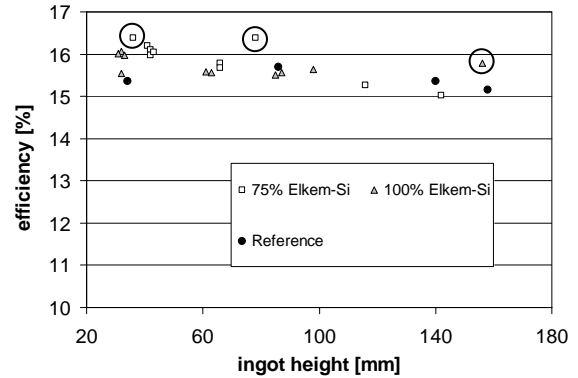
**Table I:** Best and average cell results achieved on the different grades of Elkem-Si feedstock with an advanced industrial applicable process at the University of Konstanz. The wafer resistivities were  $\rho=0.7\text{-}0.9 \Omega\text{-cm}$ .

### 3.3 Results on 75% and 100% Elkem-Si

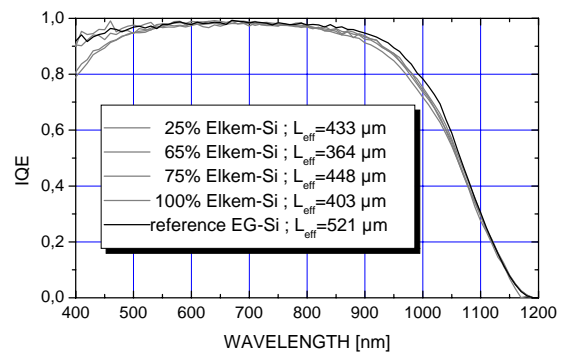
The last investigation so far targeted the proof of 75% and 100% Elkem-Si in the solar cell process. As thinner wafers are now state of the art in PV industry we choose wafer of about  $230 \mu\text{m}$  thickness and references (EG-Si) of same thickness for comparison. The resistivity of the wafers was in the range  $0.75\text{-}0.85 \Omega\text{-cm}$  for the Elkem-Si and about  $1.5 \Omega\text{-cm}$  for the reference. The cell results are plotted in Fig 7. The screen printing resulted in disconnections of the front contact fingers, therefore only results with  $\text{FF}>73\%$  are shown. The references and cells indicated with circles were additionally plated with Ag at the front contact because of the weak grid.

As thin wafers are more sensitive to the surface passivation we applied a more shallow emitter with sheet resistivity of  $58 \Omega/\text{sq}$  leading to a higher blue response as compared to cells from 25% and 65% Elk.-Si ( $52 \Omega/\text{sq}$ ), see Figure 8. With this approach we could maintain the voltage  $V_{oc}$  at above  $620 \text{mV}$  even for the thinner wafers.

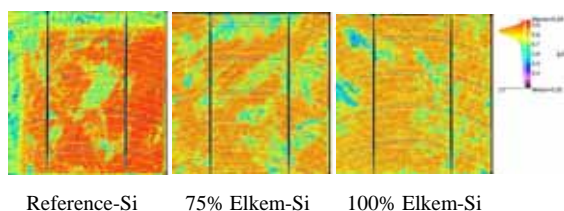
LBIC mappings (Fig 9) demonstrate slightly higher currents for the reference due to the higher resistivity.



**Figure 7:** Solar cell efficiencies dependent on wafer position in the brick from bottom to top achieved on feedstock from 75% and 100% Elkem-Si and reference EG-Si respectively. The references and cells indicated with circles were additionally plated at the front contact because of the relatively weak grid.



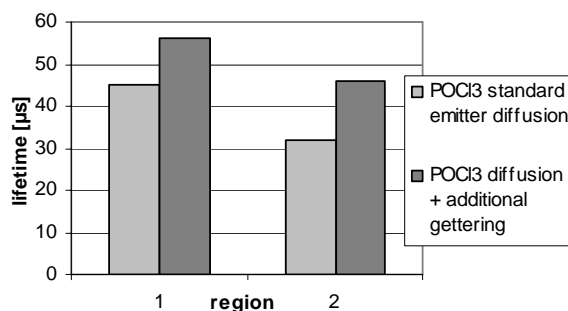
**Figure 8:** Internal quantum efficiencies (IQE) of cells from all ingots and effective diffusion lengths fitted from the long wavelength region. Cells from 75% and 100% Elkem-Si as well as the reference were processed with a more shallow emitter with sheet resistivity of  $58 \Omega/\text{sq}$  leading to a higher blue response as compared to cells from 25% and 65% Elkem-Si ( $52 \Omega/\text{sq}$ ).



**Figure 9:** LBIC (Light Beam Induced Current) mappings at 980 nm wavelength of cells from the different ingots (Ref, 75%, 100%). The reference shows a higher current possibly due to the higher resistivity by factor 2.

#### 4 A PHOSPHOROUS GETTER ANALYSIS

The wafers from 65% SoG-Si were exposed to prolonged phosphorous gettering after  $\text{POCl}_3$  emitter diffusion. Before unloading they remained in the process tube for additional 60 minutes at  $\text{N}_2$  atmosphere and  $700^\circ\text{C}$ . 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  $\text{POCl}_3$  diffusion one with and one without the additional gettering step. We mapped two regions of 40 mm x 40 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 1mm and the average lifetime results are illustrated in Fig 10. The wafer exposed to the longer getter time shows a clear lifetime improvement in both regions.



**Figure 10:** 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.

However, after processing and characterization of complete solar cells we didn't definitely find any consistent difference in solar cell parameters between cells with and without prolonged phosphorous gettering times. It is well known that the Al alloying process leads to additional gettering which may make redundant the prolonged phosphorous gettering step. We therefore did not apply the extended phosphorous gettering to wafers other than those coming from the 65% ingot. This may be different than future high efficiency cell concepts, where the full area Al back surface field might e.g be replaced by boron diffusion or passivation via wet oxidation or amorphous Si layers.

#### 5 CONCLUSIONS

It is demonstrated that for all investigated ingots from Elkem-Si, efficiencies higher than 16% can be reached on several wafers using only industrial process steps. The reference wafers showed slightly lower efficiencies due to a lower  $V_{OC}$  coming from the higher resistivity of the material ( $\sim 1.5 \Omega\text{-cm}$ ). It is confirmed that the solar grade silicon from metallurgical route is clearly competitive to other PV grade silicon sources.

The chemical isotropic texturisation is of high relevance for the investigated Elkem-Si. The method is already implemented in advanced cell lines and other cell manufacturers will follow. The longer  $\text{POCl}_3$  diffusion time could create higher cost (max 0.05 €/Wp), but it seems to be not necessary for the current cell concept based on full area rear side aluminum alloying.  $\text{SiN}_x$  deposition by direct PECVD needs only slight deposition time adaptation, depending on wafer resistivity and texturisation. Optimal Al alloying and gettering is achievable by process parameter adaptations without additional cost.

From the results of this work it is concluded that the achieved efficiencies are rather process limited than material restricted. The Elkem-Si must therefore be tested and carefully analyzed on a lab scale higher efficiency level ( $\eta=18\text{-}20\%$ ) in further investigations to ensure that the feedstock can keep up with future cell concepts.

Elkem started already to produce the solar grade 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.

#### ACKNOWLEDGEMENTS

The authors are grateful to E. Wefringhaus, D. Kunz, P. Perez-Diaz, N. Gawehns, H. Riazi-Nejad, M. Nalbant from the University of Konstanz for assistance during cell processing and characterisation. The authors also like to thank M. G. Dolmen, J. Heide, J. T. Hakedal T. Buseth, A. K. Søyland, H. Schjeldrup and E. Offergaard at Elkem Solar for assistance.

The investigation on thin wafer solar cells in this report was supported with funding of the German BMU under contract number 0329914A. The content of this publication is the author's responsibility.

#### REFERENCES

- [1] Karl E. Knapp, Ph.D., Energy & Environment. Econ. <http://www.homepower.com/files/pvpayback.pdf>
- [2] C. Zahedi et al., "Solar Grade Si from Metallurgical Route", PVSEC-14, Bangkok, Jan 26-30, 2004.
- [3] K. Friestad et al., "Solar Grade Si from Metallurgical Route", EPSEC-19, Paris, June 07-11, 2004.
- [4] K. Peter et al., "Analysis of multicrystalline solar cells from solar grade Si feedstock", 31<sup>st</sup> IEEE PVSC, Orlando, January 3-7, 2005