FIRST RESULTS ON INDUSTRIALIZATION OF ELKEM SOLAR SILICON AT PILLAR JSC AND Q-CELLS

V. Hoffmann[1], K. Petter[1], J. Djordjevic-Reiss[1], E. Enebakk[2], J. T. Håkedal[2], R. Tronstad[2], T. Vlasenko[3], I. Buchovskaja[3], S. Beringov[3] and M. Bauer[1]

[1] Q-Cells AG, OT Thalheim, Guardianstr. 16, 06766 Bitterfeld-Wolfen, Germany
[2] Elkem Solar AS, P.O.Box 8040 Vaagsbygd, NO-4675 Kristiansand S, Norway
[3] Pillar JSC, Mateyuka 4, 02156 Kiev, Ukraine

ABSTRACT: After the development of the Elkem Solar Silicon process, Q-Cells AG, Pillar JSC and Elkem Solar AS have started the qualification program for Elkem Solar Silicon on solar cells out of an industrial manufacturing process on large scale. In the presentation details on the status and most recent results from the test program are given.
The manufacturing process in the pilot plant of Elkem Solar AS is in terms of scale-up factors and critical equipment very close to the planed production process on industrial scale. A significant amount of Elkem Solar Silicon was converted to ingots, wafers and solar cells, using industrial standard equipment and slightly modified manufacturing processes. The material yield for the volumes shipped to Q-Cells AG was comparable to virgin poly-silicon taking into account standard specifications. The results on a block level confirmed same lifetime levels as in the blocks made from the virgin poly-silicon reference. Results on multicrystalline solar cells demonstrate average efficiencies well above 15% and no significant difference compared to the poly-silicon reference. Finally the potential for application of ESS feedstock in future high efficiency cell concepts is addressed.
Keywords: Metallurgical Si, Manufacturing and Processing, Solar Cell Efficiencies, Degradation

1 INTRODUCTION

Growth of the photovoltaic industry in the past 4 years was and still is limited by the availability of poly-Si feedstock [1],[2]. Since 2002, the feedstock price went up by a factor 5-10 at the spot market up to now. This has a considerable impact on the cost structure of a PV system. A significant cost reduction within the next years is needed, so that PV can become a competitive energy source [3].

Elkem Solar (ES) has been developing a proprietary process of upgrading metallurgical silicon within the last 7 years. Elkem Solar Silicon (ESS) is upgraded metallurgical silicon (umg-Si), which can be used as additional new feedstock for solar cell production in standard industrial lines.

The purification of metallurgical silicon (mg-Si) to umg-Si is much less energy intensive than with the conventional purification via trichlorosilan (TCS) and deposition in a Siemens reactor to poly-Si rods [4]. Energy is a major cost contribution of poly-Si production. Therefore, the metallurgical route gives a cost reduction potential. Additionally, the energy payback time of a PV system with cells from umg-Si could be shorter than using poly-Si feedstock, if the cell performance were comparable [4].

The present work is dedicated to the evaluation of ESS as feedstock for mass production of solar systems. Reliable feedstock quality in industrial production scale requires a robust process and a thorough quality control. Stable feedstock quality is needed to assure high yield and productivity in production of ingots, wafers and cells. Additionally, long term stability of cell performance is required for the PV system, which is supposed to effectively generate electricity for more than 20 years.

2 INDUSTRIAL SCALE EVALUATION PROGRAM

ESS was produced in the pilot plant in Kristiansand. The pilot plant is very similar in terms of critical equipment dimensions to the industrial plant, which is under construction right now. Parameter variations in the directional solidification process at Elkem Solar have been tested to evaluate the new industrial sized solidification furnaces.

ESS bricks have been recrystallized to multi crystalline ingots at Pillar JSC in Kiev. This was done in standard production furnaces, keeping the information of parameter variations at ES. ESS was used as 100% feedstock and with mix-in ratios down to 33%. The ingots were sliced into 180 µm wafers at Pillar and processed to cells at Q-Cells (QC) in a standard production line in Thalheim.

Over 150000 cells were made from this test run. Light induced degradation of umg-Si cells was measured in order to simulate the effect on module performance. Modules were made from the cells at QC and tested outdoor as well as in conditions for the lifetime performance test after IEC 61215 norms, like it is done at TÜV and VDE.

3 RESULTS AND DISCUSSON

3.1 Elkem Solar Silicon

ESS is produced from mg-Si of 99 % purity, which is produced in the same plant in a Si furnace. Starting materials are quartz, coal and wood chips. The purification process from mg-Si to umg-Si is a sequence of refining steps as shown in diagram 1, starting with slag treatment, followed by wet chemical leaching, directional solidification, and final cutting into bricks with material quality meeting the specifications.

Diagram 1: Process sequence from mg-Si to ESS

The pilot plant operates equipment comparable in size with the industrial scale equipment. The presented results are from ESS made with the new industrial size directional solidification furnace, already. The process window of the new furnace was tested with a set of parameter variations.

ES has a dedicated laboratory for quality control of the ESS. B, P, and metals are measured by ICP-OES / ICP-MS, and C with LECO. Typical impurity levels in ESS are shown in Table 1.

Element	Unit	Method	typ. concentration
P	Ppmw	ICP-OES	<1,5
B	Ppmw	ICP-MS	≈ 0,4
Metals	Ppmw	ICP-OES	< 30

Table I: Typical impurity level in ESS feedstock measured by ICP-OES/MS

3.2 Ingot and Wafer production at Pillar

ESS was processed at Pillar in standard ingot production furnaces. The ingots were sliced to 180 µm wafers, also in standard production wire saws. Over 150000 wafers were produced within this test. For quality control, Pillar measures lifetime and resistivity on the blocks, as well as the C and O concentrations at the bottom and top of the ingot. ESS was used in different mix-in ratios from 33% up to 100% feedstock. Reference ingots with virgin poly-Si were made before and after the ESS test ingots in the same furnace.

The yield of the ingot was according to the p/n transition at the top part of the ingot, due to the P and B concentration. No problems were observed in the wafering process. Typical lifetime maps measured with µ-PCD at block level are shown in Diagram 2.

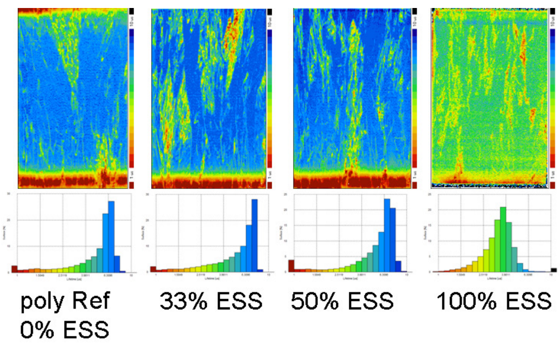

Diagram 2: µ-PCD lifetime maps from blocks with 100%, 50%, 33% and 0% ESS. 0 % ESS is the standard poly-Si feedstock. The scale from 1 µs to 10 µs is the same for the 4 histograms.

The lifetime levels of the blocks with up to 50% ESS are similar to the reference with standard poly-Si feedstock. For the 100% ESS Ingot, slightly lower lifetimes were observed. The absolute value of lifetime is 3.5 µs which is still clearly above 2 µs which is considered to be the critical value.

3.3 Cell production and results at Q-Cells

The 180 µm thick umg-Si wafers made from ESS, were processed in a Q-Cells standard production line. The cells were processed ingot wise, maintaining the information of the parameter variations in the previous production steps at Pillar and ES. All of the cells were processed with the same recipe to avoid further variations. Some blocks were sorted and processed by the position as grown in the ingot.

Special attention was paid to the cell efficiency, yield, shunting, and light induced degradation. The average cell efficiencies by different mix-in ratios are shown in diagram 3.

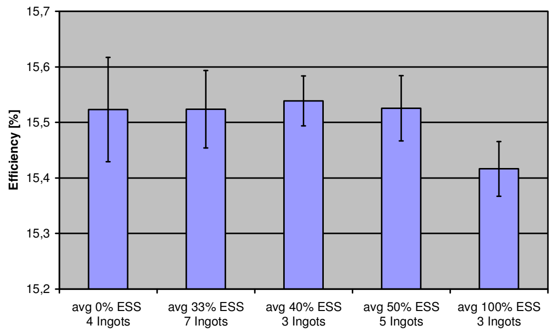

Diagram 3: Average cell efficiencies with different mix-in ratios of ESS and poly-Si feedstock

The cell efficiencies are well above 15% for all of the tested parameter variations at ES and Pillar. Cells with mix-in ratios of 33% to 50% have the same efficiency of 15,5% in average as the reference with poly-Si feedstock. Cells with 100% ESS feedstock, processed in the same production run, show 15,4% efficiency, which is 0,1% less than the reference. This is in good agreement with the lower lifetime on block level as shown in diagram 2.

With regard to shunting, cells with up to 50% ESS fulfil Q-Cells' standard cell specification. Cells with 100% ESS were shunted, due to the reduced breakthrough voltage. The effect of a reduced breakthrough voltage can be compensated by an adapted module design.

The yield in the cell production process was similar to standard production with wafers of the same thickness.

3.4 Light induced degradation measurements

Cells with different ESS mix-in ratios were illuminated with halogen lamps simulating 1 sun, in order to measure the light induced degradation (LID) [5],[6]. Efficiency measurements were done after different cumulative illumination time, adding up to 24 h. The LID of ESS cells in comparison to standard multi- and mono crystalline cells is shown in diagram 4.

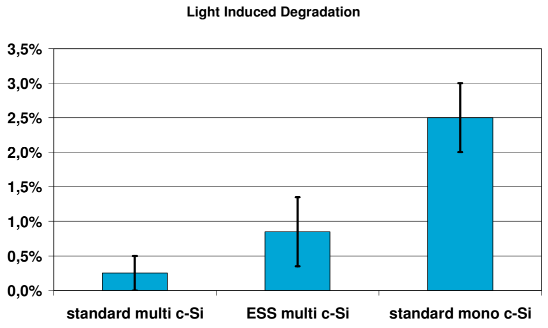

Diagram 4: Light induced degradation of different Si cell types

The LID of multicrystalline cells with 100 % ESS feedstock is around 0,7 – 1,0 % in average over the block. This is well below the 2,5 % degradation of standard monocrystalline cells. Compared to standard multicrystalline cells from poly-Si, the degradation of cells with ESS is roughly 0,5 – 0,8% relatively higher.

Note that the standard deviation on degradation data is relatively large. This is partly due to the measurement stability at these low differences. Additionally, it is due to the systematic degradation increase in wafers with positions towards the bottom of the ingot. The LID of cells from ESS and poly-Si, respectively, are shown in diagram 5, by position of the wafers in the ingot.

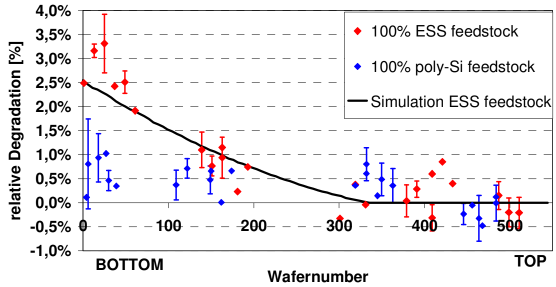

Diagram 5: Relative degradation of cells by position of wafers in the ingot from bottom to top and simulation accounting for the effect of B-O defect pair formation

These findings are in good agreement with the effect of the known B-O defect pair formation [7]. The degradation is stronger towards the bottom of the ingot due to the gradient of the oxygen concentration [8]. The higher degradation in ESS cells compared to mc-Si cells is due to the higher amount of B concentration in ESS feedstock ~ 0,4 ppmw, compared to standard multicrystalline wafers with ~ 0,1 ppmw made with poly-Si.

In monocrystalline cells made with poly-Si, the degradation is considerably higher despite the low B content, because there is a much higher oxygen concentration in the wafer due to the CZ production method. The oxygen is mainly introduced by the quartz crucible [9],[10].

Normally, cells in a module are mixed from positions all over the ingot. Therefore, after LID these cells have a slightly different performance. Simulations on the effect of cells with different performance connected in series in a module, show that this will result mainly in averaging over the different cell efficiencies. There is just a minor additional effect due to the mismatch of the cells. This mismatch effect becomes considerable, if the difference in cell efficiency becomes larger than 5 – 10% relatively.

3.4 Module results at Q-Cells

A set of modules with 60 cells per module were produced at Q-Cells using cells with 100% ESS feedstock, as well as standard mc-Si cells as reference. Part of the modules was submitted to the lifetime performance test after IEC 61215 norm in Q-Cells' module test facility. This test is still ongoing.

The other part of the modules was mounted on our rooftop test system in Thalheim. The modules were measured before mounting on the rooftop system, and after production of 270 kWh per installed kWp. The power loss compared to the reference modules from poly-Si feedstock was 0,5 - 0,9 %. This is in good agreement with the measurements on cell level.

Additional performance tests were made with single cell modules. These mini modules of just one cell, were exposed for one month to 200°C on a heated plate under illumination. No indication of a further degradation in addition to the LID was observed.

3.5 Carrier lifetime in ESS wafers after P-gettering

In order to estimate the potential of ESS feedstock for future high efficiency cell concepts, a series of P-gettering tests were done to study the influence on the carrier lifetime at the Institute for Energy Technology, IFE in Kjeller, Norway.

ESS wafers and reference wafers from poly-Si were taken out of different positions in the respective ingots. The wafers were wet chemically cleaned, and the surface passivation was made by amorphous Si using PECVD.

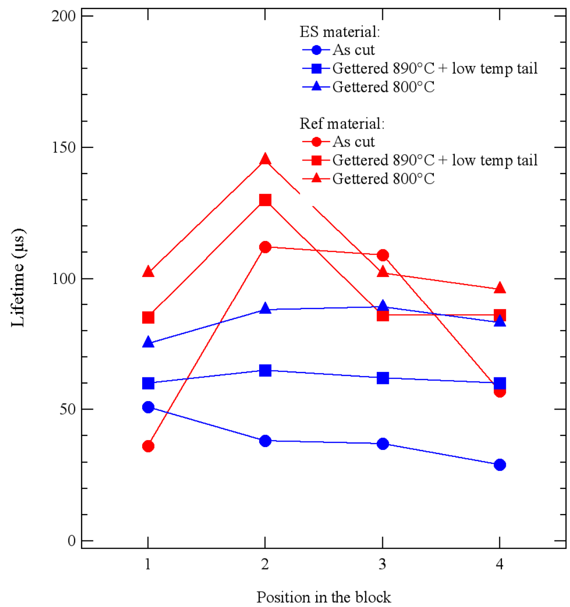

Diagram 6: Minority carrier lifetime of surface passivated wafers from ESS and poly-Si feedstock after P-gettering at IFE

Two different temperature profiles with peak temperatures of 890°C and 800°C, respectively, were applied for the P-gettering step. For comparison, surface passivated as cut wafers without the P-gettering step, were included. The results on minority carrier lifetime measured by microwave photocurrent decay (µ-PCD) are shown in diagram 6.

The lifetime increases at wafers with an additional P-gettering step compared to as cut wafers. This is clearly seen, as well for ESS as for poly-Si wafers. For different temperature profiles, lifetimes above 60 µs and 75 µs, respectively, were achieved with ESS wafers from different positions in the ingot.

Although these lifetimes are lower than in the poly-Si reference wafers, the values are high enough to open the potential for future use in high efficiency cell concepts.

4 CONCLUSIONS

The quality of Elkem Solar Silicon material which was delivered over time was very stable. The effect of process variations at Elkem Solar on the cell efficiencies was rather small. This shows the robustness of the process in the pilot plant, and control of the final product.

Wafers and cells with up to 100% ESS were made in industrial scale. The processability of the feedstock and the mechanical strength of wafers and cells, were very similar to the poly-Si reference. Cell efficiencies above 15,5% on average were achieved in industrial production with no significant difference to the reference, using mix-in ratios up to 50%. Also cells with 100% ESS feedstock showed very good cell efficiencies above 15,4%, just 0,1% lower than the poly-Si reference cells.

Light induced degradation is the main mechanism for performance loss on cell level. This effect is stronger in umg-Si cells due to the higher Boron concentration compared to standard multi crystalline Si cells. With ESS feedstock, the LID is roughly 0,5 – 0,8% relatively higher, but 1,5 – 2% lower than with standard poly-Si mono crystalline cells.

The module performance in long term indoor and outdoor tests, up to now showed no indication for concern. There are not yet outdoor data available in the range of several years, because the development of umg-Si as new feedstock for high quality solar cells is so recent.

Elkem Solar Silicon has shown to be a high quality umg-Si feedstock for solar application, even with the potential for future high efficiency cell concepts. Now, with the ramp up of industrial ESS production, the material availability will allow for the use in large standard PV systems.

5 ACKNOWLEDGEMENTS

The authors are grateful to Arve Holt and Jeyanthinath Mayandi from IFE in Norway for the lifetime studies. We also like to thank our colleagues from Q-Cells Sebastian Falkner, Markus Träger and Michael Mette for the module design and tests, Nora Buschmann and Edeltraud Rittel for the cell characterization, and Achim Schulze for the simulation of the module performance.

6 REFERENCES

[1] M. Rogol et.al, 5th Solar Silicon Conference (2008)
[2] S. Chin, K.-C. Tan, P. Hummel, J. Iyer, A. Zaman, UBS Investment Research Solar Industry, (January 2008)
[3] T.P. Kimbis, Perspectives on U.S. Solar Market Trajectory, U.S. Department of Energy, (May 2008)
[4] R. Glockner, J.-O. Odden, G. Halvorsen and R. Tronstad, M. J. de Wild-Scholten, Silicon for the Chemical and Solar Industry IX, (2008) 235
[5] H. Fischer and W. Pschunder, Proc. 10th IEEE PVSC (1973) 404.
[6] S.W. Glunz, S. Rein, W. Warta, J. Knobloch and W. Wettling, Proc. 2nd WCPSEC (1998) 1343.
[7] J. Schmidt and R. Hezel, 12th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Breckenridge, Colorado (August 2002)
[8] Z. Xi, J. Tang, H. Deng, D. Yang and D. Que, Solar Energy Materials & Solar Cells 91, (2007) 1688
[9] K.M. Kim and W.E. Langlois, J. Electrochem. Soc 138, (1991) 1850
[10] W.E. Langlois, K.M. Kim and J.S. Walker, J. Cryst. Growth 126, (1993) 352