OVERVIEW AND RESULTS OF THE EC HEXSI PROJECT

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ABSTRACT: Computer based calculations have been used to simulate the behaviour of mechanically V-textured solar cells. Several generations of structuring tools have been developed and tested with the latest structuring wheel having a width of 65 mm (two cuts per 12.5x12.5 cm^2 wafer).
A solar cell process based on screenprinting 10x10 cm^2 technology and a firing through SiN_x sequence was adapted to the processing of mechanically structured mc Si wafers. Conversion efficiencies of 16.6% were obtained.
Wafers textured by the structuring wheel technique have been processed in an industrial production line. A module made from mechanically textured cells showed reduced power losses at low angles of light incidence compared to a standard module. Comparing standard wafer processing technology (alkaline etched) and mechanically structured wafers, a cost evaluation has been carried out to calculate the cost effectiveness of the high throughput structuring wheel method for wafer texturing.
The Bayer RGS silicon sheet material fabrication process was further developed and optimised. The material has been studied and characterised using various techniques. A standard high efficiency process (including photolithography) has been adapted to RGS wafers. By the use of H-passivation and a mechanically textured wafer surface efficiencies up to 12% were achieved on 4 cm^2 RGS solar cells, which is by far the highest value reached on this very promising material.
A new process of silicon sheet recrystallisation based on a closed molten zone was developed and first test solar cells have been processed and characterised using a simple cell process.
Keywords: Multi-Crystalline - 1: Texturisation - 2: Ribbons - 3

OBJECTIVES

The HEXSI project (High Efficiency Xstalline SIlicon solar cells based on low cost materials) aimed at the development of low cost multicrystalline (mc) silicon sheet material and the demonstration of highly efficient solar cell structures in this material. Furthermore, the processing of mechanically structured mc silicon solar cells in an industrial type environment had to be shown.

The main objectives of the HEXSI project were:

- Demonstration of a mechanical wafer engineering technique and its implementation in an industrial environment with existing solar cell technology (University of Konstanz, Eurosolare).
- Demonstration of the cost effectiveness of the wafer engineering method on advanced cast mc Si (IMEC, University of Konstanz).
- Development of RGS solar cells with 12% efficiency (Bayer AG, University of Konstanz).
- Development of molten zone sheet material. Demonstration of laboratory size high efficiency cells based on this material (University of Lisbon).

COMPUTER SIMULATIONS

Computer based calculations have been used to simulate the behaviour of mechanically V-textured solar cells. Textured wafers show less reflection, an altered charge carrier generation profile and a higher collection probability. Detailed analysis of these features were performed[1,2] and were the basis of the following studies on mc silicon wafers and solar cells. Fig. 1 shows the charge carrier collection probability for a flat and two macroscopically textured surfaces with an assumed diffusion length L_{diff} of 50 µm. A significantly enhanced collection probability is clearly visible in both cases of a textured surface.

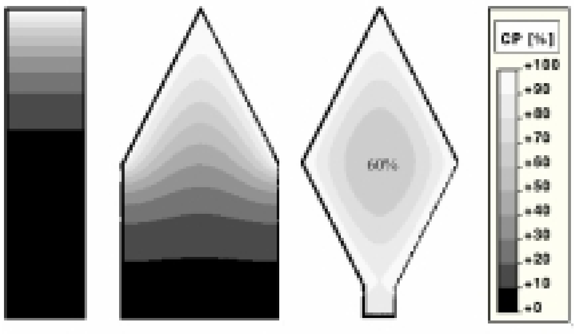

Figure 1: *Collection probability CP for minority charge carriers generated in the base of solar cells with different surface texture (maximum cell thickness 300 µm, diffusion length L_{diff} = 50 µm).*

MECHANICALLY TEXTURED SOLAR CELLS

Several generations of structuring tools have been developed and tested on a wafer and solar cell level with regard to geometrical and efficiency performance (Fig. 2).

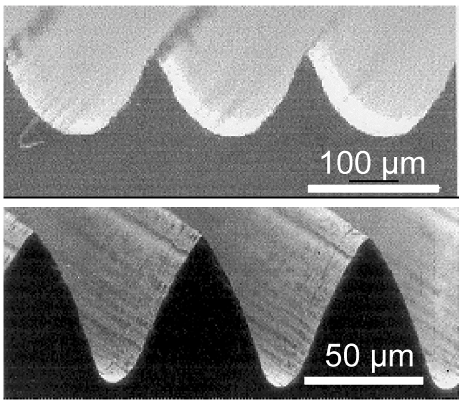

Figure 2: *Profiles of wafers textured with the latest generation of high throughput structuring tools (top) as well as a single blade texture (bottom).*

Mechanically textured wafers, structured with a high throughput texturing wheel, were processed in a commercial production line at Eurosolare using standard production technology. A module made out of mechanically textured wafers was produced which showed a reduced power loss at low angles of light incidence compared to a standard Eurosolare module. Furthermore investigations on the texturing damage depth have been carried out using the photoconductivity decay method. It could be shown, that the surface damage is in the range of just 3-4 µm.

A solar cell process based on screenprinting 10x10 cm^2 technology and a firing through SiN_x sequence was adapted to the processing of mechanically structured mc wafers in order to reach high efficiencies in the 17% range[3]. Initially the $POCl_3$ diffusion was optimised for textured wafers regarding uniformity. In a second step the screen printing was investigated. It could be shown, that printing the fingers parallel to the V-grooves using modern screen printers is favourable compared to printing the fingers perpendicular to the grooves. An optimisation of the SiN_x antireflection coating concerning refractive index and extinction coefficient was carried out resulting in record high short circuit current densities J_{sc} > 36 mA/cm^2 for mc Si. Reflection and IQE measurements clearly demonstrated the positive effect of the texture on J_{sc} due to light trapping (Fig. 3) and a higher collection probability.

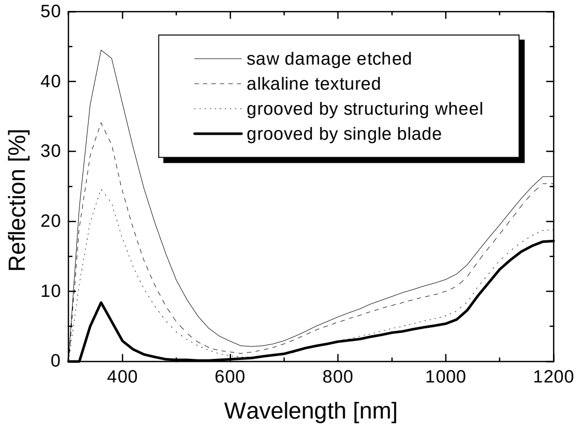

Figure 3: *Reflection comparison between differently textured mc substrates with SiN_x as single layer ARC illustrating the light trapping effect.*

It was not possible to contact very shallow emitters in the range of 50 Ω/sq in the case of mechanically structured wafers (unlike for alkaline textured cells). The reason is a high I_{02} indicating a high recombination in the space charge region of the cell. This can be caused by the indiffusion of particles from the paste in combination with the presence of the extended space charge region following the grooves. As a result, the fill factor of mechanically structured cells is lower than the fill factor of alkaline textured cells unless a deep emitter is used beneath the contacts. For this reason, the highest efficiency cells are made using a two-step selective emitter process. A large area (98 cm^2) V-textured mc cell made on Baysix material was confirmed by the FhG-ISE calibration lab as having an efficiency of 16.6%.

Table 1: *Highest efficiencies obtained on Baysix mc cells with a two-step selective emitter process (double layer ARC, 98 cm^2, *confirmed by FhG-ISE, Freiburg)*

Surface treatment	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	Eff. [%]
Alkaline textured	34.5	624	75.9	16.3* ±0.3
Mechanical structuring (Single blade)	35.7	617	76.6	16.9
Mechanical structuring (single blade)	35.2	616	76.4	16.6* ±0.4

18 single blade grooved cells were processed according to a homogeneous emitter process sequence. Their average efficiency was 15.5%. Eight of these cells were incorporated into a module, resulting in a recalculated cell efficiency of 15.9%.

MECHANICAL TEXTURING - COST EVALUATION

A cost comparison between the firing-through-SiN_x process applied on alkline textured and V-textured mc wafers has been carried out with the following assumptions:

- 0.8 mA/cm^2 higher J_{sc} on structuring wheel textured cells due to less reflection, no losses in V_{oc} and fill factor resulting in an absolute efficiency increase of 0.4% for the V-textured cells (14.0 to 14.4%).
- Wafer size 12.5x12.5 cm^2, 3 shifts, 240 working days, production of ~5 MWp/year.

The calculation was performed using an excel spreadsheet made at IMEC using all necessary inputs for cost calculations of cell and module productions for making a detailed business plan. The yield of the process in case of alkaline textured mc wafers was taken as 95% resulting in a cost of 1.84 EU/Wp for the cell process. The same yield of 95% in the case of 14.4% efficiency (V-textured wafers) leads to 1.78 EU/Wp. The break-even point for which the cost of V-texturing is equal to the cost of producing alkaline textured cells is at a yield of 92%. Unfortunately, no yield studies could be carried out on a broader scale in the frame of HEXSI, so this question is not answered yet for a large production scenario.

DEVELOPMENT OF RGS SILICON

The Bayer RGS sheet material fabrication process[4] was further developed and optimised. Especially the oxygen management was investigated as the concentration of New Donors, a special type of oxygen clusters, turned out to be directly correlated to J_{sc}[5]. Therefore two different types of RGS wafers distinguishable by their cooling rates have been produced. While the rapidly cooled material contains nearly all the oxygen in interstitial form, the interstitial oxygen content is reduced by about 93% in material using a slow cooling rate. A measurement of the three dimensional oxygen distribution using secondary ion mass spectroscopy (SIMS) indicated that oxygen in slowly cooled RGS is precipitated in structures very likely associated with dislocations. As metallic impurities seem to limit V_{oc} strong efforts were made to reduce these residual impurities (above all iron and nickel) originating mainly from the construction materials of the RGS plant (Fig. 4). In the following RGS wafers and cells could be produced showing further improved dark IV characteristics.

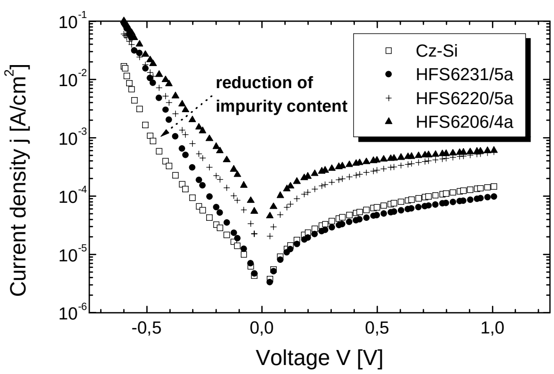

Figure 4: *Dark current-voltage characteristics of solar cells based on RGS ribbons in comparison to a mono Cz Si solar cell. Impurity level: 06206/4aL: medium; 06220/5aL: low; 06231/5aL: very low. The reduction of the impurity content of the RGS ribbons leads to a decrease of the dark current density of the corresponding solar cell.*

RGS CHARACTERISATION AND SOLAR CELLS

RGS material was characterised during the project period using various methods to determine diffusion lengths (surface photovoltage), mapped lifetimes (photoconductivity decay, Fig. 5), electrical transport properties (temperature dependent Hall measurements), and lattice defects (transmission electron microscopy and etch pit densities)[6].

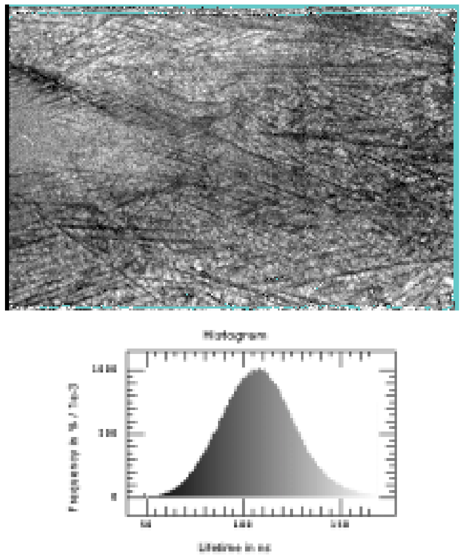

Figure 5: *µ-PCD measurement of an as grown RGS wafer (11x8 cm^2, no surface passivation).*

A solar cell processing sequence for RGS wafers was developed, which contains a mechanical levelling step using a conventional wafer dicing saw prior to standard cell processing. Within this process the application of photolithography as a front metallisation method is possible, which might cause problems in the case of as grown RGS wafers because of the uneven front surface. Inside this standard process[7] optimisations of gettering and H-passivation steps were carried out[8]. H-passivation was extensively studied with the microwave induced remote hydrogen plasma (MIRHP) method and a correlation between its effectiveness in improving cell parameters and the impurity concentration in the RGS wafers was detected. Especially in the latest RGS material containing less metal impurities large improvements in all cell parameters were possible. In this way, cell efficiencies could be increased to values exceeding 11% (4 cm^2) by applying an optimised H-passivation step.

The effect of a mechanical texture of the RGS wafer front surface on the behaviour of the cell parameters was studied using a single blade texturisation technique. Simulations predicted an increase in J_{sc} especially in material with small diffusion length which could be proven by measuring locally resolved IQEs on textured RGS wafers[9] as can be seen in Fig. 6.

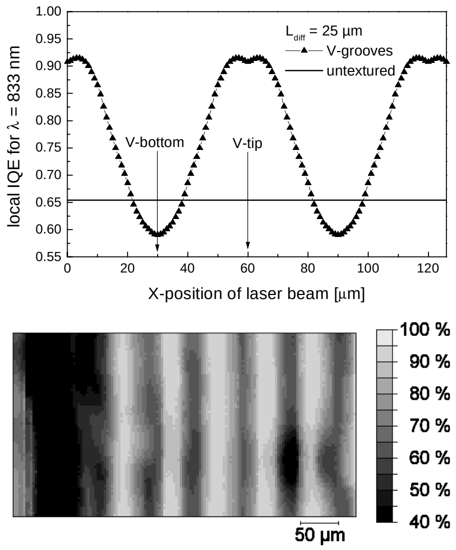

Figure 6: *Top: Simulated local IQE at 833 nm for a flat and mechanically V-textured solar cell with L_{diff} = 25 µm. Light entering in the V-tips results in an increased IQE. Bottom: Measured local IQE at 833 nm of a textured RGS solar cell with L_{diff} about 25 µm. An excellent agreement between simulation and measurement is visible.*

Therefore the mechanical V-texturing step was implemented in the RGS high efficiency cell process. This additional texturing of the wafer surface led in conjunction with the optimised H-passivation to a cell efficiency of 12% (4 cm^2, independently confirmed at FhG-ISE 11.9 ± 0.3%), which is by far the highest efficiency reached on RGS material up to now.

CLOSED MOLTEN ZONE PROCESS

A new process of silicon sheet recrystallisation, based on a closed molten zone was developed[10]. This is a laboratory scale process, aimed at demonstrating the possiblity of silicon tube growth from a molten zone. Conditions have been found for establishment of a stable molten zone, and for the recrystallisation of silicon sheet material with quality compatible with high efficiency solar cells.

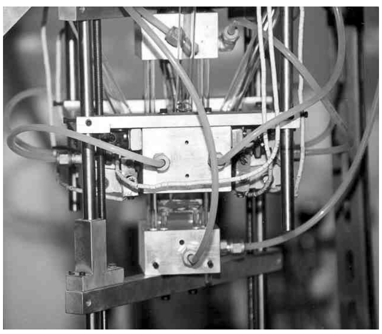

Figure 7: *Photograph of the core of the closed molten zone furnace.*

In the samples produced with the last generation system, minority carrier diffusion lengths averaged ~100 µm, as measured in test cells with no back surface gettering nor hydrogen passivation.

CONCLUSIONS

- The mechanical wafer engineering method is compatible with existing mc silicon solar cell processing equipment and leads to higher module efficiencies as compared to modules made from standard alkaline textured cells.
- Efficiencies in the upper 16% region were obtained on mechanically textured large area (98 cm^2) mc silicon solar cells using a firing through SiN_x screen printing process. A 15.9% module efficiency has been produced with V-textured mc silicon solar cells (98 cm^2) using screen printing technology.
- RGS solar cells with efficiencies up to 12% have been processed in an optimised high efficiency process on 4 cm^2 cells using a photolithography step. H-passivation and a mechanically textured front surface largely improved the cell efficiency.
- A new process of silicon sheet recrystallisation based on a closed molten zone was developed and solar cells with diffusion lengths of 100 µm (averaged) without gettering or hydrogen passivation have been processed.

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