DEVELOPMENT OF A CHEMICAL SURFACE TEXTURE FOR STRING RIBBON SILICON SOLAR CELLS

G. Hahn[1], I. Melnyk[1], C. Dubé[2], A.M. Gabor[2]
[1]University of Konstanz, Department of Physics, 78457 Konstanz, Germany, email: giso.hahn@uni-konstanz.de
[2]Evergreen Solar Inc., 259 Cedar Hill St., Marlboro, MA 01752, USA, email: gabor@evergreensolar.com

ABSTRACT: Multicrystalline ribbon silicon solar cells made from String Ribbon material have a high potential to bring down Watt-peak costs in photovoltaic. This is mainly because of the inherent advantages linked with the growth technique like the excellent silicon usage and the lack of a saw damage due to wafer cutting. On the other hand it is difficult to apply an efficient surface texture to the undamaged wafer surface. We tried to adapt existing acidic surface textures to the String Ribbon material needs and evaluated their effectiveness on reflectivity as well as solar cell efficiency level. In a first approach using existing standard etch solutions we could not observe beneficial effects on J_{sc} or η due to a preferential etching of grain boundaries. Advanced developments of new textures lead to a more homogeneous texture pattern and first results on solar cell level seem to be promising as a slight increase in J_{sc} could be observed. These new textures have to be developed further to significantly increase η of textured cells.
Keywords: Multi-Crystalline, Ribbon Silicon, Texturisation

1 INTRODUCTION

String Ribbon (SR) silicon wafers are grown directly from the melt in the desired thickness, and thereby the costly sawing steps required for ingot growth methods are avoided [1]. The lack of a saw damaged wafer surface normally is an additional advantage, as no saw damage etching steps have to be applied prior to standard solar cell processing. On the other hand, state of the art cell processes for multicrystalline wafers fabricated from ingots (standard mc) include a chemical etching step for surface texture. With this step two goals are achieved: the saw damage is removed and the reflectivity of the surface is reduced. Alkaline (KOH or NaOH) or acidic etch solutions ($HF/HNO_3/H_2O$) are commonly used for this purpose [2,3]. While alkaline etch solutions result in anisotropic texture quality for different crystal grain orientations, acidic textures show a uniform and isotropic surface morphology. This presentation deals with the development of a surface texture for String Ribbon material to reduce reflectivity and thereby reach higher efficiencies.

To reduce surface reflectivity for String Ribbon, several aspects have to be considered. The wafer surface is very smooth on a small scale and has a shiny optical appearance. Apart from large angle grain boundaries and frequent twinning, no crystal defects are visible at the surface. The attack of most etching solutions is more pronounced at areas of low crystal quality, because of the non-optimal configuration of neighbouring Si atoms. Alkaline etch solutions therefore result in deep trenches at grain boundaries (for both large angle or twin boundaries) in String Ribbon. This fact and the anisotropic texture quality on different grains leaves only acidic etching solutions for a promising surface texture by wet processing. [4]

2 FIRST APPROACH

Areas of attack for acidic etch solutions for standard mc wafers are areas of poor crystal quality with weakly bonded Si atoms, which are provided by the saw damage. This defines the scale and size of the texture pattern. As String Ribbon wafers have no damaged surface layer, acidic etch solutions used for standard mc wafers can not be applied but must be adapted and optimised for the specific material needs. Therefore in a first attempt we tested two different approaches based on several acidic etch solutions available for standard mc wafers. The results were evaluated on a reflectivity level as well as on a solar cell level to check if the desired decrease in reflectivity results in higher cell efficiencies.

The first two approaches with acidic etch solutions were based on $H_2SO_4/HF/HNO_3$ (Texture A) [5] and $HF/HNO_3/H_2O$ (Texture B) [3].

2.1 Surface Morphology

Scanning electron microscopy (SEM) images of the SR wafer surface after etching using Texture A are shown in Fig. 1. We observed that the texture attacks the SR wafer surface with no dependence on the orientation of the crystal grains. The surface shows a small scaled roughness as desired. On the other hand, it can be seen that a preferential etching of the grain boundaries occurs, leading to several microns deep trenches especially in the heavily twinned regions of the crystal.

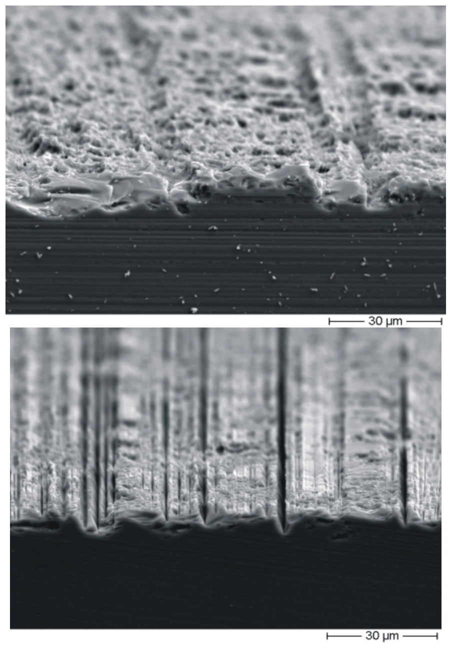

Figure 1: Surface of a SR wafer using texture A. Top: intra-grain areas, bottom: twinned area.

Fig. 2 demonstrates the effect of the two textures on reflectivity. Reflectivity is reduced significantly for both textures. Measurements on the textured wafers have been carried out on the four corners of the wafer. In this way the influence of different crystal grain orientations can be taken into account. Texture B led to similar results as were obtained for texture A shown in Fig. 1, but preferential etching of grain boundaries occurred to a lesser degree. On the other hand, a slight dependency on crystal grain orientation could be observed for texture B.

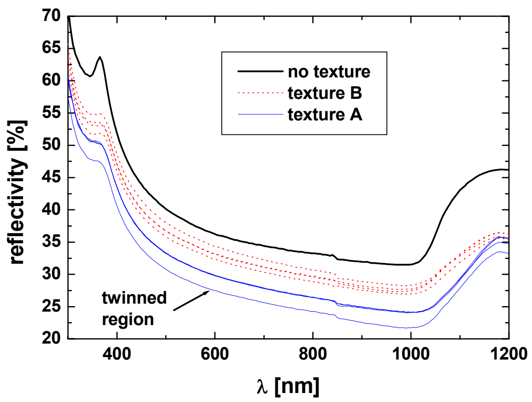

Figure 2: Reflectivity of the two acidic surface textures in comparison with an untextured String Ribbon wafer surface.

2.2 Solar cell processing

Industrial-type solar cells have been processed at University of Konstanz on these textured String Ribbon wafers using a fire through SiN process with screen-printed contacts leading to 8x10 cm^2 solar cells (details on the cell process applied can be found in [6]). Base resistivity of the SR wafers was 3 and 5 Ωcm respectively. Reflectivity after cell processing can be seen in Fig. 3. The non optimised thickness of the SiN layer results in optically thin antireflection coatings. And due to some anisotropy in dependence on crystal grain orientation and/or anisotropy because of preferential etching in twinned regions, the minima of reflection are shifting for different positions measured on the solar cell.

IV data of these solar cells can be found in Fig. 4.

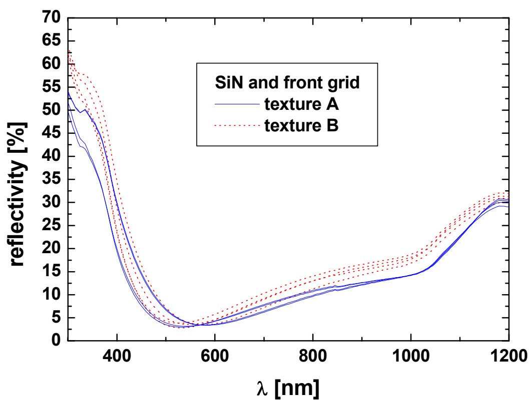

Figure 3: Reflectivity after cell processing measured in the four corners of each cell. Samples have SiN and metallization on the front side but no Al back contact.

Although reflectivity could be reduced by both textures, J_{sc} values could not be increased. For 5 Ωcm material even a decrease is visible. This effect could either be caused by the non optimum optical thickness of the SiN layer or by an effect of the surface texture on internal quantum efficiency (IQE). Fill factors of the best cells are around 76-77% independent of surface morphology. For 5 Ωcm material a drop in V_{oc} of about 10 mV can be observed for both textures A and B, whereas for the 3 Ωcm material only texture A reveals this drop. Efficiencies averaged over the 5 best cells of each group from the 3 Ωcm material are 15.0% (no texture and texture B) and 14.4% (texture A). 5 Ωcm material: 15% (no texture), 14.5% (texture B), 14.4% (texture A).

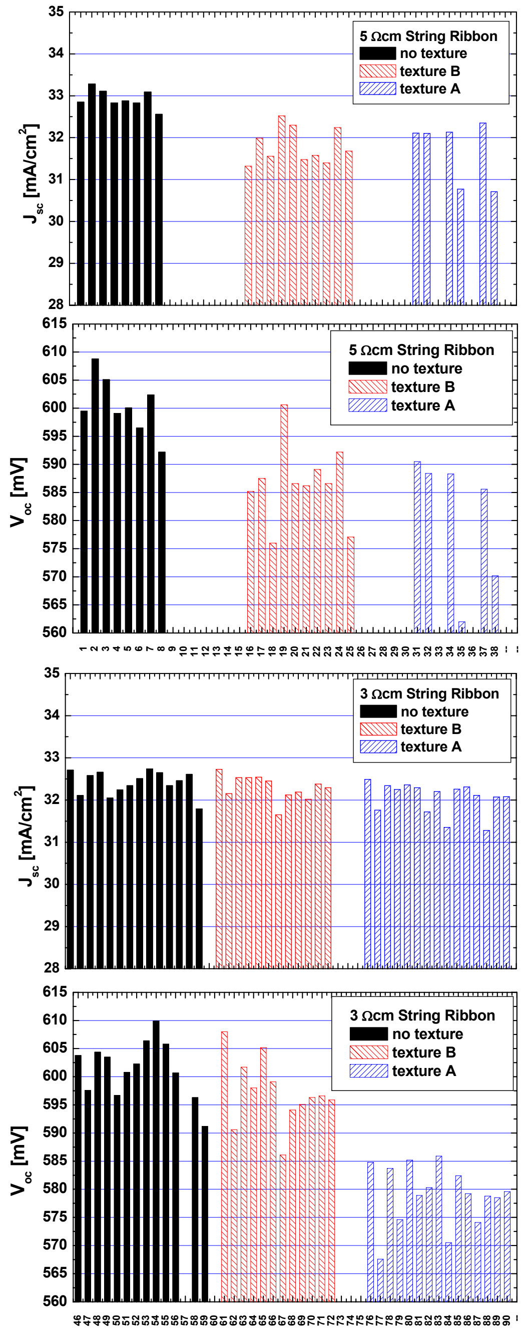

Figure 4: J_{sc} and V_{oc} data of the flat and textured String Ribbon solar cells.

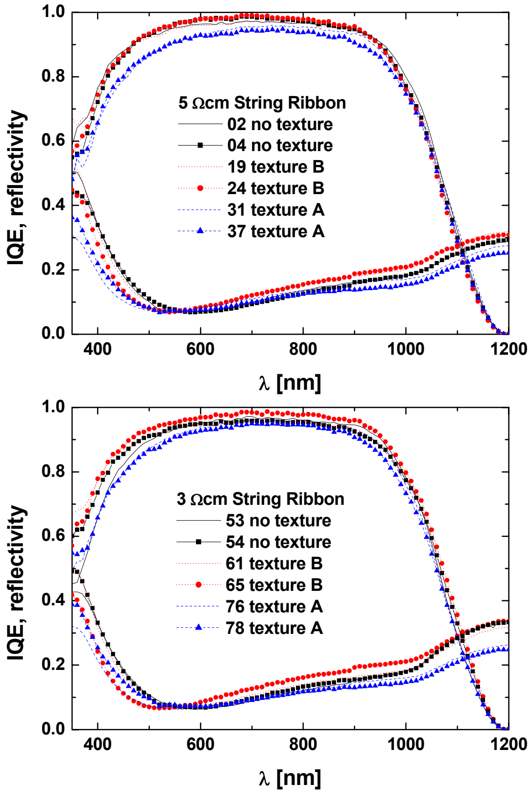

Figure 5: IQE and reflectivity data for typical solar cells of 5 Ωcm (top) and 3 Ωcm material (bottom). Cell numbers refer to numbers given in Fig. 4.

IQE measurements have been performed for selected cells and are presented in Fig. 5. Texture A leads to significantly lower IQE values in the short wavelength part of the spectrum, especially for the 5 Ωcm material. This could be explained by the largely increased space charge region, caused by the surface morphology (compare with figure 1). Fits using dark IV measurements according to the 2-diode model with fixed $n_1 = 1$ and $n_2 = 2$ reveal that the saturation current of the second diode (J_{02}) is indeed significantly increased (Fig. 6), whereas no increased values of shunt and series resistance could be detected.

From the above findings we conclude that it is possible to texture String Ribbon material effectively concerning reflectivity. But to get an increased efficiency, special care has to be taken that the texture should result in an isotropic morphology of the surface. Especially preferential etching at grain boundaries has to be avoided. And the increase of emitter surface area (and therefore J_{02}) should be restricted to be as small as possible.

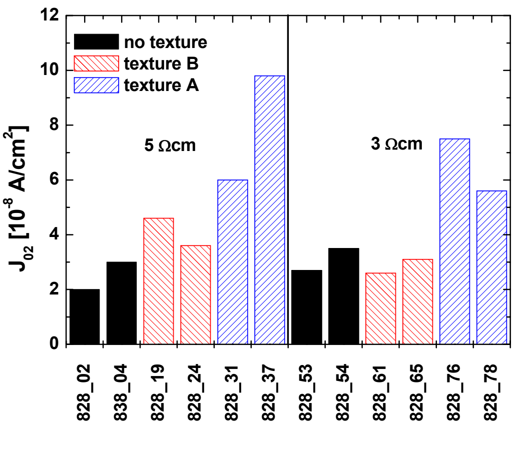

Figure 6: Fit results for I_{02} according to the 2-diode model revealing higher values for textured cells.

3. SECOND APPROACH

3.1 Surface morphology

Based on the results with textures A and B, new textures are currently being developed to get a more homogeneous nucleation of the surface etching. First results are very promising. Fig. 7 gives reflectivities of wafers treated with 4 different etch solutions. All 4 etch solutions consist of $H_2SO_4/HF/HNO_3/H_2O$ differing in composition and temperature. Texture 3 (measurements at 4 spots on the wafer) showed some preferential etching of grain boundaries, whereas the other solutions resulted in good isotropic appearance.

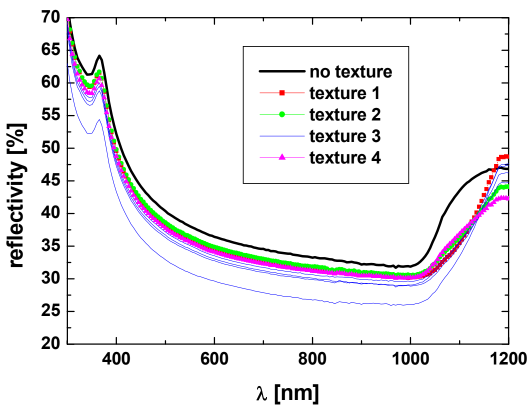

Figure 7: Reflectivities of SR wafers etched with 4 different etch solutions.

3.2 Solar cell processing

Solar cells have been processed using these etch solutions for surface texturing. This time cell processing of textured wafers (3 Ωcm material) was carried out at Evergreen Solar's production line, resulting in 8x15cm^2 solar cells. Special care was taken this time to assure similar optical thicknesses of the SiN on both the textured and flat surfaces. As the etching process is an exothermic reaction, temperature control is crucial to obtain homogeneous etching results. Results presented in figure 7 have been obtained by etching single wafers, whereas for cell processing batches of wafers have been textured, leading to somewhat higher temperatures of the etch solution. This caused surface morphologies that differ from the ones measured in Fig. 7. In Fig. 8 SEM images of wafers from the batch process are shown. Textures 1 and 2 show good homogeneity for differently oriented grains and only minor preferential etching of grain boundaries. Textures 3 and 4 in intra-grain areas look very similar to acidic textures used for cast mc-Si, although a more distinct preferential etching of grain boundaries can be detected. Average cell results are presented in Table I.

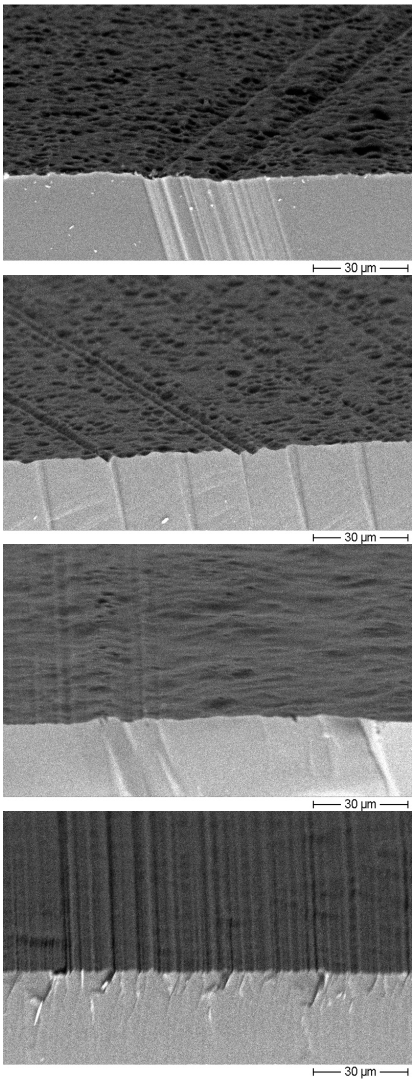

Figure 8: SEM images of SR wafers textured with etch solutions 1, 2, 3, and 4 (top to bottom) after texturing in a batch process.

Texture	FF [%]	V_{oc} [mV]	I_{sc} [mA]	η [%]
no	73.9	591	3.71	13.5
1	72.8	591	3.75	13.4
2	73.0	588	3.72	13.3
3	73.7	589	3.75	13.6
4	73.6	587	3.70	13.3

Table I: Average IV parameters for SR solar cells using textures 1-4.

Although statistic is low, it can be stated that textured cells do not show reduced efficiency values in the second approach. Still missing are detailed analysis of IQE data to check if the lower blue response that was observed for cells in the first approach could be avoided this time.

Another investigation still missing is encapsulation of textured SR cells and a comparison with flat references. This investigation will be included in the next experiments with additional emphasis on temperature stability during etching to ensure even less preferential etching of grain boundaries.

4. SUMMARY

Several acidic texture solutions have been developed for SR wafers to overcome the disadvantage of higher reflectivity as compared to ingot cast mc Si solar cells. The textures have been evaluated on both the reflectivity as well as the solar cell level. Standard industrial type cell processes resulting in large area solar cells have been applied.

In a first approach two different textures (A and B) have been investigated that already showed good performance for mc Si using similar recipes. Although reflectivities could be significantly reduced, solar cell parameters could not be increased (J_{sc} and η). IQE and dark IV analysis showed that a reduced blue response might be responsible for this behaviour, which could be caused by the increased surface area leading to higher I_{02}.

In a second approach emphasis was laid on finding new textures showing less preferential etching of grain boundaries together with an anisotropic etching of differently oriented crystal grains. First results could be demonstrated showing good surface morphology. First solar cells textured using these textures showed IV parameters similar to flat untextured references. Additional analysis of these cells including IQE measurements has still to be carried out.

Future experiments will include encapsulation of textured solar cells and a more control of temperature during etching.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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