15% EFFICIENT LARGE AREA SCREEN PRINTED STRING RIBBON SOLAR CELLS

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ABSTRACT

Large area solar cells have been processed at the University of Konstanz using a standard industrial type SiN fire-through process on Evergreen Solar's String Ribbon multicrystalline silicon material. After optimisation of the screen printing step and emitter sheet resistivity, efficiencies of 15% have been reached on 8x10 cm^2 cells almost independent of material bulk resistivity, which was varied between 1-5 Ωcm. These are the highest large-area efficiencies reached on this very promising and cost-effective material using an industrial type process. Cell parameters exhibit a high homogeneity, demonstrating the excellent post-processing material quality. Further improvements within the solar cell process are still possible and could lead to improved results in the near future.

INTRODUCTION

Evergreen Solar's String Ribbon process [1] has a high potential to significantly reduce the production costs per Wp because no material-consuming sawing steps are needed after the crystallisation process. During crystallisation two strings provide edge stabilisation for the silicon ribbon growing between the strings directly from a silicon melt. These strings remain in the wafer throughout the solar cell process.

The aim of this study was to determine the current limitations of the String Ribbon material used for solar cell production at Evergreen Solar. The passivation of crystal defects present in the material after crystallisation is an important step in order to improve the efficiencies of String Ribbon solar cells. Defect passivation via a hydrogen rich SiN_x antireflection coating is currently looked upon as the most economically favorable and effective method to reach this goal without applying additional steps during cell processing. Therefore we applied an industrial type large area solar cell process including a PECVD (plasma enhanced chemical vapour deposition) SiN_x antireflective coating deposition in combination with a fire-through process.

SOLAR CELL PROCESSING

All wafers processed at the University of Konstanz had a size of 8x10 cm^2 (as compared to 8x15 cm^2 at Evergreen). In a first experiment [2] the current Evergreen cell process was investigated by comparing different processing steps with the standard industrial type solar cell process used at the University of Konstanz. The Konstanz process consists of an acid etching step followed by a $POCl_3$ emitter diffusion, the PECVD SiN_x deposition and metallisation by screen printing (Ag paste on the front, Al paste on the back side). Contacts are cofired and edges are isolated by sawing.

In the first experiment we used material with a bulk resistivity between 1.5-2 Ωcm. Results are discussed in detail elsewhere [2]. By using a 40 Ω/sq. emitter sheet resistance, efficiencies of up to 14.3% could be obtained. The width of the front grid fingers was about 190-200 µm.

A second experiment was set up in order to study the impact of material bulk resistivity on the cell parameters. Three batches of wafers have been fabricated at Evergreen Solar with 1, 3, and 5 Ωcm respectively. These 8x10 cm^2 wafers have been processed into 8x10 cm^2 solar cells at University of Konstanz. The applied process is shown in Fig. 1.

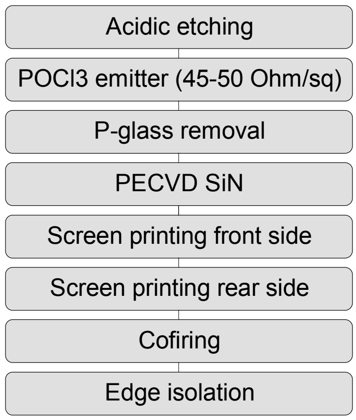

Fig. 1: Schematic processing sequence for large area screen printed String Ribbon solar cells at University of Konstanz.

Several optimisations have been carried out as compared to the first experiment: emitter sheet resistance was increased to 45-50 Ω/sq., front grid finger width could be reduced to 140-150 µm, and the as grown material quality could be improved. All cells underwent the same process described above and resulting cell parameters can be found in Table 1. Given there are the values averaged over five cells for each category.

Short circuit current density J_{sc} increases with higher resistivity as expected due to higher effective lifetimes present in the processed solar cells. This can be seen from Fig. 2 showing maps of the internal quantum efficiency (IQE) for two typical cells with different resistivity.

Table 1: Cell results for the second experiment using different bulk resistivities (averaged over 5 cells each).

Resistivity [Ω cm]	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
1	606	31.1	78.0	14.7
3	598	31.7	78.7	14.9
5	599	32.4	77.4	15.0

Open circuit voltage V_{oc} decreases with increasing resistivity as it is expected from theory. No significant difference could be detected in this investigation between 3 and 5 Ωcm material because of the poor statistic of only 5 cells per group. In combination with good fill factors excellent average efficiencies around 15% could be obtained, with the highest average efficiencies reached on 5 Ωcm material.

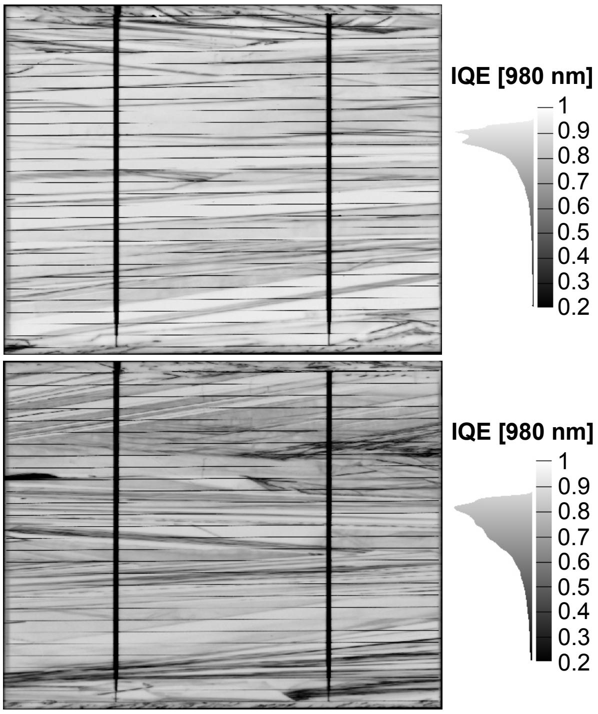

Fig. 2: Mapped IQEs at 980 nm for String Ribbon cells with different bulk resistivities. For the 5 Ωcm cell (top) a higher IQE corresponding to a higher L_{eff} could be obtained as compared to the 1 Ωcm cell (bottom).

An impression of the homogeneity of the material quality can be given by comparing the J_{sc} values of all cells from one specific resistivity. Fig. 3 demonstrates this for the 5 Ωcm group, with all cells having a variation of only 0.5 mA/cm^2.

The global IQEs for three String Ribbon cells of 1, 3, and 5 Ωcm can be seen in Fig. 4. In the short wavelength region some variations are visible, originating from slight fluctuations in sheet resistivity (45-50 Ω/sq.). In the long wavelength region the increasing L_{eff} with higher bulk resistivity can be detected. An analysis of the IQE

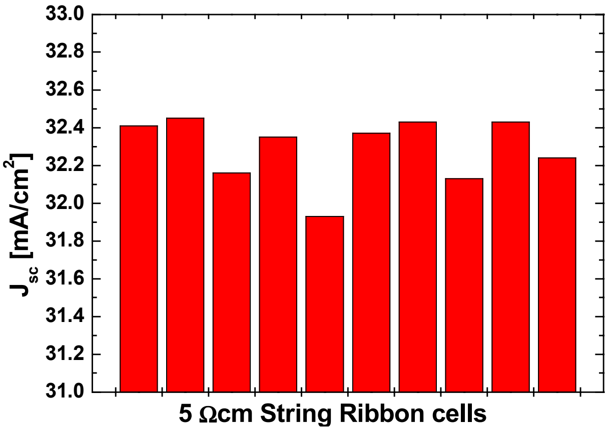

Fig. 3: J_{sc} for 5 Ωcm cells demonstrating the homogeneity of the String Ribbon material after processing.

between 800-960 nm results in values of L_{eff} given in the legend. In another study we showed that bulk lifetimes in String Ribbon material after gettering and hydrogenation in areas of good material quality can be as high as 350 µs [3]. Therefore we believe the L_{eff} values to be true, although they are extremely high for a cost-effective multicrystalline ribbon material.

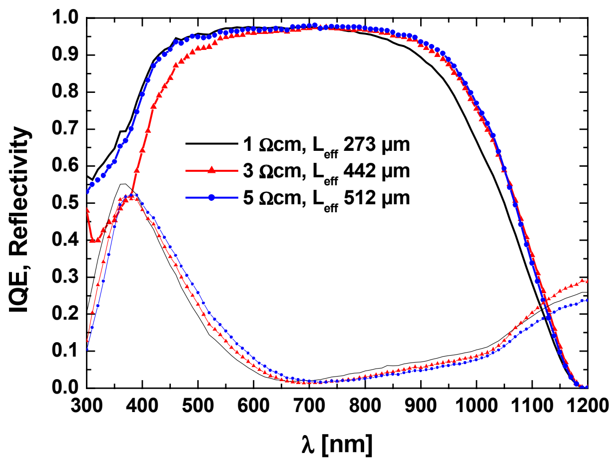

Fig. 4: IQEs and reflectivity for three cells with bulk resistivities of 1, 3, and 5 Ωcm, respectively. L_{eff} from analysis of the long wavelength part of the spectrum increases with higher bulk resistivity.

Best cell from experiment 2

The best cell processed within the second experiment resulted in a confirmed efficiency of 15.4%. Cell parameters as measured at University of Konstanz and at the Fhg-ISE calibration lab are given in Table 2. This is an increase of 1.1% absolute in maximum cell efficiency as compared to the first experiment and by far the highest efficiency reached on a large area screen printed String Ribbon solar cell.

Table 2: Cell parameters of the best String Ribbon solar cell processed from experiment 2. Shown are the confirmed data from FhG-ISE calibration lab and the data measured at University of Konstanz.

Lab	Resist. [Ωcm]	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
FhG-ISE	3	609.5	32.35	78.3	15.44
Konstanz	3	605.7	32.37	78.8	15.47

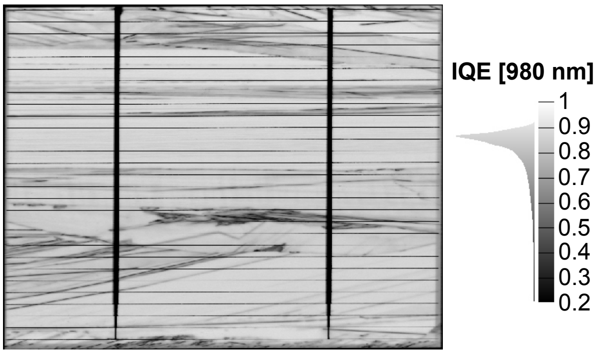

Fig. 5: Mapped IQE at 980 nm for the best String Ribbon cell processed from experiment 2 (3 Ωcm material).

The high IQE in the long wavelength part of the spectrum (Fig. 5) results in high values for L_{eff} shown in Fig. 6 as a result of an analysis of mapped IQEs at three different wavelengths (833, 910, and 980 nm).

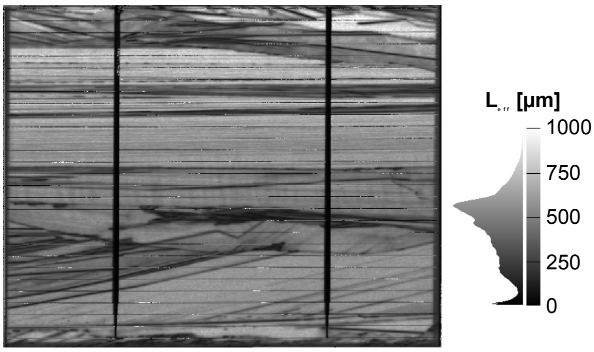

Fig. 6: Distribution of L_{eff} for the best String Ribbon cell as calculated from mapped IQE measurements at three different wavelengths.

Reflectivity

All cells from the second experiment have been processed without applying any texture on the wafer surface (acidic etching, Fig. 1). J_{sc} could be further improved if any form of texture could be realised, as can be seen from the reflectivity curves given in Fig. 4. The cells would benefit even more from their good blue response if reflectivity could be reduced in the short wavelength region. Encapsulation of the cells processed within the second experiment would therefore result in a significant improvement of J_{sc} and η.

A more homogeneous emitter sheet resistivity within one batch process of cells can increase the average J_{sc} values as well, as can be derived from Fig. 4.

REDUCING REFLECTIVITY

First tests have been performed in order to investigate how a reduced reflectivity would affect the performance of String Ribbon solar cells. Therefore, a third experiment was set up and a new batch of solar cells was processed at University of Konstanz using the process schematically shown in Fig. 1 and String Ribbon material with bulk resistivity of 3.5 Ωcm. The only difference concerning processing of the 8x10 cm^2 wafers as compared to the second experiment was the reduced thickness of the PECVD SiN_x layer. Whereas the minimum in reflectivity was in the range of 700 nm for cells processed in the first experiment (optimised for encapsulation), the minimum in reflectivity was shifted towards 560 nm for cells of the third experiment. The average cell parameters were similar to the ones obtained in the second experiment, proving that the SiN_x thickness can be varied in thickness without significantly affecting the (unencapsulated) cell efficiency. Average cell parameters are given in Table 3.

Minimum [nm]	Resistivity [Ω cm]	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
700	3	598	31.7	78.7	14.9
560	3.5	598	31.8	77.0	14.7

Table 3: Cell results for the third experiment (thinner SiN_x) in comparison with results from the second experiment (averaged over 5 cells each).

The advantage of the thinner SiN_x is the fact that a second layer antireflection coating can be deposited to demonstrate a further reduction in reflectivity. Therefore, MgF_2 was deposited by thermal evaporation on one cell. The resulting reflectivities before and after the deposition are shown in Fig. 7.

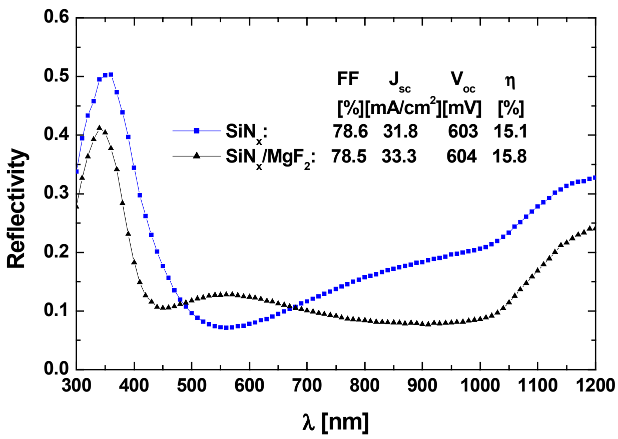

Fig. 7: Reflectivity and IV parameters of a cell from experiment 3 before and after evaporation of MgF_2 as a second antireflection coating.

The deposition of MgF_2 results in a significant reduction of reflectivity and therefore in a remarkable increase in J_{sc} of 1.5 mA/cm^2. This is due to the shiny surface of String Ribbon solar cells after the acidic etching. A standard alkaline etch as it is commonly used for ingot cast multicrystalline wafers leads to unsatisfactory results, possibly due to preferential etching at grain boundaries, and can not be applied for a reduction in reflectivity. The higher reflectivity of the String Ribbon solar cells is therefore an issue which should be addressed in order to further improve cell efficiencies. Although an encapsulation of the cells with SiN_x antireflection coating automatically leads to a lower reflectivity, still higher module efficiencies would be possible by using a textured surface.

A simulation using the best cell of experiment 2 is shown in Fig. 8. Here the external quantum efficiency as measured with the thick SiN_x antireflection coating (minimum at 700 nm) is shown together with the measured reflectivity. This leads to the given internal quantum efficiency. If we assume a reflectivity as shown in Fig. 7 for the cell of experiment 3 after the additional MgF_2 deposition, the internal quantum efficiency will not be affected, but the external quantum efficiency will change. This new (simulated) external quantum efficiency leads to a new (simulated) J_{sc} which can be calculated to be 34.1 mA/cm^2. This value for J_{sc} in combination with V_{oc} and FF of the cell from Table 2 would lead to efficiencies in the range of 16%. This simulation gives an estimation of the current potential of the String Ribbon material if some kind of surface texture could be applied.

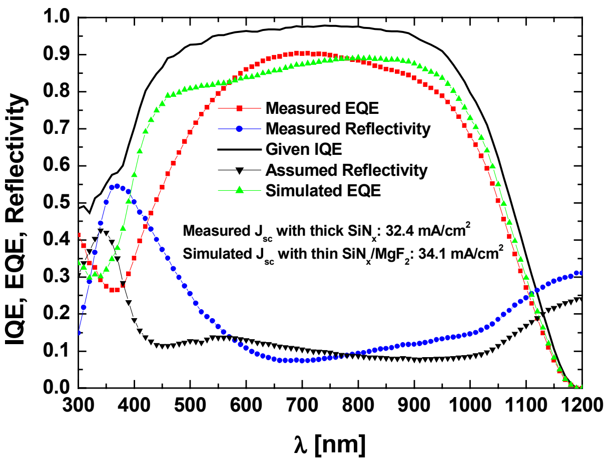

Fig. 8: Measured EQE, IQE and reflectivity of the best cell from experiment 2 and the resulting EQE of a simulated reflectivity (thinner SiN_x and MgF_2 as second antireflection coating) in order to estimate the current potential of String Ribbon material.

SUMMARY

Large area screen printed String Ribbon solar cells have been processed at the University of Konstanz using wafers with bulk resistivities of 1, 3, and 5 Ωcm. Average efficiencies of 15% (8x10 cm^2 cell size) have been reached on 5 Ωcm material, slightly lower values for the other resistivities. A very homogeneous J_{sc} for the 5 Ωcm material proves the excellent material quality after cell processing. For the best cell a confirmed record efficiency of 15.4% could be measured using an industrial type firing through SiN_x process, which is by far the highest value for a large area industrial type String Ribbon solar cell so far. The thickness of the SiN_x layer for cells from this experiment was optimised for encapsulation of the cells. Therefore, a thinner SiN_x could further enhance J_{sc} and lead to even higher cell efficiencies.

In order to demonstrate the effect of a reduced reflectivity MgF_2 was evaporated as a second layer antireflection coating on String Ribbon cells from another experiment using a thinner SiN_x. A significant increase in J_{sc} of 1.5 mA/cm^2 was observed and efficiencies in the upper 15% range have been obtained. From this experiment it can be concluded that industrial type String Ribbon solar cells will significantly benefit from an additional surface texture on both the cell and module levels.

Finally, a simulation was carried out to demonstrate the effect of a second layer MgF_2 antireflection coating for the best cell processed with the thick SiN_x. From the assumed reflectivity a simulated increase of 1.7 mA/cm^2 can be concluded which would result in an efficiency in the 16% range. This simulation gives an estimation of the current limitations of String Ribbon material using an industrial type cell process.

LITERATURE

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