16% EFFICIENCY ON ENCAPSULATED LARGE AREA SCREEN PRINTED STRING RIBBON CELL

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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. Emphasis was laid on the effect of encapsulation under module glass concerning reflection and efficiency. Therefore the optical properties of different glasses have been determined. Cells having two different thicknesses of the SiN layer have been characterised by spectral response as well as IV data analysis before and after encapsulation. The highest efficiency reached in this investigation was 16% using a 8x10 cm^2 solar cell (independently confirmed) which is the highest value reached so far on String Ribbon material using large area industrial type processing.

1. INTRODUCTION

String Ribbon silicon [1], commercially produced by Evergreen Solar Inc., is a cost effective alternative to standard cast multicrystalline materials due to the lack of kerf losses during wafer production and lower wafering costs. The good quality of String Ribbon material could recently be demonstrated by a 17.7% record efficiency cell (2x2 cm^2) fabricated in a photolithography process [2]. High efficiencies have also been achieved already on screen printed cells after applying an industrial type fire through SiN process on areas of 2x2 cm^2 (15.6%) [3] as well as 8x10 cm^2. Confirmed efficiencies of up to 15.4% could be reached on 8x10 cm^2 cells [4]. The next step with regard to industrial perspectives in the PV market is to demonstrate the performance of large area solar cells fabricated in an industrial type process after encapsulation in order to demonstrate the potential of the solar cell material on the module level. In this publication the impact of different glasses used for encapsulation on the module's optical and electrical parameters is studied.

2. CELL PROCESSING

The cell process applied at the University of Konstanz for the 3-5 Ωcm p-type String Ribbon wafers produced at Evergreen Solar Inc. is schematically shown in Fig. 1. 8x10 cm^2 wafers have been acidic etched using a modified CP6 polish etch to remove the top surface layer. The following open tube $POCl_3$ diffusion resulted in a 45-50 Ω/sq. emitter. A hydrogen-rich SiN_x layer using low frequency direct plasma PECVD (plasma enhanced chemical vapor deposition) provides a single layer ARC (antireflective coating) as well as a reservoir for hydrogen. The Hydrogen is released into the cell during the high temperature firing step and helps to passivate crystal defects. Two different thicknesses of the SiN_x layer have been tested (referred to 'thick' and 'thin' in the following). Front and back contact formation is applied by standard screen printing of Ag and Al paste, followed by the co-firing step through the SiN_x. Edge isolation was carried out by dicing the edges resulting in 8x10 cm^2 solar cells.

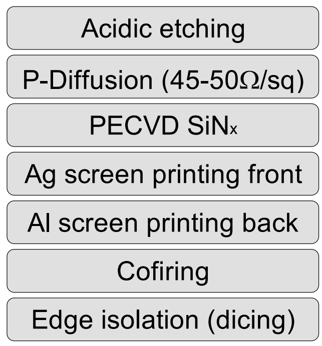

Fig. 1: Solar cell process applied for the 8x10 cm^2 String Ribbon cells processed in this study.

The best cell fabricated according to the process shown in Fig. 1 showed an efficiency of 15.6%. A MgF_2 layer was deposited as a second layer ARC to demonstrate the potential of the String Ribbon material on solar cell level. Efficiency could be increased to 16.1% after deposition of the MgF_2 layer, which is the highest value obtained on large area screen printed String Ribbon material. Cell parameters before and after MgF_2 deposition are listed in Table I. Fig. 2 shows a map of the best cell's internal quantum efficiency (IQE) at 980 nm proving the excellent material homogeneity with only a small fraction of the cell area suffering from unpassivated crystal defects.

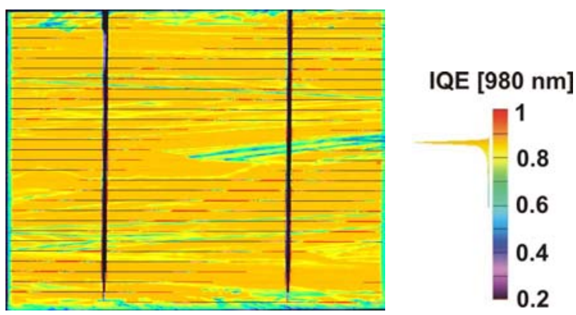

Fig. 2: IQE mapping at 980 nm of the best String Ribbon cell fabricated in this study. Only a small fraction of the cell area contains unpassivated crystal defects.

Table I: IV parameters of the best large area screen printed String Ribbon cell (8x10 cm^2) before and after deposition of MgF_2 as a second layer ARC.

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
best cell SiN_x ARC	609	33.3	77.0	15.6
after MgF_2 DARC	611	34.1	77.3	16.1

3. GLASSES FOR ENCAPSULATION

3.1 Optical Properties

Three different glasses have been characterized. Wavelength dependant transmission *T* and reflection *R* of the glass have been measured with a spectrophotometer and absorption *A* has been calculated using the relation

$$A = 1 - T - R. \quad (1)$$

In Fig. 3 the optical data are shown for normal window glass, MM glass (a standard low-Fe glass from Flabeg used for PV module encapsulation in industry) and MMAR glass (including an ARC which is formed commercially on both surfaces).

For normal window glass an increased absorption in the infrared part of the spectrum can be seen, whereas the ARC leads to low reflection losses for the MMAR glass. After encapsulation reflection losses will be reduced to roughly half of the value of the glass alone, because the second interface will not be glass/air as it is the case for the measurements in Fig. 3 but glass/EVA/SiN_x showing very low optical losses due to the matching of refractive indices.

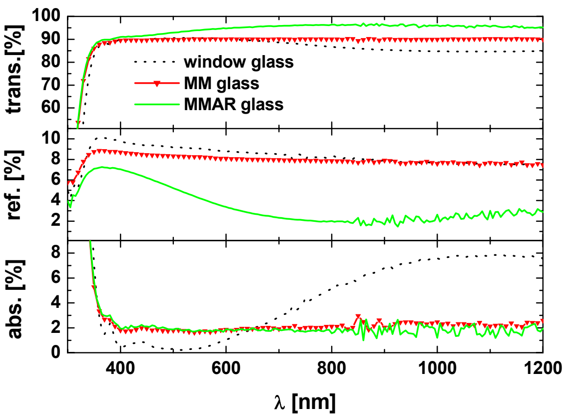

Fig. 3: Transmission, reflection and absorption data of the glasses under investigation.

3.2 Encapsulation of String Ribbon solar cells

The encapsulation of single cells was carried out using a small lab-type laminator. Tabbed cells with a size of 8x10 cm^2 are encapsulated using Ethylene Vinyl Acetate (EVA) and 14x14 cm^2 sheets of glass. Since the structure uses no backside glass or backskin, the encapsulated cells can be easily measured using a standard sun simulator for solar cells or spectral response (SR) set-up, as the backside of the cell is the backside of the structure. Additionally, by using the same solar simulator and IV tester both before and after encapsulation, we avoid any inconsistencies associated with spectral differences of say a light source for a cell tester and that for a module tester. Standard measurements carried out before and after encapsulation are illuminated IV using a shadow mask, large area spectral response to determine external quantum efficiency (EQE), as well as large area reflection resulting in internal quantum efficiency (IQE).

3.2.1 Window Glass

Fig. 4 shows the SR results for a cell encapsulated using 4 mm thick window glass. The IQE curve following encapsulation is lower in both the long and short wavelength regions as compared to the curve prior to encapsulation. If we take out the effect of the absorption in the glass (Fig. 3) we see that the IQE curves are identical in the long wavelength region both before and after encapsulation. Thus, the reduced response in the short wavelength region must be due to absorption in the EVA. As is shown in Table II, J_{sc} after lamination is decreased due to this absorption in the EVA and glass.

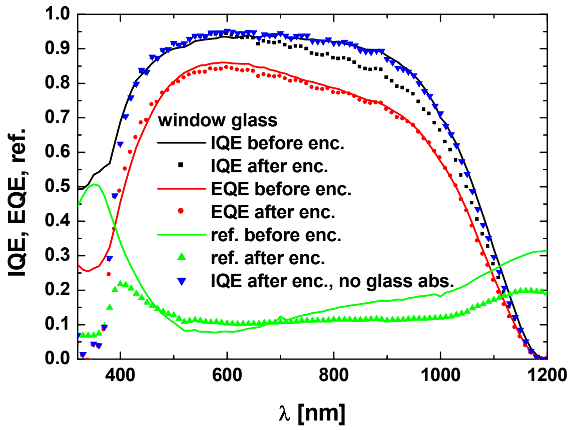

Fig. 4: SR data of a String Ribbon cell before and after encapsulation using window glass.

3.2.2 MM Glass

Fig. 5 shows the same analysis for 4 mm MM glass. Here, there is almost no IQE decrease visible for long

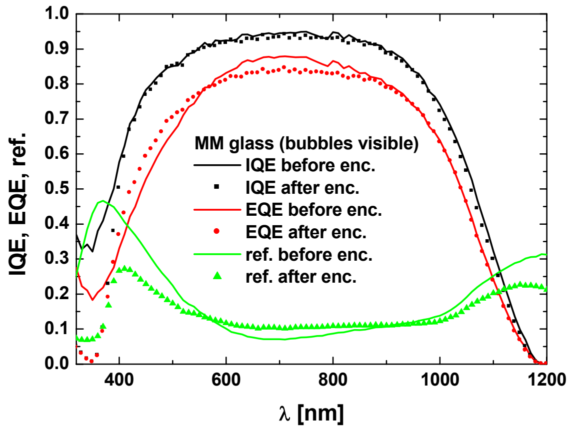

Fig. 5: SR data of a String Ribbon cell before and after encapsulation using MM glass.

wavelengths, but again the drop for short wavelengths <400 nm can be detected. Overall, J_{sc} can be increased by 0.3-0.45 mA/cm^2. After encapsulation some bubbles could be seen caused by problems during encapsulation affecting the EQE, but not the IQE.

3.2.3 MMAR Glass

The effect of the additional ARC on both sides of the MMAR module glass can be seen in Table II. The lower reflectivity leads to an increase in J_{sc} of 1.1 mA/cm^2. But the second ARC between the glass and the EVA/SiN system causes optical losses, as the refractive indices are not matched. Because of this, it would be even better to have the ARC only on the top side of the glass.

Therefore, the second ARC on the lower side of the glass has been mechanically removed in order to study the effect of a glass with only the top side having an ARC (referred to as MMAR one side). The J_{sc} increase in this case is 1.3 mA/cm^2. Fig. 6 illustrates the effects of the different MM glasses on reflectivity of the final structure. In the case of MMAR (one side) reflectivity is reduced for all wavelengths, whereas for the other glasses there are regions showing a slightly increased reflectivity.

Table II: Effect of encapsulation on J_{sc} [mA/cm^2] using different glasses.

	J_{sc} before	J_{sc} after	ΔJ_{sc}
window glass	31.7	30.8	-0.9
MM glass	32.0	32.3	0.3
MMAR glass (two sides)	31.3	32.4	1.1
MMAR glass (one side)	31.0	32.3	1.3

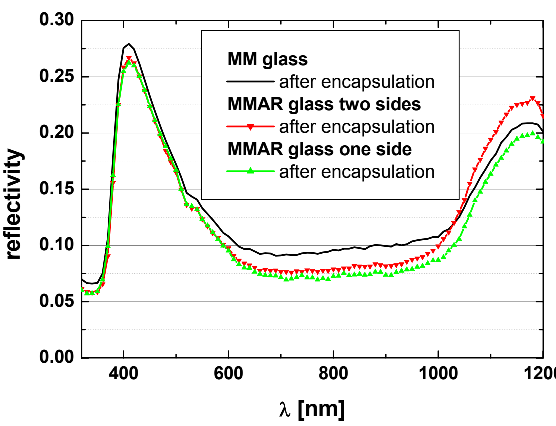

Fig. 6: Effect of the different glasses (MM, MMAR, MMAR one side) on reflectivity of String Ribbon cells after encapsulation.

3.3 Effect of SiN_x Thickness

For this investigation solar cells with two different thicknesses of the SiN_x layer have been used (minimum in reflection at 580 and 700 nm respectively). In Fig. 7 the reflection of two solar cells with different SiN_x layer thicknesses before and after encapsulation using MM glass are shown. The increases in J_{sc} for both cells are in the range of 0.3-0.45 mA/cm^2 therefore it can be concluded that similar increases in J_{sc} can be obtained for a broad range of SiN_x thicknesses. An additional study will address the effect of a medium SiN_x layer thickness in the future.

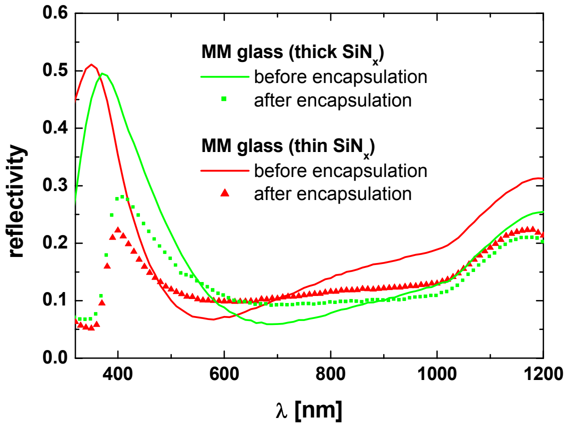

Fig. 7: Effect of SiN_x thickness on reflectivity before and after encapsulation.

3.4 Best Encapsulated Cell

Best results have been obtained by using the MMAR glass with a one sided ARC. Therefore the best String Ribbon cell has been encapsulated using this glass. Fig. 8 gives the SR data of this cell before and after encapsulation. The efficiency of this cell has been independently confirmed to be 15.8%, being the highest value reached for a large area screen printed String Ribbon cell fabricated according to an industrial-type process (Table III). By using a shadow mask 1 mm larger than the cell area, which is the more realistic case for a module, efficiency was confirmed to be 16.0%. Efficiency is higher in this case as the glass has a rough surface resulting in scattering of photons. A ray of light hitting the glass perpendicularly above the cell close to the cell's edge might be scattered and miss the cell's surface. On the other hand, a photon penetrating the glass just outside the cell area could be scattered and finally enter the cell. By using a shadow mask with exactly the size of the encapsulated cell, the second effect described above is not possible, as the shadow mask hinders the photon to reach the glass and be scattered into the cell. But the other effect (photon hitting the glass above the cell but scattered out of the cell area) is still possible. In a module both effects are possible, as there is a neighbouring cell and the 'shadow mask' is the whole module area.

16.0% is almost the same efficiency as was reached for the cell presented in section 2 with MgF_2 evaporated as a second layer ARC. Therefore it can be concluded that the performance of the cell encapsulated under glass in the module using standard industrial type processing (SiN_x as single layer ARC) can be as high as cell performance using more sophisticated processes like deposition of a MgF_2 second layer ARC to reduce reflectivity.

The remaining reflectivities of these two cells can be seen in Fig. 8. The different shape of the curves is mainly due to the different SiN_x thicknesses (thin SiN_x for MgF_2 deposited cell, thick SiN_x for encapsulated cell). Another reason is the difference of refractive indices of MgF_2 on the one hand and glass/EVA on the other.

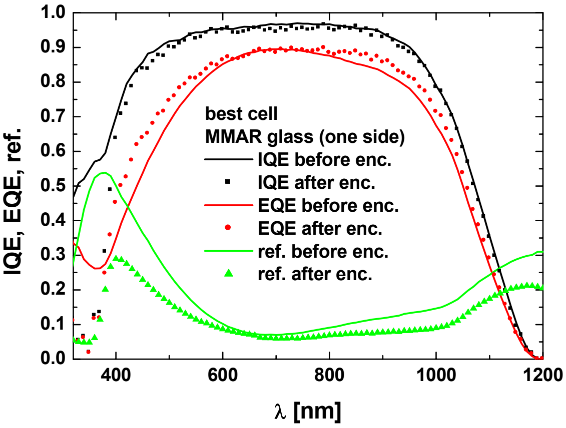

Fig. 8: SR data of the best String Ribbon cell encapsulated using MMAR (one side) glass.

Table III: IV data of the best encapsulated 8x10 cm^2 String Ribbon cell (independently confirmed at $^+$FhG-ISE, *EC JRC Ispra).

	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]	η [%]
$^+$Before encapsulation	610	32.4	78.3	15.4
*After encapsulation, mask = cell area	609	33.4	77.6	15.8
*After encapsulation, mask 1 mm > cell area	609	33.8	77.6	16.0

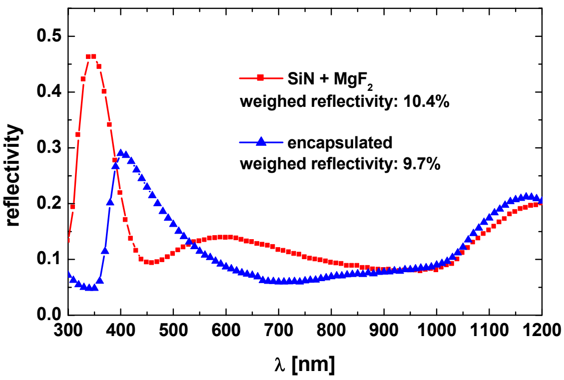

Fig. 9: Reflectivities of the best String Ribbon cells presented in this study.

4. CONCLUSION

Large area (8x10 cm^2) screen printed solar cells have been processed using String Ribbon material. Efficiencies of up to 15.6% could be reached using an industrial-type process with a PECVD SiN_x layer as single layer ARC. The deposition of an additional MgF_2 layer for a further reduction of reflectivity resulted in an efficiency of 16.1%.

We have demonstrated that encapsulating String Ribbon cells behind low-Fe glass can result in higher currents, and that the addition of a commercially available ARC on the glass can increase the currents yet higher. Ideally, this AR coating should be present only on the outside surface of the glass. Due to these higher currents we have now measured an efficiency of 16% on an encapsulated large area screen printed String Ribbon cell, which is in the same efficiency range as could be reached on cell level with a double layer ARC. Despite this achievement we have not yet demonstrated the industrial viability of such AR coatings on glass. More study concerning the effects of dirt, water, angle of incidence, and aging on the transmission of the glass needs to be performed, the aesthetics and market acceptance needs to be verified, and the additional cost of the coating needs to be justified.

5. ACKNOWLEDGEMENTS

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