TRANSMISSION ELECTRON MICROSCOPY OF AMORPHOUS TANDEM THIN-FILM SILICON MODULES PRODUCED BY A ROLL-TO-ROLL PROCESS ON PLASTIC FOIL

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ABSTRACT: An improvement of the photo-current is expected when amorphous silicon solar cells are grown on a ZnO texture. A full understanding of the relationship between cell structure and electrical performance is essential for the rapid development of high efficiency VHF-tandem cells on textured substrates. At first, we present the systematic study where amorphous cells are grown on ZnO based textures. For varying the texture, the same original master LPCVD ZnO was successively transferred to nickel molds and finally transferred to the plastic foil by roll-to-roll process. From TEM images, we show how a control-lost of shape fidelity is used to smooth the texture and make it compatible with subsequent layer growth. Then, we present the electrical performances of the most promising reference solar cell single junction which was obtained on a roll-to-roll foil. Finally, a tandem amorphous/amorphous Si reference cell was produced on textured foil with a stable efficiency of 8%. The first PV modules on UV textured plastic foil with aluminium back reflector were also produced with initial efficiency of 7%.

1 INTRODUCTION

In order to meet the price target necessary for flexible solar cell applications, roll-to-roll production processes on cheap flexible substrates need to be optimized [1]. So far, the use of nip amorphous Si (a-Si) layers allows VHF-technologies to produce low cost reliable and flexible modules with 6% efficiency [2]. Nowadays, two options are available in roll-to-roll processes to increase the module efficiency while keeping the production cost low: (1) the use of optimized textured substrates to increase light trapping efficiency [3]; (2) multi-stacking of thin active silicon layers in tandem - amorphous/amorphous or micro-morph – micro-crystalline/amorphous cells to increase the overall optical absorption range and to limit cell degradation [4].

The use of a several micrometer-thick ZnO layer on top of the glass substrate has been shown to result in a significant improvement in light trapping efficiency [5]. Due to the use of high temperature deposition and its brittle nature, a thick ZnO layer cannot be used on flexible plastic solar cells. In contrast, UV embossing technique allows ZnO-like texturation to be transferred and is fully compatible with plastic foil substrates and a low temperature deposition process. In the past, the optimisation of back contact structures has been made using chemical etching of original ZnO layers. Due to roll-to-roll industrial constrains, a direct way to transfer optimal texture to plastic substrate has to be found. In the other hand, the growth and the quality of silicon layers are highly influenced by the topography of the substrate. High efficiency is generally a trade-off between maximum current and good electrical performance of the cell. In order to relate efficiency to texturation for a minimum cell thickness, the growth of layers was investigated systematically by transmission electron microscopy (TEM).

In the present work, the process to produce optimized textured back-contact compatible with roll-to-roll process is exposed. Then, the texture is transferred using UV-Nanoimprint Lithography (NIL) and the growth parameters of the consecutive layers are optimised at a lab scale. In a second part, the optimal textured parameters are used for roll-to-roll production and cells are characterized optically and electrically. In a third part, we present an optimisation of a tandem a-Si/a-Si cell produced in roll-to-roll process. We also present the results at module scale, of a tandem, a-Si/a-Si solar cell on textured surface.

2 EXPERIMENTAL DETAILS

2.1 Mold fabrication for roll-to-roll UV embossing

We used the pyramidal surface texture of 3 μm thick LP-CVD ZnO grown (std3-ZnO) on a 0.5-nm-thick glass substrate [6].

The production of textured plastic includes nickel electroforming steps at small area scale - 100 by 100 mm - and a thermal recombination work for obtaining a larger area textured tool of 600 by 900 mm. Then, thanks to a dedicated roll-to-roll process, the texturation is transferred form the tooling mold onto the plastic foil over 530 mm width and a length up to 3000 meters. It must be noted that process and resin were optimized to get good shape fidelity, good adhesion on plastic foil and low outgasing under vaccum and at high temperature (200°C). It must be noted that the low texturation is actually the final texture that will be further used in the full roll-to-roll PV process. Thus, the major interest of performing the lab scale study is to compare the potential gain of cell performance of the original ZnO texture with final UV texture on plastic foil.

2.2 Lab cell fabrication

1 by 1 cm a-Si single junction solar cells with Ag-ZnO sputtered back-reflector were grown on different textures - type 1, 2 and 3 being for high, middle and low texturation. Nominal thickness layer of 250 nm for a-Si was deposited using VHF PECVD reactor and ITO was used as TCO. The replication of the textures from the mold was achieved using UV NIL [7].

2.3 Reference cell and module fabrication by roll-to-roll process

For the roll-to-roll and module application, the type 3 UV texture on plastic foil was transferred. Both single a-Si junction and tandem a-Si/a-Si were grown using standard VHF-technologies PECVD reactors. The reference cell and module back reflectors are made of sputtered Ag-ZnO and sputtered Al, respectively. ITO was used as TCO.

2.4 Degradation setup

Cell degradation was performed according to the procedure 10.19.3 of IEC 61646 640W/m2 (600-1000W/m2) 46° (50°C +/- 10°C) until saturation is reached, i.e the power fluctuation is below 2% for two consecutive measurements. To reduce the effect of heating of the cell by IR, a LED 6000K was used. Moreover, the spectrum of this illumination set-up fits well with the tandem a-Si/a-Si cell. In the case of reference cell (or lab cell), it is very difficult to realise the degradation under electrical load. In our case, we placed the device in open circuit condition.

2.5 TEM experimental setup

SEM cross-section sample and TEM lamella were prepared in a Helios nanolab FEI microscope. Standard lift-off process was used to prepare TEM lamella. Bright-field (BF) images were taken on an FEI Tecnai T-20 equipped with a LaB6 electron source.

3 RESULTS and DISCUSSION

At lab scale, the optimal ZnO back-contact textures for a-Si can be obtained using as-grown ZnO layers, followed by a chemical etching [7]. So far, thick ZnO as well as chemical etching are not convenient for roll-to-roll process. In this section, we develop a large scale roll-to-roll compatible process to obtain optimal texturation. The optimal texture was qualified at lab scale level.

3.1 Texturation

3.1.1 Mold production

As previously mentioned, the original ZnO textured has to be smoothed to obtain high performance solar cells. The transfer of the original texture to sub-molds is realized by tuning the shape fidelity at each transfer steps. Our original strategy is shown figure 1. The first transfer is made using electroforming step from an original 3-µm-thick ZnO layer (Fig 1 (a)) – 297 nm average RMS and 390 nm correlation length - to a Ni mold, this first replication has a good shape fidelity close to 100% (not shown). Then, the texture of this 10 by 10 cm nickel mold is transferred onto a large area mold (90 by 90cm) by a thermal recombination work and electroforming (Fig 1 (b)), 186 nm average RMS and 350nm correlation length are obtained. Finally, the texturation from the large area mold is transferred by UV embossing roll-to-roll process on plastic foil. In that case, the obtained texturation is close to the desired values (185 nm and 344 nm correlation length. [7]).

3.1.2 Transfer of the texture on glass lab cells

From these three textures, molds are produced. Then, the resin deposited on glass substrates is textured by UV-embossing. The roughness and correlation length values are shown Table 1.

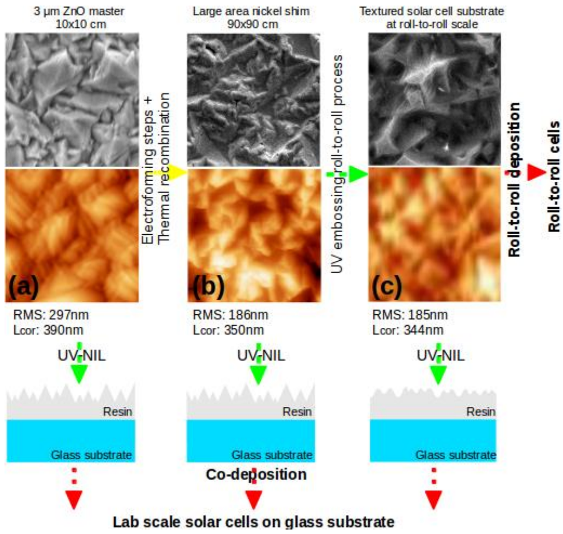

Fig 1: Process flow used to produce textured substrates. The (a) type 1: original 3 µm thick ZnO layer, (b) type 2: large scale nickel mold and (c) type 3: textured plastic substrate is used as molds to transfer the texture to the glass substrates. The textures are transferred to the glass/plastic substrates by UV-NIL embossing. Then, solar cells are grown on textured substrates. All the AFM and SEM images are at the same scale.

3.2 Solar cell on glass substrates with textured resin

3.2.1 Morphological characterization

The figure 2 (a-c) shows large field of view TEM pictures of lab solar cells grown on glass substrates with textured resin. The type 1 texture is much rougher than the other two types; however, the growth of the top layers is almost conformal. Type 1 (fig 2 (a)) has bottom interface with U-shape valleys and a-Si/ITO interface with V-shape valley. Type 2 (fig 2 (b)) also shows some V-shape valleys at the a-Si/ITO interfaces but the overall texture is smoothed compare to type 1. For type 3 (fig 1 (c)), the bottom and the top valleys are U-shape and the growth of layers is highly conformal. Figs 1 (d-f) are higher magnification on selected valleys for the three studied layers. These views highlight the transformation for U-shape to V-shape valley when solar cells are grown on highly textured substrates. Only the type 3 does not show a V-shape a-Si/ITO interface. We observe that the ZnO layer on top of the Ag back-contact layer is conformal for the three structures.

The major point to notice is the presence of denser material in the a-Si layer below the V-shape interface for the type 1 structure, most probably deposition of ITO in the voids left empty when growing a-Si layer from deep valley.

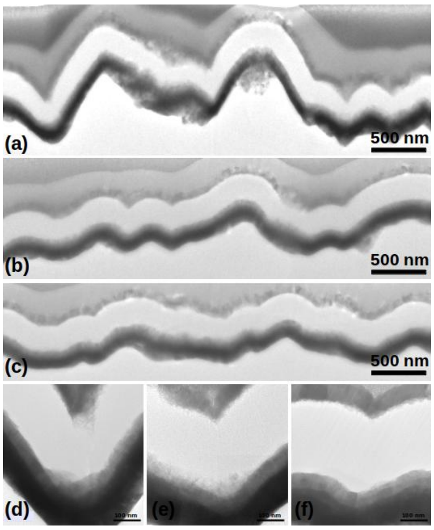

Fig 2: TEM pictures of solar cells grown on textured substrates, obtained from the (a)-(d) type 1, (b)-(e) type 2 and (c)-(f) type 3. From the bottom to the top, the layer stacking is: resin, Ag, ZnO, a-Si and ITO.

3.2.2 Electrical performances

The optical and electrical performances of the lab solar cells are reported in Table 1. We clearly notice a reduction of the Voc and of the FF for solar cells grown on highly textured substrates. The better electrical performances are obtained for type 3. So the electrical parameters are better when less texturation is used, but an increase of the electrical performance is still obtained compare to flat cell.

Texture type	Roughness [nm]	Correlation length [nm]	Jsc [A/cm²]	Voc [V]	FF [%]	Efficiency [%]
1	180	390	13.08	850	58	6.4
2	120	350	12.48	893	64	7.1
3	110	344	13.37	911	67	8.1
flat	-	-	10.6	917	69	6.7

Table 1: Morphological and electrical parameters of ZnO lab scale textured series – average values other 20 cells. The p-layer is thicker for textured cells.

3.2.3 Relation texture/electrical performances

The fig 3 shows the relation between the ZnO/a-Si and a-Si/ITO opening angles and the FF. A linear increase of the FF is observed when the angle becomes wider. In fact, due to the present of ITO in the voids of the a-Si, the resistance between the top and the bottom contacts is lowered. We also measured an increase of the shunt resistance with the widening of the valleys. So, the best efficiency cell is obtained for type 3.

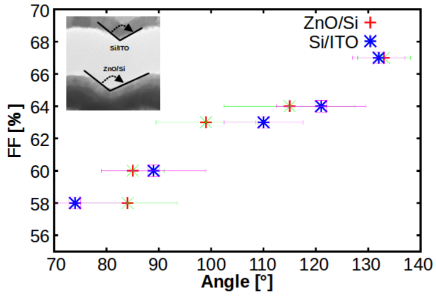

Fig 3: Fill factor as a function of opening angle measured at the ZnO/a-Si and Si/ITO interfaces. Insert shows how the angles have been measured.

3.3 ZnO texture at roll-to-roll scale

Knowing the texture which gives the optimal electrical performances, we used it in the roll-to-roll PECVD process.

3.3.1 Morphological characterization

Fig 4 (a) shows a SEM top-view of the textured substrate before the deposition of the back-contact. The conformal mapping of the layer deposition process has been checked with doing FIB-SEM cross-section (Fig. 4 (b)). The SEM overview is to compare with the fig 2 (c), only few high structures are observed, most of them being in the sub-micrometer range. The a-Si/ITO is quite round, and almost not V-shape features are observed. So according to section 3.2.3, the FF should not be affected by the texturation.

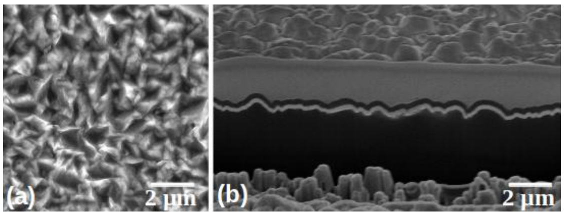

Fig 4: (a) Top view back reflector and (b) FIB cross-section of roll-to-roll scale a-Si SEM images

3.3.2 Optical and electrical performances

The spectral response of the roll-to-roll optimised cells is shown fig 5 (a), for comparison, spectral response of a flat cell is also shown. Compare to flat cell, the optical absorption is largely enhanced by the presence of a textured back-contact. Fig 5 (a) also shows the spectral response of the cell after 1000h of degradation. The degradation is measured, so even if some defects are introduced, the degradation of the cell is still reasonable with a final FF of 61.6%. Fig 5 (b) is the IV curve of the reference cell obtained in roll-to-roll, both as-grown and after degradation.

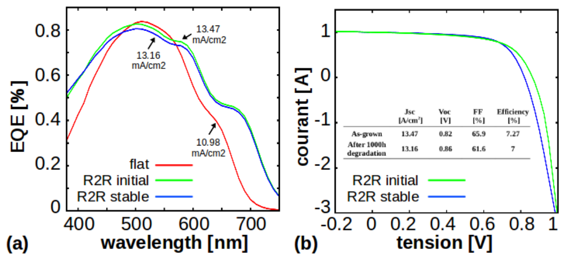

Fig 5: (a) spectral response and (b) IV curve of the cell obtained in roll-to-roll for flat and UV embossed texture.

3.4 Tandem-cell on roll-to-roll UV embossed plastic foil

Another way to improve the performance of the solar cell, other then texturation, is to decrease the degradation of the cell. This point is even more important when solar cells are grown on texture substrates, which increases the defect density in the a-Si layer. Tandem a-Si solar cells consist of a bottom and a top a-Si cells.

3.4.1 Optical and electrical performances of a reference tandem cell

The spectral response of the reference cell is shown fig 6 (a). The response of both, the top and the bottom cells are shown, as well as the total response of the tandem cell. Fig 6 (a) shows the spectra response of the cell after 1000h of degradation. Fig 6 (b) is the IV curve of the roll-to-roll grown cell, both as-grown and after degradation for a tandem cell. The IV curves show less degradation. The total efficiency after degradation is higher than 8%.

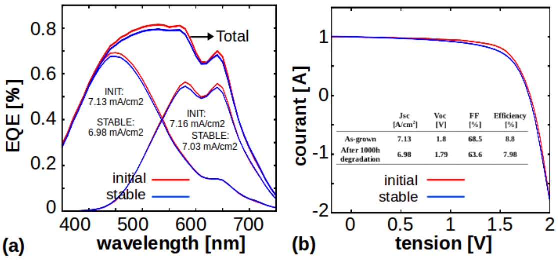

Fig 6: (a) spectral response and (b) IV curve of the tandem cell obtained at reference cell. The values in the table are average over 10 different cells.

3.4.2 Tandem cell produced by roll-to-roll at module scale

The fig 7 (a) is a large field of view TEM images of the tandem cell grown of plastic substrate by roll-to-roll process. The bottom Al layer has a U-shape; the top a-Si/ITO interface has a V-shape. It seems that when growing thicker layers on textured substrates, even if the growth seems to be conformal for the bottom layer, the top layer lost in conformal mapping. A magnified picture is shows fig 7 (c), the 300 nm bottom a-Si layer seems to grow conformally, even if the valley of the bottom/top interface cell is less round then the a-Si/back-contact interface. The clear contrast between the bottom and the top cell is due to different dilution ratio, used to tune the optical absorption range. The valley on the ITO layer has a V-shape, which should contribute to a decrease of the FF factor, as explained section 3.2.3. The initial electrical performances of the tandem module are shown fig 8. The degradation is still on-going. The initial efficiency is of 7% and the final is expected to be of 6%.

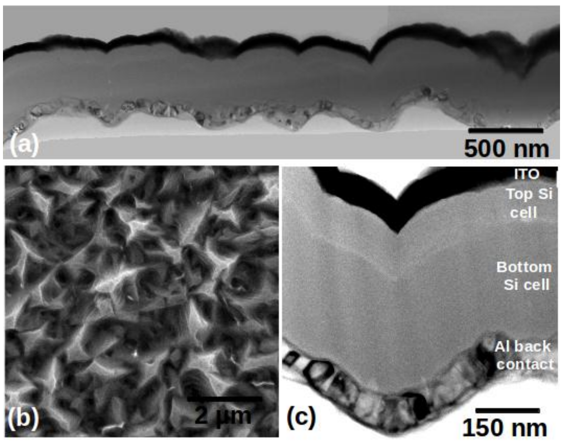

Fig 7: (a)-(c) cross-section TEM images of the a-Si tandem cell on plastic foil. (b) top view SEM images of textured plastic substrate by roll-to-roll process.

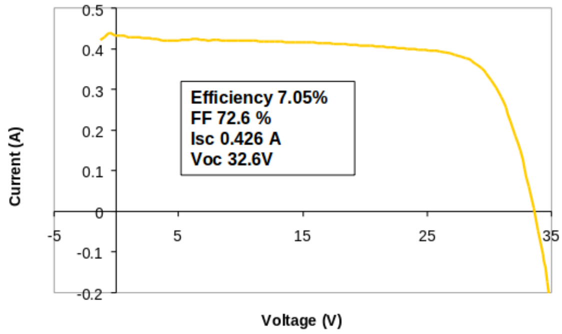

Fig 8: IV curve of the module tandem cell obtained by roll-to-roll process on plastic substrate. The initial electrical performances are shown in insert.

4 CONCLUSIONS

TEM study demonstrates the relation between texture morphology and cell performance through the increase of the FF factor with the smoothing of the texture. In fact, when a roughness of 180 nm is used for the back contact, the growth of a-Si layer does not fully fill the bottom of the valleys. We have obtained a stable efficiency of 7% on plastic substrate for reference cell on roll-to-roll process.

The optimized ZnO texture was also used as back-contact for the tandem a-Si/a-Si. 8% stable a-Si/a-Si reference cell was obtained on roll-to-roll plastic foil and 7% initial efficiency on module tandem cell obtained by roll-to-roll process on plastic substrate.

We shown that roll-to-roll UV embossing foil can be used to produce high throughput plastic module by roll-to-roll process. The next technological step for VHF-technologies will be to implement Ag-ZnO back contact on tandem cell to rich more than 7% stabilised efficiency.

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