Light trapping in amorphous silicon solar cells

Vanessa Terrazzoni-Daudrix, Joelle Guillet, Xavier Niquille, Arvind Shah
IMT University of Neuchâtel, Breguet 2,
CH-2000 Neuchâtel, Switzerland / E-mail: vanessa.terrazzoni@unine.ch

R. Morf,
PSI (Paul Scherrer Institut), Villigen, CH-5232, Switzerland

A.Tishchenko, V. Brioude, O. Parriaux
TSI Laboratory, Jean Monnet University, F-42023 Saint-Etienne

D. Fischer
VHF Technologies SA
EICN, avenue de l'hôtel de ville 7, CH-2400 Le Locle, Switzerland

ABSTRACT

In order to simultaneously decrease the production costs of thin film silicon solar cells and obtain higher performances, the authors have studied the possibility to increase the light trapping effect within thin film silicon solar cells deposited on flexible plastic substrates. In this context, different nano-structure shapes useable for the back contacts of amorphous silicon solar cells on plastic substrates have been investigated: random textures and gratings. The optimisation of such back reflectors is so far empirical. Gratings constitute a well-known optical technique and their light trapping effect can be optimised by simulation.
A first conclusion is that neither the traditional “Haze factor” determined in air for a wavelength of 650nm nor the “rms roughness” of the surfaces are sufficient as criteria to optimise the back contact roughness for light trapping in cells. The shape of grains is a further essential criterion.
The authors have so far obtained a relative current enhancement of 16% for solar cells deposited on randomly textured polyethylene terephthalate (PET) as compared to a corresponding conventional solar cell co-deposited on a flat mirror (Ag) on glass. Solar cells on PET with 6.3% stabilized efficiency have until now been obtained. Calculation predict current increase in a-Si solar cells, deposited on blazed grating, up to 30% when compared with the same solar cell deposited on flat surface

INTRODUCTION

In order to simultaneously decrease the production costs of thin-film silicon solar cells and obtain higher performances, the authors have studied the possibility to increase the efficiency (η) of n-i-p solar cells deposited on Poly(Ethylene Terephtalate) (PET). The advantages of this flexible organic polymer are first, its low price compared to more conventional substrates like Polyimide (PI), stainless steel, or glass, and second, its compatibility with roll to roll processes. However, its main drawback is the fact that it can not be heated to temperatures more than 200°C during the deposition of solar cells. Different studies have, on the other hand, already shown that depositing amorphous silicon solar cells at low temperatures has a detrimental effect on their short circuit current (I_{sc}) [1, 2, 3].
In this context the authors studied different kinds of textured back reflectors fabricated on glass or PET in order to enhance the light trapping and, thus, the short-circuit current density

J_{sc} of the cells. Thereby, different nano-structured shapes i.e. random and periodic texture-shapes, usable on glass or on PET as back contacts for nip-type amorphous silicon (a-Si:H) solar cells have been investigated.
So far the periodically-textured substrates used as back reflectors have only been fabricated on glass and incorporated in glass-Ag-ZnO-n-i-p a-Si:H solar cells. Random –textured substrates were obtained by plasma etching of PET and incorporated into PET-Ag-ZnO-n-i-p a-Si:H solar cells.

EXPERIMENTS

Different kinds of substrates, covered with an aluminum or a silver layer, were analysed by AFM, SEM, spectrometer UV-visible and tested in solar cells.

Random textures :

The randomly-textured back reflectors on PET have been produced by etching the substrate with an O_2-plasma process. Etching parameters are mainly the power and etching time. For the present study an etching series was done at 100W and the etching time was varied between 0 min and 8 min. A 1000 nm thick Ag layer was subsequently deposited on the textured PET.
The random textured substrate was then covered with a 100 nm thick ZnO:Al layer.
It is important to notice that the nano-structure sizes of all these randomly-textured back reflectors can easily be empirically optimized by changing the plasma etching parameters or methods.

Gratings

Periodic gratings on glass substrates were made by first exposing the resist-coated glass substrates to a short period interferogram of a HeCd laser. The resist thickness was thin enough to give rise to an essentially rectangular profile with grooves opening down to the substrate. After development, the resist grating was physically transferred into the glass substrate by RIBE (Reactive Ion Beam Etch), down to the requested depth.
The so-obtained periodical nano-structures have then been covered by sputtered layers: a thin (30 nm) Al layer and a very thin (50Å) ZnO:Al layer.

Solar cells

All solar cells on random textured substrates and on gratings are compared with an identically fabricated solar cell co-deposited, on a flat mirror made with glass/Cr/Ag (1000nm)/ZnO:Al(100mn). Solar cells are deposited on a 8x8cm size substrate and are subsequentially structured to obtain several individual solar cells (around 0.25cm^2 area). Top contact is a ZnO CVD layer (2 microns thick).

Random textures

The highly textured PET surface, obtained by the O_2-plasma looks like a carpet with clearly visible nano-rods-like protuberations (figure 1). These nano-rods are also visible without metal layers even on lightly etched PET. One can easily understand that it is difficult to deposit a solar cells (without creating shunts) on a very highly textured PET. On less textured PET, Ag and ZnO modified the top texture.

The AFM image and the profile of the surface of medium textured PET (which constitutes so far the most performing texture) are presented in figure 2.

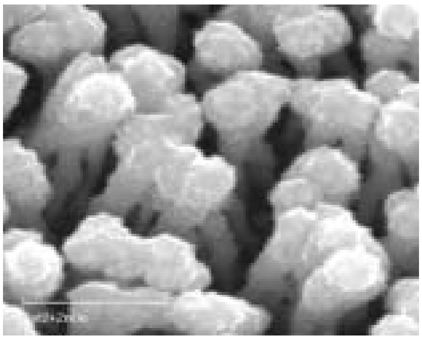


Figure1 : SEM micrograph of very highly textured PET surface covered with an Ag/ZnO layer : Because of the « nano-rods » such a surface has a very high optical absorption, but cannot be used in this form in our present solar cells.

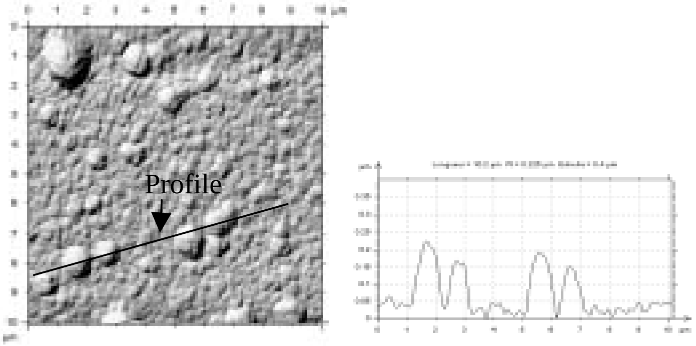
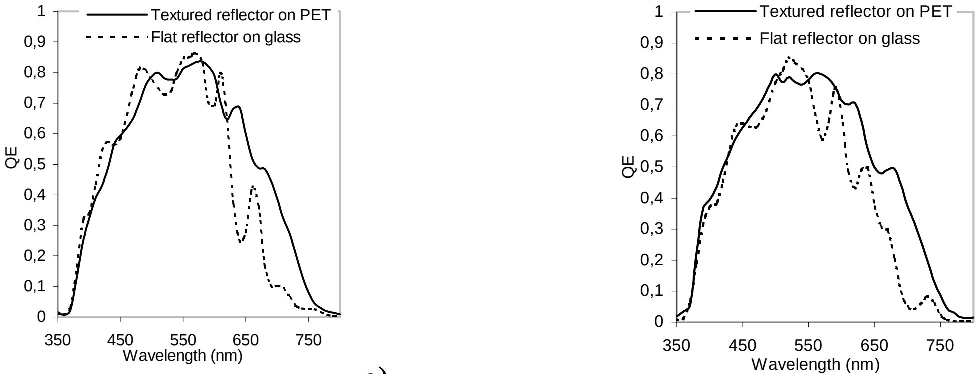


Figure 2 : AFM picture and profile of a performing randomly-textured back reflector deposited on PET fabricated by O_2-plasma etching during 2 minutes plus sputtered Ag and ZnO:Al layer depositions. In the profile, the most represented period and height are 620 nm and 80 nm respectively. The RMS roughness is 48 nm. The large conglomerates are assumed not to be taking part in the light trapping process.

This back reflector has been incorporated in a-Si:H solar cells. QE measurements carried at the initial and degraded states are presented in figure 3.



a) b)

Figure 3: QE of two co-deposited cells on randomly textured (plain line) and on flat back reflectors (dotted line) in the initial (a) and degraded (b) states. The “J_{sc} gain” is equal to 15% and 20% before and after light-soaking respectively.

First of all, such back reflectors with nano-structure sizes of 620 nm for the period and 80 nm for height is well-adapted to improve the light-trapping in 250nm thick a-Si:H cells. Indeed the J_{sc} gain of 20% obtained in the degraded state comes obviously from the range of long wavelengths (~650nm) confirming that, thanks to its scattering properties, the randomly-textured back reflector results in an enhanced absorption of these wavelengths for a-Si:H solar cells. Furthermore the "J_{sc} gain" parameter is higher in the degraded state than in the initial state one so that J_{sc} of cells deposited on textured PET seems to degrade less than that of cells deposited on flat glass. At this stage of the study, this observation could be attributed to a lower effective thickness of the cell deposited on the textured PET substrate (This was confirmed by SEM observations). Indeed, in co-deposition, deposition time and rate are the same but the surface is larger for textured substrates, therefore layers on flat surfaces turn out to be thicker than those deposited on textured substrates.

One can at any rate safety conclude that amorphous silicon solar cells deposited on randomly textured back reflectors are certainly not more prone to degradation than solar cells co-deposited on glass (flat).

Table 1: V_{oc}, FF, I_{sc} and η at initial (BD) and degraded (AD) states of nip a-Si:H thin film solar cells co- deposited on PET and glass.

	Glass (flat)		PET (textured)	
	BD	AD	BD	AD
V_{oc}(mV)	873	873	843	850
FF(%)	67	56.4	64.6	54.5
I_{sc}(mA/cm^2)	11.7	10.3	13.1	12.5
η(%)	6.9	5.1	7.1	5.8

An efficiency of 5.8% at the degraded state has so-far been obtained for cells deposited on textured back reflectors fabricated with PET substrates (compared to 5.1% for the co-deposited cell on a flat mirror on glass). Light-soaking affects especially the FF (the degradation is estimated to be equal to 0 % for V_{oc}, ~18% for FF, and between 5% and 10% for J_{sc}; a J_{sc} decrease of 5% due to degradation is valid for cells on textured substrates and of 10% for cells on flat substrates). The efficiency degradation has been estimated to be 28% on glass as compared with 23% on textured PET because of the lower decrease in I_{sc}. However, as already mentioned above, this result must still be confirmed.

6.5% stable efficiency was obtained on PET textured substrate with i layer deposited with higher silane dilution ([SiH4]/[SiH4+H2]=6). Spectral response showed that p layer as well as back reflector were so far not optimal; this lets us conclude that 8% stable efficiency should soon be possible for solar cells on randomly textured PET substrates.

Gratings

The great advantages of periodic gratings are – the possibility to calculate and, thus, to predict the ideal grating shape for one application, - the possibility to produce it easily by embossing technique. Solar cell need efficient light trapping (specially if they are thin : 1000 time thinner that c-Si solar cells!) . Nevertheless calculations must take into account all fabrications constrains concerned specially grating fabrication, solar cell deposition on these gratings and surface deformation du to layers deposited on these gratings.

1) Different structures are examined: grating on ZnO surface, on metal surface or directly on metal. The easiest solution seems to be the last one : fabricate grating directly on the substrate in spite of the fact that this surface will be covered by an Ag and ZnO layer. This fact lead us to the second point :
2) What could be the best grating shape : square, bump, triangular or blaze grating? Blaze gratings have several advantages: -reproduce blaze grating shape is theoretically possible (see figure 4) compare to square grating, -light trapping is enhance in this case: In figure 5, the diffraction properties of an asymmetric (or

blazed) grating are illustrated. In this case, it is possible to devise structures that only excite right-moving waves, and the first order mode that reaches the rear interface after one total reflection at the front surface is not necessarily coupled into a zero order wave since unlike in the symmetric grating situation, no symmetry principle demands such coupling for a blazed grating structure. So, such right-moving waves are trapped efficiently. Note also that the angle of diffraction is wavelength dependent. For red light diffraction angles are larger than for green or blue light. Thus, the path length of longer wavelength light is amplified more than for light of shorter wave length. Detailed investigations have shown that the light trapping effect based on blazed structures is particularly effectives for solar cell application [4]. For a review, we refer the reader to reference [5].

As some of the investigated structures exhibit strong resonances, numerical stability is not easy to achieve. For this reason, we have employed an unconditionally stable method of solution which has been developed by the author [6].

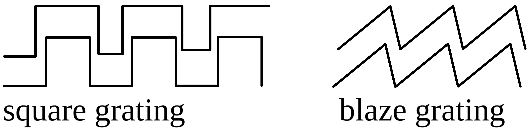

square grating
blaze grating

Figure 4: It is physically impossible to reproduce a square grating after deposit layer with thickness larger than grating period and grating height dimensions, whereas it is possible with a blaze grating.

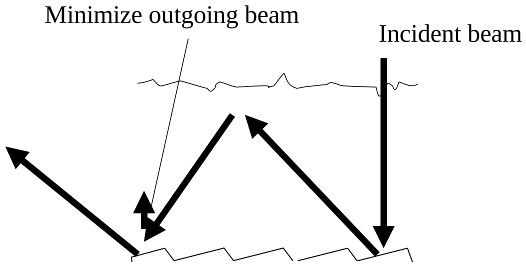


Figure 5 : Illustration of light diffraction by an asymmetric grating at the rear surface of a solar cell. The blazed grating preferentially excites right moving modes. These do not necessarily couple to the zero order outgoing mode (denoted outgoing beam). That coupling can be minimized by careful design.

First calculations by means of numerical solution of Maxwell's equations [4] shows that it is possible to increase solar cell current by near 30% compared to the same solar cell deposited on flat surface. This result was obtained with Ag back contact and by fixing the grating period dimension. In future, study will consist to find also the ideal grating period for a-Si solar cell application.

Amorphous silicon solar cells were deposited on square grating, made in glass substrate and covered with very thin Al back contact. Even with a non ideal grating and back reflector, a-Si solar cell current increased by 10% compared with the same solar cell deposited on flat glass substrate.

CONCLUSION

Two approaches are investigated to enhance the a-Si solar cell current: random textured substrates and substrates with diffraction gratings. Up to now, good results were obtained with random textures on PET: a 16% higher current was obtained than with the same solar cell deposited on flat reflector surface. If instead, diffraction gratings are used (not ideal), we find current enhancement of the order of 10%. That this is not the limit is born out by our theoretical calculations for diffraction grating structures which predict current increase in a-Si solar cells up to 30% when compared with the same solar cell deposited on flat surface. These results are very encouraging. In the future, we will fabricate and test these grating structures. The particularly convenient approach is based on the use of PET substrates, prestuctured with surface relief diffraction gratings, onto which a silver reflector and then the a-Si solar structure is deposited.

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