

ENHANCED LIGHT TRAPPING IN THIN FILM SILICON SOLAR CELLS DEPOSITED ON PET AND GLASS

Vanessa Terrazzoni-Daudrix¹, Joëlle Guillet¹, Xavier Niquille¹, Luc Feitknecht¹,

Frédéric Freitas¹, Pascal Winkler¹, Arvind Shah¹, R. Morf², O. Parriaux³ and D. Fischer⁴

1. IMT University of Neuchâtel, Breguet 2, CH-2000 Neuchâtel, Switzerland / E-mail: vanessa.terrazzoni@unine.ch

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

3. TSI (Traitement du Signal et Instrumentation), Jean Monnet University, Saint-Etienne, France

4. VHF Technologies SA, EICN, Avenue de l'Hôtel de Ville 7, CH-2400 Le Locle, Switzerland

ABSTRACT

The goal of this work is to reduce the production cost of thin-film silicon solar cells, by using PET substrates and thereby maintain a reasonable efficiency. The authors studied different kinds of textured back reflectors fabricated on glass and PET with the aim of increasing the short-circuit current density (J_{sc}) in a-Si:H and μ c-Si:H n-i-p-type solar cells: random textures and periodic gratings were both tested. Compared to co-deposited cells on flat mirrors, the gain in J_{sc} is 15% for a-Si:H solar cells on randomly-textured PET at the initial state and 20% after light soaking, 8% for a-Si:H solar cells on gratings (so far only on glass and at the initial state) and 15.2% for μ c-Si:H solar cells on randomly-textured back reflectors, on glass. Best n-i-p a-Si:H solar cells on PET and μ c-Si:H cells on glass have so far reached 5.8% (after light-soaking) and 9.2% efficiencies, resp..

1 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 Terephthalate) (PET). The advantages of this flexible organic polymer are: first, its low price compared to the substrates mostly used so far, such as glass, stainless steel and polyimide and, second, its compatibility with roll to roll processes. However, its main drawback is the fact that it can not be heated up to higher temperatures during the deposition of solar cells. Different studies have already shown that depositing amorphous silicon solar cells at lower temperatures has a detrimental effect on their short-circuit current density (J_{sc}) [1] [2] [3].

In this context, the authors have studied different kinds of textured back reflectors fabricated on glass and PET, in order to enhance the light trapping and, thus, the J_{sc} value of the solar cells. Therefore, different nano-structural shapes i.e. random and periodic textures, usable on glass and/or PET for back contacts of n-i-p-type amorphous silicon (a-Si:H) and microcrystalline silicon (μ c-Si:H) solar cells have been investigated.

In the present paper, periodically-textured substrates are studied first. These reflectors have been fabricated on glass and incorporated in n-i-p a-Si:H solar cells. Then, randomly textured back reflectors fabricated on PET and glass and incorporated in a-Si:H and μ c-Si:H n-i-p solar cells, respectively, have been tested. By comparing the J_{sc} values of co-deposited cells on flat and textured back reflectors, the performances of the latter within entire solar cells have been evaluated.

2 EXPERIMENTAL

2.1 Fabrication methods

In order to obtain periodically-textured back reflectors, square-step gratings with a one-dimensional pattern have been etched on glass using a photolithographic process developed by O. Parriaux at TSI. The so-obtained periodic nano-structures have then been covered, at IMT, by a thin Al layer (30nm thickness) and a very thin ZnO:Al layer (5nm thickness) both obtained by sputtering. The optimized dimensions of the gratings have been determined by R. Morf, using rigorous solutions of Maxwell's equations [5], [4]. Thereby, three important hypotheses have been postulated:

- (a) the incidence of the sun's light is considered to be perpendicular to the back reflector incorporated in the cells,
- (b) the back reflector is considered to consist of a single metallic (Al) layer deposited on the periodically-textured pattern on glass,
- (c) the reproductibility of the grating's print as etched in glass is considered to be 100%, at each of the internal interfaces (i.e. Al/silicon and silicon/ ZnO:B) of the 250 nm thick a-Si:H cells.

Concerning the fabrication of the randomly-textured back reflectors, two methods have been used, at IMT, depending on the substrate: The back reflectors on glass have been realized at 400°C by successively sputtering Cr, Ag and ZnO:Al layers. The randomly-textured back reflectors on PET have been produced by first etching the substrate with an O₂-plasma process and thereafter depositing an Ag layer (different thicknesses and methods have been tested) and sputtered ZnO:Al (100 nm thick)

layers. It is important to remark that the nano-structural sizes of all these randomly-textured back reflectors can easily be varied and empirically optimized by changing the methods/parameters of plasma etching and Ag deposition [6] [7] (*Figure 1*).

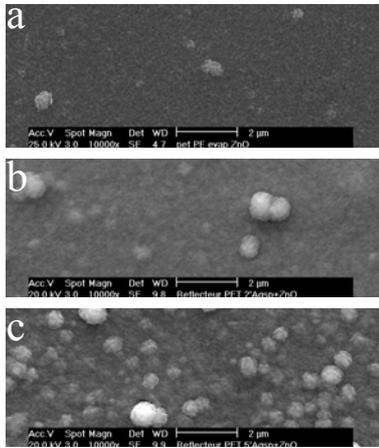


Figure 1. SEM images (identical scales) of three back reflectors deposited on PET with different fabrication parameters (a) 2 minutes O₂-plasma etching plus evaporated Ag and sputtered ZnO:Al layers, (b) 2 minutes O₂-plasma etching plus sputtered Ag and ZnO:Al layers, (c) 5 minutes O₂-plasma etching plus sputtered Ag and ZnO:Al layers.

All the a-Si:H cells have been deposited with the same displayed nominal parameters by VHF-PECVD [8] in a single chamber reactor: The deposition temperatures were 190°C for n-doped and intrinsic layers and 170°C for p-doped layers. The thickness of the a-Si:H intrinsic layers was 250nm.

The µc-Si:H cells have been deposited in the same reactor at approx 200°C, on glass. The thickness of the intrinsic layer is around 2µm. As-grown-textured ZnO:B has been used for the top contact, in all cases, assuring a low reflection coefficient of the light entering into the cells.

2.2 Characterisation of back reflectors and cells

The back reflectors have been characterised using AFM (Vista Burleigh Instruments scanning probe microscope) measurements in non-contact mode. The representative periodicity and height have been determined for each nano-structure using the maximum of the Peak Count Distribution and the Abbott-Firestone Distribution (ASME B46.1 standards).

Cells have been measured using Current-Voltage (I-V) and External Quantum Efficiency (QE) measurements. Degraded cells have been exposed to a continuous white illumination equivalent to AM1.5 during 1000 hours at 50°C.

Concerning the performance of each back reflector in cells, it has been determined either at initial or degraded states by measuring the short-circuit current density (J_{sc}) under reverse bias voltage (-1V) of co-deposited cells on textured and flat back reflectors. The "J_{sc} gain" parameter has then been calculated according to the equation below:

$$J_{scgain} = \frac{2(J_{sc}(\text{texturedsubstrate}) - J_{sc}(\text{flatsubstrate}))}{J_{sc}(\text{flatsubstrate}) + J_{sc}(\text{texturedsubstrate})} \quad (1)$$

3 RESULTS AND DISCUSSION

It is important to remark that the cells fabricated in this work have, all, not yet been optimised: neither on the nano-structured back reflectors nor at the deposition temperatures of approx. 190°C, so that the absolute values can still be improved. For this paper, the authors were interested only in comparative results.

3.1 PERIODICALLY-TEXTURED BACK REFLECTORS (GRATINGS) (A-SI:H CELLS)

According to the calculations of R. Morf, the dimensions of the periodic gratings have been fixed at certain values for the step height and for the period, with a ratio 1:1 between the width of the tops and bottoms of the steps. *Figure 2* represents the AFM image and profile of the back reflector obtained after deposition of Al and ZnO:Al layers (see fabrication method in section 2.1).

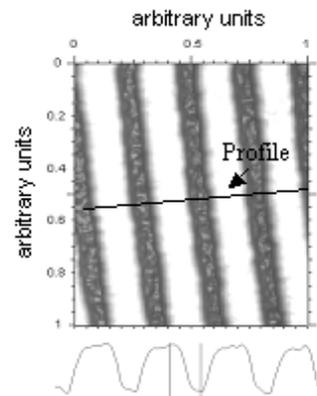


Figure 2. AFM picture and profile of the periodically textured back reflector observed after the deposition of Al (30 nm thick) and ZnO:Al (50 nm thick) layers. The RMS roughness is 23nm. The ratio 1:1 between the widths of the tops and bottoms of the grating has been checked on glass but is already no more totally reproduced at the top of the ZnO:Al layer.

nip a-Si:H solar cells have then been co-deposited on this periodically-textured back reflector and on a flat one, both realised with successive deposited Al and ZnO:Al layers. The comparison of their QE characteristics (*Figure 3*) indicates a value for the J_{sc}-gain, measured under reverse bias voltage, of 8 %. This gain comes obviously from the range of the long wavelengths (~650nm) confirming that, thanks to its scattering properties, the periodically-textured back reflector improves the light trapping of these wavelengths in the a-Si:H absorber layer of the solar cells.

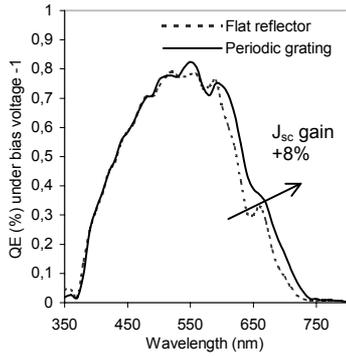


Figure 3. QE under reverse bias voltage of 1 V of two co-deposited a-Si:H cells: on a periodically-textured back reflector (plain line) and on a flat back reflector (dotted line). A J_{sc} gain of +8%, observed in the range of long wavelengths, has been measured.

However, this “ J_{sc} gain” of 8% measured experimentally is much lower than the expected calculated value of about 20 %. Several hypothesis can explain the large discrepancy between the expected and the measured values of the J_{sc} -gain, as obtained by the textured back reflector. The first, most important, hypothesis is the non-reproducibility of the grating’s print at each of the subsequent interfaces of the cells, like it had been postulated for the calculations (section 2.1). *Figure 4* illustrates this observation, which must be taken into account for continuing the development of such reflectors.

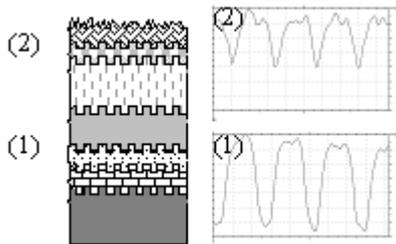


Figure 4. AFM profiles of the interfaces (1) i.e. ZnO:Al/silicon and (2) i.e. silicon/ZnO:B of 250nm thick nip a-Si:H cells. Neither the depth nor the symmetry of the grating of the first interface is reproduced at the second interface, as had been assumed for the calculation of the optimal dimensions. The depth of steps at the second interface is 2/3 lower than that at the first interface.

Second, the calculation has been effected by comparing back reflectors made from a single Al layer deposited on textured and flat substrates instead of Al plus ZnO:Al as necessary for the fabrication of performing cells. Although the ZnO:Al layer thickness has been reduced as much as possible, its presence could affect the performance of the textured back reflector and should be taken into account for further work. Third, the absorption of light in textured Al layers could be higher than in flat ones; therefore, Ag layers should now be investigated.

3.2 RANDOMLY-TEXTURED BACK REFLECTORS

3.2.1 Randomly-textured back reflectors on PET (a-Si:H cells)

Randomly-textured back reflectors with different nano-structural dimensions have been fabricated on PET (according to the method described in section 2.1) and have been tested in a-Si:H cells. The AFM image and profile of one of the back reflectors resulting in the so far best solar cell performances are presented in *Figure 5*.

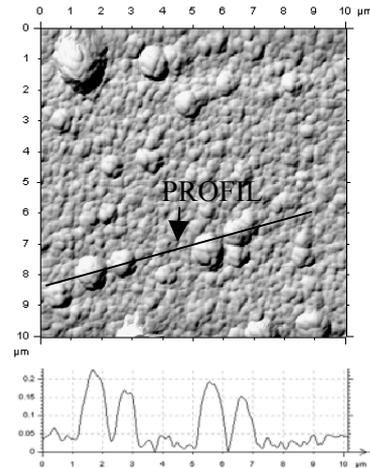


Figure 5. AFM image and profile of a performing randomly-textured back reflector deposited on PET fabricated by O_2 -plasma etching during 2 minutes plus sputtered Ag and ZnO:Al layer depositions. The most represented period and height are 620 nm and 80 nm, respectively. The RMS roughness is 48 nm. The large conglomerates are assumed as not to be taking part in the light trapping process.

This back reflector has been incorporated in a-Si:H solar cells. QE measurements realised at the initial and degraded states are presented in *Figure 6*.

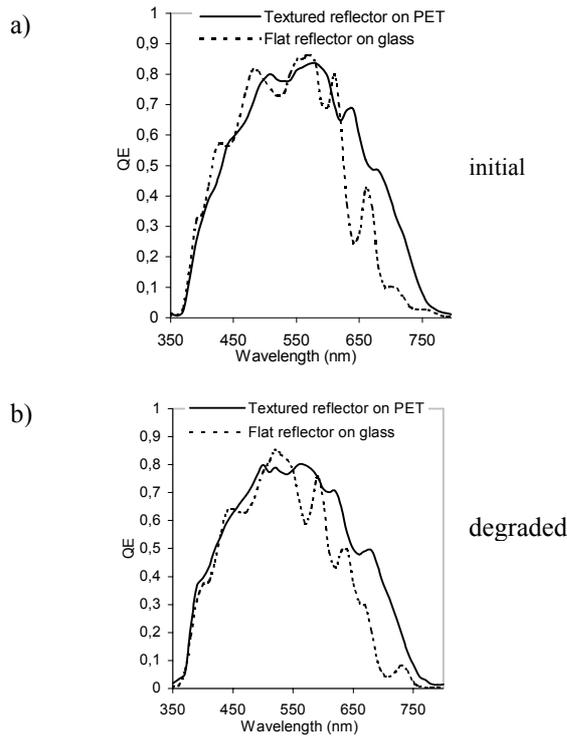


Figure 6. QE of two co-deposited cells on randomly textured (plain line) and flat back reflectors (dotted line) at the initial (a) and degraded (b) states. The “ J_{sc} gain” parameter is equal to 15% and 20%, before and after light-soaking, respectively.

First of all, such back reflectors with “average” nano-structure sizes of 620 nm for the period and 80 nm for the height can be considered to be 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 in a-Si:H solar cells. Furthermore, the “ J_{sc} gain” parameter is higher in the degraded state than in the initial state, so that apparently, the J_{sc} -value of cells deposited on PET seems to degrade less than that of cells deposited on glass. This observation could be attributed to a lower effective thickness of the cell deposited on the textured substrate[9].

For our present cells, light-soaking does not have a stronger effect on randomly-textured back reflectors on PET than on flat mirrors on glass (Table I).

Table I. V_{oc} , FF, J_{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		PET	
	BD	AD	BD	AD
V_{oc} [mV]	873	873	843	850
FF[%]	67	56.4	64.6	54.5
J_{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 on PET (compared to 5.1% for the co-deposited cell on a flat mirror on glass). Light-soaking affects especially the FF (degradation estimated equal to 0 for V_{oc} , ~18% for FF, ~5% and 10% for J_{sc} of cells, on textured and flat substrates, respectively): the efficiency degradation has been estimated to be 30% on glass instead of 20% on PET because of the larger decrease in J_{sc} .

3.2.2 Randomly-textured back reflectors on glass (μ c-Si:H cells)

μ c-Si:H solar cells have so far not been experimented on PET. Due to their longer deposition process, the maximum deposition temperature usable on PET for this kind of cells is certainly lower than that for amorphous solar cells and must still be evaluated. However, in order to determine the roughness adapted to enhance the light-trapping of wavelengths between 900nm and 1100 nm in 2 μ m thick μ c-Si:H cells, experiments have been performed on randomly-textured back reflectors deposited on glass (process described in section 3.2.2). As mentioned in this section, the size of the nano-structures can easily be varied by changing the deposition temperature during the sputtering process. The most-performing back reflector has been deposited at 400°C [7] and its texture characteristics have been determined by AFM (Figure 7).

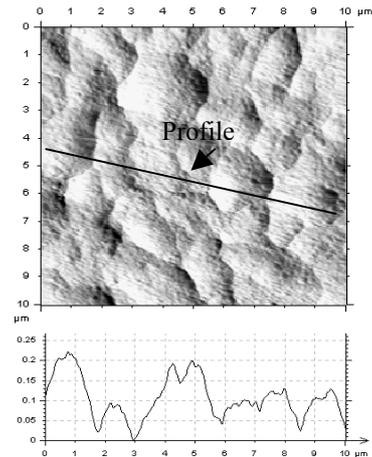


Figure 7. AFM image and profile of a performing randomly-textured back reflector deposited on glass fabricated by sputtering of Ag and ZnO:Al layers at 400°C. The most represented period and height of the “average” nano-structured feature are 2.5 μ m and 270 nm respectively. The RMS roughness is equal to 80 nm.

Single junction μ c-Si:H nip solar cells have been deposited on this textured back reflector and the performances of such kind of cells have been strongly improved: J_{sc} of 24mA/cm² (Figure 8) and a stable efficiency of 9.2% have been measured.

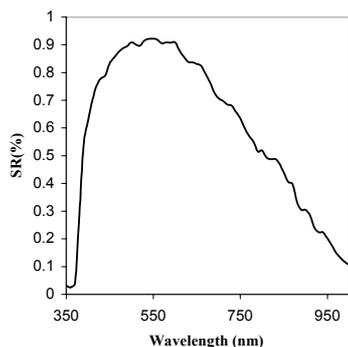


Figure 8. QE of $\mu\text{c-Si:H}$ solar cells obtained on randomly-textured back reflectors where the nano-structural characteristics are 80 nm for the RMS roughness, 270nm for the height and 2.5 μm for the period of the texture. A short-circuit current density of 24mA/cm² and an efficiency of 9.2% have been obtained.

Nano-structural sizes of around 2.5 μm for the period and 270 nm for the height are indeed effective in improving light-trapping in 2 μm thick $\mu\text{c-Si:H}$ solar cells. The positive effect of this kind of back reflector has been proven by co-depositing a similar $\mu\text{c-Si:H}$ cell on this same textured back reflector and on a flat back reflector [7]: J_{sc} and efficiency values of the cells deposited on the textured back reflector are 15.2% and 17.2% higher, respectively (Table II)

In this second experiment (co-deposition), the efficiency values reached were somewhat lower (8.2% for the textured back reflector).

Table II. V_{oc} , FF, J_{sc} and η of co-deposited nip $\mu\text{c-Si:H}$ thin-film solar cells co-deposited on textured (Figure 7) and flat back reflectors.

	Flat substrate	Textured substrate
$V_{\text{oc}}[\text{mV}]$	458	471
FF[%]	70.9	70.8
$J_{\text{sc}}[\text{mA}/\text{cm}^2]$	21.2	24.7
η [%]	6.9	8.2

4 CONCLUSIONS

In this paper, periodically and randomly textured back reflectors fabricated on PET and glass for increasing the efficiency of a-Si:H or $\mu\text{c-Si:H}$ n-i-p-type thin-film silicon solar cells have been tested.

First, the positive effect of one dimensional square shaped Al-based gratings fabricated on glass has been demonstrated for a-Si:H solar cells. Compared to Al-based flat back reflectors, such a periodically textured mirror results in an increase of 8% of J_{sc} for 250nm thick a-Si:H cells. However, this experimentally obtained result is so far much lower than the expected calculated value. A further study will have to aim at improving this result, first by

taking into account the limited reproducibility of the grating’s print at each subsequent interface of the cell, when determining the grating dimensions. Second, by using Ag-based reflectors and, third, by employing other grating shapes. For the latter case, a J_{sc} gain of up to 30% has been calculated. The fabrication of such kinds of gratings can already be implemented industrially in polycarbonate and is currently under investigation for polymer materials that can withstand higher temperatures.

Second, well performing randomly textured back reflectors for a-Si:H solar cells deposited at 190°C have been fabricated on PET: The J_{sc} value has been increased by 15% at the initial state and 20% at the degraded state compared to cells deposited on flat back reflectors on glass. The nano-structural dimensions of these back reflectors have been estimated to be equal to 620 nm and 80 nm for the representative period and height, respectively. Best nip a-Si:H cells deposited on PET have so-far reached 5.8% stabilized efficiency.

Third, randomly-textured back reflectors deposited on glass have been tested in $\mu\text{c-Si:H}$ solar cells. High-performance cells with J_{sc} and efficiency equal to 24 mA/cm² and 9.2%, respectively, have been obtained on back reflectors with representative nano-structural sizes of 2.5 μm for the period and 270 nm for the height. Further investigations must still be realised in order to, first, produce back reflectors having similar dimensions on PET and, second, determine the highest deposition temperature tolerated by the plastic for the fabrication of $\mu\text{c-Si:H}$ cells.

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