

## OPTIMIZATION OF AMORPHOUS SILICON SOLAR CELLS ON POLYMER FILM SUBSTRATES

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**ABSTRACT:** In this paper the authors present the results of different investigations concerning the development of a-Si:H solar cells on plastic film substrates. More precisely, this paper will discuss a) the evaluation and test of different polymer films as a suitable material for a-Si:H solar cell deposition, b) the optimisation of inverted n-i-p solar cells, and c) texturing of the plastic films by O<sub>2</sub> plasma etching for an enhanced light-trapping effect.

These results were successfully implemented in solar cells of n-i-p deposition order on a polyimide film (PI/Ag/ZnO/n-i-p a-Si:H/ITO). The following results were achieved: Voc = 906 mV, FF = 64%, Isc = 15.1mA/cm<sup>2</sup>.

**KEYWORDS:** Amorphous - 1: Building Integration - 2: Polymer film - 3

### 1. INTRODUCTION

In the past, in most cases glass or metal sheets were used as substrate materials for amorphous silicon solar cells. Polymer film could in the future however turn out to be more suitable substrate, for the following reasons:

At the present state of development it looks as if the efficiency of industrially produced amorphous silicon solar modules will remain for the near and midterm future clearly below 10%, in a range from 6-9%. The only way to compete at this level with the dominating crystalline silicon technology is by offering radically lower costs and application advantages like an easier integration in facades elements.

Regarding costs, only use of polymer films allows one to combine both roll-to-roll continuous fabrication, and an easy possibility of direct monolithic series connection, both key cost reduction factors. Neither glass nor metal substrates can offer this combination. In addition, the polymer substrate materials themselves could potentially be very inexpensive [1-6].

Regarding application, polymer substrates, being light, large area series-connected, flexible, and non-breaking, offer additional unique advantages, in particularly in the domain of building integration, where they can be laminated glass-less onto low-cost metal facades or roofs.

Usually, a-Si:H solar cells are on glass/TCO (Transparent Conductive Oxide) substrates applying the well-known p-i-n deposition order. With such a structure the light goes through the glass before it is absorbed in the cell.

The less studied n-i-p structure offers the possibility to use non-transparent materials as substrates (stainless steel or plastic films). In this case the cell is directly exposed to the light and the substrate must be very reflective and show – if possible – a light-trapping effect (Figure 1).

A handicap of polymer film substrates is, however, the fact that so far solar cell efficiencies have been systematically inferior to those obtained on glass or metal substrates. In this work, starting from a technology developed on glass substrates, the device performance of solar cells on polymer substrates is optimised step by step.

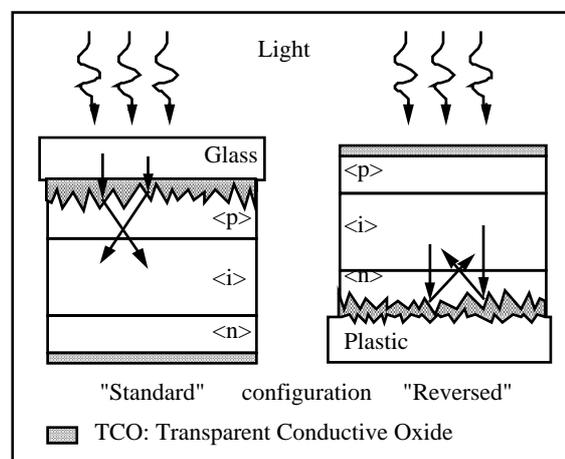


Figure 1: The "standard" p-i-n structure and the "reversed" n-i-p structure. This second structure allows the possibility to use non-transparent substrates. The name is in accordance with the deposition order of the layers .

The optimisation process addresses the following issues:

- characterisation and selection of suitable polymer film substrates (temperature resistance, price, surface defects).
- fabrication of high performance n-i-p devices by employing  $\mu\text{-SiC:H}$  p-layers [7].
- development of a Ag/ZnO back-contact, serving as back-reflector and as diffusion barrier between the polymer-substrate and the solar cell.
- texturing of polymer films by plasma treatment for enhanced light-trapping.

### 2. EXPERIMENTAL

The solar cells were deposited with the VHF-GD technique at an excitation frequency of 70MHz in a single chamber deposition system [10]. The two coplanar electrodes have a surface of 133 cm<sup>2</sup>, the substrate is fixed face down to the upper electrode. The radio frequency is applied on the lower electrode. The effective temperature was kept between 170°C and 240°C (depending on the layer) when the substrate allowed it. For plastic films with

a lower temperature resistance, the cells were deposited with an appropriated temperature (150°C).

The metallization of the back contacts was deposited by Joule effect or sputtering. The TCO layers (ZnO and ITO) were sputtered.

The cells were characterised by the illuminated j-V curves, a two source solar simulator was used. Voc and FF were determined from the j-V curves. The short circuit current (Isc) was determined by integration of the spectral response curve of a selected cell.

### 3. SELECTION OF SUITABLE POLYMER FILM SUBSTRATES

Table I shows an overview of different polymer materials which are potentially interesting for amorphous silicon deposition. The most critical selection criterion is the temperature resistance of the different materials, owing to the fact that on the one hand the optimal deposition temperature of amorphous silicon is above 200°C, while on the other hand the choice of polymers is very large at 100°C and becomes extremely limited towards 200°C. Generally, one notes that a high temperature resistance leads also to a higher price.

**Table I:** Temperature resistance, and prices (based on a very limited survey with a few polymer film producers) of different polymer film materials (50µm thickness).

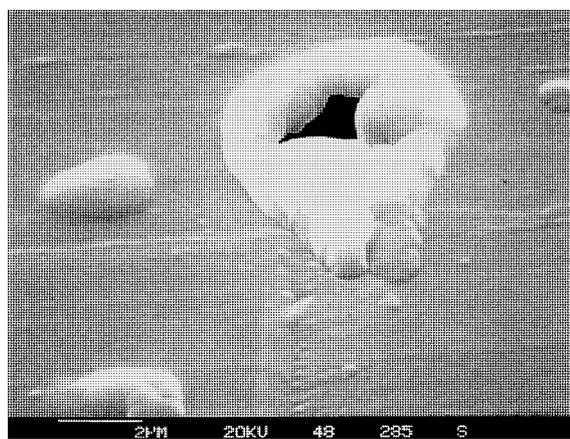
	<i>polymer</i>	<i>T max.</i> [°C]	<i>price</i> [\$/m <sup>2</sup> ]
PC	Polycarbonate	115-130	1-3.3
PET/PETP	Polyester	115-170	0.4
PEN	Polyethylene Naphtalate	155	1.1
PEI	Polyetherimide	170-200	2
PES	Polyethersulfone	180-220	4.3
PEEK	Polyetheretherketone	250	3.3
PI	Polyimide	250-320	11.7

Besides the temperature resistance, various other material properties have to be considered additionally (performance under vacuum conditions, mechanical properties, impurity contents, etc.). At this place it must be stressed that for the same basic polymer material, the properties of the films typically vary strongly from one producer to another, due to variations in the detailed production processes. This applies in particular to the important question of the surface morphology of polymer films, which in most cases is not specified by the suppliers.

Figure 2 gives an example of an isolated surface defect typically observed on a polyimide film of a certain brand. Figure 3 shows that this category of defect cannot be overgrown by the solar cell films, consequently leading to heavy shunting problems. Polyimide films of other suppliers, however, showed surfaces without critical surface defects, allowing to deposit n-i-p solar cells with high yields (see below).



**Figure 2:** SEM micrograph of surface defect of a polyimide film



**Figure 3:** SEM micrograph of same class of surface defect of a polyimide film after n-i-p solar cell deposition

### 4. OPTIMIZATION OF THE N-I-P DEVICES AND APPLICATION ON POLYIMID FILM

On polymer substrates, an n-i-p device structure is required due to a generally poor optical transparency of these materials. Unlike the typical p-i-n structure on glass/TCO, the n-i-p structure requires a microcrystalline p-layer in order to assure a good contact to the top ITO contact (which is n-type). In our case, however, we observed that deposition parameters leading to highly conductive thin p-layers when deposited directly on a glass substrate, showed a poor conductivity when grown on amorphous silicon i-layer material. Only by applying a CO<sub>2</sub> plasma treatment step to the growth of the p-layer [7], a fast nucleation, and a corresponding good junction performance could be obtained (Table II). Once optimised on a glass/TCO substrate, the n-i-p cell was deposited to a suitable polyimide film. As a back contact and back reflector, the substrate films were covered by either Ag, or Ag/ZnO layers. Table II shows that n-i-p solar cell performances similar to those on glass/TCO were obtained on polyimide substrate, when a Ag/ZnO back-contact was employed.

The good behaviour of the cells deposited on PI film substrates is understood as the effect of the excellent

properties of ZnO both as a diffusion barrier and as a back reflector, when applied on metal films.

**Table II:** J-V curve parameters of amorphous silicon p-i-n and n-i-p solar cells before degradation deposited on glass/SnO<sub>2</sub>, and on polyimide substrates. Deposition temperature was 240°C (for the i-layer).

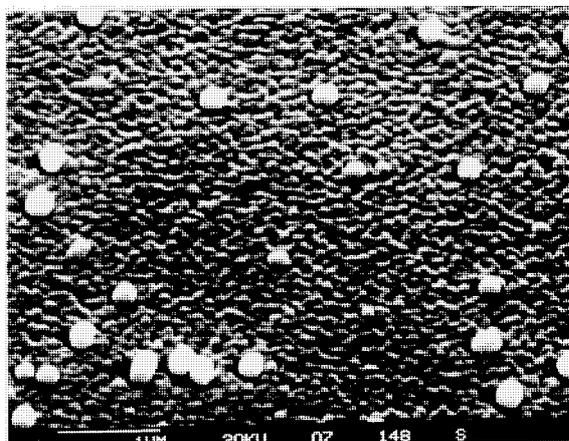
Device structure	V <sub>oc</sub> [mV]	j <sub>sc</sub> [mA/cm <sup>2</sup> ]	FF [%]	Eff [%]
glass/SnO <sub>2</sub> textured p-i-n/ITO/Ag	848	17.8	69	10.4
glass/SnO <sub>2</sub> textured n-i-p/ITO	667	15.9	53	5.7
glass/SnO <sub>2</sub> textured n-i-p*/ITO	874	15.9	63	8.7
<b>PI/Ag n-i-p*/ITO</b>	<b>906</b>	<b>14.4</b>	<b>59</b>	<b>7.8</b>
<b>PI/Ag/ZnO n-i-p*/ITO</b>	<b>906</b>	<b>15.1</b>	<b>64</b>	<b>8.7</b>

p\*: application of CO<sub>2</sub> plasma treatment to trigger the nucleation of the <p>-μc-SiC:H layer

The analysis of the j-V parameter shows that the current densities of the cells on the polyimide film are systematically lower than of those deposited on the glass/TCO substrate, which is highly textured. To further improve the cells on polyimide films it was thus crucial to develop a suitable texturing of the substrate and/or back contact.

## 5. TEXTURING OF POLYMER SUBSTRATES

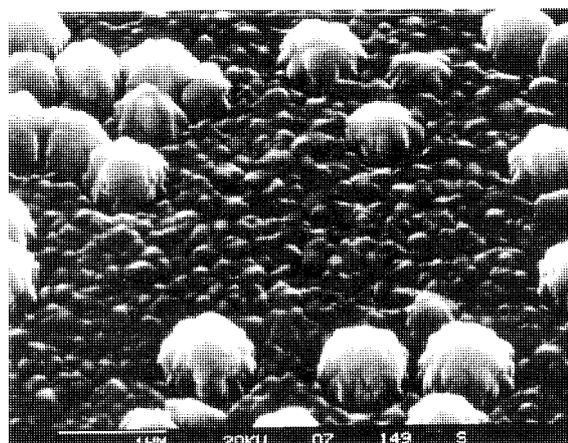
O<sub>2</sub>-plasma treatment, originally introduced to etch and clean the surface of the polymer films was found to induce strong texturing effects [8]. While the detailed mechanism of this behaviour is still under investigation, the treated substrates show, once covered with Ag or Ag/ZnO, granular features of an approximate size of 0.1-0.2 μm (note that the back contacts remain completely flat if no O<sub>2</sub>-treatment is applied). Figures 4 and 5 show the micrographs of an Ag, and of an Ag/ZnO contact on polyimide textured by this method.



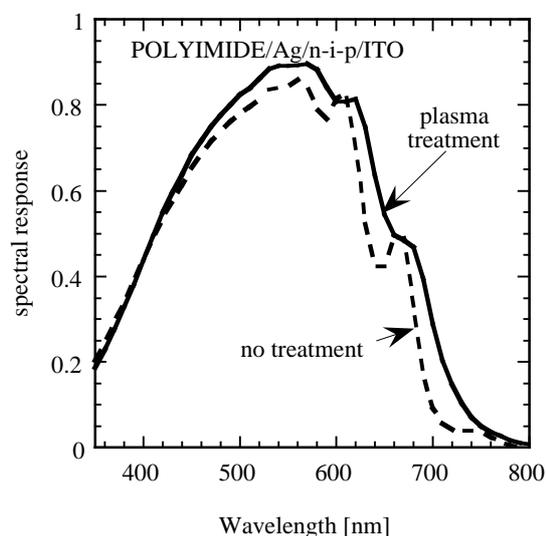
**Figure 4:** Ag back contact on textured PI film (Ag thickness 0.2μm)

Figures 6 and 7 show the corresponding spectral response data of cells deposited on these contacts, each time in comparison with cells deposited on flat contacts. A maximal current of 16.5 mA/cm was reached on a textured Ag/ZnO back contact (to be compared with the data shown in Table II).

While the current densities are thus substantially increased by the texturing, the fill factors of the cells deposited on the textured substrates so far remained low (50-60%), due to increased shunting. We attribute this to the "snow ball"-like growth-features (Figures 4 and 5) induced by the plasma treatment. Our further work will therefore be directed towards eliminating the nuclei of those features.



**Figure 5:** Ag/ZnO back contact on textured PI film (Ag thickness 0.2μm, ZnO thickness 0.5μm)

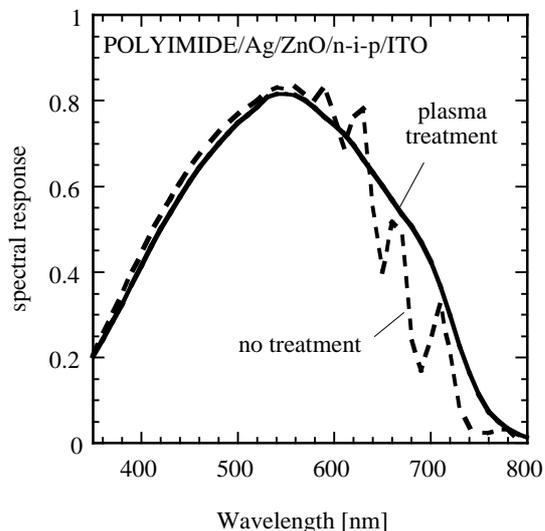


**Figure 6:** Spectral response of a n-i-p cell on flat and textured PI film (see Fig.4). Back contact: Ag.

Note that, for this study, the ZnO was deliberately flat to display prominently the effects of the texturing of the substrate. The combination of both textured substrate and textured back contact is under investigation.

In the future, the possibility of **tailoring** the surface texturing of polymer substrate films could represent a

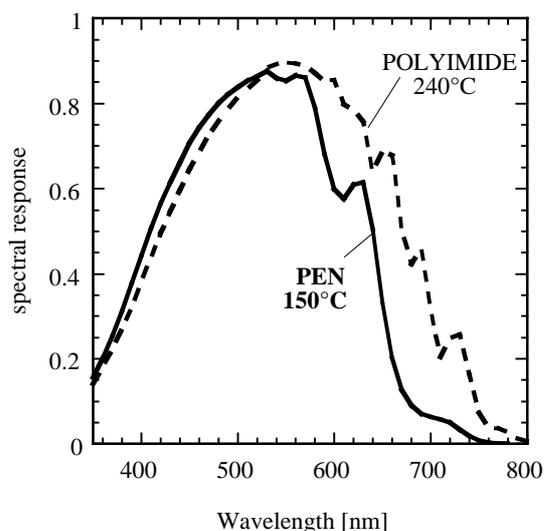
major advantage of the polymer based cells, because the large degree of freedom could lead either to better results than conventional polycrystalline materials (TCO's, Ag, ...), or to reduce costs as compared to the conventional texturing layers.



**Figure 7:** Spectral response of a n-i-p cell on flat and textured PI film (see Fig.5). Back contact: Ag/ZnO

#### 6. LOW TEMPERATURE DEPOSITION ON LOW-COST PEN SUBSTRATE

According to Table I, the substrate costs for polyimide substrates amount to 11.7 \$/m<sup>2</sup>, or 0.23 \$/W<sub>peak</sub>, if one assumes 5 % efficiency. This shows that polyimide could be too expensive to be used as a substrate material for a-Si:H solar cells. PEN (Polyethylene Naphtalate) is an alternative low-cost polymer film material. It can support, however, only approx. 150°C as a maximal temperature.



**Figure 8:** Spectral response of a n-i-p cell deposited on a

PEN film substrate at 150°C, in comparison with a cell deposited at 240°C on a PI film.

Recent results on deposition of low-temperature a-Si:H materials with hydrogen dilution, however, indicate that in the future a-Si:H solar cells of reasonable performance could also be fabricated at temperatures significantly below 200°C [9].

In a first attempt of depositing an n-i-p solar cell at 150°C substrate temperature on a PEN film, an efficiency of 6.2% was obtained. The spectral response data of this cell (Fig.8) shows that the relatively low performance is for the major part explained by a strongly reduced absorption of red light, due to the higher gap of the i-layer material deposited at 150°C. An optimal texturing will therefore be even more critical in cells deposited at low temperature on low-cost polymer substrates.

#### 7. CONCLUSION

Starting from a good know-how of the deposition of a-SiH p-i-n cells on glass/TCO by the VHF-GD technique, we have optimised a reversed n-i-p structure which allows to use non-transparent substrates like polymer films. The goal sought was to study the possibilities of deposition of a-Si:H cells on this material which is light, flexible, non-breakable and which can be very interesting in the domain of building integration.

A solar cell efficiency of 8.7% was achieved on polyimide film (PI), at a substrate temperature of 240°C. On a low cost Polyethylene Naphtalate film (PEN) and at a substrate temperature of 150°C, a maximal efficiency of 6.2% was attained (initial efficiencies).

#### 8. ACKNOWLEDGMENTS

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