LATEST RESULTS ON STABILIZED FLEXIBLE THIN FILM SILICON SOLAR CELLS

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ABSTRACT: Our primary goal is to increase the stabilized efficiency of thin film silicon solar cells in the substrate (nip) configuration by using textured substrates and tandem structures, based on amorphous (a-Si:H) and microcrystalline silicon (µc-Si:H). In order to reduce costs of mass-produced thin film solar modules, special attention has been paid in developing processes compatible with plastic foils and roll to roll technology. In this report, we give an overview on the current status of development of solar cells in the nip configuration at IMT Neuchâtel. In summary, the best stabilized efficiencies were: 7.0% for an amorphous solar cell (with an absorber layer thickness of 270 nm), 8.7% for a microcrystalline solar cell (with an absorber layer thickness of 1.2 µm), 8.0% for an amorphous tandem solar cell, and 9.0% for a micromorph tandem solar cell. In addition, damp heat tests on encapsulated flexible a-Si:H solar cells with a textured back reflector showed no degradation of the electrical parameters.
Keywords: Thin Film Solar Cells, Flexible Substrate, Roll to Roll.

1 INTRODUCTION

Thin films of silicon [1] deposited on low-cost substrates like stainless steel or plastic foils enable the fabrication of lightweight, large area, unbreakable and flexible solar cells and modules. The inherent advantages of this "flexible" thin film silicon based technology with regard to the traditional "bulk silicon" photovoltaic (PV) panels are, on one hand, the possibility of using a roll to roll in-line deposition process, which allows for the production of hundreds and hundreds of meters of solar modules in a relatively compact deposition system, and, on the other hand, it allows for an easier deployment and installation of PV modules on a variety of structures for building integration (façades, walls and roofs) whose complex shape or lightweight, as found on industrial buildings or agricultural sheds, would not support the traditional PV modules. Therefore, flexible thin film silicon solar panels fabricated in roll to roll processes are economically very promising [2] and can contribute to dissemination of PV systems worldwide.

Commonly, silicon thin film solar cells are illuminated from the p-side. This allows for a better collection of the low mobility carriers (holes) because they must drift less to reach the p-layer, resulting in a greater short circuit current when the cell is illuminated through the p-side [3]. Thus, the use of opaque substrates like stainless steel foils [4], or transparent plastic substrates [5,6,7] which are often easily damaged by ultraviolet light, requires the substrate (n-i-p) configuration, which lets the light enter the cell through the last deposited layer, i.e., through the p-layer.

Plastic substrates like PEN (polyethylene-naphtalate) require low temperature processes (below 200°C) that increase the optical gap of the absorbing medium (i-layer) resulting in a relatively low value of the short-circuit current. However, to compensate this effect and to improve light trapping, the substrates can be nanotextured by using a replication process that is compatible with roll to roll processing [5,6]. An advantage of plastic substrates, in comparison with metallic ones, is that they allow for monolithic series connection in a roll to roll process, which is an important issue towards low-cost mass-production of solar modules.

In the present paper, the authors give the development status at IMT Neuchâtel of thin film silicon solar cells in the substrate (n-i-p) configuration, involving amorphous (a-Si:H) and microcrystalline (µc-Si:H) silicon. The final goal is the deposition of high efficiency solar cells on low-cost plastic foils like PEN.

2 EXPERIMENTAL

The textured plastic substrates are covered by a double layer of Ag/ZnO or Al/ZnO as back reflector, deposited by DC and RF sputtering, respectively.

The thin film silicon layers (n-i-p sequence) are grown in static process by plasma enhanced chemical vapor deposition (PE-CVD) at very high frequency (VHF), ranging between 70 and 140 MHz. The substrate temperature is kept below 200°C, and the maximum sample size in our laboratory reactor is 8x8 cm^2.

We use silane (SiH_4) and hydrogen (H_2), with a dilution ratio $[H_2]/[SiH_4]=2$, for the intrinsic amorphous absorber layers, while for the microcrystalline ones the dilution ratio was between 14 and 25. As doping gases for the n and p layers we add phosphine (PH_3) and trimethyl-boron (TMB), respectively.

The transparent conductive oxide (TCO) front contact consists of a boron doped zinc oxide (ZnO:B) layer deposited by low pressure chemical vapor deposition (LPCVD). This process produces a pyramid-like random surface texture, whose size and morphology can be modified by its deposition time [8, 9].

The open circuit voltage (Voc) and fill factor (FF) of the solar cells are obtained from the current density-voltage (j-V) measurements performed under a dual lamp spectrum simulator (Wacom WXS-140S-10) in standard test conditions (25°C, AM1.5 spectrum and 1000 W/m^2). The short circuit current density (Jsc) of the solar cells is calculated by integration over the external quantum efficiency (EQE) curve, weighted with the AM1.5 solar spectrum; this method avoids uncertainties that arise from the determination of the cell area, of typically 5x5 mm2.

3 STATUS OF CELLS DEVELOPEMENT

3.1 Single-junction amorphous solar cells

Recently it was shown that fill factor and open circuit voltages losses in amorphous cells on textured substrates are less severe when an amorphous silicon carbide n-layer (n-SiC) is used instead of a microcrystalline n-layer [10]. Figure 1 shows the EQE of cells on a textured and on a flat reference substrate under short circuit conditions. In both cases, an amorphous n-SiC layer was used. The textured substrate consists of flexible PEN substrate coated with a flat Ag reflector followed by textured LPCVD-ZnO, whereas the flat reference consists of a glass substrate covered with a double layer of sputtered Ag (or Al) and ZnO (65nm). The initial performances of these cells are reported in table I, stabilized parameters of the textured cell after 1000 h of light soaking at 50°C are also shown in bold.

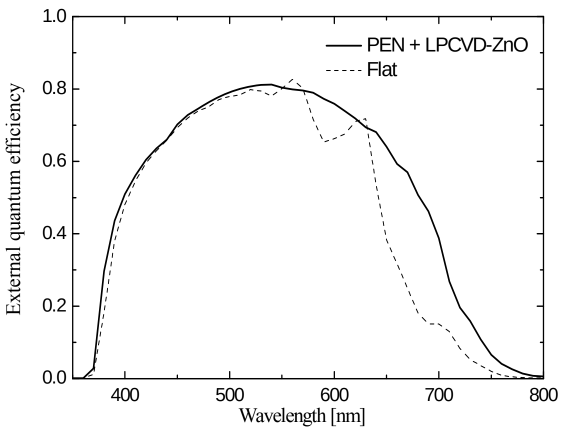

Figure 1: External quantum efficiency of n-i-p amorphous solar cells on flat and textured substrate on plastic.

Table I: Solar cell parameters of n-i-p amorphous solar cells on flat and textured substrate on plastic; stabilized values are in bold.

	V_{oc}[mV]	FF[%]	J_{sc}[mA/cm^2]	η[%]
flat	895	66	12.3	7.3
textured	888	70	14.3	8.9
	890	**59**	**13.3**	**7.0**

The use of a textured substrate enhances the short circuit current density up to a 16 %, which compensates for the slight decrease in V_{oc}, resulting in an efficiency improvement of 22% regarding to a flat substrate. The stabilized efficiency of the textured cell is 21% lower than the initial one for an i-layer thickness of 270 nm.

After encapsulation of flexible a-Si:H solar cells on a PEN textured substrate coated with sputtered Ag/ZnO, we found that they are not significantly vulnerable to damp heat effects, see Figure 2. The test was carried out in steady state conditions (1000 h at 85°C and 85% relative humidity); the electrical contacts were made on Ag and ITO with silver paste.

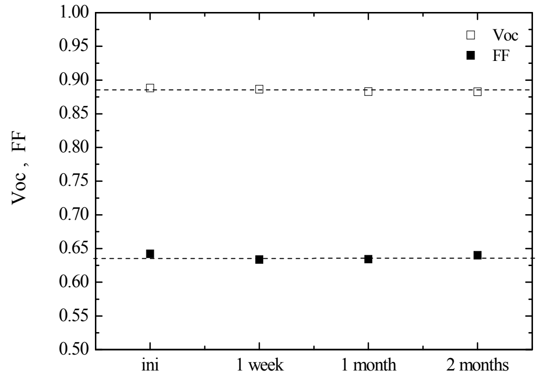

Figure 2: Damp heat tests on encapsulated flexible a-Si:H solar cells with a textured PEN back reflector.

3.2 Single-junction microcrystalline solar cells

Developing of micromorph tandem cells requires starting with the most highly efficient microcrystalline solar cell, and therefore, requires a good light trapping design. For these microcrystalline cells, it is known that not all nanostructured substrates are suitable to fulfill simultaneously a high light trapping enhancement and good electrical properties, i.e., high values of FF and V_{oc}. In particular, we have investigated a substrate texture consisting of a crossed grating with a period of 1.2 µm, which showed a good performance as back reflector [6].

Figure 3 shows the j-V characteristic of a typical microcrystalline cell. Contrary to the amorphous cell presented above, this cell has been deposited in a double chamber system to reduce the amount of cross contamination between the doped and intrinsic layers. Short circuit density currents up to 23.1 mA/cm^2 were reached on cells with 1.2 µm thick absorber layers, resulting in efficiencies up to 8.7%.

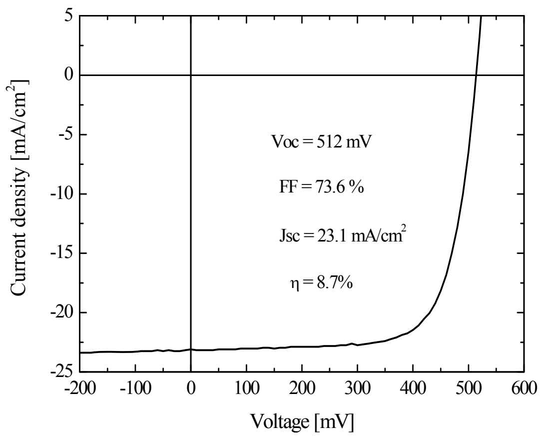

Figure 3: Current density-voltage characteristic and solar cell parameters of an n-i-p microcrystalline cell on a periodically textured plastic substrate.

3.3 Micromorph tandem solar cells

In micromorph tandem cells we stack an amorphous cell on top of a microcrystalline nip structure. The thickness of top (a-Si:H) and bottom (µc-Si:H) intrinsic layers are 1.2 µm and 270 nm, respectively. A remarkable stabilized efficiency of 9.1% is obtained for this tandem configuration, as indicated in Table II.

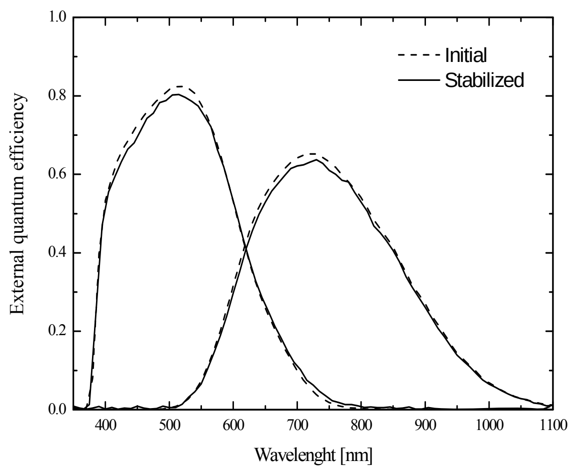

Figure 4: External quantum efficiency of a micromorph (n-i-p / n-i-p) tandem cell on a periodically textured plastic substrate.

Table II: Solar cell parameters of a micromorph (n-i-p / n-i-p) tandem cell on a periodically textured plastic substrate; stabilized values are in bold.

V_{oc} [V]	FF [%]	J_{TOP} [mA/cm^2]	J_{BOTTOM} [mA/cm^2]	η [%]
1.37	67	11.3	12.1	10.4
1.33	**61**	**11.1**	**11.7**	**9.0**

Notice that the mere fact the single-junction amorphous cell described in section 3.1 is integrated into a tandem structure reduces the impact of light induced degradation of the tandem device from 21% down to 13%, even by using the same absorber layer thickness in both cases. This is because in this configuration the top (a-Si:H) layer does not absorb the light coming back from the textured back reflector, therefore having less photogenerated recombination in the i-layer which results in a lower impact of the "Staebler-Wronski" effect [11].

Furthermore, we notice that for the same delivered power the tandem cell operates at a higher voltage and a lower current than a single-junction cell, which reduces Joule losses through the TCO; a very important factor to take into account when one makes the monolithic series connection of cells into modules.

An approach to further enhance the efficiency of the micromorph solar cell is to improve light trapping by a better choice of the textured back reflector. In particular, light absorption due to the presence of plasmon resonances effects which are mediated by the periodic structure of the substrate should be better understood [7, 12].

However, a higher short circuit current in the bottom cell also requires a high current in the top (a-Si:H) cell. This can be achieved, with a reduced top cell thickness, by incorporating an intermediate reflector (IR) between both sub-cells, as is has been successfully demonstrated for the superstrate (pin) configuration [13]. In this way, stabilized efficiencies over 10% on plastic substrates (nip configuration) should be reached in a short time. Results pointing towards such efficiencies will be discussed in another contribution [14]

3.4 Amorphous tandem solar cells

An amorphous tandem solar cell consists of two amorphous silicon sub-cells deposited one over the other. While a tandem consisting of two absorbers with identical band gap does not extend the spectral range, this configuration is still economically interesting if one takes into account its better stability with respect to single cells, the reduction of the constraint on monolithic interconnection and its shorter deposition duration and lower material consumption compared to micromorph cells.

Figure 5 shows the EQE's of three representative amorphous tandem solar cells. The only difference between them is the processes used for the substrate structuring. We use a) a flat PEN substrate covered with a double layer of sputtered Ag/ZnO, b) a textured LP-CVD ZnO:B on glass (both substrates were used as reference) and c) a replication of our textured reference onto a PEN substrate, which was made by OVD-Kinegram A.G. using a proprietary roll to roll process. This substrate was also covered with a double layer of sputtered Ag/ZnO.

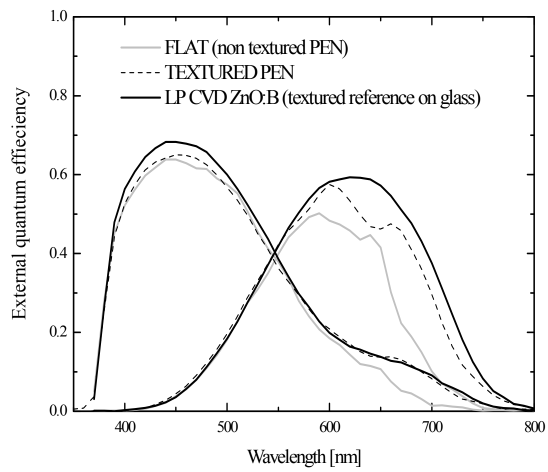

Figure 5: External quantum efficiency of amorphous (n-i-p / n-i-p) tandem cells on flat and structured substrates.

Table III: Solar cell parameters of amorphous (n-i-p / n-i-p) tandem cell on a flat PEN (first row), on a roll to roll textured PEN (second row), and on a textured "LP CVD ZnO:B" on glass (third row). The gain in current with respect to the flat substrate is represented in bold. All the values are in the initial state.

Voc [V]	FF [%]	Top/Bottom [mA/cm^2]	η [%]	J total [mA/cm^2]	ΔJsc [%]
1.698	70.0	6.58/5.53	6.6	12.11	**00.0**
1.711	71.3	7.10/7.10	8.7	14.2	**17.3**
1.742	70.2	7.41/7.83	9.1	15.24	**25.8**

As it is shown in Table III, the replicated substrate by a roll to roll process presents a less pronounced light trapping effect, and hence, a lower short circuit current in the bottom cell. Nevertheless, we obtained a short circuit current improvement, with respect to the flat reference, of about 17%, compared to the 26% of current improvement obtained on our textured reference substrate. This indicates that there is still a potential for improvements of textured plastic substrates.

With the nip/nip structure, we were able to obtain an amorphous tandem cell efficiency of 9.1% (initial) with an open circuit voltage of 1.742 V and FF of 70.2 %. After 1000 h of light soaking the stabilized efficiency was 8.0 %, which represents only a 12% of degradation with respect to the initial state. As expected, the top cell (100 nm), which is thinner than the bottom one (300 nm) in order to match both currents, suffered less light induced degradation due to the stronger electrical field in this cell, as shown in Table IV.

Table IV: Solar cell parameters of an amorphous (n-i-p / n-i-p) tandem cell on a textured substrate (LP CVD ZnO:B on glass); stabilized values are in bold.

V_{oc} [V]	FF [%]	J_{TOP} [mA/cm^2]	J_{BOTTOM} [mA/cm^2]	η [%]
1.742	70.2	7.41	7.83	9.1
1.705	**63.9**	**7.36**	**7.33**	**8.0**

4 CONCLUSIONS

We have presented our progress in thin film solar cells, based on single junction nip amorphous and microcrystalline silicon. For amorphous solar cells we developed a silicon carbide n-layer that yields high Voc on both flat and textured substrates. For microcrystalline solar cells stable efficiencies of 8.7% have been achieved, with an absorber layers thickness of only 1.2 μm. The combination of these cells into stacked structures resulted in stabilized efficiencies of 8.0% and 9.0% for amorphous and micromorph tandem cells, respectively. These results show that amorphous a-Si/a-Si tandem thin film technology has a potential to make first significant step towards to the higher efficiencies reached by its micromorph counterpart.

The current status of development of thin film solar cells in the nip configuration, which is fully compatible with plastic substrates and roll to roll technology, clearly brings us one step closer to low cost PV modules.

Future work will focus on the following issues: further investigations in the light trapping effects of textured back reflectors, improvements in the intermediate reflector and matching current in micromorph tandem cells, as well as in the electrical properties of single amorphous cells, mainly, by increasing the open circuit voltage.

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