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Dynamically deposited thin-film silicon solar cells on imprinted foil

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Abstract

ECN is developing n-i-p solar cells based on a-Si and μc-Si absorber layers deposited with inline PECVD, using linear plasma sources, on an imprint-textured UV curable coating layer on foil. We show that solar cells deposited on foil with random texture can achieve good light trapping (J_{sc} ~ 15-16 mA/cm^2 for a-Si cells). Furthermore, we show that a-Si nip cells on foil, processed in dynamic mode in an industrial pilot roll-to-roll system for 30 cm wide foils, can achieve efficiencies (of over 7%). Future work will focus on developing and implementing optimised periodic nanotextures for μc-Si and micromorph tandem.

n-i-p solar cells; amorphous Si; microcrystalline Si; embossing; roll-to-roll; PECVD;

1. Introduction

Roll-to-roll production of thin film Si solar cells has several advantages over batch-type reactor systems, for instance high-throughput fabrication and the application of cheap foil substrates. Flexible, lightweight PV modules gear up to building integrated PV: the most important market for PV in densely populated, developed countries [1,2]. Our novel concept for roll-to-roll production of high efficiency n-i-p solar cells is based on amorphous (a-Si:H) and microcrystalline (μc-Si:H) silicon thin films on steel foil coated with an insulating barrier layer and sputtered back contact and reflection layer.

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The standard way to improve the light management of thin film solar cells is to apply a light scattering structure, either on the front window or at the back reflector. Typically, the growth conditions of the TCO layers are adjusted to get appropriate surface roughness. In contrast, imprinting UV curable coating layers allows full control of the applied, random or periodic, texture to fully optimise the light trapping. Light trapping is most important for microcrystalline Si solar cells and bottom cells in micromorph tandems, due to the lower absorption strength of μc-Si. To absorb the longer wavelengths (700-1100 nm), textures with larger periods and heights than for a-Si cells are applied. In the framework of the EU project Silicon-Light [3], we are investigating and will demonstrate the fabrication of ideal periodic structures for light scattering in microcrystalline silicon solar cells and micromorph tandem cells.

Our concept for roll-to-roll fabrication of thin film silicon solar cells contains a few unique features [4], which offer great potential for high efficiencies and low cost fabrication. Two of these features are presented in this paper, i) the application of linear plasma sources for the inline deposition of silicon layers and ii) the suitability of UV curable coating as substrate for thin film Si solar cells.

1.1. Experimental details

A UV-curable barrier layer (C-Coatings B.V.) is applied by doctor blading. The texture is imprinted by a PDMS shim in the wet layer and the substrate/layer/shim stack is put through a UV belt oven to harden the lacquer. Ag/ZnO back contacts are sputtered in an AJA sputter tool. The silicon layer deposition is carried out either in a cluster tool or an inline PECVD system. The cluster tool has three separate UHV chambers for n, i and p layer deposition. Typically, four substrates of 10×2.5 cm^2 are co-deposited.

The inline PECVD system is an industrial pilot roll-to-roll system for foils of width up to 300 mm. The Flexicoat300 has three inline deposition chambers. Two chambers are equipped with the previously reported linear symmetric RF (13.56 MHz) sources [5,6], which are excellently suited for deposition of amorphous and microcrystalline doped silicon layers. The intrinsic Si absorber layers are deposited with a linear VHF plasma source (70 MHz). Samples (typically six substrates of 10×2.5 cm^2) are fixed to a custom-made sample holder, which is placed in the steel foil that is used as conveyor belt. The vacuum chambers are separated by independently pumped gas sluices to prevent (cross-)contamination. The main advantages of linear plasma sources are that deposition uniformity is only required in one direction, perpendicular to the motion of the substrate(s) and the ease of upscaling the plasma sources to enable deposition on foil substrates of one metre width or more.

The solar cells are defined by the area of the ITO front contact: 4×4 mm^2 and 10×10 mm^2. For contacting purposes a silver contact pad is e-beamed on the ITO front contact. IV measurements are done on a WACOM sun simulator. The Jsc is determined independently by convoluting the AM1.5g spectrum with the EQEs of the cells (Optosolar). For the tandem cells the EQE of the bottom and top cell were measured under red and blue bias light, respectively. For the 10×10 mm^2 cells the differences in Jsc obtained by IV measurements and SR measurements appear to be less than 1%.

2. Results

2.1. Inline deposition vs. static deposition

First, we will present the use of linear PECVD sources for the inline deposition of Si layers in an industrial pilot roll-to-roll PECVD system. We have deposited a-Si n-i-p solar cells on Asahi U-type glass, coated with a sputtered Ag/ZnO back contact. These solar cells are compared with similar cells deposited in a UHV lab scale cluster tool. Typical resulting JV curves are shown below in Fig. 1.

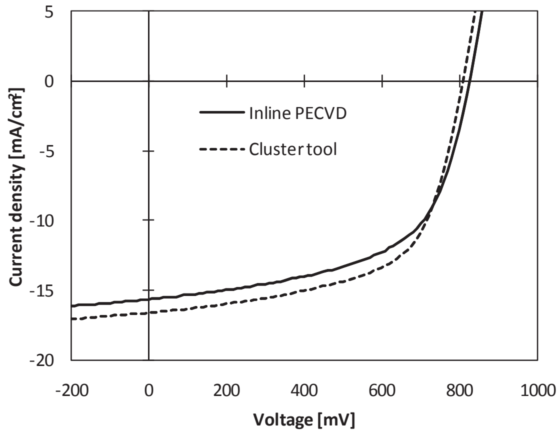

Fig. 1. JV-curves of two 4×4 mm^2 a-Si n-i-p solar cells, deposited on Asahi U-type glass coated with a sputtered Ag/ZnO back contact. The "cluster tool" solar cell is deposited in a UHV lab scale system (red, broken line), whereas the "Inline PECVD" solar cell is deposited dynamically (constant movement) in an industrial pilot roll-to-roll system (blue, solid line).

Table 1: external parameters of the a-Si nip solar cells made on Asahi U-type glass

		Inline PECVD	Clustertool
V_{oc}	[mV]	830	810
J_{sc}	[mA/cm^2]	13.0	13.2
FF	[%]	58	59
η	[%]	6.0	6.3

We observe a systematically higher V_{oc} and lower J_{sc} for the a-Si cells made in the inline PECVD compared to the values for the cluster tool (as illustrated in Fig. 1). This systematic difference is mainly related to the observed difference in band gap in the intrinsic absorber layer, which in its turn is a result of different deposition conditions: dynamic vs static, VHF vs. RF etc.. To summarise, the initial efficiency of inline deposited cells is only a few tenths of a percent lower than those fabricated in a UHV cluster tool.

2.2. Randomly textured barrier layer

The second feature that we will focus on is the barrier layer as a means to increase the light trapping. For a-Si pin cells, the texture of Asahi U-type fluorine-doped tin oxide (FTO) glass serves as a benchmark for front side light scattering. The same texture can also be applied as back side light scatterer in nip cells. For this purpose, we made nip cells on Asahi U-type glass, where the FTO, covered with Ag/ZnO serves as the back contact. In our experiments, these cells are used as benchmark for our nip cells on foil, where we investigate the light scattering of imprinted random and periodic textures in the barrier layer.

We have fabricated thin film n-i-p a-Si solar cells on imprinted barrier layers on steel foil. To minimise differences due to back reflection and back contacting properties, both the barrier layer and the textured FTO surface are coated with the same reflecting, conducting Ag/ZnO back contact layers. Then, the Si layers are co-deposited on both substrates in the roll-to-roll PECVD system. Fig. 2 shows the JV-curve for a cell on steel foil with an Asahi-U replication imprint in the barrier layer ("randomly imprinted barrier layer"), compared with a cell on the Asahi U-type glass reference.

As seen in Fig. 2, the a-Si solar cells on imprinted substrates have slightly higher V_{oc} (810 mV) and slightly lower short-circuit current than n-i-p Si solar cells grown on Asahi U-type substrates. The fill factor is comparable (57 and 58%). The small differences in V_{oc} could be due to a temperature difference between the two substrates as we place different substrates in identical process conditions.

The UV curable barrier layer is well-suited to be used as imprintable layer to improve the light trapping as the electrical properties of the solar cells are not affected by the barrier layer, as seen in Fig. 2. However, the short-circuit current, as indicator for the light trapping, is not completely the same as that of the Asahi U-type glass substrate. This is probably due to a combination of using non-ideal masters in the first place and not-perfect copying of the texture from master to shim to barrier layer. This is confirmed by the lower red-response of the solar cell on textured barrier layer. The higher response at short wavelengths might be related to the lower net substrate temperature during p-a-SiC deposition.

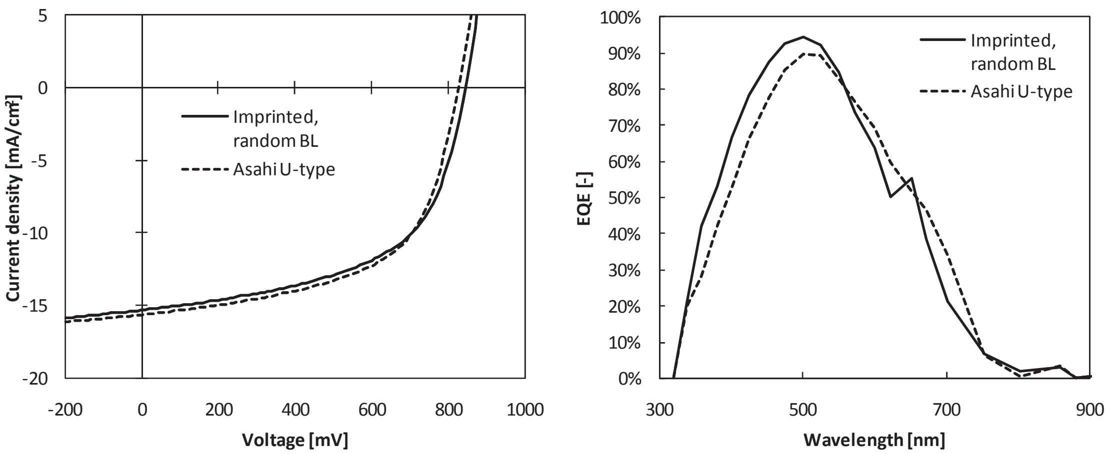

Fig. 2. JV-curves (left) and external quantum efficiency (right) of two co-deposited 4×4 mm^2 a-Si n-i-p solar cells, comparing two rough substrates: Asahi U-type glass (red, broken line) and steel foil, coated with an imprinted barrier layer (blue, solid line). Note: both substrates have a sputtered Ag/ZnO back contact.

As next steps, the shape conformity in the imprinting step could be further improved. To get the amount of light trapping towards and beyond that of optimised random textures, we will also test periodic textures that are modelled to have an additional increase in light trapping [7,8].

2.3. Micromorph solar cells

We have performed the first preliminary trial fabrication of micromorph tandem solar cells. The sub cell thicknesses are 2000 and 240 nm, respectively for the μc-Si bottom and the a-Si top cell. In Fig. 3, JV-curves are shown for a set of tandem cells, deposited in the same run on different substrates. Typically, we observe that substrates without barrier layer have a 1 mA/cm^2 higher J_{sc} than substrates with barrier layer, but the FF is 2% higher with barrier layer. The V_{oc} also depends on the substrate with flatter substrates tending to have higher Voc than rougher substrates.

The spectral response data are shown in the right panel of Fig. 3. The response of the top cell, measured under red bias light, has a lower maximum of the EQE than that of an a-Si nip cell on glass substrate, but the red response is identical. Also the response at higher wavelengths, >800 nm, for the bottom cell is comparable to the response of single junction µc-Si solar cells.

The variations in solar cell characteristics for the trial deposition of tandem cells are probably related to the substrate properties. The different substrates (glass / steel foil) and whether or not an (imprinted) barrier layer is applied to the steel foil will have some effect on the details of the layer growth. Small variations in growth rate will lead to variations in bottom cell thickness. Dissimilarities in nucleation and crystal growth will also affect the microcrystalline fraction (distribution) and the µc-Si/a-Si interface. These deviations might again influence the layer growth rate for the a-Si top cell.

In summary, the trial tandem fabrication has been rather successful, with tandem cell efficiencies >9% on glass and around 8% on steel foil, with or without imprinted barrier layer. Further development of micromorph tandem cells, including optimised textures, will take place within the Silicon-Light project [3].

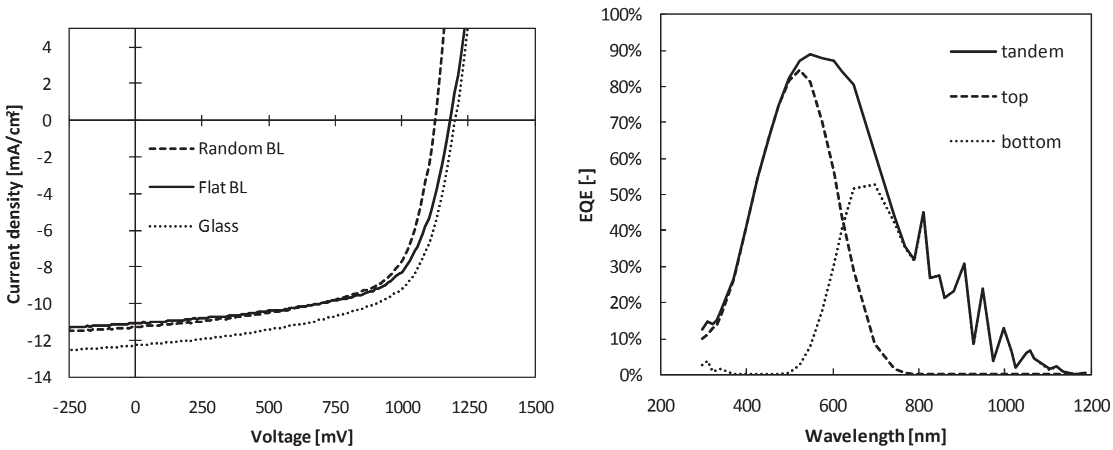

Fig. 3. Left: JV-curves of co-deposited micromorph solar cells on three substrates: steel foil with flat barrier layer (red, dashed), idem with random texture (violet, long dashed) and standard alkali-free glass (blue, solid). Note: all substrates have a sputtered Ag/ZnO back contact. Right: EQE curves for the micromorph solar cell on glass substrate.

3. Conclusion

Using linear VHF- and RF-PECVD sources, we have deposited thin film silicon n-i-p solar cells on flexible steel foil substrates. Our UV curable lacquer is well-suited as imprintable barrier layer between the steel foil and the active layers, as the light trapping, by imprinting the barrier layer with a random texture, is comparable to that of Asahi U-type textured TCO glass. Furthermore, we show that inline (dynamically) processed a-Si nip cells have efficiencies of over 6%, which is approaching the performance of similar cells made in a UHV lab-scale cluster tool. Finally, the trial deposition of a micromorph tandem solar cell on steel foil with barrier layer show a promising initial efficiency of ~8%.

Acknowledgements

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