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INLINE PROCESSED FLEXIBLE THIN FILM SILICON SOLAR CELLS USING LINEAR PECVD SOURCES

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ABSTRACT: Using linear VHF- and RF-PECVD plasma sources, we have deposited intrinsic and doped silicon layers for roll-to-roll fabrication of thin film silicon solar cells on flexible steel foil substrates. First amorphous silicon solar cells have been made using this PECVD system resulting in efficiencies up to 6.6%.
Keywords: a-Si solar cells, in-situ monitoring and diagnostics, large area deposition

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 opportunity to make lightweight and flexible products. Flexible and lightweight PV modules gear up to building integrated PV: the most important market for PV in densely populated, developed countries [1,2].

ECN is developing a pre-pilot line for roll-to-roll production of high efficiency n-i-p solar cells 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. The main purpose of the barrier layer on the steel foil is to enable monolithic series interconnection of cells as the final process step of the fabrication process, after deposition of all layers [3]. As part of the pilot line, we have developed, in collaboration with Roth&Rau AG, a roll-to-roll PECVD system for the Si layer deposition. The Flexicoat300 has three deposition chambers and can handle webs with a width up to 30 cm [4].

Production cost reduction and suppression of light-induced degradation are strong drivers to minimise the thickness of the silicon absorber layers. In order to harvest all light in very thin silicon layers, light trapping is crucial, for instance by implementation of scattering back reflectors. In the ECN concept we fabricate scattering back reflectors by nano-texturisation of the barrier layer. The texture is applied using a hot embossing process and can either be a random texture, like the roughness of Asahi-U type superstrates, or a designed periodic texture, for instance a diffraction grating [5]. In collaboration with partners the "ideal" textures for single junction a-Si and μc-Si and tandem cells of a-Si and μc-Si are being investigated and implemented. We expect an increase in the current by the improved light trapping because of the texture and preliminary results of hot embossed regular textures show the same performance as embossed random texture [6]. Progress is reported in a separate Paper at this Conference [7]. Applying a proper light management is particularly important for the microcrystalline layers because they have a lower absorption coefficient.

This contribution focuses on the transition from depositing on rigid substrates in a batch-step process to fabricating flexible thin film Si solar cells using inline processing.

2 EXPERIMENTAL SETUP

2.1 Flexicoat300

For developing the pre-pilot line, we have built a roll to roll PECVD system in a joint development by Roth&Rau AG and ECN. The Flexicoat300 contains 5 vacuum chambers: a pay-off chamber, 3 PECVD chambers for the deposition of intrinsic and n- and p-doped Si layers and a take-up chamber. The system is designed for continuous roll-to-roll deposition on flexible metal foils and can handle webs with a width of up to 30 cm (see sketched cross-section in Figure 1).

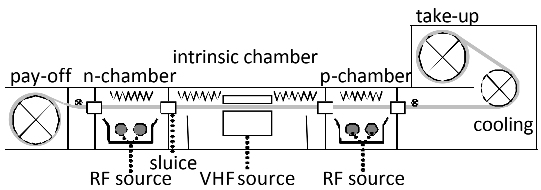

Figure 1: Cross-section through the Flexicoat300 roll-to-roll PECVD system.

The foil moves in continuous mode through the chambers and in order to prevent cross contamination of process gases, gas gates are applied between the deposition chambers. In the take-up chamber an in-situ Kelvin Probe is installed to monitor the surface voltage of doped layers or the surface photovoltage of nip solar cells [8,9]

The intrinsic layers are deposited by VHF-PECVD, operated at 60 MHz, as this source combines good layer quality and uniformity with high deposition rates. The rectangular VHF electrode has a width of 150 mm.

For the deposition of doped layers, a linear RF source has been developed [10,11], consisting of two parallel linear electrodes. These symmetric RF sources do not require the grounding of the substrate, and the indirect plasma causes only a very mild ion bombardment on the surface of the substrate or growing layer. The lower deposition rates for RF-PECVD with respect to VHF-PECVD are not a bottle-neck in high-throughput processing since the thicknesses of doped layers in thin film Si solar cells are small (≤ 20 nm) with respect to the required thickness of the intrinsic layer (≥ 1000 nm for μc-Si).

For initial experiments, we have deposited layers and solar cell stacks on glass and CZ wafer substrates and also on a range of steel foil, with or without coatings. As the PECVD sources deposit upwards, we have to open the steel foil and insert a sample holder to transport and hold the various samples.

As a reference cell process, we have fabricated nip solar cells on Asahi U-type glass. The rough FTO surface of the Asahi substrate is covered with an Ag/ZnO back contact layer to mimic our solar cell concept. This way, we ensure that the n-type layer is grown on the same surface for all presented solar cells. We apply device quality n-type Si and p-type SiC layers by RF-PECVD as reported before

[10,12] aiming for standard thicknesses of 20 nm and 10 nm, respectively. As intrinsic absorber layer, a standard amorphous Si layer of about 350 nm is applied with the VHF source. On top of the nip stack we deposit an ITO layer (thickness 80 nm). Finally we evaporate a silver grid as front side contacts.

The nip cells on foil have a similar structure, but here the Asahi substrate is replaced by a steel foil, thickness ~100 µm, with a barrier layer, thickness ~10 µm. The barrier layer can either be flat or hot-embossed with a light-trapping texture. To obtain the best comparison between flexible and rigid substrates, we have also created a texture in the barrier layer which has an excellent agreement with the roughness of the FTO layer on Asahi U-type glass. Details are presented elsewhere at this Conference [7].

The Flexicoat300 can be operated in several modes. On small substrates, single layers or layer stacks can be deposited "statically", by transporting the substrates directly above the PECVD sources. After the required deposition time, the sample is moved quickly out of the plasma zone, a so-called step-roll process.

Larger substrates or a number of substrates cannot be deposited in this way, as the width of the deposition zone is limited. To ensure a uniform coating, we have to deposit on these substrates "dynamically", by slowly moving the steel foil over the PECVD sources. This can be done either inline, that is one Si layer at a time, or fully continuously. In the latter mode, all PECVD sources are switched on and all three Si layers are deposited at the same time. In both modes, the substrates "see" the edges of the plasma zone, where conditions might be different from the centre of the deposition zone.

In dynamic mode, the deposited layer thickness not only depends on the "static" growth rate of the plasma process, but also on the web speed and the width of the deposition zone and, where installed, the width of the diaphragm. The RF-sources can only be uniform for a few centimetres around the centre, therefore these are equipped with diaphragms to ensure a constant quality over the whole width. Note, the growth rate over the width of the deposition zone might not be uniform. This complicates the determination of the layer thickness in dynamic mode.

3 RESULTS AND DISCUSSION

3.1 Statically deposited solar cells

As a reference sample, we have fabricated nip solar cells on Asahi U-type glass in the substrate configuration. Figure 2 shows the dark and light JV-curves of a typical 4×4 mm^2 nip cell. Without any layer thickness or interface optimisation we obtain reasonably good solar cell characteristics of 845 mV and 13.7 mA/cm^2. However, the fill factor FF = 54% should be improved and we expect to achieve this by fine-tuning of the substrate temperatures.

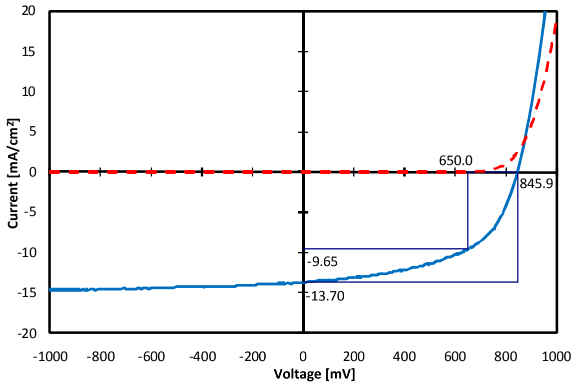

Figure 2: JV-curve of nip solar cell on a rigid substrate: Asahi U-type glass coated with a sputtered Ag/ZnO back contact.

SEM pictures, see Figure 3, of the Asahi U texture and the ITO surface of a nip solar cell deposited on Asahi glass shows rough, irregular pyramids and a cauliflower-like surface, respectively. We conclude that the layers grown on the Asahi U texture loose the conformity of this texture. For (periodic) artificial textures made by hot-embossing, this effect can be optimised to achieve lower reflection and increased light trapping.

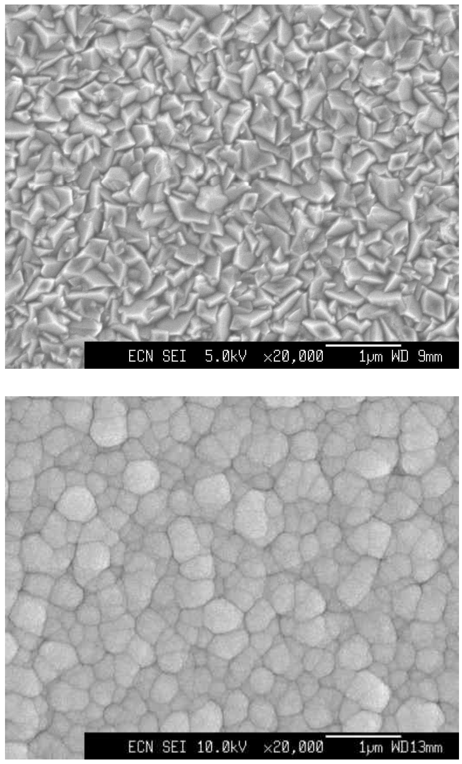

Figure 3: SEM picture of an Asahi U texture (top) and the ITO surface of a nip solar cell grown on Asahi-U glass substrate coated with a sputtered Ag/ZnO back contact (bottom).

3.2 Dynamic depositions

The next development towards continuous roll-to-roll deposition of all three Si layers is to deposit each layer whilst continuously moving the steel carrier foil through the PECVD chambers. Initially, we use only one source at a time and have the same gas conditions, i.e. pressure and

H_2:SiH_4 ratio, in all three chambers. The results of the inline deposition are shown in Figure 4, compared with a step-roll deposition. Both samples consists of a-Si nip solar cells on Asahi-U glass substrates.

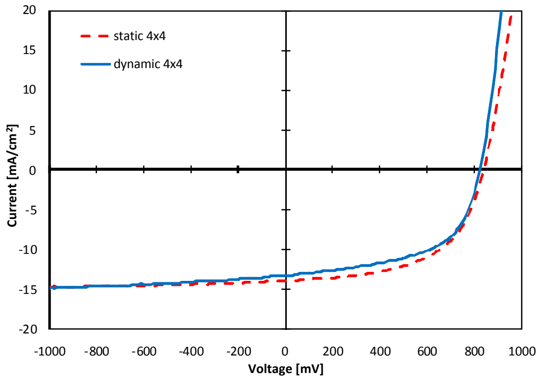

Figure 4: Comparison of JV-curves of nip solar cells on Asahi glass substrates deposited in-line (solid, blue) with those deposited in a step-roll process (dashed, red).

Comparing the dynamically grown solar cell with the "static" solar cell, we observe a small drop in most key parameters. Exact reproduction of "static" layer thicknesses in the inline processing is non-trivial, and final fine-tuning of all layers and interfaces has to be done in dynamic mode. Therefore, we suspect that small differences in both doped and intrinsic layer thicknesses contribute to the observed small deviations in solar cell parameters between dynamic and static solar cells.

Figure 5 shows the JV-curves for nip solar cells on steel foil substrates. One sample was made with a nearly texture-less barrier layer and the other with the above mentioned Asahi-like roughness. Both samples are compared with a co-deposited solar cell on an Asahi glass substrate.

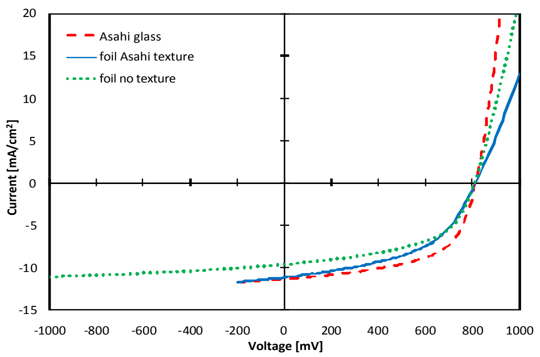

Figure 5: JV-curve of nip solar cell deposited on steel foil coated with Asahi-textured barrier layer and Ag/ZnO back contact compared with nip solar cell deposited on Asahi glass (dashed, red). Flexible cells with Asahi-textured barrier layer and flat barrier layer are shown, respectively as solid blue and dotted green lines.

All solar cells have very similar V_{oc} of 815 mV. The decrease in J_{sc} in the texture-less sample is attributed to the lack of light trapping. Very striking is the nearly identical current density obtained on the commercial Asahi glass substrate and on the Asahi-like texture embossed in the insulating barrier layer. On the other hand, the foil substrate samples have a significantly lower FF, amongst others due to the high series resistance. This is partly attributed to the combination of flexible foil, barrier layer and sputtered back contact. Note that probably the texture itself also negatively effects the series resistance, as seen in the slope above V_{oc}.

Another reason for the lower performances of the cells made on foil might be a suboptimal substrate temperature during deposition of the silicon layers. The clamping of flexible substrates and Asahi substrates in the sample holder probably leads to small but significant differences in surface temperature for the two substrates.

The spectral response curves of three nip solar cells are shown in Figure 6 for three different configurations of deposition mode and substrate. The EQE curves of the solar cells on Asahi-glass substrates are very similar. Comparing the dynamic deposition with the static one, we observe a small decrease in the higher wavelength region, >550 nm, and a similar increase around 400-500 nm. This is attributed to a slightly thinner intrinsic layer in the dynamic deposition.

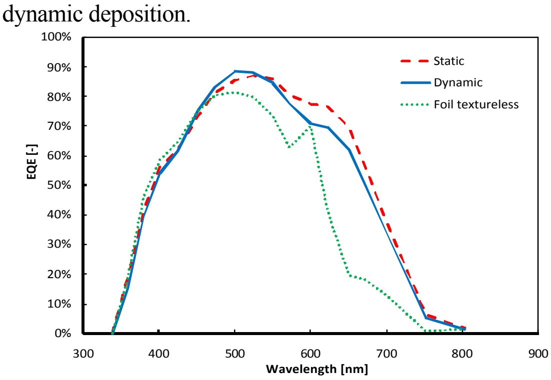

Figure 6: EQE curves of the presented solar cells: step-roll (dashed, red), in-line on rigid substrate (solid, blue) and in-line on flexible, texture-less substrate (dotted, green).

The spectral response of a nip solar cell, grown on flexible substrate, the green, dotted curve in Figure 6, shows a large decrease in response above 500 nm. This is consistent with the observed large decrease of the short-circuit current for the texture-less foil substrate solar cell caused by the expected lack of light trapping.

4 CONCLUSIONS

We have reported inline thin film Si nip solar cells, fabricated using linear VHF- and RF-PECVD plasma sources in an industrial deposition system. We fabricated amorphous silicon solar cells on Asahi-glass substrates in the nip configuration, both in step-roll mode and under continuous movement of the samples. The dynamic mode had almost no effect on the quality of produced solar cells. Small differences are due to variations in layer thicknesses.

We also compared solar cells fabricated on a variety of flexible substrate configurations with co-deposited cells on Asahi-glass. The present combination of metal foil, barrier layer and back contact leads to deteriorated shunt and series resistances. However, significant light trapping effects related to the presence or absence of texture in the barrier layers have been observed. More work is needed to optimise the combination of textured barrier layer and the processing conditions of back contact and Si layers.

Next steps will be to extend our experience to fully continuous deposition of roll-to-roll flexible nip a-Si solar cells and to fabricate μc-Si solar cells and micromorph tandem cells.

To conclude, amorphous silicon solar cells have been made using this PECVD system resulting in efficiencies up to 6.6% on Asahi glass in nip configuration and up to 4.5% on steel foil coated with a textured barrier layer.

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