ROLL TO ROLL FABRICATION PROCESS OF THIN FILM SILICON SOLAR CELLS ON STEEL FOIL

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ABSTRACT

ECN is developing a novel fabrication process for thin film silicon solar cells on steel foil. Key features in this process chain are: 1) application of an insulating barrier layer which enables texturization of the rear contact with submicron structures for light trapping; 2) Si deposition with remote, linear PECVD; 3) series interconnection by laser scribing and printing after deposition of the layers (reducing the total number of process steps). The barrier layer is primarily an enabler for monolithic series interconnection of cells, but we show that we can also fabricate any arbitrary sub-micron structure in this layer by hot embossing to achieve optimum light trapping in the solar cells. For deposition of doped and intrinsic silicon layers we use novel remote and linear plasma sources, which are excellently suited for continuous roll-to-roll processing. We have been able to fabricate device-quality amorphous and microcrystalline silicon layers with these sources. First pin a-Si solar cells have been made on FTO glass, yielding initial efficiencies up to 4.5%. First nip a-Si cells made on steel foil plus textured barrier layer yielded efficiencies of about 3.7%.

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 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, in a later stage of the fabrication process, after deposition of all layers. Details of this interconnection process will be presented in another paper in this conference [3]. The cell and module design of the ECN concept is depicted in Fig.1.

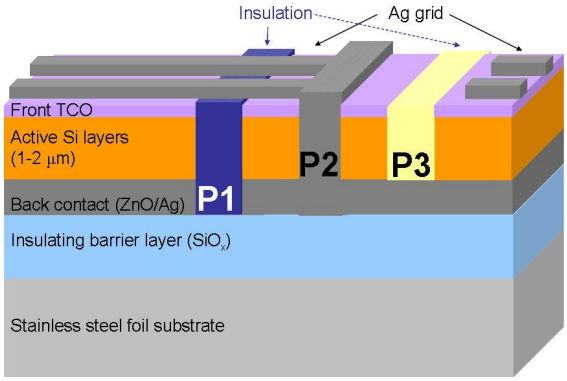

Fig. 1: cell and module layout

APPROACH

Application and nano-imprinting of barrier layer on steel foil

Monolithic series interconnection, to be obtained by combining depth selective laser scribing and screen printing requires a uniform, pinhole-free barrier layer, with sufficient electrical resistance (typical breakdown voltage should be higher than 1000 V). The insulating barrier layer that we use consists of a heat-curing SiOx-polymer sol-gel coating that can by applied by either roll coating or spray coating. After application, the layer is dried for a short time such that the surface is dust-dry but the bulk of the layer is still plastically deformable. At this point, a texture can be applied to the sol-gel layer by nano-imprint lithography (see Fig. 2). For our batch-type laboratory tests a master structure of up to 25 cm^2 is placed on top of the coated steel foil with its texture towards the barrier layer. The texture is transferred by applying pressure in a hydraulic press with heated anvils, resulting in the inverse of the master's morphology. Several different master structures were tested for their replication and optical properties. Due to the (lightly) dried surface of the sol-gel

layer, an anti-sticking layer is not required on these masters. Metal masters with diffraction gratings were used for the 1-D periodic structures.

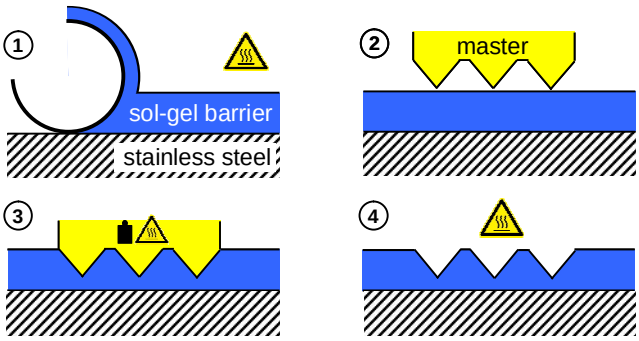

Fig. 2: Schematic process steps for hot embossing.

Silicon deposition process

As part of the pilot line, we have developed, in collaboration with Roth&Rau AG, a roll-to-roll PECVD system, the FLEXICOAT300, for the Si layer deposition [4]. The FLEXICOAT300 has three deposition chambers and can handle webs with a width up to 30 cm (see sketched cross-section in Fig. 3). The intrinsic layers are deposited by microwave (MW) PECVD as this combines good layer quality and uniformity with high deposition rates [5]. However, this linear MW source is not suitable for deposition of doped layers, as the quartz tube, shielding the antenna, does not transmit EM radiation when covered by a highly conductive (doped silicon) layer. A novel, linear RF source has been developed to circumvent this problem [6]. Just as the linear microwave sources, 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 MW-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 (≥ 1 µm for µc-Si).

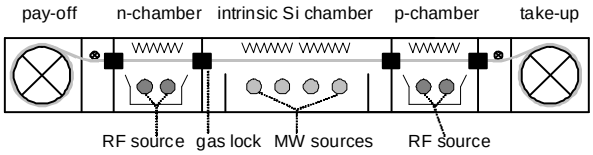

Fig. 3 Cross-section through the FLEXICOAT300 roll-to-roll coater. Both RF sources, in the n- and p-chamber, contain two parallel linear electrodes, whereas the four MW sources have one antenna each in a quartz tube.

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.

RESULTS

Nano-texturization of barrier layer

Periodic textures

Fig. 4 shows SEM images of a metal master with a periodic one-dimensional diffraction grating and its replica. This and other tested gratings comprise U-shaped grooves of 300 nm deep, with periods of 500, 750, and 1000 nm. For all three periods, the replicas compare well with their originals. Experiments are in progress to compare masters and replicas more quantitatively with respect to groove depth and shape by using atomic force microscopy.

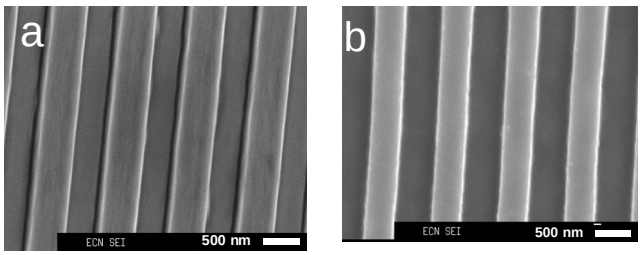

Fig. 4 SEM images of a metal master with a 1000 nm period grating (a) and its replica in the sol-gel barrier layer (b). The scale bar in both images represents 100 nm.

Haze measurements on the masters and Al-covered replicas show that for wavelengths larger than the period of the grating no diffraction occurs (Fig 5). At wavelengths equal to the period of the grating, the angle of diffraction θ is 90°. For longer wavelengths no diffraction occurs and all light is reflected specularly. Qualitatively the haze of the masters and Al covered replicas match, but quantitatively there are deviations due to the different dielectric functions.

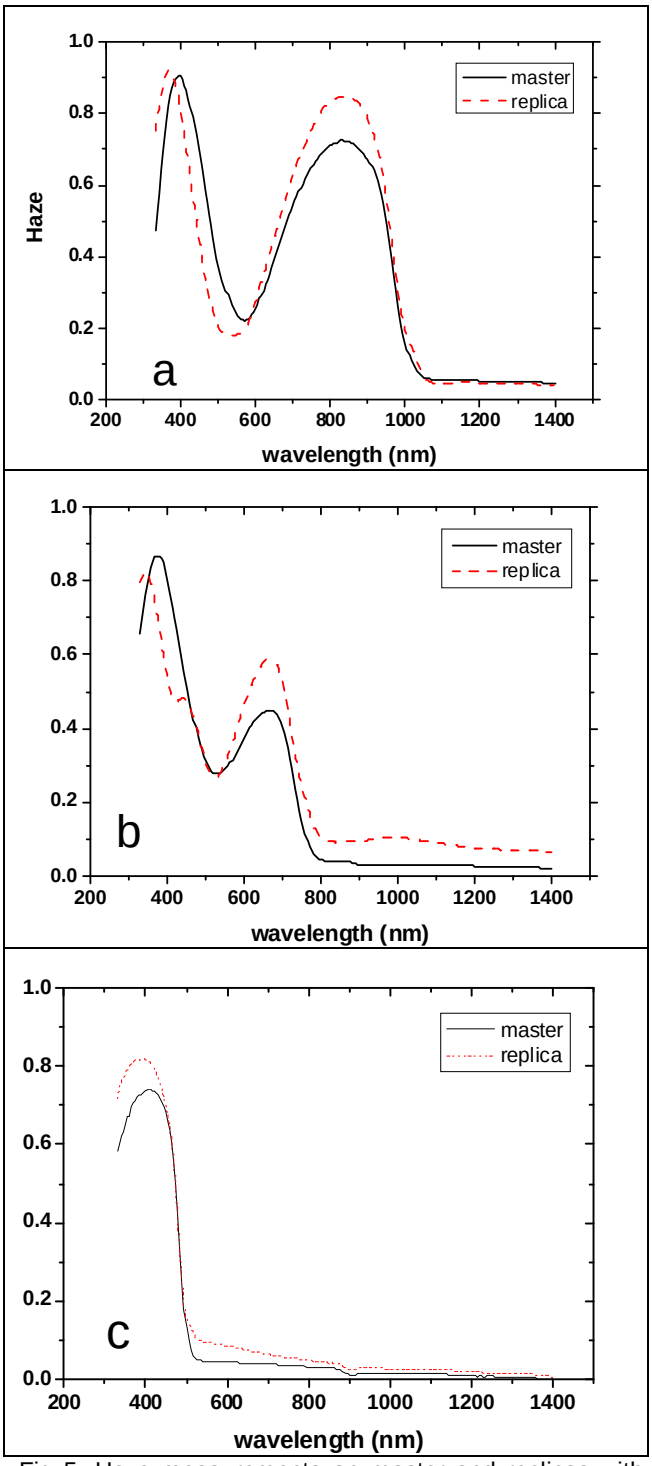

Fig 5. Haze measurements on master and replicas with diffraction gratings of (a) 1000 nm, (b) 750 nm, and (c) 500 nm.

Insulating properties of barrier layer after embossing

A periodic structure consisting of a mixture of submicron grooves was used to test the electrical insulation of textured barrier layers with various feature sizes in one experiment. The flat reference sample was part of the same 10×10 cm^2 piece of coated foil, in order to exclude any differences of the layers themselves, e.g. in layer thickness between different barrier layer depositions. Although texturing the foil reduces the resistance of the layer typically by a factor 4, the breakdown voltage remains higher than 1000 V. Thus, the electrical properties remain well within the limits for application in the ECN solar cell concept.

Si layer fabrication

Doped layers made by linear RF PECVD

We have succeeded in growing p-type and n-type a-Si:H and µc-Si layers by using respectively diborane and phosphine as dopant gas, applying the linear RF-PECVD source. The growth rate r_d is typically ~0.4 Å/s for the amorphous layers and one order of magnitude less for the microcrystalline layer. Table 1 gives an overview of the relevant material properties of these layers for layer thicknesses of 20-30 nm.

Table 1: properties of doped Si layers made with linear RF PECVD

Material property	n-type a-Si	p-type a-Si	p-type SiC	n-type µc-Si	p-type µc-Si
σ_d [S/cm]	3×10^{-3}	3×10^{-4}	5.4×10^{-7}	9.2	0.6
E_a [eV]	0.27	0.19	0.40	0.026	0.06
E_{gap} [eV] (Tauc)	1.75	1.74	1.91	1.80	1.80
α [cm^{-1}] @ 600 nm	2.0×10^{4}	2.4×10^{4}	2.1×10^{4}	7×10^{4}	1.2×10^{4}
ϕ_c [-]				50%	55%

Intrinsic layers made by MW PECVD

Following work presented on previous conferences [7] we continued to improve both deposition rate and electronic quality of intrinsic microcrystalline silicon layers made by MW PECVD. In particular, we investigated the transition regime between amorphous and microcrystalline material and the role of the applied MW power and the process pressure. In the lower pressure regime of the source, we observed a rather sharp transition from amorphous to microcrystalline material upon increasing MW power (see Fig. 6). Such a sharp transition could make it hard to control the crystalline fraction in an industrial scale production process. On the other hand however, we observe that in the high pressure regime the current MW generators (maximum power:

2kW) cannot deliver enough power to accomplish material with high crystallinity.

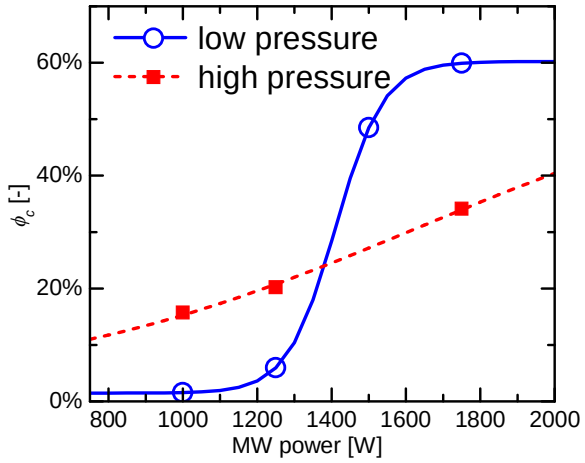

Fig. 6: Crystalline fraction of microcrystalline silicon layers, as a function of the applied microwave power.

a-Si solar cells

First attempts to make pin a-Si solar cells were made using Asahi U-type TCO glass as superstrate. Small samples of 10×2 cm^2 were mounted on the steel foil and moved from chamber to chamber in the FLEXICOAT300. After deposition of the silicon layers, a rear side contact of silver was made using electron beam evaporation, and applying a mask to create individual cells of 4×4 mm^2. As deposited, the V_{oc} of the amorphous cells is rather low (about 710 mV), but annealing at 150 ºC for about half an hour lifts the V_{oc} up to about 750 mV. Best cell efficiencies of these (world first) solar cells for which the Si absorber layer was made by microwave PECVD are about 4.5 %.

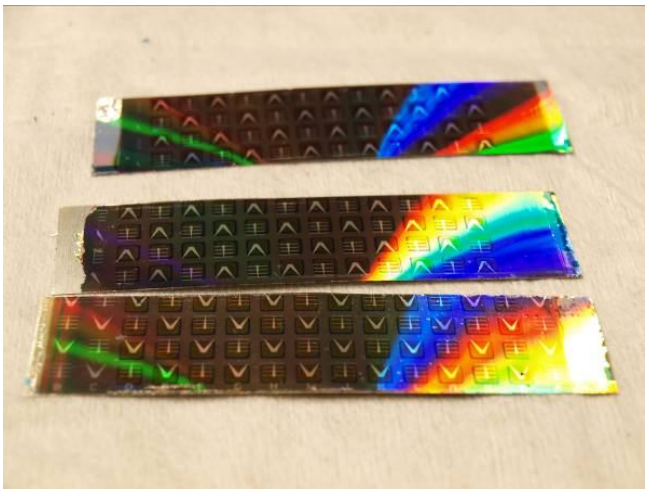

Fig. 7: First nip a-Si solar cells on steel foil + barrier layer + periodic texture.

In collaboration with the Delft University of Technology, we also fabricated first nip a-Si cells on steel substrates with barrier layer and periodic texture (See Fig. 7). Although the cell efficiencies are still moderate the results proof the feasibility of the concept. Best cells were obtained for a periodic grating of 750 nm; providing V_{oc} of 800 mV and J_{sc} of 11 mA/cm^2.

CONCLUSIONS

ECN is developing a novel fabrication process for thin film silicon solar cells on foil. Steel foil is a suitable substrate and when a proper barrier layer is applied, monolithic series interconnection of cells can be accomplished *after* deposition of all functional layers of the cell. We have shown that any arbitrary sub-micron structure can be applied to this barrier layer by hot embossing, and that this texturization method significantly can contribute to enhanced light-trapping in the solar cells. Using the FLEXICOAT300, a roll-to-roll PECVD system equipped with linear RF and MW plasma sources, we were able to fabricate first a-Si solar cells both on FTO glass and on steel + textured barrier layer, with efficiencies of respectively 4.4 and 3.8%, proving the feasibility of the concept.

Acknowledgements

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