ROLL-TO-ROLL NANOTEXTURISATION OF LAYERS ON STEEL FOIL SUBSTRATES FOR NIP SILICON SOLAR CELLS

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ABSTRACT: Light management is of utmost importance for thin film silicon solar cells. For nip cells, light management can be provided by textured back reflectors. In this paper, we demonstrate the fabrication of textured back contact foil on an industry compatible scale. A UV-curing lacquer on a stretch of 80 m of 30 cm wide steel foil was nanotextured in roll-to-roll mode, using the contact imprint method. Lab-scale samples were textured statically to test the effect on the growth of silicon by PECVD and cell efficiencies. The light trapping effect increases with decreasing lateral feature size. High aspect ratio structures result in strong domain boundaries defined by the period of the gratings and in non-conformal growth of the active layers of the cell. In its turn, this non-conformal growth, with thinner coverage of the steep slopes of the texture can lead to shunting problems in the solar cells. So, a balance needs to be found between optimum light scattering of the textured back contact and optimum layer growth on that back contact.
Keywords: Light trapping, thin film solar cell, substrates

1 INTRODUCTION

Roll-to-roll production allows for flexible PV modules and a significant decrease in production cost of thin-film solar cells compared to batch-type reactor systems. 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 and microcrystalline silicon thin films on steel foil coated with an insulating layer and sputtered back contact and reflection layer. The main purpose of the insulating 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. The cell and module design of the ECN concept is depicted in Figure 1.

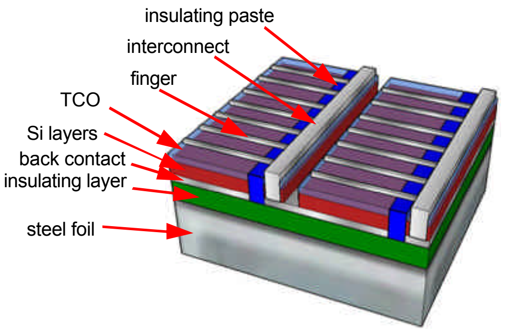

Figure 1: ECN's thin film Si solar cell and module concept.

For thin-film silicon solar cells, light trapping schemes are of uppermost importance to harvest all available sunlight. These schemes typically comprise the use of textured surfaces with lateral and vertical dimensions in the submicron range. For pin silicon solar cells on glass, naturally textured or etched TCOs are used to provide the light-scattering texture [3,4]. Whereas etching or natural growth processes for acquiring textures limit the possibilities for size and geometry of the texture, nanoimprint allows for any master structure to be replicated; the nanotexture applied can be, within limits, any kind of random or periodic texture.

Roll-to-roll nano-replication is usually performed on plastic substrates, allowing for illumination through the substrate. Here, we demonstrate replication of submicron textures in UV-curing lacquers on steel foil. The aim of this work is to demonstrate a roll-to-roll nanoimprint process on coated steel foil substrates that is feasible to be applied on an industrial scale to produce large-scale light trapping textured substrates for thin film PV.

2 ROLL-TO-ROLL NANOTEXTURISATION

2.1 Industrial production with contact imprint

In order to produce structured materials with significantly higher speed while maintaining quality and producing under industrial conditions, at Nanoptics we follow the contact imprint technology as a new and innovative machine concept dedicated for UV and e-beam embossing of opaque substrates.

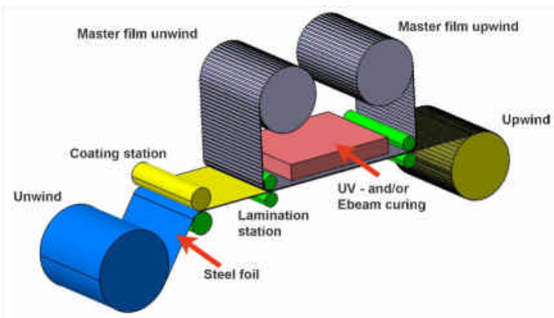

Figure 2: Schematic showing the principle of the contact imprint technology.

Unlike embossing with a structured cylinder, on this system a freshly coated base film will be laminated by a so called master film. After a long period in contact with the lacquer it will be cured by UV- and / or electron beam radiation (see Figure 2). It is technically feasible on metal film which has been demonstrated successfully. In addition it allows a huge number of other base films to be structured which cannot be done by conventional methods.

2.2 Contact imprint results

A stretch of 80 m long steel foil with a web width of 30 cm was used to demonstrate the contact imprint method on opaque films. A demonstrator master film with submicron features was used for texturing the insulating lacquer on the steel foil. The demonstrator was not optimized for light trapping for solar cells, but does have features in the typical length scale needed for light management. Figure 3 shows a photograph of the roll-to-roll nanotextured foil. The colour effects are a result of diffraction of light by the submicron periodic structures.

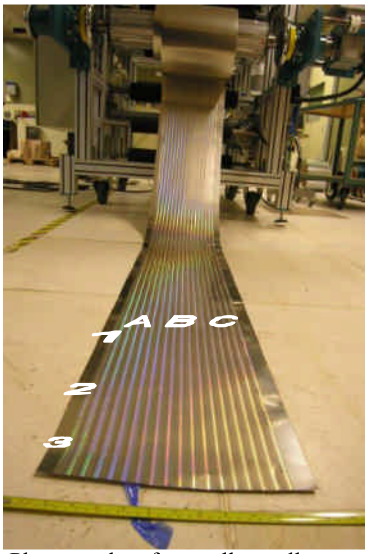

Figure 3: Photograph of a roll-to-roll nanotextured lacquer on steel foil substrate. The numbers and characters correspond to the matrix of SEM images in Figure 4.

To check replication quality on a large scale, scanning electron microscope (SEM) images were made on nine different locations on the foil (see Figure 4). Columns A, B, and C are spaced 10 cm apart, while rows 1, 2, and 3 have 30 cm in between. The matrix of locations is shown in Figure 3. The periods of the diffractive pattern were measured by averaging over 10 grooves per image for each of the nine locations. Table I shows that all periods are within 0.8% of the average period of 863 nm. Thus, the microscopic pattern replicates well over macroscopic areas.

Table I: Overview of the grating periods on the nine locations depicted in Figure 3. The periods are given in nanometres.

	A	B	C
1	863	856	866
2	862	866	861
3	860	869	862

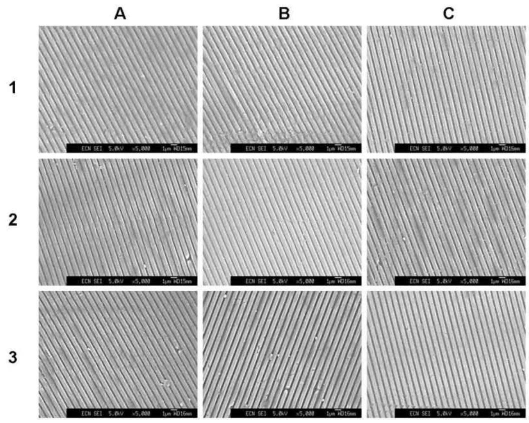

Figure 4: SEM images on the nine locations depicted in Figure 3, showing the nanotexture in the lacquer on steel foil.

3 STATIC NANOTEXTURIZATION

3.1 Substrate preparation

To test nanotextures on their suitability for light trapping in thin film silicon solar cells, laboratory scale textured substrates were made by hot embossing. Diffraction gratings with periods of 500 nm, 750 nm and 1000 nm, all with a groove depth of 300 nm, were replicated by hot embossing in a polymer layer on steel foil. A copy of the Asahi U-type glass texture was made in the barrier layer by hot embossing as substrate for a reference solar cell.

3.2 Optical characterisation

For optical characterisation, Ag/ZnO back contacts were deposited onto the textured polymer layers by sputtering. Using an integrating sphere, the total and diffuse reflection of the three grating back contacts was measured. From the ratio between diffuse, $R_{diffuse}$, and total reflection, R_{total}, the haze is calculated:

$$Hz(\lambda) = \frac{R_{diffuse}(\lambda)}{R_{total}(\lambda)}. \qquad (1)$$

Figure 5 shows the total reflection of the textured substrates and Figure 6 shows the haze for the same samples.

Compared to the flat samples, the textured back contacts show a general reduction of reflection in the short wavelength range of 300-600 nm and specific dips in total reflection for wavelengths shorter than the grating period. Dips at wavelengths equal to the period or integer fractions thereof may be the result of Woods anomalies [5] for 1st and higher order diffraction peaks; i.e. part of the diffracted light is diffracted at near 90° angles and do not contribute to the total reflection. The general loss in total reflection may be attributed by plasmonic losses. Corrugated surfaces allow for plasmonic modes along the metal-dielectric interface. In the case of textured back contacts the silver-zinc oxide provides the interface of propagation (see e.g. [6]).

Although overall the 1D gratings show reflection loss, the diffraction of light into high angles result in a high haze factor (Figure 6). Specifically the 1000 nm period grating shows a wide flat haze of 0.6 in the wavelength range of 600 to 1000 nm, indicating that more than 50% of the light is diffusively reflected.

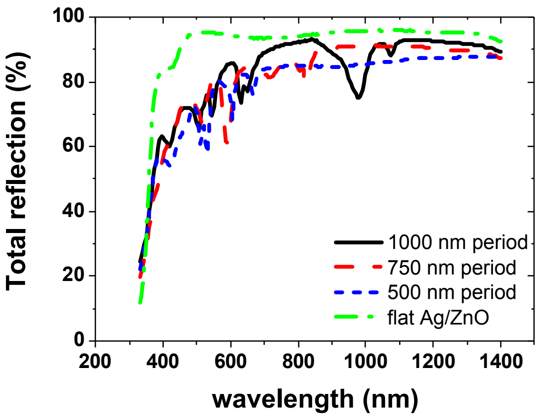

Figure 5: Total reflection spectrum of three differently textured Ag/ZnO back contact diffraction gratings and a flat reference back contact.

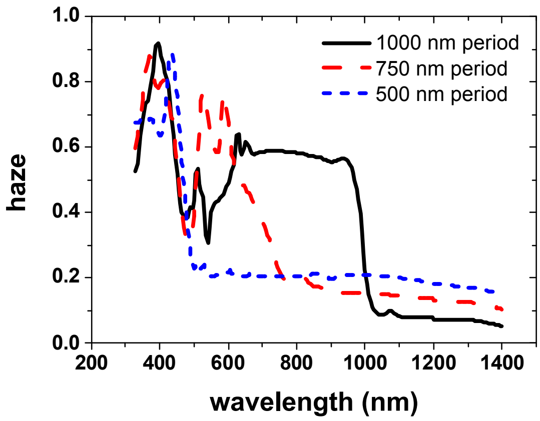

Figure 6: Haze of three differently textured Ag/ZnO back contact diffraction gratings.

Based on measurements in air the 1000 nm period grating is the most suitable to use as a substrate for thin film silicon solar cells because it has a high haze in the 600 nm to 1000 nm range. However, both the plasmonic losses observed in Figure 5 and the haze depend on the dielectric properties of the layers on top of the grating structure. The diffraction formula takes into account the refractive index in which the diffraction takes place, effectively lengthening the wavelength:

$$d(\sin\theta_m - \sin\theta_i) = \frac{m\lambda}{n}, \qquad (2)$$

with d the grating period, m the diffraction order, θ_m the angle of diffraction, θ_i the angle of incidence, λ the wavelength, and n the refractive index. A large part of the reflection of the back reflector will occur at the Si-ZnO interface because of he refractive index difference (~3.5 for Si versus ~2 for ZnO). Thus, the shorter grating period textures are expected to perform better in actual solar cell devices.

3.3 Solar cells

Amorphous silicon thin film *nip* cells were deposited by PECVD onto 10 by 2.5 cm^2 sized diffraction grating back contact substrates to evaluate the effect of the gratings on cell efficiency. ITO was deposited on top of the silicon layers to serve as front electrode. Reference cells were made on a 10 by 2.5 cm^2 piece of coated foil textured with the Asahi U-type texture. For these cells the IV curves were measured using a WACOM solar simulator at AM1.5 illumination. The cells were defined by 4 by 4 mm^2 ITO squares. Further details of the cell processing can be found in another paper presented at this conference [7].

Table II shows the cell parameters of the cells on textured steel foil substrates. For increasing period, the short circuit current decreases, suggesting a lower photocurrent generation. This trend is in compliance with theoretical investigations by computer modelling [8] showing that for a one-dimensional grating the optimal period from an electro-optical point of view for an a-Si:H cell is in the order of 300 nm with a groove depth of 300 nm.

Table II: First cell results on textured foil substrates.

Texture	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)
Asahi-on-foil	13.2	814	50	5.4
500 nm grating	13.5	826	39	4.4
750 nm	11.9	841	41	4.1
1000 nm	11.1	794	43	3.8

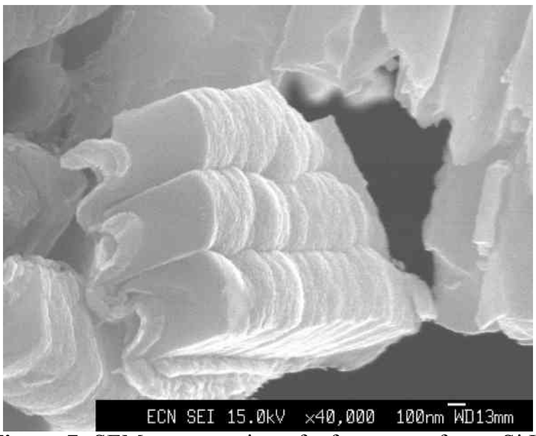

Figure 7: SEM cross section of a fragment of an a-Si:H solar cell on a 500 nm grating back contact.

Compared to the cells on the Asahi texture, the cells on diffraction gratings show low fill factors. Figure 7 shows a SEM cross section image of a fragment of the a-Si:H on the 500 nm grating back contact. Clearly visible is that the silicon has started to grow mainly on top of the grating, while in the grooves the growth has lagged behind. As a result, domains of silicon have formed following the 500 nm periodicity. These domain boundaries may give rise to defects and recombination of electron-hole pairs. Thus, the texture has a large influence of the growth mode of silicon, as observed by others [9]. For optimal light trapping, a compromise between optimal optical properties and device building has to be found.

4 CONCLUSIONS

We have demonstrated that UV curing coatings on steel can be roll-to-roll nanotextured using the contact imprint approach. This allows for scaling up to industry size the production of light trapping back contact substrates on steel foil and conceivably any type of web substrate.

Optical measurements on diffraction gratings show high haze but also optical losses in total reflection. First cell results on textured steel foil substrates support theoretical predictions that for a-Si cells structures with a period in the range 300-500 nm are to be favoured. Best optical scattering is obtained for high aspect ratios of these structures, but we have also observed non-conformal growth of the active layers of the solar cell on such structures, which implies that here a trade-off needs to be found.

5 ACKNOWLEDGEMENTS

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