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Nanoimprint lithography of textures for light trapping in thin film silicon solar cells

Wim Soppe*[,1], Maarten Dörenkämper[1], Jean-Baptiste Notta[1], Paul Pex[1], Wilfried Schipper[,2], and Rene Wilde[2]**

[1] ECN-Solliance, High Tech Campus 5, 5656 AE Eindhoven, The Netherlands
[2] Nanoptics GmbH, Innungsstrasse 5, 21244 Buchholz, Germany

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* Corresponding author: e-mail soppe@ecn.nl, Phone: +31 88 515 4087, Fax: 31 88 515 8214
** e-mail ws@nanoptics.de, Phone: +49 4536 891456, Fax: +49 4536 891457

Nanoimprint lithography (NIL) is a versatile and commercially viable technology for fabrication of structures for light trapping in solar cells. We demonstrate the applicability of NIL in thin film silicon solar cells in substrate configuration, where NIL is used to fabricate a textured rear contact of the solar cells. We applied random structures, based on the natural texture of SnO/F grown by APCVD, and designed 2D periodic structures and show that for single junction μc-Si cells these textured rear contacts lead to an increase of Jsc of more than 40% in comparison to cells with flat rear contacts. Cells on optimized periodic textures showed higher fill factors which can be attributed to reduced microcrack formation, leading to less shunting in comparison to cells on random textures.

1 Introduction To boost cell efficiencies, while reducing materials costs, all thin film PV technologies seek ways to reduce the thickness of absorber layers. This, however, requires improved light management strategies even for strong light absorbing materials like CIGS. In order to tailor the light management for various cell concepts and optical properties of all cell components a flexible light management strategy is highly desired. UV nanoimprint lithography (NIL) texturization offers this flexibility since virtually all imaginable textures can be made by this technology [1–3].

ECN and Nanoptics are developing a novel fabrication process based on NIL of textures for light trapping in thin film solar cells such as thin-film Si, OPV, CIGS, and CdTe.

The process can be applied in roll-to-roll mode when using a foil substrate or in roll-to-plate mode when using a glass substrate. The UV lacquer also serves as an electrically insulating layer for cells if steel foil is used as substrate, to enable monolithic series interconnection.

2 Experimental

2.1 Nanoinprint lithography (NIL)

Nanoimprint lithography starts with designing or selection of the master structures that will be used in the replication process. Basically two routes can be followed in this: usage of a designed periodic structure, which is typically a result of optical modeling of light trapping or the usage of naturally grown random structures, which have proven to be good light scatterers, like the texture of SnO/F grown by APCVD or of ZnO/B grown by LPCVD. In our research program we follow both routes. As a reference process we use masters originating from the texture of SnO/F, namely the Asahi-U type glass. In the competing process we use periodic 2D sinusoidal structures. The ideal periods and heights were obtained from optical modeling of 1D structures [4]. These periodic master textures are typically made by interference lithography (IL). The dimensions of both type of masters is typically in the range of $10 \times 10\,cm^2$. The next step is the fabrication of stamps based on the master structure. For smaller stamps, used in the ECN base line process, with substrate sizes up to $10 \times 10\,cm^2$ we can make these stamps by 1:1 replication of the masters. For the larger scale imprinting, where larger stamps up to $100 \times 200\,cm^2$ stamps are required, these stamps (called shims) are made by a step and repeat process.

The substrates used for the solar cells presented in this paper consist of steel foil on which we applied a UV hardening lacquer. With a stamp made of PDMS we printed the desired texture and then hardened the lacquer by UV radiation through the PDMS stamp.

2.2 Optical properties We measured the diffuse and the total reflection of the textured back contact (stack configuration: steel foil/textured UV lacquer/Ag/ZnO) with an integrating sphere in the wavelength region from 350 to 1300 nm. The reflection measurements were done for various orientations of the samples and then averaged, to compensate for imperfect random scattering inside the integrating sphere.

2.3 Solar cells The solar cells were processed according to the following scheme: (i) steel foil cleaning; (ii) application of UV lacquer; (iii) NIL; (iv) Ag/ZnO back contact formation by magnetron sputtering; (v) deposition of silicon nip layer stack by RF-PECVD; (vi) ITO front contact formation by magnetron sputtering; (vii) evaporation of Ag grid contacts; (viii) annealing. We made single junction μc-Si cells and varied the thickness of the μc-Si absorber layer: 500, 750, and 1000 nm.

After annealing the V_{oc} and FF of the cells were determined by IV measurements in a solar simulator with a light intensity of AM1.5. J_{sc} of the cells was determined by spectral response measurements at 0 V and no bias light.

3 Results

3.1 Replication quality and Si layer growth The replication method that we have developed appears to provide excellent replication quality. For the periodic textures, the period and height of the replicated structures are – within error margins – identical to that of the original. For the random texture the RMS roughness as determined by atomic force microscopy (AFM) is likewise identical for master, stamp and replication in UV lacquer.

In Fig. 1, a SEM image of the replication of the periodic texture in UV lacquer, coated with an Ag/ZnO back contact is shown. The thickness of the back contact is, respectively, 200 and 80 nm for the Ag and the ZnO layer and it can be observed that the back contact forms a conformal coating on the periodic structure.

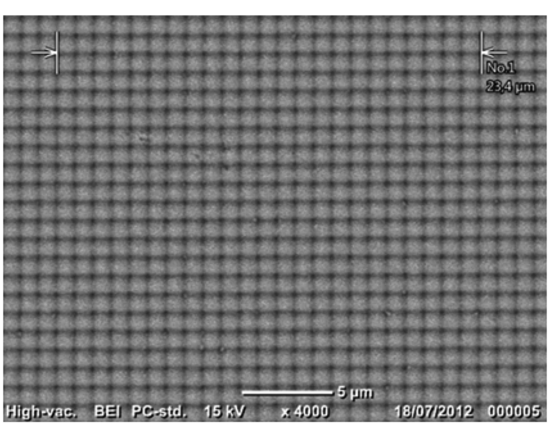

Figure 1 SEM image of a replica of the periodic structure in lacquer on steel foil. The structure is covered by an Ag/ZnO back contact.

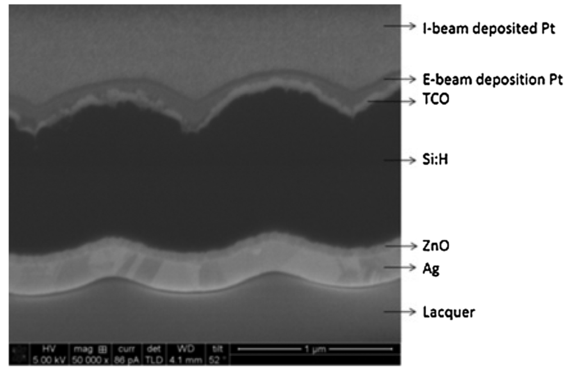

Figure 2 Cross sectional SEM image of a single junction μc-Si cell on periodic texture. The period of the sinusoidal texture is about 1 μm.

The conformal growth of the Ag/ZnO back contact is succeeded by initial conformal growth of the silicon layers. But beyond a certain thickness, space limitation forces the silicon layers to adjust the structure and the structure at the top of the layer is not conformal to the bottom anymore. This is confirmed by cross sectional SEM images of the entire cells. In Fig. 2, we show a typical example; in this case a μc-Si cell with a thickness of 1000 nm. It is interesting to see that – for this layer thickness – the initial conformal growth finally leads to a reversed periodic structure at the top of the cell.

3.2 Light scattering properties The haze values of the reflection of the random and periodic textured back contacts are shown in Fig. 3. The non-randomness of the scattering inside the integrating sphere leads to haze values that are somewhat too high for the periodic textures but still the haze factor of the periodic texture is appreciably higher than that of the random texture in the crucial wavelength region from 700 to 1000 nm. But one has to be cautious to draw quick conclusions from this since the haze factor is only

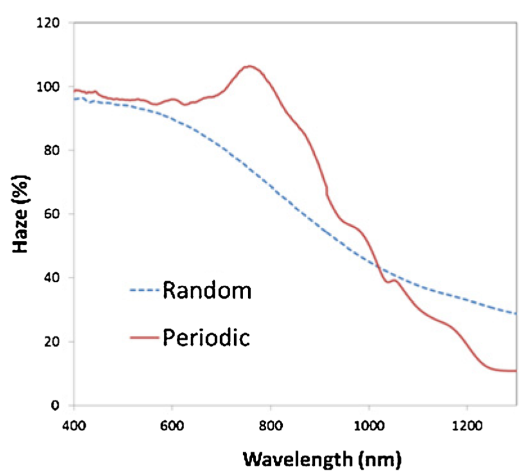

Figure 3 (online color at: www.pss-a.com) Haze values for the reflection of the random and the periodic textured back contacts.

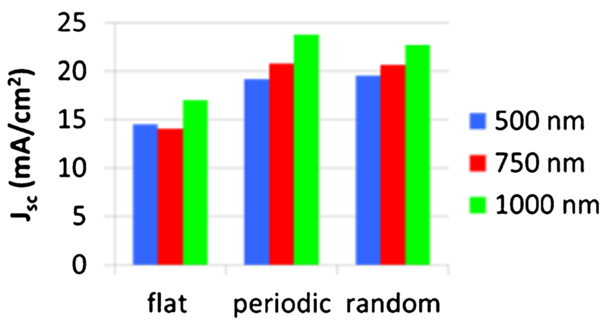

Figure 4 (online color at: www.pss-a.com) J_{sc} of single junction μc-Si cells with various absorber thicknesses on periodic and on random textures.

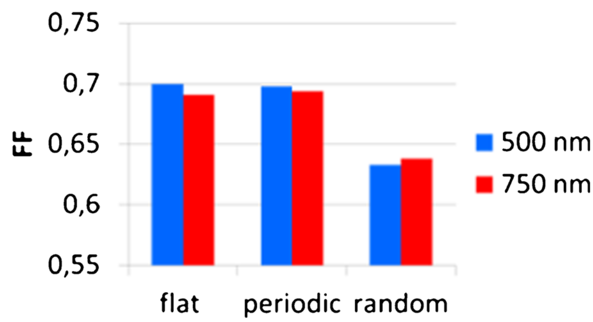

Figure 6 (online color at: www.pss-a.com) Fill factors of single junction μc-Si cells with various absorber thicknesses on periodic and on random textures.

a limited predictor of the light trapping capability. For more accurate predictions of the light trapping, angular distribution functions of the reflection are required and we hope to be able to present these too in near future.

3.3 μc-Si cells We made larger series of nip μc-Si cells with areas of $4 \times 4\,mm^2$ and $10 \times 10\,mm^2$, on flat substrates, on substrates with a random texture (replica of Asahi-U type) and substrates with a periodic texture. In general the cells on the flat substrate had the highest Voc (typically 530 mV) and FF (typically 70%), whereas the cells on periodic textures showed similar FFs, but smaller V_{oc}s (typically 500–510 mV). The cells on random textures had both lower V_{oc} (in the same range as for the cells on periodic textures) but also lower FFs (in the range of 65%). We attribute the lower V_{oc} values to the increase of the junction area due to the texture, leading to larger dark currents. The decrease in FF is clearly related to the observed decreased R_{shunt}; which is probably due to an increased number of shunting paths in cells with a sharply textured back contact.

The light trapping effect of the textured back contact can be clearly observed when comparing the J_{sc} of the cells. Highest values of more than 24 mA cm^{-2} were obtained for the cells on periodic textures (see Fig. 4). The increase of J_{sc} with respect to a flat back contact is 41%! This increase is even larger than predicted by opto-electrical modeling of the 1D structure [4].

The spectral response of cells with an absorber layer thickness of 750 nm is shown in Fig. 5. The gain of J_{sc} resulting from the texture at the rear side is roughly the same in the long wavelength regime, for the periodic and the random texture. It is noteworthy that the periodic texture leads to a higher response in the blue part of the spectrum than the random texture. This is due to lower reflectivity of these cells. The texture that develops at the front side of the cells apparently leads to better anti-reflection properties for the choosen periodic textures than for the random textures.

Comparison of the fill factors of the different groups of cells learns that cells on flat substrates and the cells on the periodic textures have approximately the same values of about 70% (see Fig. 6). The cells on the random textures

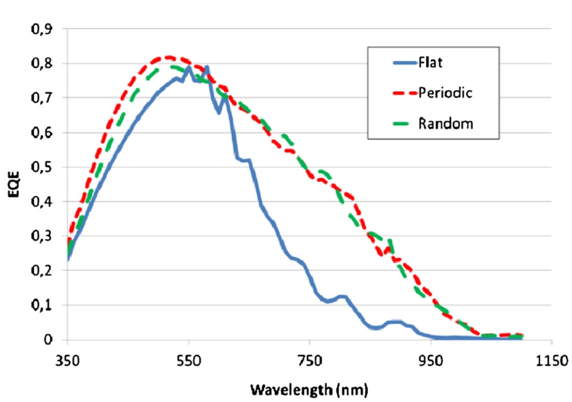

Figure 5 (online color at: www.pss-a.com) Spectral response data of cells made with an absorber layer thickness of 750 nm.

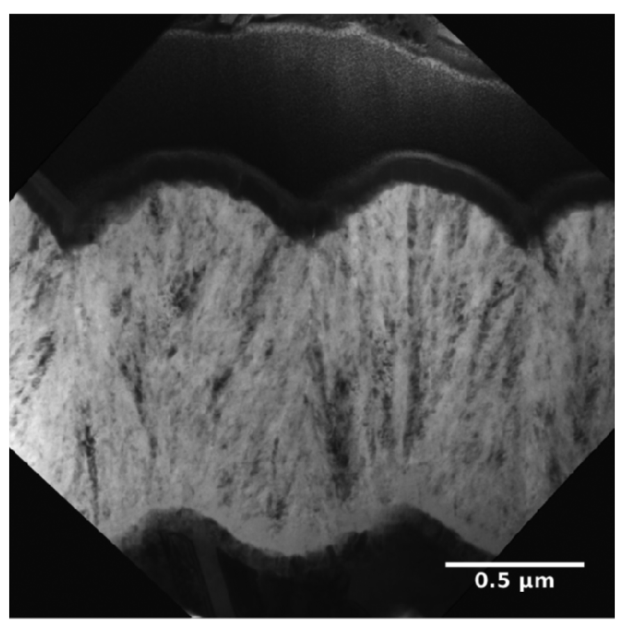

Figure 7 Bright field cross sectional TEM image of a single junction μc-Si cell with an absorber thickness of 1000 nm on a periodic texture.

however, have significantly lower fill factors, with values just above 60%, which is due to lower shunt resistances.

Growth of microcrystalline silicon layers on textured substrates often leads to the formation of microcracks which form shunting paths [5]. Cross sectional TEM analysis of the μc-cells we made on the periodic textures, however, show very homogeneous layer growth, without microcracks (Fig. 7)

4 Discussion and outlook Nanoimprint lithography is a versatile technology to fabricate light scattering structures in solar cells. Since scaling up to large areas is also well possible, we foresee industrial implementation on a relatively short term. In this paper, we have shown that NIL can be well applied for fabricating light scattering textures at the rear side of thin film silicon solar cells. With the periodic sinusoidal structure we obtained a J_{sc} of 24 mA cm^{-2}, an increase of more than 40% in comparison with a flat back reflector. The same increase in J_{sc} could be achieved using a random texture but the periodic texture clearly outperforms the random texture with respect to the quality of the microcrystalline silicon layers. On rough random textures the deposition of μc-Si layers typically leads to formation of microcracks resulting in shunting paths if no mitigating actions are undertaken. On the periodic textures that we have developed, we show that the growth of microcrystalline silicon without crack formation is possible.

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