ADVANCED LIGHT MANAGEMENT FOR THIN FILM SILICON SOLAR CELLS ON FOIL

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ABSTRACT: We present different new concepts to improve the light trapping in thin film silicon solar cells on steel foil. One of these concepts is to incorporate a textured back reflector, where the light scattering texture is made by Nano-Imprint Lithography (NIL). In this concept, we imprint a texture in a UV-hardening lacquer that has been applied on the steel foil. This texture then is covered by a silver layer, serving as a reflector and a back contact. Any arbitrary texture can be imprinted, and we have shown in the past that by this method we can obtain short circuit current density (J_{sc}) of more than 24 mA/cm^2 for cells with a nanocrystalline silicon (nc-Si) absorber layer of only 1 micron. Here we present results showing that the concept can also be applied to fabricate thin film silicon solar cells on paper. Another approach is to replace this silver layer by a white back reflector (WBR). Since, in contrast to the utilization of a WBR in superstrate cells, in substrate-type n-i-p cells the WBR has to undergo all the different steps of the cell processing, there are strict requirements to the material of the WBR, in terms of degasing and temperature stability. We have identified suitable materials and applied these in amorphous silicon (a-Si) solar cells. The J_{sc} values of these cells were equal to those of cells with a NIL back reflector. Finally, we present a-Si/nc-Si tandem cells on foil in which we combine the NIL back reflector concept with an incorporated intermediate reflector (IR) based on n-type doped SiO_x.
Keywords: a-Si/µ-Si, Light Trapping, Nano Imprint Lithography, white back reflector, intermediate reflector

1 INTRODUCTION

Usage of foil as the substrate for thin film silicon solar cells has specific advantages in comparison with the more conventional concept of using glass superstrates. One of the advantages is that it is easier to implement light management solutions at the rear side of the solar cell: the location where the non-absorbed light needs to be bounced back into the solar cell. Nano-imprint lithography (NIL) offers the possibility to create virtually all relevant textures for reflective scattering at the rear side of the solar cells. UV NIL offers great flexibility in light management strategies since it can be applied at various locations in devices, and can be used to fabricate features as small as 10 nm up to sizes of 10 micron and more [1,2,3,4].

Usually silver is used as back reflector material because of its very good reflective properties. For cost reasons, however, cheaper alternatives are preferable. Further, textured Ag also often leads to parasitic losses due to plasmonic resonances. White paint is an option that does not have these disadvantages and has successfully been applied to thin film silicon solar cells in superstrate configuration [5,6,7]. There are some issues, though, when silver is replaced by white paint. First: white paint is non-conductive, so the current at the rear side of the solar cell has to be collected by an another - transparent - layer, and secondly (in case of substrate cell processing on foil) the paint needs to be compatible with the other cell processing.

2 EXPERIMENTAL

2.1 Nano Imprint Lithography (NIL)

NIL 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_2:F, namely the Asahi-U type glass. In the competing process we use periodic 2-D sinusoidal structures with ideal periods and heights resulting from optical modeling [8]. These periodic master textures are typically made by interference lithography (IL). The dimensions of both type of masters is typically in the range of 10x10 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 10x10 cm^2 we can make these stamps by 1:1 replication of the masters. For the larger scale imprinting, where larger stamps up to 100×200 cm^2 stamps are required, these stamps (called shims) are made by a step and repeat process.

In the figure below a typical example of replica of a SnO_2:F texture is shown that we have applied for the solar cells reported here.

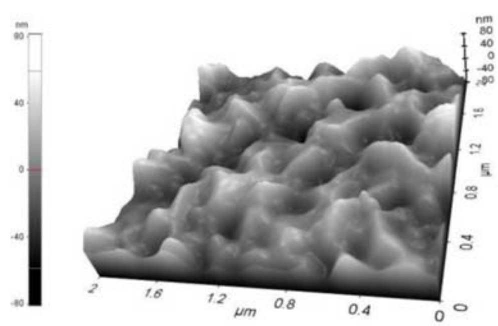

Figure 1: AFM image of a replicated SnO:F texture. The rms roughness is 29.6 nm, whereas the rms roughness of the orginal was 32.9 nm

2.2 Solar cells

The solar cells were processed according to the following scheme: 1) steel foil cleaning; 2) application of UV lacquer; 3) NIL; 4) Ag/ZnO back contact formation by magnetron sputtering; 5) deposition of silicon n-i-p layer stack by RF-PECVD; 6) ITO front contact formation by magnetron sputtering; 7) evaporation of Ag grid contacts; 8) annealing. We made single junction n-i-p a-Si and n-i-p a-Si/nc-Si tandem cells with thicknesses of 350 nm for the a-Si top cells and 1200 nm for the nc-Si bottom cells, and applied both 2D sinusoidal periodic textures, and random textures (replica of Asahi U-type glass/FTO substrates) in the NIL process.

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

2.3 White Back Reflector

We investigated several materials as back reflector and tested them on optical properties but also on compatibility with the other process steps in the cell manufacturing: temperature stability and degassing. A commercially available white paint finally turned out to be the best solution. The reflection (in air) of this layer is as good as for silver, whereas the haze factor of the WBR, when applied on a replica of a natural SnO_2:F (Asahi U-type) texture is much higher than for silver on the same texture.

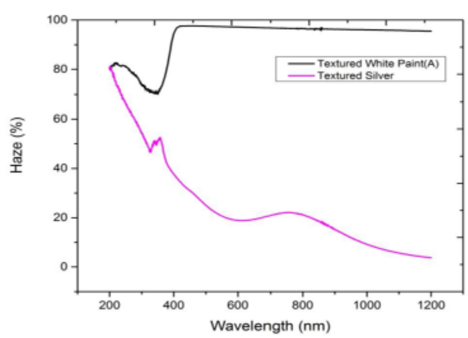

Figure 2: Haze factor of silver and WBR, both applied on a replica of a natural SnO_2:F texture

2.4 Intermediate Reflector

We developed an n-type nc-SiO_x:H layer to be used as IR layer in a-Si/nc-Si tandem cells, using SiH_4, H_2, PH_3 and CO_2 as process gases. The layer thickness is typically 100 nm, with a band gap E_{04} of 2.5 eV, a refractive index of 2.2 at the wavelength of 600 nm and dark conductivity of 2.8×10^{-5} S/cm.

3 RESULTS

3.1 a-Si cells with white back reflector

The layout of the cells with WBR and that of the reference cells is displayed in **Figure 3**. To collect the current at the rear side of the cells with WBR, an ITO layer was applied. We used two layer thicknesses of 160 and 200 nm, to investigate the effect on the series resistance of the cells but did not observe a significant effect. The relatively high series resistance of the ITO layer, in comparison with silver, however, leads to a slightly lower FF for the cells with WBR in comparison with the cells with silver back reflector.

In spite of the excellent haze, the J_{sc} of the cells with WBR did not outperform that of the reference cells. For both configurations the J_{sc} of the best cells was about 14 mA/cm^2. But although the FF of the cells with WBR was slightly less than for the reference cells, the cell efficiencies were equal (8.3%) for both configurations showing that a WBR in combination with 160 nm ITO is a proper alternative for a silver back reflector.

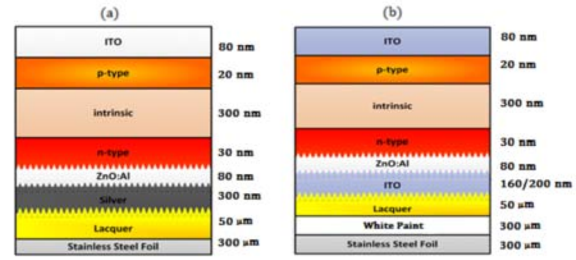

Figure 3: Configurations of (a) standard cell and (b) WBR cell design

3.2 a-Si cells on paper

The surface of ordinary paper, like used for copying and printing is too rough to serve as substrate for a-Si solar cells. But the standard UV curing lacquer that is used for the nanotexturization of the back contact can planarize the rough fiber structure of paper and thus enables the usage of paper as substrates for thin film silicon solar cells. We performed experiments in which we applied the lacquer on paper and subsequently imprinted it with a periodical texture. The paper withstands the high process temperatures of around 200°C and the cells had reasonable efficiencies of around 8%. This shows that lacquers that are used for the nano-imprint process can in addition equalize rough surfaces, enabling fabrication of thin film silicon solar cells on paper and on textiles.

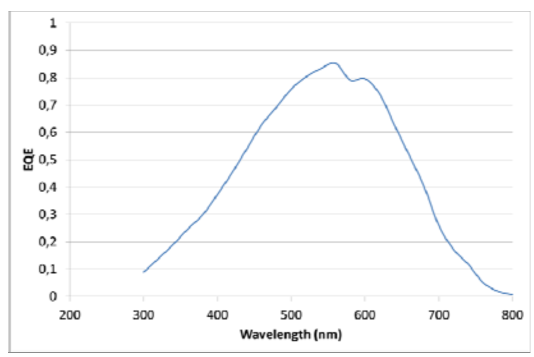

Figure 4: EQE spectrum of a typical a-Si cell made on ordinary white copy paper. IV parameters of the cell are: V_{oc}=867mV, J_{sc}=13.6mA/cm^2, FF=66.3%, eff.= 7.8%

3.3 Tandem cells with intermediate reflector

The tandem cells were made on substrates with a replica of the random texture of SnO_2:F. In the table below we present the average results of 4 best cells of each run. The size of these cells is 4×4 mm^2.

Without IR, the current of the tandem cell is strongly limited by the top cell. With IR, there is better current match, leading to an improvement of the cell efficiencies.

Table 1: Parameters of tandem solar cells on periodic texture replicated into UV-lacquer on steel substrate (initial values)

IR	V_{oc} (mV)	FF (%)	J_{sc} (top) (mA/cm^2)	J_{sc} (bottom) (mA/cm^2)	efficiency (%)
None	1321	69	10.8	12.3	9.9
100 nm μc-SiO_x	1323	68	11.2	11.3	10.1

Results of spectral response measurements are shown in the figure below. As we can see, the IR leads to a an increase of 0.3 mA/cm^2 for the top cell but to a decrease of 1 mA/cm^2 in the bottom cell. This difference is due to the parasitic absorption of the IR layer

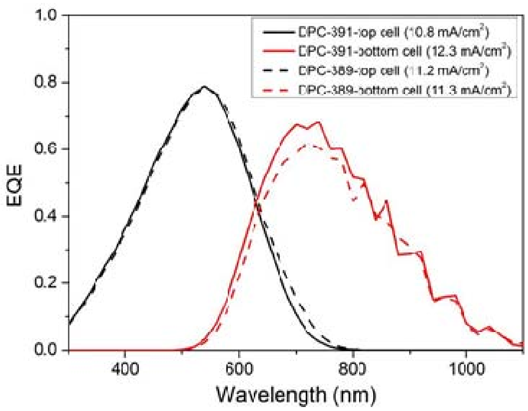

Figure 5: EQEs of tandem cells on textured steel foil with and without IR

4 DISCUSSION AND OUTLOOK

We have presented thin film silicon cells on foil with various light management concepts. Nano-imprint lithography (NIL) has been applied to fabricate very effective light scattering textures on the rear side of the solar cells. This method even allows fabrication of solar cells on ordinary paper and textiles: substrates which fiber structures which are in untreated form far too rough to be used as substrates for thin film solar cells. This opens perspectives for new applications of thin film solar cells directly on e.g. solar shading, clothing and tents.

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