LIGHT MANAGEMENT IN THIN FILM SOLAR CELLS

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ABSTRACT: Application of structured back reflectors, made by Nano-Imprint Lithography is shown to result in excellent light trapping in a-Si and nc-Si cells on steel foil. Applying these concepts we managed to achieve back reflectors with a Haze factor of more than 95% for the entire visible wavelength regime. On these back reflectors, nc-Si and a-Si cells were fabricated and J_{sc}s of more than 24 mA/cm^2 for nc-Si cells with an absorber layer thickness of 1000 nm were obtained. We applied the anti-reflection texture on the front glass of a hybrid tandem (in which a c-Si bottom cell was combined with a semi-transparent a-Si top cell) and reached an improvement of the J_{sc} of the bottom cell of 1.7 mA/cm^2. The lacquer that has been developed for textured back reflectors in CIGS solar cells has been applied to make periodic and random textures. First experiments to implement these back reflectors in thin CIGS solar cells were carried out indicating that the growth of CIGS on textured substrates is non-conformal on textures with high aspect ratios. Further modeling, in which this non-conformity is taken into account, is required to determine the optimum textures for CIGS
Keywords: Thin Film Solar Cell, a-Si/nc-Si; CIGS; Light Trapping; Nano Imprint Lithography

1 INTRODUCTION

Improvement of the light management is one of the key routes to increase the efficiency of thin film solar cells. The first step here is obviously to minimize the reflection losses at the front side of the solar cell. The common way to realize this is to implement an anti-reflection (AR) layer at the front and/or to introduce a scattering texture which further minimizes the reflection. Main issues here are the optical absorption losses in these layers and the production costs [1]. In this paper we will demonstrate a low cost approach to fabricate AR textures on glass by Nano-Imprint Lithography (NIL).

The next step is to increase the optical path length in the absorber material by creating textured interfaces in the solar cell. Yablonivitch in 1980 determined an upper boundary for the optical enhancement factor that can be obtained by this approach: the famous $4n^2$ limit [2]. Already in 1986, Derrick et al presented optical modeling results of the light trapping effect of periodic grating textures in amorphous silicon solar cells [3]. It took however decades before such grating textures could be realized in an affordable way. It is through NIL that the fabrication of light trapping textures has become practically relevant [4].

2 APPROACH

Within the project LIMANIL we investigated the implementation of textures made by NIL in thin film solar cells, to improve the light trapping in these cells. The first step in this approach was to perform optical modeling to determine the ideal textures for the different solar cells. The next step was to implement these textures in small area solar cells. Finally, we up-scaled the NIL process to larger areas, to demonstrate the industrial applicability of the technology.

2.1 Modeling

We used Finite Difference Time Domain FDTD software (MEEP and Comsol) for optical simulations of periodic textures in a-Si/nc-Si tandem cells and in CIGS solar cells.

2.2 Implementation in solar cells

In the project we implemented AR textures on hybrid tandems, consisting of wide bandgap amorphous silicon top cells and c-Si bottom cells; we implemented Distributed Bragg Reflectors (DBR) in a-Si/nc-Si tandem cells and we implemented textured back reflectors in CIGS cells. All textures have been made by NIL.

2.3 Upscaling of NIL

In collaboration with the Dutch equipment manufacturer, Morphotonics and Solliance designed and built a roll-2-plate pilot system for semi-automatic nano-imprinting on glass sheets with sizes up to 0.6x1.2m^2.

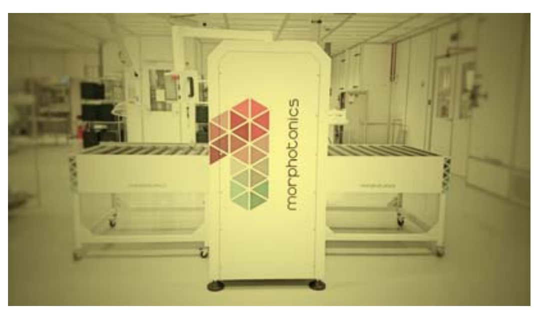

Figure 1: Roll2sheet NIL tool in the clean room of Solliance.

3 RESULTS

3.1 Modeling

<u>a-Si/nc-Si tandems</u>

These simulations have been carried out on thin-film silicon based tandem solar cells on glass in which a grating structure was implemented and using a three-layer DBR as intermediate reflector between the a-Si:H top cell and nc-Si:H bottom cell.

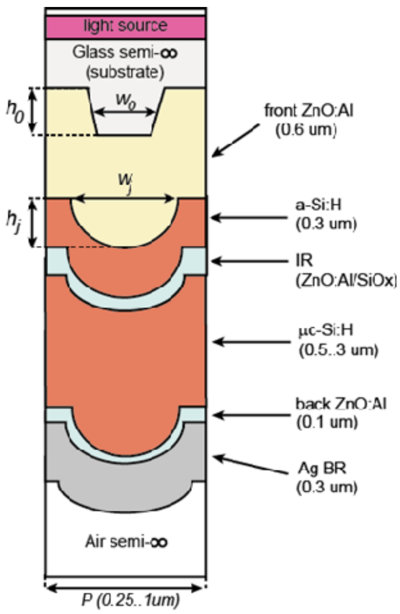

Figure 2: Schematic lay-out of a thin-film silicon tandem solar cell on a regular grating. The grating is characterized by the width, w0, and the height, h0, of the trapezoid. A leveling parameter, not shown here, indicates the degree of leveling of the layers deposited on top of this grating.

The important parameters in the simulations are: the width and the height of the trapezoid making up the grating; the leveling parameter that indicates the degree of conformity of the grating structure upon film growth, and the optical properties of the individual layers (in particular the complex refractive index). As intermediate reflector a DBR was used with the following structure: ZnO/a-Si:H/ZnO. The major results of these simulations are presented in the figure below.

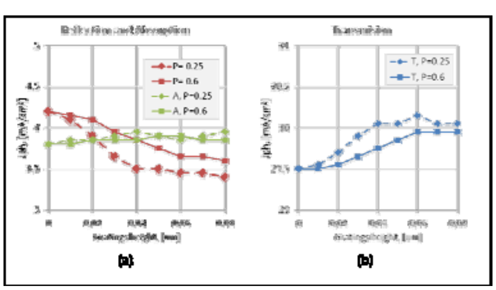

Figure 3 (a) The reflection of and absorption in the DBR as a function of grating height, h0, for two different grating periods. (b) transmission of the DBR as a function of grating height, h0, for two different grating periods. Note that all properties are expressed in the photocurrent under AM1.5

the absorption in the DBR is not affected by the grating. The reflection and transmission of the DBR are influenced by the grating, although operation of the DBR can still be observed; b) the degree of levelling of the layers has an effect on the current matching of tandem solar cell (not shown here).

<u>CIGS solar cells</u>

We modelled the effect of various periodic textures of the back reflector in CIGS solar cells with 2D simulations. We varied the geometry (triangles, rectangles, sinusoidals) and the pitch and height of these textures and determined the absorption in the CIGS. In the figure below some typical results are shown for triangular textures.

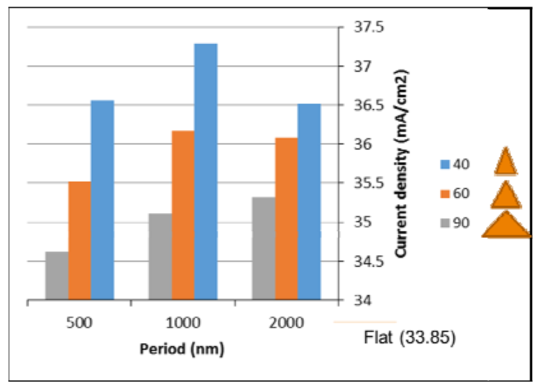

Figure 4: Enhancement of J_{sc} for 2000 nm absorbers through triangular textures with different top angles and periods.

A general trend is that textures with higher aspect ratios theoretically yield the highest light trapping enhancement. The practice however is less ideal, and side-effects like increased shunting of the solar cells on textured back contacts, play also a role.

3.2 Implementation in solar cells

<u>Hybrid tandems</u>

In Figure 5 the effect of an AR texture (a replica of a random pyramid structure of silicon) on the current of the bottom cell in an a-SiOx/c-Si tandem is shown. Note that the AR texture is applied on the front glass of the device, e.g. in front of the PSC top cell. The AR texture virtually has no effect on the light trapping of the PSC top cell.

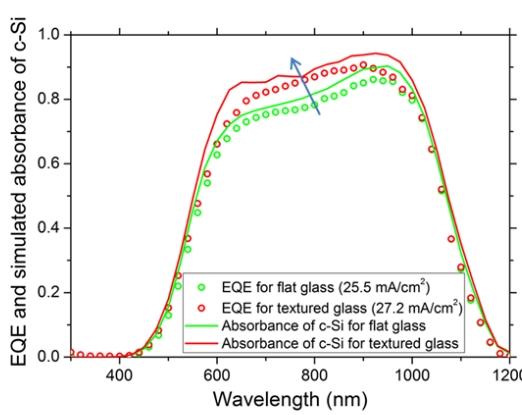

Figure 5: EQE of the c-Si bottom cell of a hybrid tandem, for which the front glass was flat (green) or coated with an AR texture (red)

Application of NIL structured back reflectors results in excellent light trapping in a-Si and nc-Si cells on steel foil. Applying these concepts we managed to achieve back reflectors with a Haze factor of more than 95% for the entire visible wavelength regime. We made nc-Si and a-Si cells on these back reflectors and J_{sc}s of more than 24 mA/cm^2 for nc-Si cells with an absorber layer thickness of 1000 nm.

<u>CIGS cells</u>

New UV curing lacquers were developed for the NIL process, which can withstand the higher processing temperatures of CIGS. This development was a challenge because of crack-formation and shrinkage of the material. Some shrinkage must be accepted and can be accommodated by anticipation when selecting the feature sizes of the stamp. In the figure below a typical example of an imprint is shown.

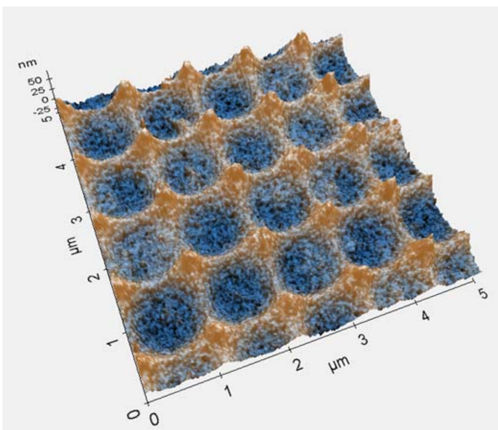

Figure 6: 2D periodic texture imprinted in a UV curable lacquer, after annealing at 550 ^{0}C. The R_{pv} is about 80 nm; i.e. about 50% of the R_{pv} of the master.

The growth of CIGS material on a textured substrate, however appears to develop differently than on a flat substrate. In the figure below one can see that on a textured surface the grains are smaller than on a flat surface, and that the overall morphology is different.

This is probably the reason that the cells that we made so far on textured substrates suffer from lower *FF* and V_{oc} than for cells made on flat substrates. Next experiments therefore will focus on textures with larger periods.

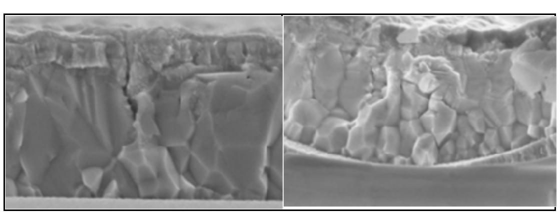

Figure 7: SEM cross section of CIGS solar cells on flat surface (left) and testured surface(right).

3.3 Upscaling of NIL

Morphotonics has developed a pilot system for semi-automatic nano-imprinting on glass sheets with sizes up to 0.6x1.2 m^2 and together with NTS a fully automatic industrial production system. Furthermore, an in-house capability was developed for nano-imprinting of substrates up to 1.6x2.0 m^2 which was used for the implementation of NIL on substrates for CIGS samples. For these samples a texture was selected based on sputter-etched AZO (aluminum doped zinc oxide) which provides U-shaped features that are known to prevent defects compared with V-shaped features..

These samples were manufactured with high temperature resistant lacquer provided by C-Coatings and tested with CIGS deposition conditions demonstrating the scalability of the concept. Next to the LIMANIL application of light trapping for thin -film PV these systems are also used for the display and lighting markets which can be considered as spin-off activities.

Figure 8: Large area shim (left) and imprint of a replica of sputtered-etched AZO (right)

4 CONCLUSIONS

The project LIMANIL has resulted in various new concepts for light management in thin film solar cells. The key technology used: NIL, has shown to be a very viable, and industrially applicable technique to implement flexible light management strategies.

ACKNOWLEDGEMENTS

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