SUPERIOR LIGHT TRAPPING IN THIN FILM SILICON SOLAR CELLS THROUGH NANO IMPRINT LITHOGRAPHY

W. Soppe, M. Dörenkämper, R.E.I. Schropp, and P.P.A.C. Pex
ECN-Solliance, High Tech Campus 5, 5656 AE Eindhoven, The Netherlands
Phone: +31 88 515 4087, Fax: +31 88 515 8214, E-mail: soppe@ecn.nl

ABSTRACT: ECN and partners have developed a fabrication process based on nanoimprint lithography (NIL) of textures for light trapping in thin film solar cells such as thin-film silicon, 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 lacquer also serves as an electrically insulating layer for cells if steel foil is used as substrate, to enable monolithic series interconnection. In this paper we will show the superior light trapping in thin film silicon solar cells made on steel foil with nanotextured back contacts. We have made single junction a-Si and uc-Si and a-Si/μc-Si tandem cells, where we applied several types of nano-imprints with random and periodic structures. We will show that the nano-imprinted back contact enables more than 30% increase of current in comparison with non-textured back contacts and that optimized periodic textures outperform state-of-the-art random textures. For a-Si cells we obtained J_{sc} of 18 mA/cm^2 and for μc-Si cells more than 24 mA/cm^2. Tandem cells with a total Si absorber layer thickness of only 1350 nm have an initial efficiency of 11%.
Keywords: a-Si/μ-Si, Light Trapping, Nano Imprint Lithography

1 INTRODUCTION

Improved light management is a prerequisite for all PV technologies, but in particular for thin film Si PV, in order to improve cell efficiencies and reduce costs for absorber materials. In order to tailor the light management for various cell concepts and optical properties of all cell components a versatile light management strategy is highly desired. UV NIL texturization offers this versatility since virtually all imaginable textures can be made by this technology. In collaboration with partners we developed UV NIL and applied it for thin film silicon 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].

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_2: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 [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 x 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 x 10 cm^2 we can make these stamps by 1:1 replication of the masters. For 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 a 2D structure is shown that we have applied for the solar cells reported here.

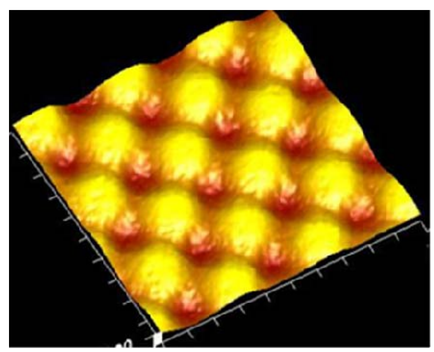

Figure 1: AFM image of 2D structure applied: period ≈ 1 μm; height ≈ 300 nm

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 n-i-p a-Si/μc-Si tandem cells with thicknesses of 300 nm for the a-Si top cells and 1000 nm for the μc-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 IV measurements in a solar simulator. J_{sc} of the cells was determined by spectral response measurements at 0 V.

3 RESULTS

In the following table we present the results of the best cells of the best run. The size of these cells is 4×4 mm^2. In this series we obtained the best fill factors for the cells on random textures, which is in contrast with the results of the single junction µc-Si cells, as reported in [5]. It seems like the FF of the tandem cells is not predominantly determined by the shunting of the bottom cell. It is still unclear what is the reason for the (slightly) higher FF of the cells on random textures, but this is most likely related to the current mismatch of bottom and top cells.

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

Texture	V_{oc} (mV)	FF (%)	J_{sc} (top) (mA/cm^2)	J_{sc} (bottom) (mA/cm^2)	efficiency (%)
random	1381	67.0	11.84	12.31	11.0
periodic	1366	65.7	11.90	13.24	10.7

Results of spectral response measurements are shown in the figure below. As we can see, the light trapping for the longer wavelengths is still not perfect since some interference effects can be observed but still the bottom cell current of more than 13 mA/cm^2 is very good for a µc-Si bottom cell of only 1000 nm.

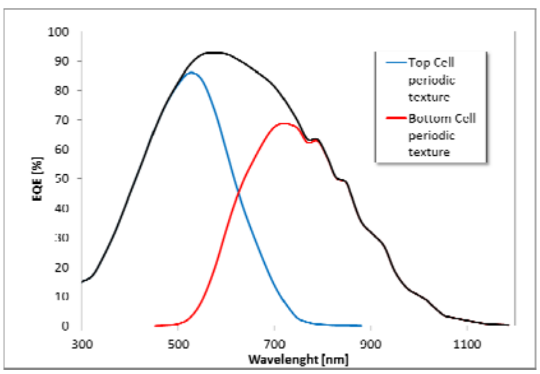

Figure 2: EQEs of tandem cell with 300 nm thick top and 1000 nm thick bottom cells on steel substrate with UV lacquer embossed with periodic texture.

4 DISCUSSION AND OUTLOOK

We have presented preliminary thin film silicon tandem cells on steel foil in which a back reflector was applied which was textured with NIL. Initial cell efficiencies of 11% have been obtained, both for random and for 2D periodic textures. Light soaking will have to done to determine the stabilized efficiencies. However, the devices presented here do not include an intermediate reflector yet. Introduction of an intermediate reflector will allow to apply thinner top cells and facilitate further increase of the cell efficiencies.

5 ACKNOWLEDGEMENTS

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