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# Thin-film silicon solar cell development on imprint-textured glass substrates

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ABSTRACT

In this work, we report on the fabrication of microcrystalline thin-film silicon solar cells on textured glass substrates. The development of transparent and conductive front contacts for these solar cells is presented. State-of-the-art random textures for light-trapping were replicated into a glass-like resist on glass substrates with an imprint process. We applied an industrial relevant soft polymer mold that gives excellent replication accuracy. The necessity of applying thin front contacts for enhanced incoupling of the incident light is shown. An increased series resistance of these thin front contacts caused a decrease of the fill factor of the solar cells. One way to surpass this decrease in fill factor by reducing the solar cell width is demonstrated. In addition, the light-trapping and the light-incoupling for solar cells deposited on three different types of random textures were compared.



## 1. Introduction

State-of-the-art thin-film silicon solar cells apply random light-trapping textures at the front and rear side to scatter and diffract the incident light into the optically thin silicon absorber layers. Thereby, the light incoupling as well as the light trapping in the solar cell is enhanced leading to an enhanced short-circuit current density ($J_{sc}$) of the solar cell [1,2]. For microcrystalline silicon (μc-Si:H) solar cells of p-i-n deposition sequence in superstrate configuration, the texture for light trapping is induced at the front contact which consists of a transparent and conductive oxide (TCO). Prominent TCO materials are as-deposited grown $SnO_2$, and ZnO:B layers [1–5]. In this work, a state-of-the-art wet-chemically etched sputtered ZnO:Al is used [6,7]. Its surface texture exhibits randomly distributed craters of lateral size in the micrometre range and depth up to 500 nm which proved to be beneficial for the light trapping in thin-film silicon solar cells [7].

The key challenge for the fabrication of any TCO with light-trapping texture is the optimal compromise between the electrical, the optical and the light-trapping properties. At the same time, the TCO must be highly conductive, the TCO must be highly transparent and the TCO must exhibit an optimal texture for light trapping. Since, the electrical and optical properties as well as the texture of TCO layers depend on the preparation parameters such a compromise does not lead to the optimum layer for solar cell applications regarding transparency, conductivity and light-trapping properties. One solution to this problem is to decouple the light-trapping properties by texturing the glass substrate itself on which the TCO is deposited. Previous studies show that using an imprinting technique randomly distributed features which are similar to state-of-the-art light-trapping textures of TCO can be replicated with very high accuracy on the glass-like resist on a glass substrate [8–14].

The objective of this work is to demonstrate approaches for the fabrication of high-efficiency μc-Si:H thin-film solar cells on imprint-textured glass-like substrates. The development of the transparent and conductive front contact for these solar cells is presented. Different ZnO:Al front contact layer thicknesses, solar cell sizes and light-trapping textures were investigated. Additionally, an improvement of the imprint process (with respect to our previous work [10]) using soft polymer molds is demonstrated. Applying a soft and flexible mold a very high replication accuracy is achieved which is of great interest for the industrial mass production where polymer molds can be applied e.g. in a roll-to-roll imprint process [15–19].

## 2. Experimental details

The μc-Si:H thin-film solar cells were fabricated on $5 \times 5\,cm^2$ glass substrates (Corning Eagle 2000). A glass-like resists on

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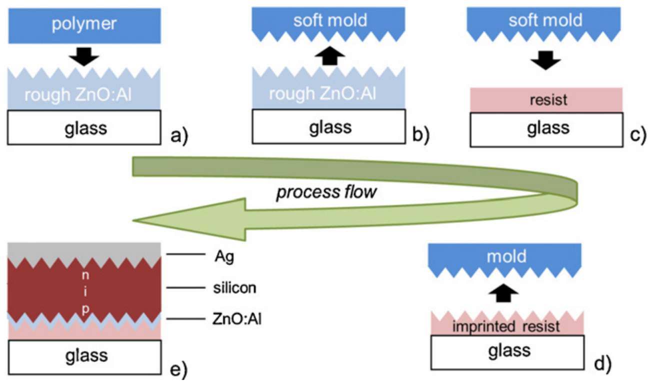


**Fig. 1.** Process flow of the fabrication process of microcrystalline thin-film silicon solar cells including the substrate patterning by an imprint process (a–d).

the entire glass substrate was structured by an imprint process using a commercial imprint system of Nanonex (NX2000) [20]. The complete process flow of the solar cell fabrication with focus on the substrate patterning is schematically illustrated in Fig. 1.

### 2.1. Master fabrication

The microcrystalline thin-film silicon solar cells apply a wet-chemically etched ZnO:Al front contact. It is deposited by radio-frequency magnetron sputtering at substrate temperatures of 300 °C onto a glass substrate. The light trapping texture of the front contact is induced by etching the ZnO:Al surface for around 40 s in 0.5 w/w% HCl. This texture is the state-of-the-art texture for light trapping in μc-Si:H thin-film solar cells [7]. In this work, such a ZnO:Al front contact was used as the master for the imprint process. In addition, two alternative textures have been replicated. One master was prepared by etching a sputtered ZnO:Al front contact for only 5 s in 0.5 w/w% HCl. The other master is the commercially available as-deposited grown $SnO_2$:F (called Asahi Type U from Asahi Glass Co.).

### 2.2. Soft polymer mold fabrication

The textures of the masters were transferred into a polymer material (polyolefin plastomer, POP) [21]. This polymer was pressed against the master substrate with a pressure of 400 kPa while heating it up over its glass transition temperature where the material becomes viscous (Fig. 1a). When the master structures were totally filled with the viscous polymer material the polymer is hardened again by cooling it below the glass transition temperature. Afterwards, the master and the polymer were separated (Fig. 1b). In a subsequent step, the polymer was used as a stamp containing the inverse structures of the master. Therefore, it is named soft mold.

### 2.3. Fabrication of the textured glass substrates

Using the soft polymer mold, the glass-like resist on the glass substrate was patterned via an UV-nanoimprint process. An UV-sensitive resist (Ormocomp from Microresist Technology GmbH) was spun onto the glass substrate (Fig. 1c). Afterwards, the soft mold was pressed with 400 kPa against the coated glass. While keeping the pressure constant the resist was hardened under UV illumination for 6 minutes. Finally, the soft mold was separated from the replica (i.e. the textured glass substrate) (Fig. 1d). More details on the nanoimprint process can be found in the reference [10].

### 2.4. Solar cell fabrication

Subsequent to the replication of the master texture onto the glass substrate, the μc-Si:H solar cell is fabricated on the textured glass substrate (Fig. 1e). First, a thin layer of ZnO:Al with three thicknesses (60 nm, 150 nm and 250 nm) was sputtered onto the textured glass substrate. The ZnO:Al layer was deposited by radio-frequency magnetron sputtering at a temperature of around 230 °C. The p-doped, intrinsic and n-doped μc-Si:H layers of the solar cells were deposited using plasma enhanced chemical vapor deposition (PECVD) at 13.56 MHz. The thickness of the i-layer was around 1 μm. The deposition temperature was below 200 °C. More details on our deposition process of the μc-Si:H layers of the solar cells can be found in the reference [22]. Ag back contacts were thermally evaporated through a shadow mask which defined the active cell area. The solar cell area was varied between 0.1 $cm^2$, 0.5 $cm^2$, and 1 $cm^2$ while the width of the solar cell with respect to the contacts is 3 mm, 8 mm, and 12 mm, respectively. In addition to the imprint textured substrates, reference solar cells were fabricated on wet-chemically etched ZnO:Al front contacts which exhibit the state-of-the-art texture for light trapping in μc-Si:H thin-film solar cells. The ZnO:Al front contacts for the reference samples were deposited by radio-frequency magnetron sputtering at substrate temperatures of around 300 °C. The texture is induced by etching the ZnO:Al surface for around 40 s in 0.5 w/w% HCl [6,7].

### 2.5. Characterization techniques

For the investigation of the replication precision of the imprint process, atomic force microscopy (AFM) measurements of the master and the imprinted replica substrates were performed. The intermittent contact mode was used. The AFM probes were supplied from the company Nanoworld (AFM probe series NCHR-50). They have a pyramidal shape, a tip radius curvature of less than 8 nm and a cone angle below 30°. Macroscopic marks were induced into the master texture with an UV-laser prior to the imprint process. These marks were replicated via the imprint process into the texture of the replica. As the marks are visible under the microscope that is aligned with the AFM system, it was possible to scan similar surface areas of the master and the textured glass substrate which exhibit a sufficient overlap of the texture. In addition, the UV-laser was used to remove selectively ZnO:Al material such that the thickness of the ZnO:Al layers could be measured at the edge of the layers by AFM measurements. In order to correct the measured AFM data for the drift of the AFM probe and the tilt of the samples, a third order plane-fitted background was subtracted from the original AFM image data. The origin of the height ($z$-axis) of the AFM data was set to the bearing height of each scan. The height and surface angle distributions were determined with the software SPIP, version 5.1.6 (Image Metrology A/S, Horsholm, Denmark). The surface angle of a plane formed by three adjacent data points was defined as the angle between the plane and the flat surface. For the evaluation of the height distribution, the height of each data point was evaluated relative to the bearing height of the AFM scan.

The IV-parameters for the solar cells, i.e. the fill factor ($FF$), the open-circuit voltage ($V_{oc}$) and the series resistance evaluated at open-circuit voltage ($R_{s,Voc}$), were measured using a double source WACOM-WXS-140S-Super (Class A) AM 1.5 sun simulator. The measurement of external quantum efficiency ($EQE$) was performed under 0 V bias using a grating. From the $EQE$ data the short-circuit current density ($J_{sc}$) of the solar cells was determined by the spectral integral of the product of the $EQE$ data and the AM1.5 spectrum. The reflectance ($R$) of the solar cells was measured from the glass side using a UV–Vis–NIR photo spectrometer with