Improved Light Management in Crystalline Silicon Thin-Film Solar Cells by Advanced Nano-Texture Fabrication

David Eisenhauer, Grit Köppel, Bernd Rech, and Christiane Becker
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Kekuléstr. 5, 12489 Berlin
david.eisenhauer@helmholtz-berlin.de

Abstract: We present a texturing method for liquid phase crystallized silicon thin-film solar cells enabling a maximum achievable short-circuit current density of 36.5 mA cm^{-2} due to optimized light management compared to current textured devices.

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1. Introduction

Liquid phase crystallization (LPC) of silicon on glass is a technology that allows manufacturing high-quality polycrystalline silicon thin-films between $5-40\,\mu$m in thickness, so far leading to solar cell efficiencies of up to 13.2% [1]. With decreasing cell thicknesses light-management measures, specifically anti-reflection and light-trapping, gain in importance. An efficient way for anti-reflection in LPC silicon thin-film solar cells is nano-structuring of the glass-silicon interface with smooth [2] or sinusoidal [3] nano-textures. These approaches also allow for an excellent electronic material quality with open-circuit voltages (V_{oc}) above 600 mV. However, the height-to-period ratio (h/P) of the nano-textures was limited to about 0.3 due to shrinkage of the involved nano-imprinted sol-gel materials [3, 4], hence also limiting the anti-reflective properties.

In this contribution, we introduce a method to replicate these nano-structures with a height-to-period ratio of 0.5 by combining nano-imprinting and reactive ion etching, allowing to optimize optical performance of $10-15\,\mu$m LPC silicon absorber layers grown and crystallized on sinusoidal textures.

2. Experimental

The liquid phase crystallized (LPC) silicon thin-film solar cells contained in this study are fabricated on glass substrates coated with a 250 nm Silicon Oxide (SiO_x) / 70 nm Silicon Nitride (SiN_x) / 10 nm SiO_x interlayer stack (Fig. 1(a)), serving as diffusion barrier against glass impurities, anti-reflective coating and passivation layer, respectively [5, 6]. Onto this stack a $10-15\,\mu$m thick silicon absorber is deposited using high-rate electron-beam evaporation and subsequently liquid phase crystallized (cf. inset in Fig. 2).

The interlayers between glass and LPC silicon are critical for device performance. Recently, it was demonstrated that interlayers produced by plasma-enhanced chemical vapour deposition (PECVD) are superior to those from physical vapour deposition [5, 7]. If nano-structures are introduced using high-temperature stable sol-gels, the texture is positioned between the diffusion barrier and anti-reflective coating. Hexagonal sinusoidal nano-textures with a period of $P = 750$ nm and a height-to-period ratio of 0.5 were produced by interference lithography [8]. In order to make the sol-gel compatible with LPC processing, a hard bake at 600°C for 1 hour is required to drive out organic compounds. This leads to substantial shrinking of the nano-structures [4], limiting the height-to-period ratio of the imprinted sinusoidal texture to 0.3. In the following this approach is referred to as high-temperature stable sol-gel method.

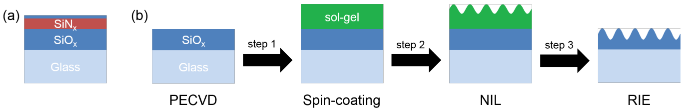

Fig. 1. (a) Optimized interlayer stack with SiN_x anti-reflective layer. (b) Schematic production process of sinusoidal textures combining nano-imprint lithography (NIL) and reactive ion etching (RIE).

In the newly developed method presented here, the PECVD diffusion barrier is deposited in a first step with a thickness of 1000 nm, such that the minimum thickness after texture replication is sufficient to serve as diffusion barrier. The texture is then imprinted into a commercially available organic sol-gel (UVcur06 produced by micro resist technology) with low-temperature stability but low shrinkage after its deposition onto the glass substrate via spin-coating (cf. Fig. 1(b), step 1 and 2). The nano-structured sol-gel layer serves as a three-dimensional etching mask during the subsequent dry reactive ion etching (RIE) step (Fig. 1(b), step 3). A gas mixture of 25 sccm CHF_3 / 25 sccm Ar, chamber pressure of 30 mTorr and a radio frequency power of 200 W is found to provide the desired selectivity of sol-gel to PECVD SiO_x of close to 1:1, allowing to replicate the imprinted structure into the SiO_x layers with high structural fidelity. An oxygen plasma treatment removes possible organic sol-gel residues, ensuring the compatibility with subsequent high-temperature processes. The presented method of nano-texture production will henceforth be referred to as *NIL+RIE* texture.

If a textured glass substrate is used and the absorber is capped by a SiO_x layer prior to crystallization, double-sided textured silicon layers are obtained [9]. Liquid phase crystallization is performed using a line-shaped laser beam of 808 nm wavelength and a scanning speed of 3 mm/s under vacuum or ambient air.

For the planar sample, a rear-side pyramidal texture using an isopropylic-alcohol free KOH based process with a texturing agent from GP Solar (Alkatex) is introduced [1]. This step is omitted for the textured samples as it has been shown that a KOH pyramid texture does not improve absorption for double-sided sinusoidal textures [10]. Optical characterization was performed using a Perkin Elmer Lambda 1050 photo-spectrometer with an integrating sphere.

3. Results

The absorption properties of a silicon absorber with sinusoidal texture prepared by the newly developed NIL+RIE technique (cf. inset in Fig. 2) is depicted in Fig. 2 (blue), compared to a planar interlayer stack (black) and a state-of-the-art sinusoidal textured produced by the high-temperature stable sol-gel method with a h/P ratio of 0.3 (red, data from ref. [3]). Both textures efficiently enhance light absorption over the whole wavelength regime. This can be attributed to both an anti-reflective and light-trapping effect. The anti-reflective properties without influence of back-side textures are assessed for wavelengths < 600 nm by mean reflectance ($\tilde{R}_{300-600}$), where the penetration depth is smaller than the cell thickness. In this regime, the NIL+RIE ($\tilde{R}_{300-600} = 8.0\%$) exceeds both the texture imprinted into high-temperature stable sol-gel (10.1%) and the planar reference (16.3%) due to its higher height-to-period ratio. It should be noted that 4% reflection (dotted line in Fig. 2) takes place when light first enters the solar cells device (cf. inset in Fig. 2). This 4% loss could be adressed by additional anti-reflective measures in future solar cells device designs.

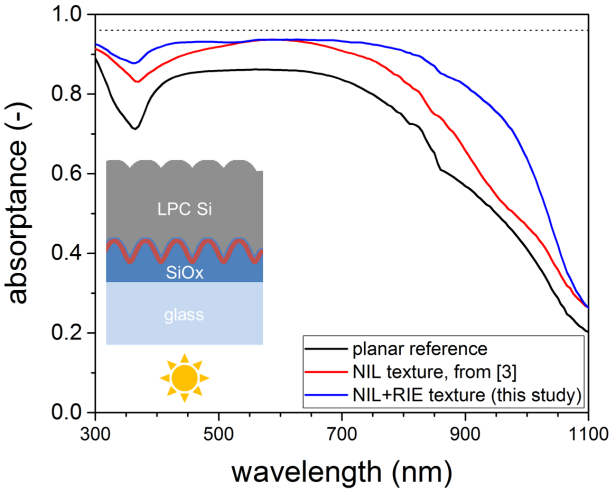

Fig. 2. Absorptance in 15 µm thick silicon absorbers with a planar interlayer stack (black), a sinusoidal texture produced by the high-temperatue stable sol-gel method (red) and the NIL+RIE method (blue). The inset depicts a schematic stack of the NIL+RIE sample.

The same trend is observed for the long wavelength regime, where anti-reflective properties at the front-side and light-trapping properties at the back-side of the silicon absorber are superimposed. Both texture's absorption exceeds the planar reference, with the NIL+RIE texture outperforming its high-temperature stable counterpart. In terms of maximum achievable open-circuit current density $j_{sc,max}$, calculated assuming that every incident photon generates an electron-hole pair, the improved light management leads to an increase from $j_{sc,max} = 30.7\,\mathrm{mA\,cm^{-2}}$ for the planar reference to $34.0\,\mathrm{mA\,cm^{-2}}$ for the sinusoidal texture produced by the high-temperature stable sol-gel method and $36.5\,\mathrm{mA\,cm^{-2}}$ for the silicon absorber with a NIL+RIE texture, corresponding to a 19% (relative) increase compared to the planar reference.

4. Conclusion

An advanced method for texturing interlayers for liquid phase crystallized silicon thin-film solar cells on glass was introduced using nano-imprint lithography (NIL) in combination with reactive ion etching (RIE). The nano-imprinted texture serves as three-dimensional etching mask during the anisotropic etching. Optimized process parameters allow a pattern transfer with high structural fidelity.

Using this method, sinusoidal textures with a height-to-period ratio of 0.5 could be produced compared to 0.3 for the state-of-the-art method using high-temperature stable sol-gels. The higher nano-structures allowed to enhance the absorptance of 15 µm thick silicon absorbers further, reaching maximum achievable short-circuit current densities of $36.5\,\mathrm{mA\,cm^{-2}}$ compared to $34.0\,\mathrm{mA\,cm^{-2}}$ for the high-temperature stable and $30.7\,\mathrm{mA\,cm^{-2}}$ for a planar interlayer stack.

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