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Optical properties of smooth anti-reflective three-dimensional textures for silicon thin-film solar cells

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Abstract

In recent years, thin-film silicon solar cells on glass prepared by liquid-phase crystallization have made progress towards high efficiency solar cells. Current record cells reach wafer-equivalent material quality and morphology using thin-film technologies. However, short-circuit current densities and hence, efficiencies, are still limited. The reflection at the interface between glass superstrate and silicon absorber layer has been identified as one major loss mechanism. These optical losses can be reduced by nanostructuring of the interface. It is important, however, that this nanostructured interface does not lead to a deterioration of silicon material quality simultaneously. Recently, we introduced SMooth Anti-Reflective Three-dimensional (SMART) textures, which consist of temperature-stable SiO_x sol-gel nanostructures and a smoothing layer of spin-coated TiO_x. These SMART textures on glass superstrates exhibit a smooth interface morphology and hence allow growing high-quality silicon absorber layers by liquid phase crystallization. Here, we investigate the optical properties of the SMART textures with and without an additional SiN_x layer in experiment and by 1-dimensional optical simulations. It is shown that both, the SMART textures with and without additional SiN_x layer, can outperform the optimized planar interlayer system of current record solar cell devices. Very low mean reflectance values of 11.2% are found in the wavelength regime from 400 nm to 600 nm for an optimized texture consisting of a 50 nm thick SMART texture with additional 15 nm SiN_x layer.

Keywords Liquid-phase crystallization; nanostructuring; anti-reflection; light management

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1. Introduction

Thin-film crystalline silicon solar cells on glass have shown a drastic improvement of material quality in recent years, especially by substituting solid-phase crystallization with liquid-phase crystallization techniques [1,2]. In 10 µm thick liquid-phase crystallized silicon thin-film solar cells, a wafer-equivalent morphology and material quality could be reached, enabling to surpass an open-circuit voltage V_{oc} of 650 mV [3]. However, short-circuit current densities are still limited due to incomplete light absorption in the thin silicon films. Therefore, light-trapping schemes become increasingly important with decreasing cell thickness. For laser crystallized silicon thin-film solar cells on glass, reflection losses have been identified as one major loss mechanism, mainly at the glass-silicon interface [4].

Reflection could efficiently be reduced by nanostructuring the glass-silicon interface, either by directly patterning the glass [5,6] or by nano-imprint lithography employing high-temperature stable sol-gels [7–9]. However, the introduction of nanostructures was shown to disturb the material quality of the silicon absorber, leading to a drop in quantum efficiency [9]. Thus, increased light-incoupling could not yet be translated to an increase in short-circuit current densities in solar cell devices [7,8].

This trade-off between optical and electrical performance is well-known from other thin-film solar cell technologies, e.g. nano-crystalline silicon solar cells [10–12]. One concept that was proposed to overcome this issue is the use of flat light scattering substrates (FLiSS) [13]. FLiSS structures consists of ZnO gratings [13] or random ZnO pyramids [14,15] which are flattened by deposition of amorphous silicon and subsequent mechanical polishing. Implementing the FLiSS approach into nano-crystalline silicon thin-film solar cell devices allowed increasing light-trapping without deteriorating the silicon material quality. For amorphous silicon superstrate devices, a similar approach has been proposed employing random pyramids produced by nanoimprint lithography and ZnO nano-particles as scattering layers that smoothen the pyramid texture, leading to a significant gain in solar cell efficiency [16].

Recently, we have introduced SMooth Anti-Reflective Three-dimensional (SMART) textures for crystalline silicon thin-film solar cells. The SMART texture consists of nano-imprinted silicon oxide (SiO_x) nano-pillars smoothed by spin-coated titanium oxide (TiO_x) films. The use of such SMART textures has proven to enable anti-reflective properties without detrimental effects on material or interface quality in laser-crystallized silicon thin-film solar cells on glass [17].

In this paper, we investigate and optimize the optical properties of SMART textures for crystalline silicon thin-film solar cells. The influence of geometrical nanostructure parameters on the optical properties is investigated experimentally and numerically, employing a one-dimensional effective medium approach. On the basis of these results, double-interlayers consisting of a SMART texture and a silicon nitride (SiN_x) anti-reflective layer are introduced and an optimum geometry is determined by numerical calculations using 1-dimensional modeling. This optimum structure geometry is subsequently realized experimentally, providing excellent AR properties compared to planar reference samples.

2. Experimental and numerical methods

2.1. Sample preparation and characterization

The preparation of SMART textures is sketched in Fig. 1. 5 × 5 cm² sheets of 1.1 mm thick Corning Eagle XG glasses serve as substrates. After a cleaning step with the commercially available cleaning agent Mucasol©, a 250 nm thick layer of SiO_x is deposited onto the glass by sputtering. This layer serves as a diffusion barrier against metal impurities from the glass into the silicon during liquid-phase crystallization. Nanostructures are produced by nanoimprint lithography (NIL) [18], using a high-temperature stable SiO_x-based sol-gel [19]. A detailed description of the process is included in Ref. [20]. For the SMART texture, a hexagonal array of nano-pillars with a period of 750 nm is used as master structure. Polydimethylsiloxane stamps are used to replicate the master structure in the SiO_x sol-gel layers (step 1). Thermal annealing for 1 hour at 600°C removes all organic constituents, hence ensuring the high-temperature stability of the imprinted nanostructure. Subsequently, a TiO_x precursor solution [21] is spin-coated onto the nanostructure (step 2) and thermally annealed. The spin-coating leads to a preferential material