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Double-side textured liquid phase crystallized silicon thin-film solar cells on imprinted glass

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ABSTRACT

Emerging liquid phase crystallization (LPC) techniques recently rendered a possible substantial progress in the fabrication of high quality crystalline silicon thin-film solar cells on glass. The implementation of an efficient light trapping texture into such LPC silicon devices is still challenging as an excellent bulk material quality and well-passivated interfaces have to be guaranteed. In this paper we present recent advances in light management for LPC silicon thin-film solar cells on imprinted glasses. A double-sided 2 μm periodic texture is realized by sandwiching the silicon film during the electron-beam induced crystallization process between an imprinted glass substrate coated with silicon oxide and a silicon oxide capping layer. Amorphous-crystalline silicon (a-Si:H/c-Si) heterojunction solar cells with single sided contacting scheme are fabricated. Textured prototype devices and simultaneously processed planar solar cells exhibit a comparable electronic material quality featuring open circuit voltages above 550 mV and efficiencies up to 8.1%. Optical absorption properties of 10 μm thick double-side textured silicon films even predict maximum achievable short circuit current densities in solar cells up to 38 mA/cm^2 assuming zero parasitic absorption.

1. Introduction

Crystalline silicon (c-Si) thin-film solar cell technology recently underwent rapid advances in high-quality absorber fabrication by liquid phase crystallization (LPC) techniques [1–8]. The LPC technology enables an excellent electronic material quality with record open circuit voltages exceeding 650 mV [8], extremely short processing times, and it has the inherent advantages of thin-film technology, namely low material usage, large area processing and monolithic device fabrication. In this approach the initial silicon precursor film on a glass substrate is molten and crystallized by using a line-focussed energy source which is moved with respect to the silicon layer resulting in a silicon material with grains up to a centimeter in size. Crystalline silicon thin-film solar cell devices on glass with 11.7% (initial)/10.4%(stable) efficiency have been reported using a laser [6] and with 11.5%(stable) efficiency using a line-shaped electron-beam [8] as the energy source. However, both of these top devices still suffer from incomplete light absorption exhibiting only a random single sided texture on the silicon surface in case of the laser crystallized and very basic light trapping without any texture in case of the electron-beam crystallized device.

Parallel to the developments in LPC silicon, there has been a vivid progress in nanophotonic light trapping for thin-film photovoltaics including periodic, quasiperiodic or designed disordered absorber geometries [9–13] theoretically even allowing to surpass Yablonovitch's limit of light path enhancement of $4n^2$ in a weakly absorbing medium with refractive index n [14]. Nanoimprint-lithography has been identified as a promising technology for photovoltaics as it permits manifold degree of freedom to systematically control size and shape of the light trapping features at low fabrication costs [15–20,4]. The challenge is now to implement nanophotonic light management concepts into LPC silicon thin-film solar cell devices maintaining the bulk material quality including a smart interface design.

In this paper, we present recent advances and challenges of a light management concept for liquid phase crystallized 10 μm-thick silicon films on imprinted glass substrates featuring a 2 μm-periodic double-side textured silicon absorber. The compatibility of LPC silicon with such a strongly textured substrate interface has been proven recently [4,21]. By sandwiching the silicon film between a silicon oxide (SiO$_x$) barrier layer on the imprinted substrate and a SiO$_x$ capping layer on top during the crystallization process [7], a double sided texture is realized. These double-side textured c-Si films are analysed with respect to their optical performance and applied as absorbers in amorphous–crystalline silicon (a-Si:H/c-Si) heterojunction solar cell devices. Current limitations of this solar cell concept regarding the

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optical and electronic performance are identified. Approaches for overcoming them are discussed.

2. Material and methods

A 2 μm periodic square lattice texture was imprinted into a hybrid polymer sol–gel on 5 × 5 cm^2 SCHOTT AF 37 glass substrates. By UV-curing and thermal annealing the sol–gel was converted into an essentially glassy structure exhibiting a high temperature-stability [22]. On these textured substrates a layer stack was deposited consisting of 200 nm SiO_x, 10 μm nanocrystalline silicon and 400 nm SiO_x (Fig. 1a). The SiO_x films were deposited by reactive RF magnetron sputtering using a 6N silicon target. The nanocrystalline silicon layer was electron-beam evaporated at a temperature of 600 °C with a rate of 600 nm/min while co-evaporation of boron yielded a p-type doping of 1–2 × 10^{17} cm^2. Subsequently, the silicon was recrystallized using a line-focussed electron-beam with an energy density of about 1 J/mm^2 moved with a scanning speed of 6 mm/s. The SiO_x capping layer fulfils two functions during the liquid phase crystallization process: It inhibits dewetting of the silicon on the SiO_x substrate layer [7] as even a textured substrate is not sufficient to prevent delamination, and it prevents the upper texture from flattening resulting in a double-side textured crystalline silicon film (Fig. 1b).

After removal of the SiO_x capping by buffered oxide etch and subsequent etching in an $HF/HNO_3/H_3PO_4$ based silicon etchant for 1 min, the samples were exposed to hydrogen plasma at 600 °C for 15 min. Subsequently the samples were treated again with the silicon etchant for 1 min in order to remove plasma induced surface damage of the topmost 500 nm. Residual surface contaminations were removed by RCA cleaning before amorphous silicon deposition. Silicon heterojunction solar cells with single sided contacting scheme based on these double side textured crystallized silicon thin films were prepared with hydrogenated amorphous silicon buffer and emitter layers (a-Si:H(i) and a-Si:H(n+)), a transparent conductive oxide (TCO) acting as antireflection coating (ARC) and emitter contact layer, and two metal grids placed on top of each other and separated by an isolation layer [3] (Fig. 2a). The cell area defined by the a-Si:H(n+) emitter is 0.6 × 1 cm^2. A white back reflector (BR) is painted on the rear side of the glass substrate.

Optical absorption was measured with a Perkin Elmer LAMBDA 1050 spectrometer with the samples illuminated from the silicon side and mounted inside the integrating sphere. In order to assess the optical performance of the c-Si structure geometry beside from parasitic absorption in the functional layers (a-Si:H, TCO) and such enabling the comparability with many theoretical studies, simpler samples were prepared containing the structured c-Si absorber only with optionally a 73 nm thick silicon nitride ARC (with a similar refractive index like the TCO of the solar cell devices but less parasitic absorption) and white paint BR (Fig. 2b). Scanning electron microscope images were done with a Hitachi S 4100 SEM using a cold field electron emitter. The current voltage characteristics of the solar cells were measured at a temperature of 25 °C using a Wacom WXS-156-L2, AM1.5GMM dual source sun simulator. External quantum efficiency was measured using a custom made tool.

3. Results and discussion

3.1. Optical properties

The optical absorption of various 10 μm thick liquid phase crystallized silicon films illuminated from the silicon side is shown in Fig. 3. An antireflective effect of the structuring becomes obvious when comparing the absorption spectra of a bare planar film (grey dashed line) with a bare structured layer (blue dashed line). The crystalline silicon film with double-side texture shows an increased absorption in the whole spectral range. Reflection losses are decreased by 20–25% absolute in the ultraviolet and visible spectral range where transmission can be assumed as being neglectable. For the planar sample also large transmission losses are observed in the near infrared region owed to the low absorption coefficient of crystalline silicon near the band edge. By structuring light trapping in the near infrared is strongly increased, e.g. enhancing the absorption at $\lambda = 950$ nm by more than a factor of five from about 13 to 65%. In order to estimate the optical potential of these double-side textured films as solar cell absorbers in a device an ARC and a BR were implemented (solid

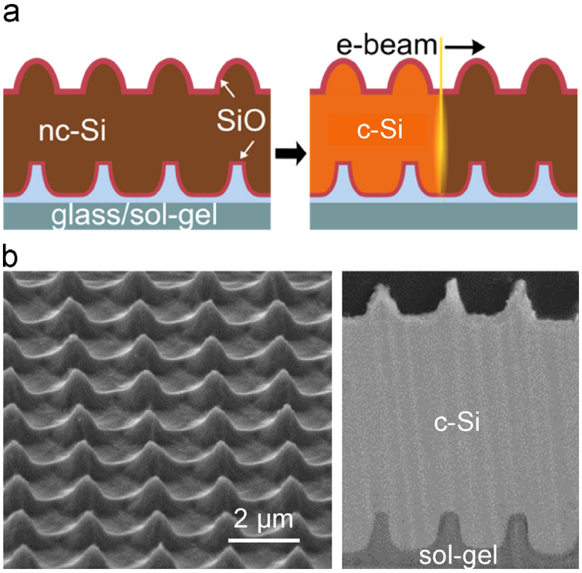

Fig. 1. Double-side textured liquid phase crystallized silicon thin films on imprinted glass substrate with 2 μm periodic square lattice geometry. (a) Schematic drawing of the layer stack before and during liquid phase crystallization using a line-focused electron-beam (e-beam). (b) Scanning electron microscope images of double-side textured silicon thin films after removal of the SiO_x capping layer and short treatment in a Si etchant (30° top view and cross section, here with 6 μm Si thickness).

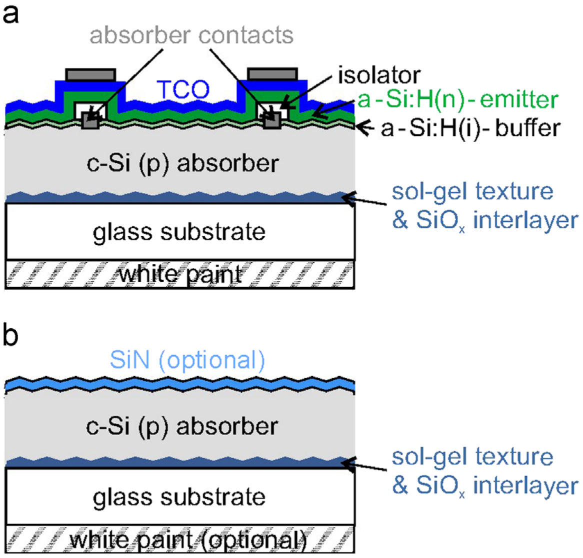

Fig. 2. (a) Silicon heterojunction solar cell device structure as also described in Ref. [3]. (b) Sample structure for optical characterization experiments.

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