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Rear texturing for light-trapping in laser-crystallised silicon thin-film solar cells on glass

Mohd Zamir Pakhuruddin[a,b,*], Jialiang Huang[a], Jonathan Dore[a], Sergey Varlamov[a]

[a] Australian Centre for Advanced Photovoltaics, School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia

[b] Nano-Optoelectronics Research and Technology Laboratory, School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia

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ABSTRACT

This paper presents optimisation of rear Si texturing by KOH-based solution for enhanced light-trapping in liquid-phase crystallised Si thin-film solar cells on glass. Texturing with 3 µm Si removal exhibits the largest absorption enhancement (compared with 1 and 2 µm Si removal) due to the enhanced light scattering by the rear pyramidal features. In the solar cells with $SiO_x/SiN_x/SiO_x$ buffer layer (with anti-reflection effect), the J_{sc} is found to increase from 20.4 (planar reference) to 22.6 mA/cm^2 (10.8% enhancement) with the optimised rear Si texturing. The V_{oc} and pFF are not degraded. After incorporating white paint back surface reflector and front anti-reflection foil to the rear-textured solar cells, J_{sc} up to 25.4 mA/cm^2 (24.5% relative enhancement) is achieved.

1. Introduction

Crystalline Si (c-Si) thin-film solar cell on glass is an attractive technology because it uses less Si material by at least a factor of 20, compared to the present mono and multi c-Si wafer-based solar cells (typically with about 200 µm absorber thickness) (Green, 2009). Besides, it also combines the material and technological advantages of c-Si wafers with benefits of thin-films technologies (Shah et al., 2013; Gall and Rech, 2013). Liquid-phase crystallisation (LPC) by line-focus energy sources such as electron beams and continuous wave diode lasers is the latest proven method to fabricate high quality polycrystalline silicon (poly-Si) on glass (Vetter et al., 2017, Haschke et al., 2016). Very recently, efficiency of 14.2% has been achieved on n-type 13 µm-thick LPC Si solar cells on glass superstrate (Thi Trinh et al., 2018; Amkreutz et al., 2017). In the solar cells, short-circuit current density (J_{sc}) of 29 mA/cm^2 and open-circuit voltage (V_{oc}) of 654 mV have been demonstrated. The solar cells adopted heterojunction interdigitated back-contacted (IBC) device architecture with rear-textured Si surface and front anti-reflective (AR) foil.

To further enhance the light absorption in the thin LPC Si, effective light-trapping (LT) has to be incorporated into the solar cells. The glass superstrate can be textured at the air-glass, glass-Si or both interfaces (Pakhuruddin et al., 2015; Koppel et al., 2016). Texturing glass superstrate has been shown to improve both light-coupling and light scattering in LPC Si films (Pakhuruddin et al., 2016; Becker et al., 2015). Besides, the rear surface of LPC Si can also be textured (Sonntag et al., 2017). The purpose of rear texturing is to scatter the long wavelength lights that reach the back surface of solar cells for further absorption. Rear Si texturing is a more straightforward approach compared to fabricating the solar cells on textured glass (at the glass-Si interface) since it does not affect the electronic quality of the LPC Si absorber (Preidel et al., 2015). Rear Si texturing is usually carried out using wet chemical techniques similar to ones used for standard Si wafers in the industry (Hussain et al., 2013; Neuhaus and Munzer, 2007).

This paper investigates rear Si texturing by wet chemical technique using potassium hydroxide (KOH)-based solution in order to enhance light absorption and J_{sc} in the LPC Si thin-film solar cells, particularly in the long wavelength region. Texture features, angles, surface roughness and optical absorption are systematically studied. The optimum Si texturing is then used in the LPC Si in combination with $SiO_x/SiN_x/SiO_x$ buffer layer (with optimised front AR effect), white paint back surface reflector (BSR) and front AR foil to further enhance light absorption in the films. The enhanced LT features are incorporated into LPC Si solar cells on glass superstrate. In the solar cells, external quantum efficiency (EQE) and J_{sc} enhancement are studied. The effects of the optimised wet chemical technique on open-circuit voltage (V_{oc}) and pseudo fill factor (pFF) are also investigated.

* Corresponding author at: Australian Centre for Advanced Photovoltaics, School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia.

E-mail address: zamir@usm.my (M.Z. Pakhuruddin).

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2. Material and methods

Schott Borofloat33 planar glass of 3.3 mm thickness is used as the superstrate. To limit the investigation to texturing effects only, the glass is coated with 100 nm of SiO_x intermediate layer (without AR effect) by RF magnetron sputtering. 10–13 µm thick Si films are deposited by e-beam evaporation at 500 nm/min rate and 650 °C substrate temperature. Note that for device fabrication, Si films are evaporated with in-situ n-type doping (with phosphorus effusion cell heated to 740 °C) at concentration of $\sim 5 \times 10^{16}\ cm^{-3}$. To achieve n-type doping, the substrate temperature is set at 300 °C because the impurity concentrations were found to be significantly lower than at higher temperatures from SIMS scans (not shown here). Before laser crystallisation, the Si films are pre-heated up to 650 °C for 3 min to reduce thermal stress. The films are then crystallised by scanning a line-focus continuous wave (CW) diode laser beam (808 nm center wavelength, 12-mm top-hat length, 170 µm FWHM width) across the surface at a speed of 400 mm/min.

After the laser crystallisation process, the exposed rear Si surface is textured by wet chemical technique using KOH-based solution. The LPC Si films are etched at 95 °C in a solution which contains a mixture of KOH, polyethylene glycol (PEG200) and isopropyl alcohol (IPA). In this texturing, PEG200 is added to improve etching uniformity due to better wetting of the Si surface (Dove et al., 2012). By introducing the PEG200 in the mixture, the solution also becomes less volatile, since IPA has a low boiling point and is lost by evaporation during the etching process. The films are textured for 2.5, 5 and 7.5 min to remove 1, 2 and 3 µm of Si respectively at an etch rate of about 400 nm/min. Note that the etch rate of 400 nm/min is calculated based on the measured average thickness removal of the LPC Si after etching the films for 2.5, 5 and 7 min respectively, in the KOH-based solution. To keep the benefit of low material usage in the LPC Si films, the removed Si thickness (i.e. sacrificial layer) during each texturing technique is limited to 3 µm. After texturing, all the Si films have the thickness of about 10 µm. Untextured LPC Si films on glass are also prepared as a reference.

For characterisation, oblique view (40° tilt angle) and cross-sectional view (20° tilt angle) of the textured Si surface are taken by Hitachi SEM 3400I. Surface morphology (including RMS surface roughness) of the textured film is inspected by SPM Icon AFM with 30 µm × 30 µm field size at 512-pixel resolution. Feature angles of the textured Si surface are calculated from AFM raw data. The details of the calculation are described elsewhere (Cui et al., 2012). Note that the RMS and feature angle analysis are carried out on regions with standing pyramids after the etching (i.e. at original (100)-oriented surfaces). Reflection (R) and transmission (T) of the planar and textured LPC Si films are measured by Perkin Elmer LAMBDA 1050 UV/VIS/NIR spectrometer (beam size: $16 \times 3\ mm^2$) with a 150-mm integrating sphere, illuminated in superstrate configuration. Absorption (A) is then calculated as A = 100%–R–T.

Before solar cell fabrication, the LPC films are passivated in a hydrogen plasma chamber, at 600 °C for 15 min (Gorka et al., 2009). Then, 500 nm of the Si layer is etched off using HNO_3, H_2O and HF in 50:20:1 vol%, to remove plasma-induced surface defects from the passivation process (Kühnapfel et al., 2015). A standard RCA cleaning is then carried out to prepare the LPC Si surface for emitter deposition. Then, an a-Si:H (i, p^+) heterojunction emitter with doping concentration $\sim 5 \times 10^{19}\ cm^{-3}$ is deposited by low-temperature PECVD (Korte et al., 2009; Mews et al., 2013).

After the heterojunction emitter deposition, the device is metallised using test structures, which aims for a fast and easy preparation process (Haschke et al., 2015). The test structures are fabricated with 80 nm of sputtered ITO layer of a circular shape ($0.5\ cm^2$ area) using a shadow mask. The ITO acts as a contact material to the p^+-type a-Si:H layers. Due to the dimension of the test structures and lack of narrowly-spaced contact grids, series resistance is expected to be high. Schematic of the LPC Si solar cell on glass (in superstrate configuration) is shown in Fig. 1. Absorber contacts made of Ti/Ag stack are evaporated outside the ITO-covered areas (serves as a contact material to the n-type LPC Si absorber).

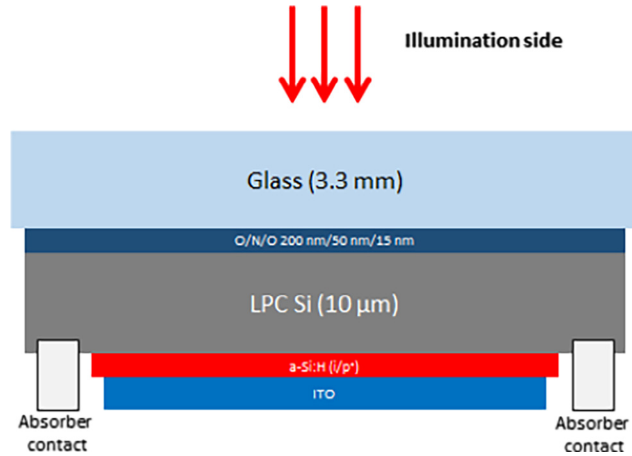

Fig. 1. Schematic diagram of LPC Si solar cell on glass superstrate.

After the fabrication, EQE (Model: Bentham PVE300) and Suns-V_{oc} (in-house built) (Kunz, 2009) are used to characterise the solar cells. From the best EQE curve, J_{sc} of the solar cells are calculated using Eq. (1), for the 300–1100 nm wavelength region.

$$J_{sc} = q\int EQE(\lambda)\cdot S(\lambda)d\lambda \quad (1)$$

where q is the electron charge and S(λ) is the standard spectral photon density of sunlight for AM1.5 spectrum. In this work, LT performance in the solar cells is evaluated by EQE measurement (i.e. I-V curve not included). This is because the EQE result is already sufficient to evaluate relative performance of the LT features being investigated. Furthermore, uncertainties associated with spectral mismatch introduced by solar simulator (during I-V curve measurement) can be avoided (Ouyang, 2011). Suns-V_{oc} is used to determine V_{oc} and pFF of the LPC Si solar cells before and after rear Si texturing.

3. Results and discussion

3.1. Evaluation of rear Si texturing by KOH-based solutions

Fig. 2 shows that texturing by the KOH-based solutions produces LPC Si surface with random standing and tilted pyramids. The standing pyramids are formed on regions with {1 0 0} orientation while tilted pyramids are formed on regions with other than {1 0 0} orientations since the KOH etches the Si surface anisotropically, with the highest etching rate on {1 0 0} plane and the lowest etching rate on {1 1 1}

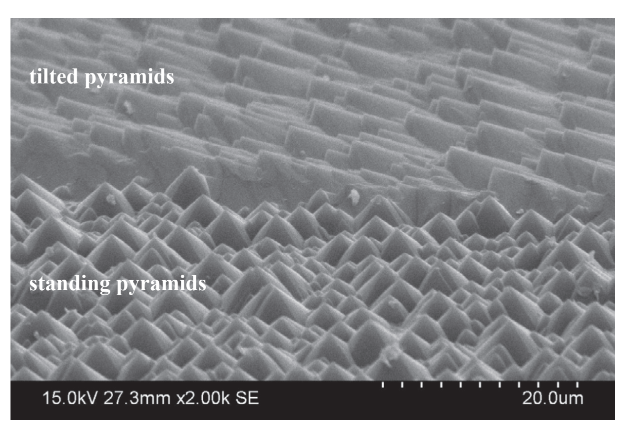

Fig. 2. Cross-sectional SEM image (at 20° tilt angle) of LPC Si film showing regions of random standing and tilted pyramids.