Etch-Back Silicon Texturing for Light-Trapping in Electron Beam Evaporated Thin-Film Polycrystalline Silicon Solar Cells

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Abstract

Effective light trapping is critical for polycrystalline silicon thin-film solar cells to generate sufficiently high photocurrent. Glass substrate texturing is a standard and very effective light-trapping approach for poly-Si solar cells fabricated by plasma enhanced chemical vapour deposition but it cannot be applied to poly-Si cells deposited by electron beam evaporation, which is a preferred deposition process. In this study light-trapping is implemented by texturing of the rear surface of e-beam poly-Si films deposited on planar glass. Water-based solutions of KOH, NH₄F and NH₄F/H₂O₂ are found to be able to texture poly-Si films and, thus, to significantly improve light-trapping. The related texturing processes and resulting textures are characterised by Si etching rates, the surface roughness versus removed Si thickness, texture angle distributions, optical absorption and spectral response enhancement. The RMS roughness increases with the removed thickness and can be as large as 276 nm. Also, the texture angle distribution can reach its maximum at about 20° and has a long tail of larger angles. The absorption at 800 nm can increase up to 75% compared to 30-40% in planar films. The short-circuit current of 26.6 mA/cm² was demonstrated for a cell made of 3.6 µm thick poly-Si film textured by the KOH solution, which is ~21% enhancement compared to a reference planar cell with a rear reflector. A larger roughness and steeper texture angles produced by NH₄F-based etching solutions compared to KOH-based textures indicate that even higher currents are achievable for e-beam poly-Si thin-film cells on planar glass.

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Keywords: Thin-film solar cells; polycrystalline silicon; light-trapping; silicon texturing
1. Introduction

Thin-film polycrystalline silicon (poly-Si) on glass solar cells is a photovoltaic (PV) technology promising to combine advantages of wafer-based crystalline Si PV with benefits of a thin-film approach [1, 2]. Poly-Si thin-film cells have a typical thickness of 2-3 µm, and because of being composed of an indirect bandgap semiconductor only a small fraction of incident light is absorbed and converted into electricity unless effective light-trapping is implemented. Glass substrate texturing (Fig. 1(b)), such as bead-texturing, abrasion, Al-induced texturing [3-5], has been successfully used to improve light-trapping in poly-Si cells fabricated by plasma-enhanced chemical vapour deposition (PECVD), which allowed achieving the short-circuit current density ($J_{sc}$) up to 29.5 mA/cm². However, since recently a technologically preferred Si film deposition method has changed to electron beam (e-beam) evaporation [6, 7] and this method due to its directionality is not compatible with textured substrates [7-9]. It was previously demonstrated [7] that texturing of an evaporated Si film itself, so-called etch-back texturing, could provide an alternative approach to light-trapping but such texturing was relatively mild and the resulting $J_{sc}$ was 22.55 mA/cm², nearly the same as $J_{sc}$ for planar cells with a diffuse rear reflector and significantly lower than a typical $J_{sc}$ for PECVD cells. A challenge of this approach is that a light-trapping texture with a feature size of a micron order needs to be formed in a film of a similar thickness without removing too much of the film material and avoiding pin-holing and/or excessive etching of defects, which are plenty in poly-Si. In this work etch-back texturing of poly-Si films (Fig. 1(c)) is studied in detail, different chemical solutions (KOH, “acidic mixtures”, and NH₄F and its mixtures with H₂O₂) are investigated, developed surface topographies are characterised and resulting cell efficiency enhancement is assessed.

2. Experimental methods

The poly-Si films and cells in this study are prepared in the following way. Amorphous Si films are deposited by e-beam evaporation onto 3 mm planar borosilicate glass. The films used to make cells for electrical characterisation have the glass coated with PECVD silicon nitride as an antireflection layer (ARC) while the films for texturing process experiments are without ARC. The films are crystallised at 600°C for 24 hours. Texturing of poly-Si films is performed by immersing the samples into etching solutions held at a certain temperature for a few minutes. Then the samples undergo rapid thermal annealing and hydrogenation as described elsewhere [10]. For cell fabrication out of textured poly-Si films a back-surface field layer (sheet resistance of ~1500 Ω/sq) was introduced by thermal diffusion from a spin-on B dopant source followed by interdigitated aligned metallisation [9]. Before optical and electrical characterisation a white paint as a rear diffuse reflector (RDR) is applied to the film Si side. Atomic force microscopy (AFM) is used to investigate the topography of textured surfaces. Texture feature angles are then calculated from AFM data using an algorithm developed in-house. The optical
reflectance $R$ and transmittance $T$ are measured by a spectrophotometer equipped with the integrating sphere and the centre-mount accessory and the absorption is calculated as $A = 1 - R - T$. The cell spectral response is measured using the external quantum efficiency system and $J-V$ is recorded by the halogen lamp based light $J-V$ test station under 1 sun with cell temperature at 25°C.

3. Results and discussion

Wet-chemical texturing is a well-known and developed process in Si wafer-based PV. Typically, alkaline solutions are applied to single-crystal Si wafers to form a pyramidal texture and acidic-based solutions are used for multi-crystalline wafers to form a random texture [11-13]. Thus, these two types of solutions are natural first candidates to be tested on poly-Si films. However, tens of microns of the Si material are usually removed during such texturing, which is obviously cannot be directly applied to poly-Si thin-film cells, which thickness is 2-3 µm only. It is then necessary to firstly have poly-Si films thicker than required for cell fabrication to include a ‘sacrificial’ layer, which is etched off during etch-back texturing. To keep the benefit of a low material usage it is sensible in practice to limit the thickness of such a sacrificial layer to the thickness of the cells, i.e. 2-3 µm. Secondly, it has to be possible to thoroughly control a texturing process to avoid over etching, which means moderate to slow etching rates.

It has been found in initial tests that acidic solutions (e.g. HNO$_3$;HF-based) do not produce any textures on poly-Si films and result in smooth etching instead. For this reason such solutions were excluded from further studies. However, KOH-based solutions do produce random rough topographies on poly-Si films after etching off more than 1 µm of Si [14]. The etch rate is ~4 µm/min for 30% KOH at 90°, which is at the upper limit of what can be considered as a controllable process. The roughness increases with the removed thickness (Fig. 2) while the texture angle distribution [15] remains relatively constant with the maximum at around 6-8° (Fig. 3). Although the KOH etched texture is relatively shallow, with the RMS roughness of 100-120 nm and small feature angles, after removing about 3 µm of poly-Si it significantly improves the optical absorption from about 40% to about 70% at 800 nm compared to a planar sample of the similar thickness of 3 µm (Fig. 4). Implementing this texture into e-beam poly-Si thin-film solar cells results in 15-25% higher $J_{sc}$ compared to equivalent planar cells while having no detrimental effect of other cell performance parameters, such as $V_{oc}$ and FF. $J_{sc}$ of 26.6 mA cm$^{-2}$ has been achieved for a 3.6 µm thick etch-back textured cell (Fig. 4), the highest current ever reported for e-beam poly-Si cells [14], which compares to 21.9 mA/cm$^2$ for the equivalent planar cell. It is a good demonstration that etch-back texturing is a very promising approach to effective light trapping in e-beam poly-Si cells.

![Fig. 2. (a) Surface roughness versus removed thickness for etch-back texturing of poly-Si by KOH etching; (b) AFM image of the KOH etch-back textured poly-Si film surface; the image size is 10×10 µm$^2$.](image-url)
Fig. 3. Texture angle distribution in KOH etch-back textured poly-Si films for the various removed thickness and surface roughness.

Fig. 4. (a) Absorption; (b) EQE and (c) I-V results for 3.6 µm thick KOH etch-back textured poly-Si thin-film cell. As-deposited cell thickness ~7 µm. The dashed line refers to 4 µm thick planar cell shown as a reference.
In attempts to form rougher and steeper textures, which can provide even better light-trapping, other etchants were tried and it was found that an aqueous mixture of NH₄F and H₂O₂ in different proportions (including a NH₄F-only solution) can perform required texturing. The etching mechanism of such mixtures is similar in principle to acidic etching of Si: H₂O₂ as an oxidant turns surface Si into SiO₂ while NH₄F serves as HF carrier dissolving formed oxide. The whole reaction taking place in presence of both H₂O₂ and NH₄F can be written as following:

\[
\text{Si} + 2\text{H}_2\text{O}_2 + 6\text{NH}_4\text{F} = (\text{NH}_4)_2\text{SiF}_6 + 4\text{NH}_4\text{OH}
\]

It is not straightforward to explain the exact mechanism of etching by the NH₄F-only solution but one can reasonably speculate that it can either involve Si oxidation by dissolved oxygen or proceed as electrochemical etching of Si by fluoride ions [16]. As shown in Fig. 5, the poly-Si etch rate increases with a higher NH₄F content in mixed NH₄F/H₂O₂ solution. When the ratio of NH₄F to H₂O₂ changes from 1 to 2, the etch rate correspondingly increases from 1.5 µm/min to 5.2 µm/min. However, for the NH₄F-only solution, the etch rate reduces to 256 nm/min. This low etch rate allows very good process control.

![Fig. 5. Poly-Si etch rate under various ratio of NH₄F/H₂O₂.](image)

The surface roughness produced by NH₄F/H₂O₂ and pure NH₄F etching presented in Fig. 6 is much larger than the roughness produced by KOH-based solutions. The RMS roughness increases quickly (a lot quicker than that for KOH etching) initially with the removed Si thickness and then saturates in the 250-300 nm range. For the NH₄F-only solution in particular, the RMS roughness larger than 200 nm is achieved after only about 0.5 µm of Si is etched off, while it takes about 4 µm of removed Si for the mixed NH₄F/H₂O₂ solution to produce the similar roughness. The RMS roughness as large as 276 nm can be achieved using the mixed NH₄F/H₂O₂ solution but it requires removing 12 µm of Si, which is impractical.
Figure 7 presents texture angle distributions versus the removed Si thickness and the RMS roughness. Unlike for the KOH-based textures, where the texture angles stay nearly the same, about 6-8°, regardless the etched thickness, the angles gradually become steeper as more Si is removed by both NH$_4$F/H$_2$O$_2$-based solutions and the angle distribution maximum is at significantly larger angles, up to 20°. Again, NH$_4$F-only etchant is a lot more effective at creating a steeper texture: the angle peak at around 18° is obtained after etching off only 0.5 µm of Si. It is also worth noting that the angle distribution for the NH$_4$F/H$_2$O$_2$-etched textures has a long tail of larger angles extending up to about 50°, which is very important for effective light-trapping, while this tail for the KOH-etched textures ends at about 20°. Thus, it is demonstrated that NH$_4$F/H$_2$O$_2$ and particularly NH$_4$F-only etching solutions are able to create very rough textures with steep feature angles on the poly-Si film surface, which should lead to better light-trapping than by KOH-etched textures.
Fig. 7. Poly-Si film texture feature angle distribution for various removed Si thickness and surface roughness after etch-back texturing: (a) NH$_4$F/H$_2$O$_2$ texturing and (b) NH$_4$F-only texturing.

Finally, the optical absorption in 3 µm thick poly-Si films textured by these two types of etchants has been measured and presented in Fig. 8. The absorption increases with the surface roughness (according to the removed Si thickness) as expected. The maximum absorption at 800 nm is 68% and 74% (note no AR layer between glass and poly-Si film) for the films textured by NH$_4$F/H$_2$O$_2$ and NH$_4$F etching respectively compared to about 40% for a planar sample. These values are similar to 70% absorption in the film textured by KOH but taking into account the absence of the AR layer in NH$_4$F/H$_2$O$_2$-textured films the absorption is expected to increase significantly when such a layer is introduced. Thus, higher currents than 26.6 mA/cm$^2$ demonstrated for a cell with the KOH texture are likely to be achieved. Cell fabrication using new etch-back textured poly-Si films is currently in progress and results are to be reported in near future.
Fig. 8. Optical absorption in planar, NH₄F/H₂O₂ and NH₄F-only textured samples. N+H means NH₄F/H₂O₂; T* means texturing. The poly-Si films are on glass without ARC and a white paint is used as a RDR.

4. Conclusions

Wet-chemical etch-back texturing using solutions containing KOH, and mixtures of NH₄F and H₂O₂ was applied to e-beam evaporated poly-Si thin-film solar cells on planar glass to introduce light-trapping and improve light absorption. Films textured by KOH have roughness of about 100 nm RMS, the feature angle distribution peak at about 8° and absorption of about 70% at 800 nm (with ARC) after etching off a few microns of a sacrificial Si layer. A KOH textured poly-Si thin-film cell has demonstrated the record J_sc of 26.6 mA cm². Textures etched by NH₄F/H₂O₂ solutions have larger roughness up to 276 nm RMS, steeper peak feature angles up to 50° and absorption up to 74% (without ARC) and require significantly less of the sacrificial Si thickness. These textures are expected to lead to even higher J_sc when applied to poly-Si cells. Thus, it has been demonstrated that a wet-chemical etch-back texturing is a very promising approach to light-trapping in e-beam evaporated poly-Si thin-film cells on planar substrates.

Acknowledgements

The authors thank Oliver Kunz, Robert Dumbrell and Kyung Kim of CSG Solar for help with film processing, Oliver Kunz for his contribution to texture angle calculation, and Patrick Campbell for assisting with optical characterisation. Q. Wang acknowledges her PhD scholarship from the University of New South Wales (UNSW). The Photovoltaics Centre of Excellence at UNSW is one of the Centres of Excellence established and supported by the Australian Research Council (ARC).

References


