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Influence of random pyramid surface texture on silver screen-printed contact formation for monocrystalline silicon wafer solar cells

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ABSTRACT

Most industrial monocrystalline silicon wafer (mono-Si) solar cells are metallised by screen printing. Silver (Ag) pastes are commonly used to form electrodes to phosphorus-doped n^+ Si. However, there is still ambiguity about the influence of the random-pyramid surface texture on Ag screen-printed contacts for mono-Si solar cells. We present an experimental study to investigate this influence using screen-printed p-type mono-Si cell groups fabricated with a controlled variation in the alkaline surface texturisation process. It is observed that cell groups fabricated on Czochralski (Cz) wafers with smaller pyramids achieve higher average fill factor (*FF*) and lower average specific contact resistance than cell groups fabricated on Cz wafers with larger pyramids. To explain these observations, the pyramid texture height distributions are characterised statistically and the distribution statistics are correlated to electrical solar cell measurements and microstructure investigations of the Ag/n^+ Si contact interface. Microstructure investigations reveal that most Ag crystallite growth is concentrated around the upper part of the pyramids and hence pyramid density is identified as an important parameter influencing contact formation. The influence of average pyramid height and pyramid height uniformity within a pyramid texture height distribution is also clarified with regards to contact formation. It is further observed that direct Ag crystallite contacts to the bulk Ag metallisation are not a prerequisite for achieving high *FF* ($>80\%$). Based on the study, guidelines are developed for tailoring random-pyramid surface textures to optimise Ag screen-printed contact formation to n^+ Si for mono-Si solar cells.
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1. Introduction

Most industrial monocrystalline silicon wafer (mono-Si) solar cells are metallised by screen printing using thick film pastes. Silver (Ag) screen-printed pastes are generally used to form electrodes to phosphorus (P)-doped n^+ Si. Traditionally Ag crystallites grown into the n^+ Si during the firing step have been identified to be primarily responsible for contact formation [1]. In the Ag crystallite model of contact formation it is assumed that current transport between bulk Ag and n^+ Si takes place either directly via Ag crystallites in direct contact with bulk Ag or via tunnelling through a sufficiently thin glass layer separating Ag crystallites and bulk Ag [1,2]. Tunnelling through the interfacial glass may be enhanced by dispersed Ag in the glass layer [3,4]. Some authors have recently stressed the importance of nano-Ag colloids dispersed in the interfacial glass layer for contact formation and suggested that Ag crystallites may not be necessary for contact formation [5,6]. The nano-Ag colloids dispersed in glass are assumed to aid a multi-step tunnel contact through the glass layer. It has also been suggested that current transport via Ag crystallites and nano-Ag colloids dispersed in the interfacial glass layer may co-exist [7].

The contact formation of Ag thick film pastes to n^+ Si regions depends on various aspects, including: surface topography, doping (commonly by diffusion) profile, dielectric layers, paste composition, and contact firing. The influence of doping profile [8,9], dielectric layers [10], paste composition [11–13], and firing profile [8] on screen-printed contact formation is understood well enough to tailor these aspects to improve contact formation. However, there is still ambiguity about the influence of surface topography in terms of the influence of random-pyramid surface texture on contact formation for mono-Si solar cells. As a result, there are no clear guidelines to tailor the anisotropic alkaline surface texturisation to improve Ag screen-printed contacts for mono-Si solar cells. Such guidelines would be especially useful

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since it has been shown in several previous studies that additives for alkaline texturisation baths enable improved control over the height and uniformity of pyramidal surface textures [14–19].

In previous investigations, Cabrera et al. [20] and Han et al. [21] have both observed a sharp fall in fill factor (*FF*) for screen-printed p-type mono-Si solar cells when the surface is textured with pyramid heights smaller than 300 nm. Cabrera et al. explained this observation by suggesting that direct Ag crystallite contacts to the bulk Ag at pyramid tips are primarily responsible for current conduction to the n^+ Si surface and discussing the glass coverage of pyramid tips [20,22]. However, Cabrera et al. [20] observed almost no influence of pyramid height on *FF* for pyramids larger than 300 nm, whereas Han et al. [21] observed a variation in *FF* without a clear trend. Additionally, in [20] a large fraction of the surface was observed to be untextured for three out of the five texture groups studied. This is undesirable with regards to a contact formation study, especially since it was shown in the same study that untextured surfaces lead to poorer Ag screen-printed contact formation than pyramid-textured surfaces. In another investigation, Ximello et al. [23] also observed an unclear trend in *FF* variation with pyramid height variation for screen-printed p-type mono-Si solar cells and attributed higher *FF* to "homogenous textures" without specifically addressing differences in contact formation. Therefore the influence of random-pyramid surface texture on Ag screen-printed contact formation is still unclear.

We present an experimental study to investigate the influence of random-pyramid surface texture on Ag screen-printed contact formation using screen-printed p-type mono-Si cell groups fabricated with a controlled variation in the alkaline surface texturisation process. The pyramid heights are varied within mono-Si solar cell relevant ranges (no sub-micrometer height pyramid groups) and simultaneously, full pyramidal coverage is obtained for textured surfaces. It is observed that the cell groups fabricated on Czochralski (Cz) wafers with smaller pyramids achieve higher average *FF* and lower average specific contact resistance than the cell groups fabricated on Cz wafers with larger pyramids. The variation in the surface texturisation process recipes and cell fabrication is discussed in detail by Basu et al. [24]. We focus on microstructural aspects to gain insights on contact formation. The height distribution of the developed random-pyramid groups is statistically characterised, followed by a thorough scanning electron microscope (SEM) study of the Ag/n^+ Si interface. The SEM observations are correlated with statistical parameters of pyramid height distributions to develop clear guidelines for tailoring random-pyramid surface textures to optimise Ag screen-printed contact formation to n^+ Si.

2. Experiment

In a recent study by Basu et al. [24], three alkaline surface texturisation process recipes using potassium hydroxide (KOH), isopropanol (IPA) and potassium silicate (K_2SiO_3) solutions were optimised, which led to random-pyramid surface textures on Cz Si wafers with small ("process A", pyramid heights $< 5\ \mu m$), medium ("process B", pyramid heights $< 6\ \mu m$) and large ("process C", pyramid heights $< 8\ \mu m$) pyramid heights as characterised by SEM (Fig. 1). The surface texture heights were varied by adjusting process temperature and KOH concentration. Process time was kept constant and optimally set (20 min) to ensure that all processes led to full pyramid coverage of the textured surface. Brief details regarding the texturisation process recipes are given in Table 1. The role of the K_2SiO_3 additive in KOH-IPA texturisation baths is discussed in reference [14]. With each of the three texture processes, forty five p-type Cz wafers (156 mm × 156 mm, pseudosquare, 1–2 Ω cm resistivity) were textured and used for fabricating standard screen-printed solar cells with the following process sequence after texturisation: inline P emitter diffusion followed by inline chemical edge isolation and emitter etch back (final emitter sheet resistance 70 Ω/sq, surface dopant concentration $\sim 3 \times 10^{20}\ cm^{-3}$) [25], front PECVD amorphous silicon nitride (SiN_x) coating, screen printing (front Ag paste: DuPont PV 17F, rear Al paste: Monocrystal PASE 12D), co-firing. The cell processing after texturisation was identical for the three cell groups. Similar average open-circuit voltages (V_{oc}) and short-circuit current densities (J_{sc}) were obtained for the three groups. High average *FF* ($> 79.4\%$) were obtained for all groups but a significant variation in *FF* was observed, with cells in group A (small pyramids) showing the highest *FF*, followed by group B (medium pyramids) and group C (large pyramids). The *FF* variation led to a variation in cell efficiency (η). Average specific contact resistances (ρ_c) for the front Ag screen-printed contacts were determined based on a combination of transfer length method (TLM) and end line measurements [26] on several ladder TLM structures cut (using a dicing saw) from nine representative finished cells (three from each of the surface texture groups). The variation in ρ_c was proposed as the factor primarily responsible for *FF* variation within the groups. The *J–V* data and ρ_c values are summarised in Table 1.

3. Statistical characterisation of pyramid height distribution

Statistical characterisation of pyramid height based on confocal microscopy has been proposed as a means of accurately describing random-pyramid surface textures [27–30]. In the previous section texture groups A, B and C were classified according to maximum heights (from SEM, Fig. 1) of $\sim 5\ \mu m$, $\sim 6\ \mu m$, and $\sim 8\ \mu m$, respectively. We further characterised the pyramid height distribution of each group statistically using an optical profiling microscope (Zeta Instruments) and the method discussed in reference [28]. For each texture group three representative finished cells were chosen and each cell was imaged (between grid fingers) at four spots. Each measurement spot represents an optical field of

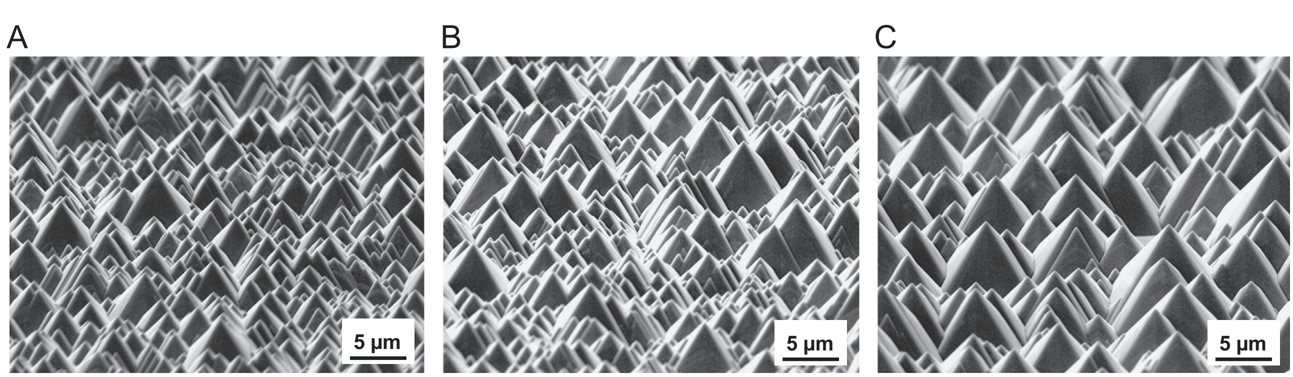

Fig. 1. SEM micrographs of Cz Si wafer surfaces textured with processes A (pyramid heights $< 5\ \mu m$), B (pyramid heights $< 6\ \mu m$) and C (pyramid heights $< 8\ \mu m$).

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