

The effect of front pyramid heights on the efficiency of homogeneously textured inline-diffused screen-printed monocrystalline silicon wafer solar cells

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ABSTRACT

The majority of industrial monocrystalline silicon (c-Si) wafer solar cells are alkaline textured (at least the illuminated surface) to reduce reflection and increase absorption of incident light. Therefore, understanding the influence of front pyramid heights on the solar cell parameters is essential for further improving cell efficiency. In this work we report the impact of pyramid height on the performance of inline-diffused c-Si solar cells. Three alkaline texture processes with potassium silicate additives are optimised to result in homogeneous coverage of pyramids. By modifying the process, surface textures with small ($\sim 5\ \mu\text{m}$ maximum), medium ($\sim 6\ \mu\text{m}$ maximum) and large ($\sim 8\ \mu\text{m}$ maximum) pyramid heights are formed. The impact of pyramid size on cell parameters is experimentally studied using industrial-grade 156-mm pseudo-square *p*-type Czochralski wafers. It is found that within the pyramid size range studied here, there is no significant variation in effective minority carrier lifetime, reflectance, open-circuit voltage or short-circuit current. However, fill factor and hence efficiency is significantly impacted by pyramid size. While cells in all three groups demonstrate high fill factor ($>79\%$), it is shown that an average fill factor gain of up to 1% absolute can be achieved by using the best-suited texture process.

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1. Introduction

The large availability of crystalline silicon (both mono and multi) wafers helps in rapid expansion of the global photovoltaic market. The key challenge for monocrystalline silicon (mono-Si) wafer solar cell is further reduction of the dollar per Watt cost. A route to achieve higher solar cell efficiency is optimisation of key processes, such as an alkaline texturing. The textured surface, due to the so-called 'double-bounce' effect, reduces the reflectance from the illuminated surface [1–3]. The anisotropic selective chemical etching of the $\langle 100 \rangle$ Si surface with sodium hydroxide (NaOH) or potassium hydroxide (KOH) solutions has been used to form random upright pyramidal textured surface [1]. Iso-propyl alcohol (IPA) is commonly added to the alkaline texture solution; it

modifies the surface wettability to controllably nucleate the texturing process [4] and thus helped to achieve good lateral uniformity of the pyramids across the entire wafer. Recently Basu et al. [5] have used potassium silicate (K_2SiO_3) as an additive to the alkaline textured solution. This advanced solution reduces IPA consumption, while enhancing texturing process; thus, increases throughput.

Previous studies have analysed the influence of pyramid height on the solar cell performance by simulations or experiments [6–11]. From a geometric optics (ray tracing) point-of-view the size of regular upright pyramids does not affect the front surface reflectance and the obtained short circuit current (J_{sc}). However the geometric optics simulation approach is only valid when surface feature sizes are larger than the interacting wavelength, this condition is not strictly fulfilled for solar cells as wavelengths up to 1100 nm are relevant for crystalline silicon solar cells and random pyramid texture processes may lead to some sub-micrometre pyramids. A rigorous simulation study by Llopis and Tobías [6]

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involving numerical solution of the electromagnetic wave equations concluded that diffraction effects are significant only for pyramid smaller than 300 nm, in this case the reflectance increases beyond the geometric optic limit. Typically simulation studies are limited to include the effects of the pyramids size distribution and therefore experimental studies provide better insights on this effect on the solar cell's optical performance. In terms of open-circuit voltage (V_{oc}) pyramidal textured surfaces increase surface recombination due to an enhancement of surface area (corresponding to the planar surface). For pyramids of standard geometry the area enhancement is independent of the pyramid size (if the surfaces are fully textured) and no effect on V_{oc} is expected. The influence of pyramid sizes on the fill factor (FF) has been studied, however contradicted results were reported. Cabrera et al. [7] and Han et al. [8] observed reduction in FF for pyramid sizes smaller than 300 nm. However, while Cabrera et al. observed no impact of pyramid height (KOH–IPA texture chemistry) on FF for pyramids larger than 300 nm [7], Han et al. [8] observed a variation in FF without a clear trend (NaOH–IPA + variable additives). Note that modification of the pyramids size can result with non-uniformity of the texturing. Ximello et al. [9] used an alkaline texture process based on a KOH and “high boiling alcohol (HBA)” process chemistry (different from standard KOH–IPA chemistry) and varied texture time to generate different pyramid sizes. Although a significant variation was observed in J_{sc} , V_{oc} and FF [9], the variations were attributed to texture uniformity.

Other studies focused only on the impact of the pyramid size. For examples, King and Buck [10] investigated only the impact on front surface reflectance, while Kegel et al. [11] studied the influence on intrinsic amorphous-Si passivation for heterojunction cells. It seems that comprehensive study regarding the impact of pyramids height on the solar cell electrical parameters is required.

In this study, three different texturing recipes were developed to generate three different homogeneous pyramidal structures with maximum heights varying from 5 μm to 8 μm , with good uniformity of pyramid heights within each group. The pyramids size was controlled by varying the alkali concentration, the texturing temperature and the amount of potassium silicate in the KOH–IPA solution. It was found that textured wafers from all the three groups have similar solar spectrum weighted average reflectance (WAR) in the range of 11.5–11.8%. Wafers from all groups were used to fabricate conventional 156 mm pseudo-square inline-diffused screen-printed solar cell with average efficiencies in the range 18.4–18.6%, using the pilot line at the Solar Energy Research Institute of Singapore (SERIS). Details and characterisation of the new texturing process and the resulting solar cells will be presented, including scanning electron microscope (SEM) images, reflectance, quasi-steady state photoconductance (QSSPC) and contact resistance measurements, series resistance imaging from a combination of photoluminescence (PL) and electroluminescence (EL) images, and 1-Sun I – V measurements.

2. Experimental details

2.1. Texturisation

In this experiment 150 wafers of industrial grade mono-crystalline Cz silicon wafers were used (156 mm pseudo-square, p -type, boron doped, $\langle 100 \rangle$ orientation, 1–2 $\Omega\text{-cm}$ resistivity, 170–190 μm thickness). Pre-cleaning and damage removal process of the wafers prior the texturing was performed following the process developed by Basu et al. [12]. It used KOH (20% by weight) and sodium hypochlorite (NaOCl) solution in a ratio of 1:3 (by volume). The wafers were immersed in the solution for 2 min (min) at 80 °C to remove the surface damage ($\sim 3 \mu\text{m}$ per side, as measured

by measuring the change of the wafer's weight). The wafers were split into three groups of 50 wafers each, corresponding to three different pyramid heights (groups A, B and C). A mixture of KOH, IPA and K_2SiO_3 was used to form homogeneous (or uniform) pyramidally textured surfaces [5]. The texturing chemical bath was made from polyvinylidene difluoride (PVDF) material and was heated from the bottom by a flat Teflon coated heater. This bath is an overflow bath fitted with an external pump which circulates the texturing solution in order to minimise variation of the solution concentration and temperature. The texturing solution temperatures were maintained at a constant value of 80 °C and 85 °C corresponding to different texturisation recipes. However, the texturing time maintained constant as 20 min for all the processes. In this study, the KOH concentration was varied from 1.4% to 2.5% (by weight), while the amount of K_2SiO_3 and IPA were varied from 60 to 100 ml and from 2.5 to 3.2 L, respectively in a 40 L bath.

After texturing, all the wafers were neutralised in 1:1 solution of hydrochloric (HCl) acid and de-ionised (DI) water at 60 °C for 10 min followed by a dip in dilute hydrofluoric acid (HF). The complete process flow of the different groups is shown in Fig. 1. Following the texturing, the wafers were processed together as a single batch.

2.2. Cell fabrication

The textured wafers were diffused in an industrial inline-diffusion furnace (Despatch, DCF-3615). After an atmospheric-plasma pre-treatment step at the entry to the doper (to create a hydrophilic Si surface), a spray-on dopant source was applied uniformly to both sides of the wafer at 30 L/min rate [orthophosphoric acid (H_3PO_4) mixed with ethyl alcohol]. The diffusion was performed at a belt speed of 390 mm/min using a peak diffusion temperature of 895 °C for all the wafers to achieve an emitter sheet resistance (R_{sq}) of $\sim 40 \Omega/\text{sq}$, as measured by four-point-probe measurements (Cresbox, NAPSON). The parasitic rear-junction and the front phosphosilicate glass (PSG) were removed in an industrial inline wet chemical tool (InPilot, RENA GmbH) using solution mixture of HF, nitric acid (HNO_3) and sulphuric acid (H_2SO_4) at 6–8 °C. The etch-back was performed using ‘SERIS etch’ [13,14] to achieve the targeted final R_{sq} of $\sim 70 \Omega/\text{sq}$. Amorphous silicon nitride (SiN_x) antireflection coating (ARC) was then deposited onto the front surface using an industrial plasma enhanced chemical vapour deposition (PECVD) system from Roth & Rau (SiNA-XS). The film thickness and refractive index (at 633 nm) were measured to be 70 nm and 2.05, respectively. Lastly, front and rear contacts were formed by screen printing (PVP1200, DEK) and subsequently co-fired in an industrial fast firing furnace (Ultraflex, Despatch), using a Monocrystal PASE 12D aluminium (Al) paste for the rear and DuPont PV17F Ag paste for the front contacts. The summary of the complete cell fabrication process flow is shown in Fig. 2.

2.3. Characterisation

Representative samples from the three groups were removed after various process stages for additional surface characterisation studies. Prior to these measurements, the representative samples were cleaned in IPA, followed by DI rinsing and drying. A scanning electron microscope (SEM) from Carl Zeiss Auriga was used for the surface topography analysis and a spectrophotometer (Perkin Elmer, Lambda 950) was used for the reflectance measurement. For calculation of the WAR, the diffuse reflectance of the textured surfaces was measured using a 150 mm diameter integrating sphere over the wavelength range of 300–1000 nm and weighted with the AM1.5 spectrum. The effective minority carrier lifetime was subsequently measured using a lifetime tester (Sinton

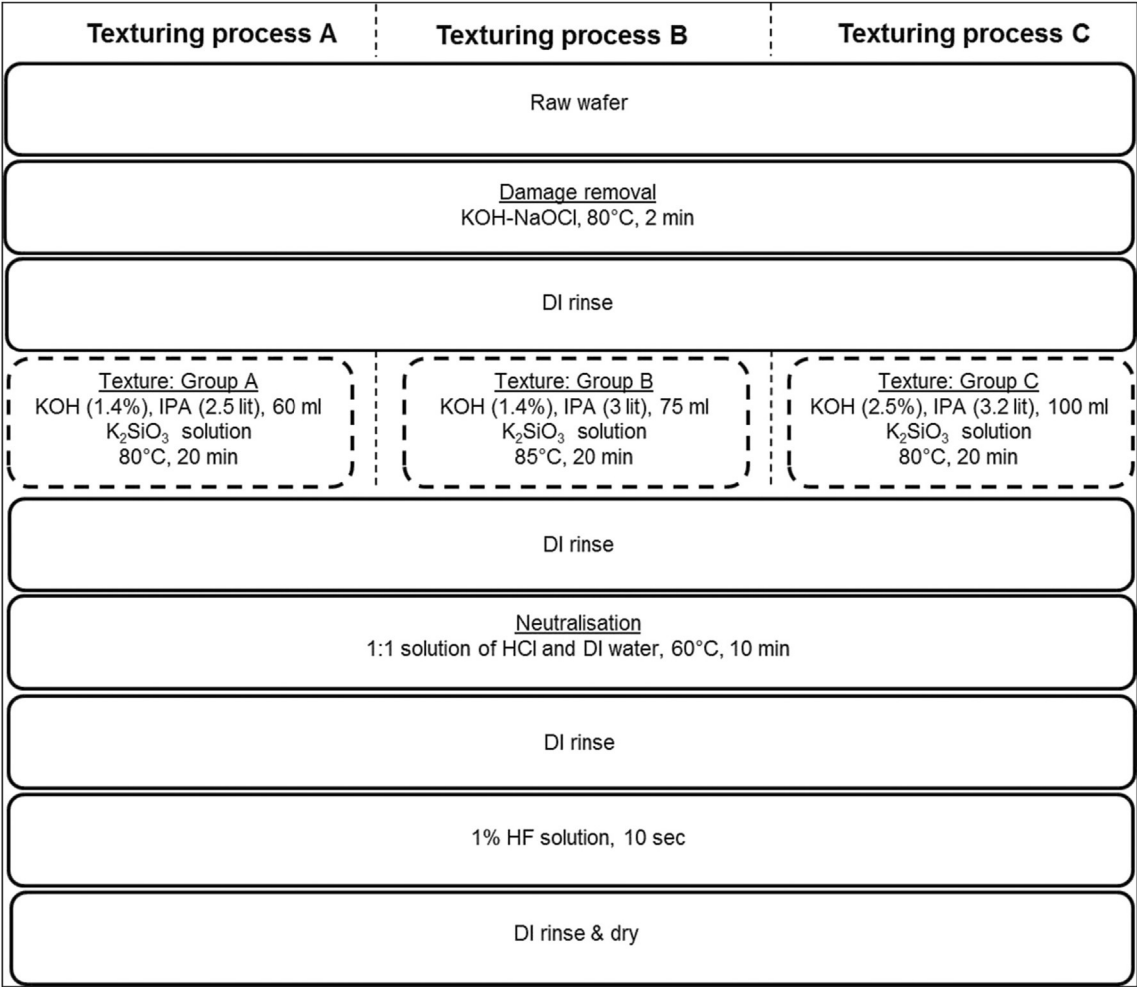


Fig. 1. Process flow diagrams of the three texturing processes. For the texturing processes, the modified texture recipes are shown as dashed box.

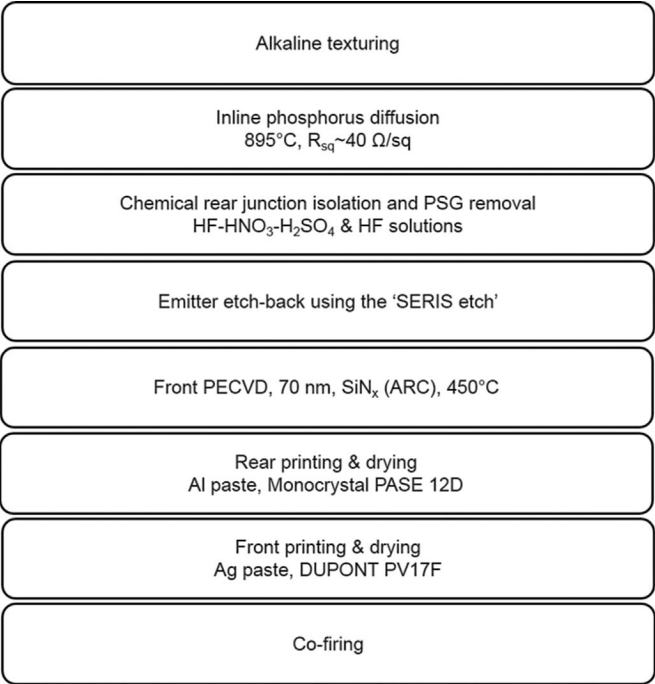


Fig. 2. Schematic illustration of the solar cell processing flow used in this work.

Consulting WCT-120). A BT Imaging LIS-R1 system was used for electroluminescence and photoluminescence imaging. The illuminated current–voltage (*I*–*V*) characteristics of the solar cells were measured on a super class-A solar simulator (AESCUSOFT, SolSim

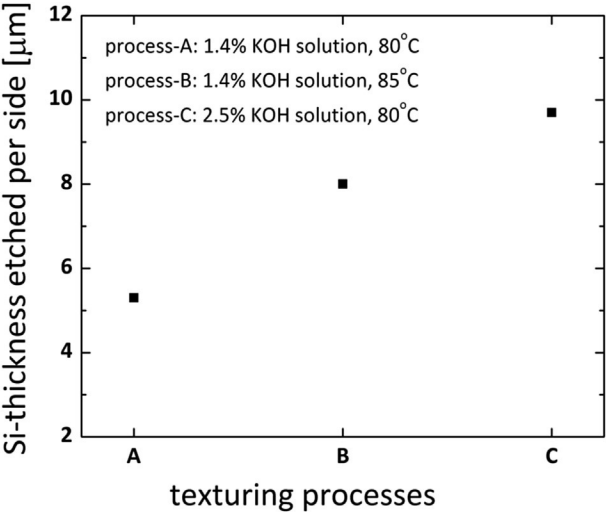


Fig. 3. Graph indicating the average variation of the amount of Si thickness etched per wafer side for the texturing processes A, B and C.

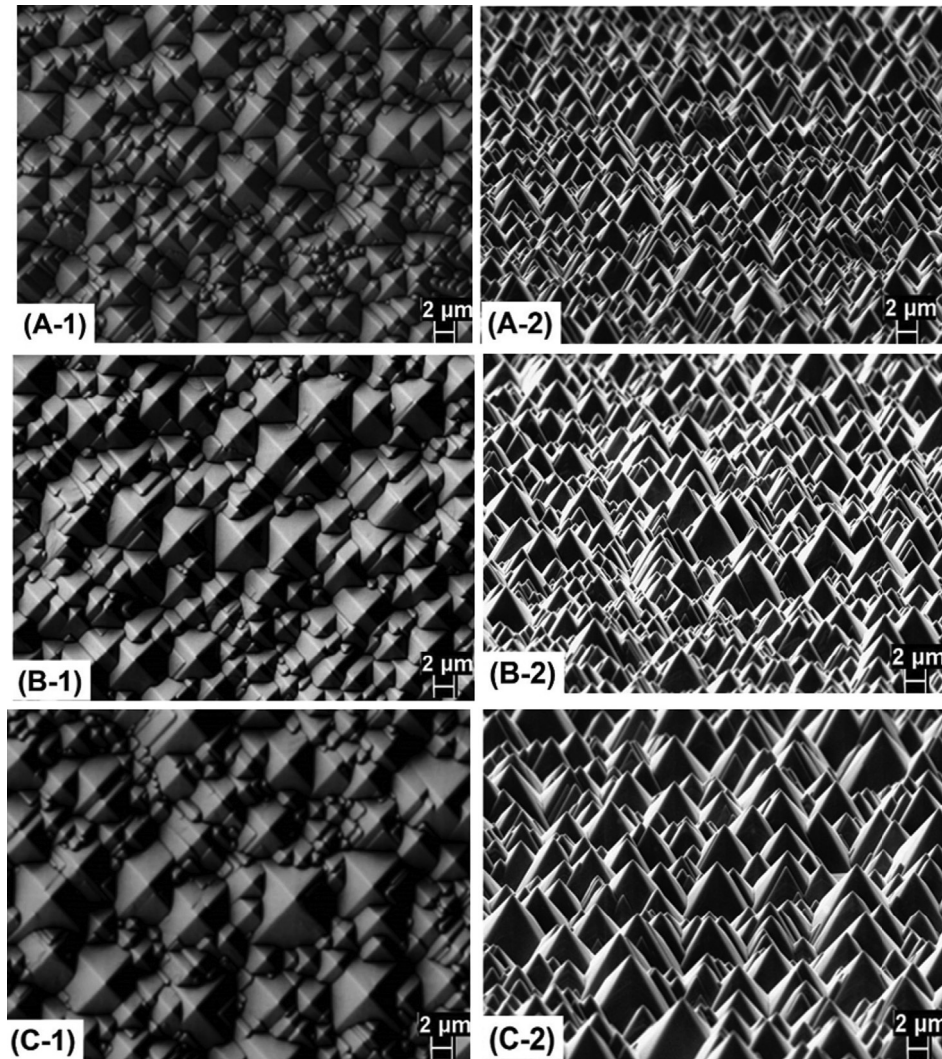


Fig. 4. Plane-view (A-1, B-1 and C-1) and angular-view (A-2, B-2 and C-2) SEM micrographs of textured wafers (magnification = 2000×) of process A (A-1 and A-2), process B (B-1 and B-2), and process C (C-1 and C-2).

210) under standard testing conditions (STC). The calibration solar cell used during the measurements was certified by Fraunhofer ISE Cal Lab, Germany. After the I – V measurements, three representative finished cells from each group cut into $5\text{ mm} \times 156\text{ mm}$ strips (parallel to the busbars) using a dicing saw and the specific front contact resistances were measured using an automated tool (Kalio Binder GBR, KB-100).

3. Results

3.1. Texture process

The KOH-based alkaline texturisation process is governed by the following chemical reaction [15]:



During the anisotropic etching of Si by KOH hydrogen (H_2) bubbles are released [see Eq. (1)]. These H_2 bubbles have a tendency to stick to the Si surface [15] and to act as a locally mask which prevents texturing at those spots resulting in a non-uniform texturing. IPA enhances Si surface wettability and effectively

removes these H_2 bubbles from the entire wafer's surface, improving the uniformity and homogeneity of the texturing process. The concentration of the reaction by-product, K_2SiO_3 , also has stronger influence in Si etching rate and stability of the texturing solution; it can even lead to uncontrolled texturing with wide variation in pyramid sizes [5]. Basu et al. [5] have added K_2SiO_3 to the texturing baths to “initialise” the solution by raising the dissolved Si concentration (i.e. silicates) in attempt to stabilise the concentration of both reactants and products in the solution.

In this work we have varied the amounts of K_2SiO_3 and IPA in the process (namely, A, B and C) to control the etching rate. Fig. 3 presents the thickness change at the end of 20 min processes. The processes were optimised in earlier experiments which are not in the scope of this work. Process A used solution with 1.4% KOH, 60 ml K_2SiO_3 and 2.5 L of IPA in a fresh bath at temperature of 80°C . The amount of Si removal per wafer's side was determined to be $\sim 5\text{--}6\text{ }\mu\text{m}$ (see Fig. 3). In process B, the KOH concentration was maintained the same; however, bath temperature was increased to 85°C . The higher temperature resulted in a faster etching rate ($\sim 8\text{--}9\text{ }\mu\text{m}$ per wafer's side). The larger amount of K_2SiO_3 (75 ml) needed to stabilise this process resulted with increased Si etching rate. Besides, due to the higher temperature, higher formation rate

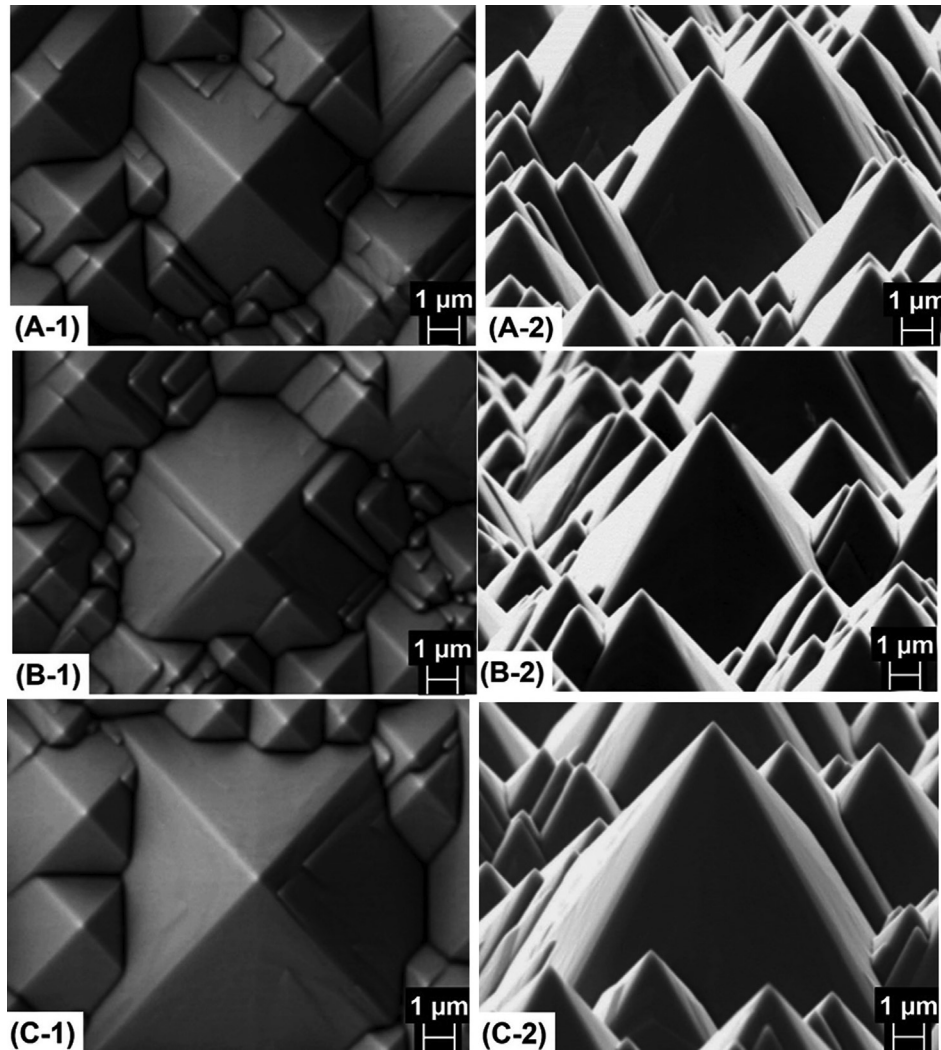


Fig. 5. Plane-view (A-1, B-1 and C-1) and angular-view (A-2, B-2 and C-2) SEM micrographs of textured wafers (magnification = 8000 $\times$) of process A (A-1 and A-2), process B (B-1 and B-2), and process C (C-1 and C-2).

of H_2 and higher evaporation rate of IPA, lead to higher consumption of IPA (3 L) as compared to process A. In process C, the KOH concentration was changed to 2.5%; however, bath temperature was maintained at 80 $^{\circ}C$. The high KOH concentration leads to the highest Si etching rate (~ 10 – 11 μm per side) with higher H_2 formation rate [17]. This process requires 100 ml of K_2SiO_3 and 3.2 L of IPA in order to establish a homogeneous texturing process window.

3.1.1. Surface morphology study

The uniformity of the texturing and the pyramid heights were analysed by SEM at relatively low magnification. Fig. 4 shows both the plane-view and angular-view (at 70 $^{\circ}$) SEM micrographs of the textured surfaces of processes A, B and C under a magnification of 2000 $\times$. Unlike previous reported results [7], all the texturing processes lead to uniform texturing, with no planer untextured regions are observed. As can be seen from Fig. 4(A-1) and (A-2) process A creates, pyramids with height in the range 2–5 μm . Process B [Fig. 4(B-1) and (B-2)] forms slightly larger pyramids (~ 6 μm maximum height), while process C [see Fig. 4(C-1) and (C-2)] generates larger pyramids with a maximum height of ~ 8 μm . The maximum pyramid heights were estimated using the SEM at higher magnification. Fig. 5 shows both the plane-view and angular-view (at 70 $^{\circ}$) SEM micrographs of the different processes under a magnification of 8000 $\times$. The SEM study seems to indicate that the

pyramid size primarily depends on the KOH concentration in the texture solution; whereas, the texturing bath temperature has only a secondary influence.

3.1.2. Surface reflectance study

Achieving low surface reflectance values is very important from the point of view of photocurrent generation of the completed solar cell. The surface reflectance of representative wafers from groups A, B and C was measured. The front surface reflectance was first measured after texturing and was re-measured after ARC SiN_x deposition and densification. For each wafer the reflectance measurements were carried out at five points and the average WAR value was calculated. Fig. 6 presents the variation of the WAR values. After texturing the WAR values are 11.6%, 11.6% and 11.7% for processes A, B and C, respectively; whereas, after ARC SiN_x deposition, the WAR is 1.9% for all the processes. Due to the minimal WAR variations (both with and without SiN_x), it can be concluded that the investigated homogeneous pyramidal surfaces are optically similar, irrespective of the pyramid heights.

3.1.3. Lifetime study

Symmetrical lifetime test structures were fabricated to investigate the impact of the surface texturing on the effective lifetime and related parameters. Emitter was formed, on both sides of

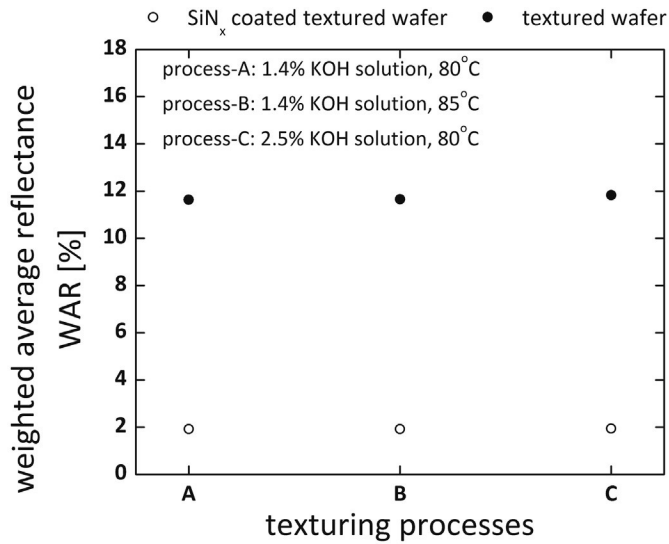


Fig. 6. Variation of WAR values of the front surfaces with or without ARC SiNx deposition for the textured wafers from processes A, B and C. The weighted average reflectance (WAR) is weighted using the AM1.5G solar spectrum over the 300–1000 nm wavelength range.

wafers from all three groups (as described in Section 2.2), using inline diffusion and emitter etch-back. The process was completed by deposition of a 70 nm thick ARC SiNx layer on both surfaces followed by fast firing in an industrial belt furnace to simulate a realistic effective lifetime expected after contact firing. The injection dependant effective lifetime was measured under quasi-

steady-state (QSS) conditions [16] using the Generalised analysis [17]. In this study the effective lifetime (τ_{eff}) at excess carrier of 10^{15} cm^{-3} is reported, together with the implied V_{oc} (iV_{oc}) at one sun. The emitter saturation current density (J_{oe}) was extracted at excess carrier concentration of 10^{16} cm^{-3} using the Kane–Swanson method [18].

Fig. 7 shows the variations of τ_{eff} , iV_{oc} and J_{oe} , for representative wafers from groups A, B and C. No significant variation is observed in these three parameters for the different texture processes. As the impact of the relatively low bulk quality on J_{oe} is small, this parameter is more suitable to evaluate the influence of the texturing process on the surface recombination. It was concluded that the surface passivation quality offered by the SiNx layer is not significantly affected by the pyramid height. Since wafers from the same brick (and from the same region in the brick) were used in this study, similar bulk lifetime can be assumed. Four-point probe mapping indicates that all emitters have identical sheet resistance ($R_{sq} \sim 70 \Omega/\text{sq}$). We therefore assume that variation of τ_{eff} indicates only variation of the surface passivation quality. Note that the reported τ_{eff} values are without an activation of the boron–oxygen defects (before light induced degradation [19,20]).

3.2. Solar cell results

3.2.1. Cell electrical parameters

The statistical distribution of the one-sun electrical I – V parameters (J_{sc} , V_{oc} , FF and efficiency) for all the cells, measured directly after fabrication, is shown in Fig. 8. Each group consists of 45 cells textured using different processes (A, B and C). Fig. 8 clearly indicates negligible variation of J_{sc} and V_{oc} between the groups. This is as expected given the minimal variation in WAR and the iV_{oc} , observed on test structures (Figs. 6 and 7). However, a variation of

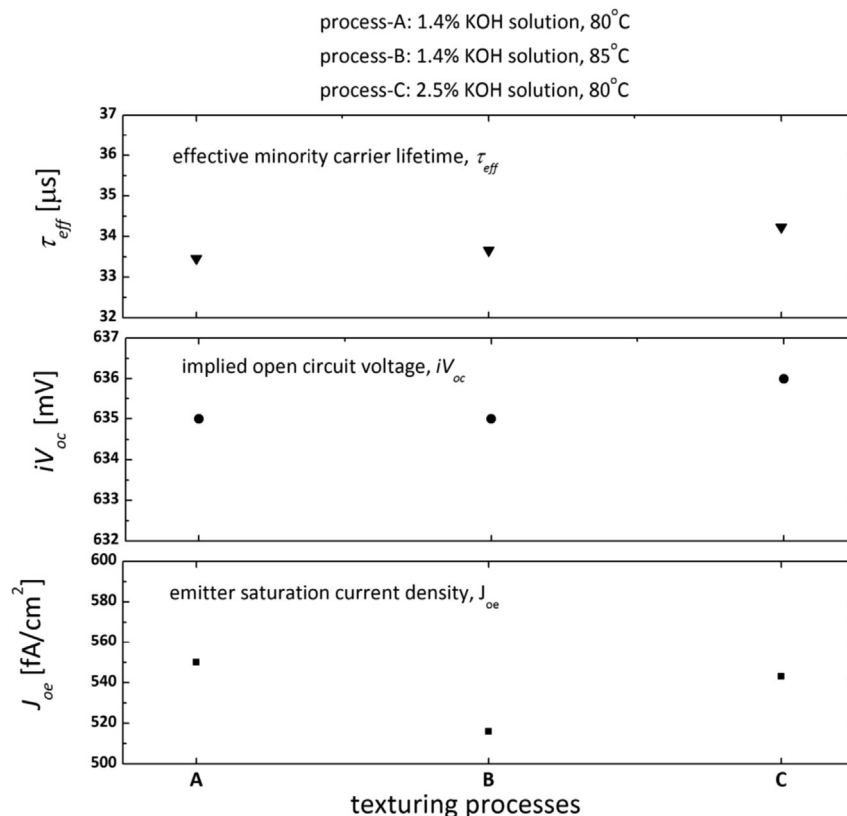


Fig. 7. The average J_{oe} , τ_{eff} and iV_{oc} of representative samples from groups A, B and C.

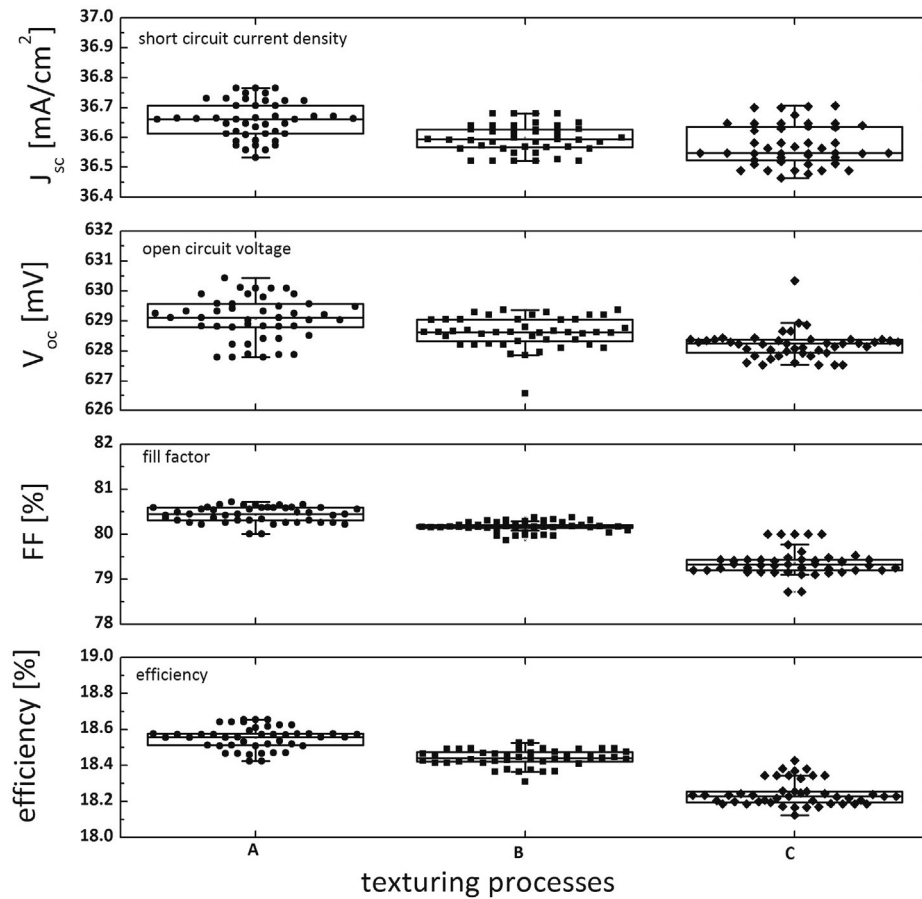


Fig. 8. Distribution of the electrical one sun parameters (J_{sc} , V_{oc} , FF and efficiency) for all the cells fabricated using the texturing processes A, B and C (45 cells each).

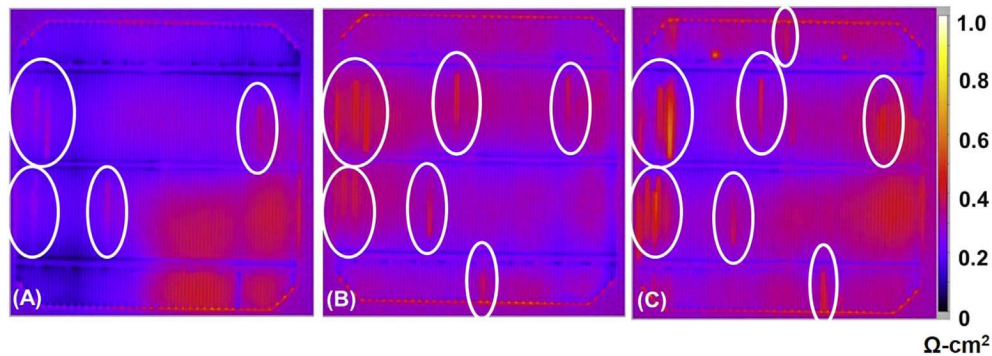


Fig. 9. R_s images of the inline-diffused emitter solar cells (best cells) textured with processes A (FF = 80.7%), B (FF = 80.4%) and C (FF = 80%).

the average FF values (80.4%, 80.2% and 79.4% for wafers with different texturing processes A, B and C respectively) was observed. This variation in FF leads to variation of up to 0.4% absolute in the cell efficiency [between the largest pyramid height (group C) and the smallest pyramid height (group A)].

3.2.2. Series resistance study by luminescence imaging

Fig. 9 shows series resistance (R_s) images extracted from photoluminescence (PL) and electroluminescence (EL) images based on the method of Kampwerth et al. [21] for the best solar cells from each group. All images were taken under the same illumination and using the same exposure time. All cells show an R_s distribution typical of screen printed solar cells. Some broken fingers are

observed in the different locations (marked by white loops in Fig. 9) for all the cells, indicating some issues with the printing screen. However, the numbers of broken fingers seems to be increasing from process A to C. As such broken finger issues are common, the screen was designed such that the fingers are connected in pairs at the edges (see Fig. 10) to minimise the influence of broken fingers. As can be seen, the percentage of regions with local R_s values above $0.3 \Omega\text{ cm}^2$ increases for the cells from process A to process B to process C. Given that the three solar cell groups have identical processing, apart from the surface texturing, the difference can arise only from variations of the sheet resistance (diffusion) or in the metallisation. We confirmed similar sheet resistances ($70 \Omega/\text{sq}$) and comparable finger width/height after screen printing.

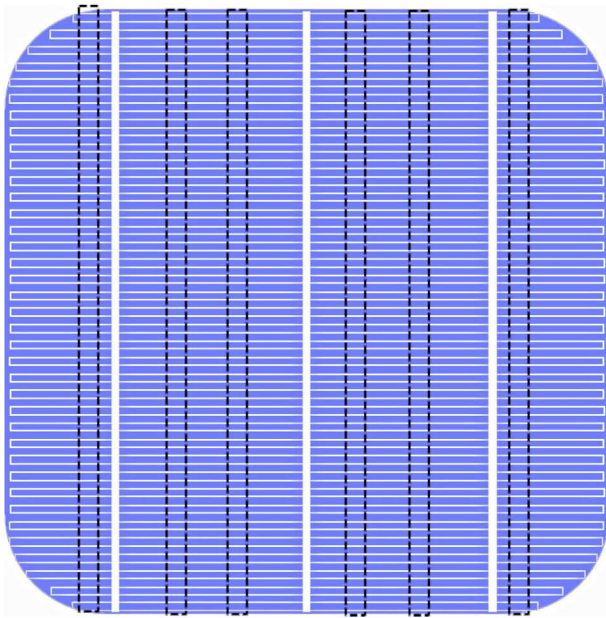


Fig. 10. Schematic showing the approximate locations (black dashed lines) of the sawed strips used for the specific contact resistance measurement.

Therefore, the differences are likely to be due variation in the contact formation.

3.2.3. Contact resistance analysis

To analyse possible differences in front contact resistance due to the different texture processes, three representative finished cells from each group were chosen. The cells were cut using a dicing saw into $5\text{ mm} \times 156\text{ mm}$ strips to isolate measurement structures from the rest of the cell as shown in the schematic in Fig. 10. Transfer length method (TLM) and contact end resistance measurements [22] were performed on the cut strips. While specific contact resistivity (ρ_c) can also be measured via TLM alone, this approach assumes that the sheet resistance under the contacts is the same as the sheet resistance between the contacts. For fired screen printed solar cells, it is desirable to avoid this assumption as the contact

formation process involves etching and crystallite growth which may alter the sheet resistance under the contact. The use of TLM and contact end resistance measurements in tandem is a rigorous approach that avoids this assumption and includes the possibility of different sheet resistances directly under the contact and between the contacts. The fingers on isolated strips were contacted using probes and ladder pattern TLM measurements and Contact End Resistance measurement were carried out which included eight fingers per measurement. On each strip measurements were carried out in three locations: in the centre, between top edge and centre, and between bottom edge and centre. Specific contact resistivity was determined from these measurements as per the procedure described in Ref. [20]. Two reliability criteria were set for these measurements: (1) the TLM linear fit coefficient of determination (r^2) should be ≥ 0.999 and (2) the R_{sq} determined from the TLM linear fit slope should be within $70\text{ }\Omega/\text{sq} \pm 10\%$. The measurements that fulfilled criteria (1) and (2) are summarised in Fig. 11. The average ρ_c for front contacts on cells textured with processes A, B and C were $2.9\text{ m}\Omega\text{ cm}^2$, $3.4\text{ m}\Omega\text{ cm}^2$ and $5.3\text{ m}\Omega\text{ cm}^2$ respectively. While all cells have acceptably low ρ_c , the ρ_c is found to deteriorate with increasing pyramid height, within the pyramid height variation studied here. As other causes to explain a variation in FF were ruled out in Section 3.2.2, it follows that variation in the contact resistance is responsible for the FF variation for these texture process groups.

A detailed microstructural investigation of the front contacts revealed that the difference in contact resistance for the three pyramid groups is linked to the difference in the pyramid count density (number of pyramids per unit area) [23]. Pyramid tips represent favourable sites for screen printed silver–silicon contact formation [23,24] and increasing average pyramid height reduces the pyramid count density and hence the number of potential sites for contact formation. Consequently, the small pyramid group achieved the lowest ρ_c , followed by the larger pyramid groups.

4. Conclusions

In the present work three alkaline texture processes were optimised to lead to three different pyramid heights. The texturing bath chemistry (amounts of KOH, IPA and K_2SiO_3) and the bath temperature were varied to develop three processes leading to surface textures with small ($\sim 5\text{ }\mu\text{m}$ maximum), medium ($\sim 6\text{ }\mu\text{m}$ maximum) and large ($\sim 8\text{ }\mu\text{m}$ maximum) pyramid heights. The pyramid structures were analysed through a comprehensive SEM study. Within each process group a relatively narrow range of pyramid heights was observed. The front surface reflectance and lifetime analysis indicated that WAR, τ_{eff} , iV_{oc} and J_{oe} , are nearly identical for all the three groups. Screen printed solar cells made using these texturing processes demonstrate a variation in the FF. The FF was found to decrease with increasing maximum pyramid heights within the variation studied here and smaller pyramids were found to give the highest FF and hence efficiency. A variation in specific contact resistance was identified experimentally as the most likely cause for this FF variation. While all the texturing processes led to high FF ($>79\%$), it was demonstrated that by using the optimised texture process a FF gain of up to 1% absolute can be obtained (corresponding to an efficiency gain of 0.4% absolute). Average solar cell efficiency (of 45 cells) of 18.6% (18.7% max) and an average FF of 80.4% (80.7% max) was achieved using the optimised pyramid process and inline-diffusion.

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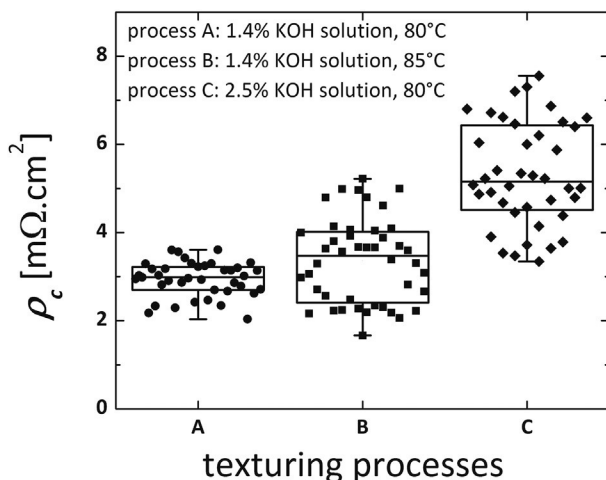


Fig. 11. Boxplots of ρ_c extracted from TLM and contact end resistance measurements for front contacts on cells textured with processes A, B and C.

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