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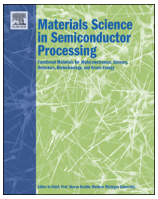

Influence of small size pyramid texturing on contact shading loss and performance analysis of Ag-screen printed mono crystalline silicon solar cells

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ABSTRACT

Front side textured random pyramids are widely utilized in major industries for the performance enhancement of crystalline silicon (c-Si) solar cells. Random pyramids not only reduce the surface reflectance but also improve the light trapping effect. Therefore, it is necessary to understand the pyramid height affecting the cell performance, further improving cell efficiency. In this work, we present an experimental study to investigate the influence of pyramids size on the contact shading loss mechanism of silver (Ag) screen-printed p-type c-Si solar cells. Three alkaline texture solutions with sodium silicate additives were optimized to develop the small pyramid (0.5–2.0 μm) size, middle pyramid (5.0–9.0 μm) size and large pyramid (10–15 μm) size on the c-Si surface, respectively. It was noticed that screen-printed finger width strongly depends on pyramid size. Even though, same mesh patterns and screen printing conditions resulted in 20 μm widening of metal finger width on the large pyramids as compared to the small pyramids. This was attributed to the increase in the size of cell surface pyramids that not only varied the gap between the screen mesh and cell surface while screen-printing but also hindered the contraction of metal electrodes during the firing process. The c-Si solar cells with large pyramids suffered from an extra shading loss during fabrication, thus, led to the reduction of the short circuit current density (~0.7 mA/cm^2) resulting in lower efficiency (~17.72%) as compared to efficiency (~18.60%) of small pyramid based cells.

1. Introduction

Crystalline Si (c-Si) wafers are the paramount material in the field of Si solar cells and showed a predominant growth in the global photovoltaic market, due to its high conversion efficiency, long-term stability and easy optimized fabrication process [1–3]. The key challenge of the mono-crystalline Si wafer is to improve the cell efficiency with a simple fabrication step and reduce the output power cost. Further, to improve the cell efficiency, the textured random pyramid formation on the Si surface through alkaline texturing is a well-known process [4]. These pyramids, due to the so-called “double bounce effect”, suppress the front surface reflectance and heavily incorporate the light absorption near the bandgap of semiconductor, which results to improve the cell efficiency [5,6]. In general, anisotropic etchants like, sodium hydroxide (NaOH) or potassium hydroxide (KOH) chemicals were used to form the random pyramids on the Si surface [7]. Addition of iso-propyl alcohol (IPA) to the texturing solution archives the superior lateral uniform pyramids on the entire wafer by changing the Si surface wettability to control & nucleate the texturing process [8]. An optimized texturing process is required to improve the textured surface quality and control the etching rate of Si surface. Luo RZ et al. reported that the addition of potassium phosphate tribasic (K_3PO_4) and potassium silicate (K_2SiO_3) to the alkaline solution reduce IPA consumption and improve the texture quality through a better throughput [9,10].

Various simulation and experimental studies have reported the variation of pyramid size for solar performance [11–13]. From the geometric optics (ray-optics) aspect, the straight upright pyramids size variations do not influence on front surface reflectance and thereby the upright pyramids offer the high short circuit current density (J_{sc}). Llopis and Tobías reported a fine simulated study related to numerical approaches of the electromagnetic wave equation, where the diffraction effects were significant when the size of the pyramids were less than 300 nm range. In that case, reflectance increases ahead of geometric limit (optic limit) [11]. However, the simulation studies were limited to

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explore the pyramid size distribution effects; therefore, the real solar cell fabrication results are significant to study the pyramid size distribution effect on the solar cell optical characterizations. G. Pingqi et al., have presented a novel approach for texturing the large area of Si surface, which produce periodic nano texturing (nano-pencils, inverted-nanopyramids and nanopillar) on the surface with reach throughput of 3000 wafers/ hour and sustaining with high light trapping effect [14]. In the recent studies of F. Wang et al., obtained that continuous and uniform micro-scale pyramids were reported in the range of (~ 8 µm) size cover entire Si wafer by simple saw damage etching (SDE) process achieved with high cell efficiency [15,16]. In addition, F. Wang et al., also have reported a novel and time efficient Si texturing methods based on inorganic (sodium hydroxide) and organic (tetramethylammonium hydroxide) etching process for attaining various ranges of pyramid sizes for improving the device performance [16,17]. E. Vazsonyi, reported that uniform small pyramids with the size of 0.5–1 µm were obtained through expansion of pyramid nucleation by adding Neutral Tenzids (surfactant) to the texturing solution [18]. Cabrera et al. and Han et al. have witnessed a drastic reduction of fill factor (FF) was observed when the pyramid size less than 300 nm range [12,19]. In addition, Cabrera et al. observed that when the pyramid size was more than 300 nm ranges there was no variation in the FF, whereas Han et al. noticed a small variation in the FF but there is no clear trend of explanations [12,19]. Ximello et al. have reported an indefinite variation of FF with respect to pyramid height variation effect, whereas the improvement of the FF in the homogeneous pyramids in contrast, decreased inhomogeneous pyramids without clear distinction [20]. Z. Sihua et al. achieved higher V_{oc}, FF and cell efficiency (η) with nano-pyramids (size 200–1200 nm) as compared with the micro-pyramids (size 1–10 µm) Si textured surface [21]. W. Xixi et al., reported 1.7% higher power conversion efficiency with nano-pyramid as compared with micro-pyramid Si textured surface [22].J. Lee et al. have reported the pyramid size should be at least 4 µm ~ 6 µm in order to cover the whole of crystalline silicon surface [23,24]. For large pyramids, the contact property with metal is poor and they have an adverse effect on the solar cell efficiency due to high surface recombination rate [25,26]. However, the important factor for the high efficiency of solar cells was the shading loss of front electrodes. E. Denis et al., reported 50 µm size mesh pattern of screen printing front electrode finger width, after firing the real finger width widening to 71 µm (alkaline textured sc-Si) and 64 µm (acid textured mc-Si), respectively [27]. Whereas J. Minkyu et al., also noticed that 80 µm and 30 µm mesh pattern of front electrode finger width, after firing the real finger width widening to 95 µm and 45 µm, respectively [28]. Therefore, the contact wildness formation of the Ag screen-printed solar cells shading loss on the random textured surfaces need to be address.

In this study, we report three different pyramid heights such as 0.5–2 µm small, 5–9 µm middle and 10–15 µm large pyramids developed by controlled adding of sodium silicate (Na_2SiO_3) into standard alkaline solution (NaOH & IPA). The sizes of the pyramids are confirmed from the SEM images and the optical reflectance of the textured samples are analyzed. Further, we investigate the effects of textured pyramids size variation on the contact shading loss mechanism of Ag screen-printed mono-crystalline Si solar cells and optimized cell characteristics are studied.

2. Experimental setup

2.1. Surface texture formation

In this experiment p-type boron doped < 100 > having a resistivity of (1–3.5 Ω-cm and 200 µm thick) 12.5 × 12.5 cm, mono crystalline Si substrate was used in this study. The saw damage removal (SDR) and subsequent cleaning of the Si substrate prior to the texture process development was reported by Basu et al. [29]. The samples were dipped in SDR solution to remove the surface damage; the samples were treated in the solution of 12 wt% sodium hypochlorite (NaOCl) and 40 wt% NaOH in the 1:1 ratio and the constant temperature range of 85–90 °C for 10 min. After SDR the samples were subjected to Standard Radio Corporation of America (RCA) cleaning to remove the remaining chemicals on the surface. Further cleaning was followed by HCl and HF dip to remove the metal ions and native oxide with a continuous rinse in the de-ionized water. After cleaning, samples were processed for texturing of three different kinds of pyramids with the small, middle and large size of straight uphill pyramids. The texturing process was carried out in a standard etching solution that contains 2 wt% NaOH and 12.5 vol% IPA and the temperature at 81–83 °C for 30 min. The etching rate and pyramid size controlled by mixing 25, 12.5 and 0 wt% of Na_2SiO_3 with NaOH and IPA to develop the small, middle and large size textured pyramids. The detailed etching rate analysis and the formation of pyramid size can be found in our previous report [30].

The reflectance of after SDR, small, middle and big size pyramid surface samples were measured by IPCE (Incident Photon to current Conversion Efficiency) Qex7 system, in the wavelength range of 300–1100 nm, respectively. Size of the textured pyramid was confirmed from Scanning Electron Microscope (SEM) images.

2.2. Cell fabrication process

Three kinds of textured pyramid Si wafers were carried out for the cell fabrication. After texturing, the samples were immediately transferred into diffusion furnace to form the phosphorous emitter layer carried out at 810 °C for 20 min and $POCl_3$ used as a source material. After diffusion, the sheet resistance of the emitter archived from 80 to 85 Ω/sq. The phosphorous silicate glass (PSG) was removed after diffusion process by HF 5%solution. A 77 nm thick SiN_X: H layer having a 2.1 refractive index of passivation and anti-reflective (AR) layer was deposited on the front side of the wafer by plasma enhanced chemical vapour deposition. The metallization was carried on the front and the rear side of the wafer by the screen-printing method using silver and aluminium paste respectively followed with the co-firing process in the conveyor belt furnace. In order to optimize the firing process for different surface structures, conveyor belt speeds and peak temperatures were controlled accordingly. The co-firing temperature profile was measured with the tracker system (model Datapaq 9000). The light I-V performance of the solar cell was tested by PASAN (model CT801). The sizes of actual metal finger widths confirmed from SEM analysis. In order to investigate the size and distribution of Ag particles in the front electrode paste of solar cells, the paste was dissolved in ethanol and analyzed through Particle Size Analyzer (PSA) and SEM.

3. Result and discussion

Pyramid size and growth mechanism was regulated by varying the Na_2SiO_3 concentration in the standard alkaline texture solution of NaOH and IPA amalgamation. The textured random pyramid size of Si front surface was affirmed from SEM images as shown in Fig. 1. Before the treatment by alkaline texture solution, the SDR cleaned Si surface without pyramid development is shown in Fig. 1(a). By altering the Na_2SiO_3 concentrations as in the range of 25, 12.5 and 0 wt% in the alkaline texture solution, the formation of pyramid size resulted in 0.5–2 µm small pyramid Figs. 1(b), 5–9 µm middle pyramid Fig. 1(c) and 10–15 µm large pyramid Fig. 1(d), respectively. We observed from the chemical reaction that, the Na_2SiO_3 functioned as a wrapping layer on the Si surface during the texturing process. Increase in the Na_2SiO_3 ratio in standard texturing solution reduced the etch rate of Si surface by forming sodium silicate nucleation sites [22]. The same as defined from SEM images by decreasing the Na_2SiO_3 concentration cause to increasing the etch rate of the Si surface, that leads to developing the pyramid size from small to large size.

The reduction of front surface reflectance was the key parameter to improve the photo-generation current of c-Si solar cell. The optical