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Influence of micro-texture sizes towards light absorption improvement in hybrid microtextured/nanotextured black silicon for solar cells

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ABSTRACT

Increasing wideband absorption in crystalline silicon (c-Si) solar cells is a task that is vital in order to improve the power conversion efficiency of the device. The low light absorption of incident photons is discovered in this type of solar cell due to the bulk c-Si indirect band gap as well as low absorption coefficient characteristics. This work reports on the micro-texture size influence towards enhancing wide/broadband light absorption in hybrid microtextured/nanotextured c-Si for solar cell applications. Sodium hydroxide (NaOH) solution is used to fabricate a Microscale pyramid on c-Si. The NaOH etching is performed at different durations between 25-40 min. The one step silver-assisted wet chemical etching (one-step $AgNO_3$-based MACE) method is applied to prepare nanowires on the pyramid. After 30 min of etching, a range of pyramids with heights between 3-7 µm and 3-10 µm of widths are formed. After the one-step $AgNO_3$-based MACE, nanowires with 300-800 nm heights and 40-50 nm widths are obtained on the pyramids. After the fabrication of nanowires on the pyramids, considerable suppressed weighted average reflection (WAR) is obtained in all the samples, due to improved light trapping and augmented light scattering by the nanowires and the base pyramids respectively. Lowest broadband reflection (9.0 % WAR), is obtained after 30 min of etching and 80 s one-step $AgNO_3$-based MACE. This translates to 38.9 mA/cm^2 maximum short-circuit current density (maximum J_{sc}), or 14.1% improvement compared to the maximum J_{sc} of the pyramids without nanowires (34.1 mA/cm^2). The findings indicated that the hybrid textured surface in c-Si is a promising approach to enhance wideband light absorption and potential photocurrent for application in photovoltaic devices.

Keywords: *Absorption, Alkaline texturing, Hybrid textures, Nanowires, Pyramids*

1. INTRODUCTION

Solar cells based on crystalline silicon (c-Si) remain the dominant technology with more than 90% market share in the photovoltaic (PV) industry. This owes to the abundance, technological maturity, economies, and non-toxic nature of c-Si absorber material [1]. In addition, the c-Si-based solar cells improving power conversion efficiency and reducing production cost (presently around $0.24/ Wp) made them more attractive to the market [1]. Even with these advantages, the low light absorption of incident photons is exhibited by this category of solar cells. This is represented as a 35 to 40% reflection of incident light photons, which is unwanted for an efficient solar cell power conversion process. This is due to the bulk c-Si (absorber material) indirect band gap as well as low absorption coefficient characteristics [1, 2]. Owing to these issues, considerable optical losses, which mostly correspond to low maximum short circuit current density (maximum J_{sc}) in the c-Si solar cells, is one of the impinging challenges for this technology [3].

In the industry, different surface texture types like inverted pyramids, random upright, and grooves surface textures are being investigated to improve light absorption in the c-Si material for solar cells. With the surface textures on the c-Si absorber, light absorption of incident photons can be enhanced due to minimized broadband reflection [4-7]. Furthermore, potassium hydroxide (KOH) or sodium hydroxide (NaOH) anisotropic wet chemical etching at 80–90°C, in the presence of isopropanol (IPA) is being used to suppress wideband reflection and improve the light trapping capability of mono c-Si based solar cells [8-10]. This approach yields optimal random upright pyramids that snare incident light via enhanced scattering of incident photons from solar radiation independent of the angle of incidence [10-11]. However, it is thought-provoking to suppress the surface of the mono c-Si absorber broadband reflection to lower than 10% via anisotropic etching [11, 12]. This issue is usually tackled by depositing indium tin oxide (ITO) or silicon nitride (SiN_x) thin films of about 75 nm thickness as an anti-reflective coating (ARC) on top of the upright random pyramids [13-16]. However, ARC based on SiN_x only helps to suppress surface reflection around the peak power (at 600 nm wavelength region) for the AM1.5G solar spectrum [13].

Incorporating nanotextures on top of the random pyramids (hybrid-textures) on c-Si is an alternative viable method to further decrease the wideband reflection to below 10.0% without additional ARC [17, 18]. The nanotextures reported smaller dimensions than the incident light wavelength; this causes improved light coupling into the material through the refractive index grading effect [19, 20]. Moreover, processes such as reactive ion etching and metal-assisted chemical etching (MACE) are considered promising approaches for fabricating nanotextures on c-Si or random pyramid surfaces. For the MACE process, the silver-assisted wet chemical etching ($AgNO_3$-based MACE) method due to its easy processing approach and cost-effectiveness is established to be a promising technique for producing nearly nanowires with uniform length and width on Si or random pyramids [21-24].

For this purpose, a reduction in wideband reflection to below 10 % around the ultraviolet-visible-infrared region of the spectrum has been reported and proven when a one-step $AgNO_3$-based MACE process was attempted with a duration of 3-15 min [21, 25]. P. Singh et al. highlighted at room temperature, a one-step $AgNO_3$-based MACE process in an aqueous solution consisting of 5M of HF and $AgNO_3$ for 15 minutes to fabricate vertical arrays of black silicon (b-Si) nanowire on micro pyramids for various applications such as solar cells and surface improved Raman spectroscopic investigations [26]. In their work, studies on the formation mechanism of the vertically aligned nanowires on micro pyramid structures and the impact of the $AgNO_3$ concentration on the morphology and optical properties of the hybrid micro/nano-textures have been analyzed.

Recently, C-H Hsu et al. reported on the formation of nanostructured pyramidal b-Si with ultra-low surface reflectance for application in solar cells by a one-step $AgNO_3$-based MACE process [27]. In their work, within a 3minute duration, the random pyramidal wafers in a solution containing 3 M HF and $AgNO_3$ at 50 °C were etched. The effect on the properties of the b-Si was investigated for a range of concentration of the $AgNO_3$ from 0.015 to 0.075 M. However, limited researches were reported on hybrid micro/nano-textures in which the nanowires (b-Si) via one-step $AgNO_3$-based MACE are incorporated on the random pyramids within a short process duration (less than 2 min) to study hybrid micro/nano-textures on the surfaces of c-Si for PV applications. For practical mass production, a hybrid texturing process in which the b-Si nanowires are incorporated on the random pyramids by one-step $AgNO_3$-based MACE within a short process duration is indispensable. This is to ensure high process output (i.e., number of wafers/hour). Besides, a study of the impact of the micro-texture sizes on the suppression of broadband light reflection will be a way forward towards optimization of such absorber materials for potential applications in PV systems.

This paper reports a one-step $AgNO_3$-based MACE method of incorporating b-Si nanowires onto micro-textured surfaces (hybrid micro/nano-textured). Here, the nanowires (the b-Si) are incorporated into the random pyramids within a short process duration for improved wideband light absorption in c-Si within the ultraviolet-visible-infrared region of the spectrum for PV application. The influence of micro-texturization on wideband light suppression of the hybrid micro/nano-textured surface is further investigated. The pyramids and hybrid micro/nanotextures surface morphological and optical properties were characterized. The maximum potential values of the short circuit current density (maximum potential J_{sc}) from the absorption results were calculated to evaluate the relative light coupling and trapping ability of the hybrid structure.

2. METHODOLOGY

In this work, a mono c-Si wafer [p-type, 250 µm-thick, boron, 1–10 Ω cm] is used. The oxide layer, organic residues, as well as metallic contaminants from the surface of the wafers, are cleaned using Radio Corporation of America (RCA) practice, and the details of the RCA technique can be seen in related publications [28, 29]. After the RCA cleaning, the c-Si wafers are then treated in 20% NaOH by weight for 5 min at 80 ºC to get rid of the saw damage. On the upright pyramids(random) fabrication, the c-Si wafers are etched in IPA ($CH_3CHOHCH_3$) 20% (by volume), NaOH buffered solution of 1.5% by weight at 80ºC for different etching durations between 25-40 min at an interval of 5 min [30]. Furthermore, a one-step $AgNO_3$–based MACE process is used for the preparation of nanowires on random pyramids. In this regard, hydrofluoric acid (HF) and $AgNO_3$ (Sigma Aldrich) with 20 g/mol (49%) and 169.87 g/mol respectively are used. Under room temperature, a 5:6 molar ratio solution is prepared in a polypropylene beaker and the etching was performed by dipping the resulting wafers with the random pyramids in the solution for 80 seconds [31]. Moreover, the AgNPs are removed after the formation of the nanowires on pyramids, in a sonication bath containing concentrated HNO_3 (60%) for 5 min. Because of the AgNPs removal step, and to take out the grown thin silicon oxide (SiO_2) layer that formed due to this step, the fabricated hybrid textured samples are then dipped in a solution of HF. In the case of nanowire fabrication, etching is done using the same parameters for all samples. This is done to obtain nanowires of the same properties on the pyramids. For characterization purposes, the samples are labeled as 25 min and 80 s, 30 min and 80 s, 35 min and 80 s, and 40 min and 80 s, according to the NaOH etching durations (25, 30, 35, and 40 min respectively).

Surface morphological analysis was conducted using Field Emission Scanning Electron Microscopy (FESEM). FESEM Model: FEI Nova NanoSEM 450 is employed for surface top view and cross-section analysis of pyramids and hybrid textures on c-Si wafers. Surface roughness values including height, and root mean square (RMS) of the random pyramid textures before nanowires incorporation samples are evaluated using Atomic Force Microscopy (AFM). AFM Model: Dimension EDGE, BRUKER of 512 resolution of pixels, and a scan range of 30×30 μm^2 is used. The hybrid textured hemispheric reflection was measured using a UV-VIS NIR spectrophotometer equipped with an integrating sphere (Cary 5000), within the 300-1100 nm wavelength region of the spectrum). Weighted average reflection (WAR %) is calculated from the reflection result by integrating the surface reflection of hybrid textures wafers with AM1.5G solar spectrum as shown in Eqn. (1), where R(λ) and S(λ) denote the reflection and standard spectral photon density of sunlight for the AM1.5G solar spectrum respectively [3]. Absorption A is calculated from the relation A = (100–R–T) % and the hemispherical surface reflection results. Because of the opaqueness nature of the c-Si wafer base the transmission (T) is assumed to be zero [3, 32]. Detector switching occurs in the course of the hemispherical reflection measurement at around 800 nm wavelength region. As a result of this, at around this wavelength, a slight step change is likely in absorption and reflection results.

$$WAR(\lambda) = \frac{\int_{300nm}^{1100nm} R(\lambda)S(\lambda)d\lambda}{\int_{300nm}^{1100nm} S(\lambda)d\lambda} \quad (1)$$

As shown in Equation (2, where q stands for the electron charge), maximum J_{sc} is evaluated from absorption results to relatively estimate the potential of light trapping and coupling of the hybrid structures [33, 34]. Unity charge assumption is considered for the internal quantum efficiency, INQE=1, in the calculation (for all samples as well as the flat c-Si reference sample) using the relation; EXQE = INQE x (1-R-T1), where term T1 is zero and EXQE refers to external quantum efficiency. The maximum potential J_{sc} improvement of the hybrid textures structure is calculated (from the preceding calculated result) by normalizing their maximum potential J_{sc} to that of the c-Si microtextured samples. Calculating the maximum potential J_{sc} and the corresponding improvement is essential as it indicates the maximum realisable J_{sc} assuming solar cells are prepared with the hybrid textured,

$$Maximum\, J_{sc} = q \int_{300nm}^{1100nm} ENQE(\lambda).S(\lambda)d\lambda \quad (2)$$

3. DISCUSSION AND RESULTS

The random pyramids FESEM images produced on c-Si wafers from the anisotropic NaOH etching along (100) and (110) planes are shown in Figure. 1. From the figure, FESEM top view images of the wafers (a; c; e and g at the top) is presented after etching time of 25 to 40 min, at 5 min interval respectively. The corresponding FESEM cross-sectional images are shown in (b, d, f, and h) from the same figure. It is observed that at 25 min of etching, the micro-textures start protruding with some small-sized micro pyramids (having heights of less than 1 µm) seen at some regions of the wafer (Figure 1 (a)). This shows that an etching time of 25 minutes is not adequate for complete micro-texture fabrication on c-Si [34]. At 30 min of etching, complete random pyramids are realized which covered completely the surface of the c-Si (Figure 1 (c)). From Figure. 1(d), between 3-7 µm pyramids heights and 3-10 µm base widths can be observed. At 35 min etching time, the pyramids gradually begin to be over-etched with the eruption of new pyramids on previously formed pyramids (marked with yellow arrows in Figure. 1 (e) and (f)). Compared to the 30 minute etching time, the base widths remain at around 3-10 µm. However, the heights reduced marginally owing to the gradual start of over-etching. Over-etched pyramids were obtained with a prolonged 40 min of texturing. In this case, the pyramid's heights and base widths decreased to 1-5 µm and 2-5 µm respectively.

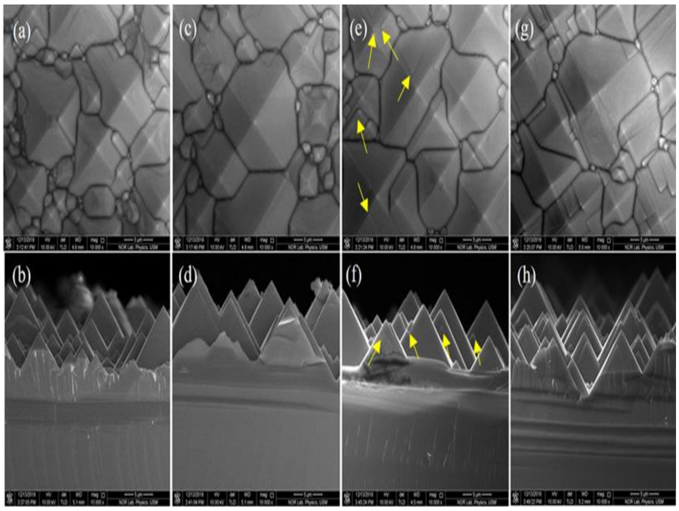

Figure 1. FESEM top view images at etching time of (a) 25 minutes; (c) 30 minutes; (e) 35 minutes; and (g) 40 minutes with their corresponding cross-sectional images:(b);(d);(f); and (h) respectively. For the entire images, the scale bar shows a 5 µm length

To further study the coverage of the micro-textures on c-Si, surface topology analysis of micro-textured pyramids was conducted using the AFM technique as presented in Figure. 2. Like FESEM findings, micro-textured pyramids of diverse sizes were characterized on the surface of the wafers. As can be seen, the pyramids start forming at 25 min of etching. Complete and dense pyramids were obtained on the wafer's surface at 30 min and 35 min of etching. Over-etched pyramids were obtained at 40 min of etching and some regions seem to be almost planar with pyramids of small size on the surface of the c-Si wafer. Furthermore, the etched wafer's surface roughness is investigated and analyzed. Root mean square (RMS) values at 25 minutes; 30 minutes; 35 minutes; and 40 minutes etching time were found to be 520 nm, 965 nm, 669 nm, and 658 nm respectively. It is noted that the results are consistent with FESEM and AFM findings. The decreasing trends seen for the RMS values with increasing time between 30, 35, and 40 min of NaOH texturing confirms the over-etching of micro-pyramids as seen from FESEM observations and reported in other work [30]. Moreover, the distribution of small-sized micro-textured pyramids at 25 min of etching as observed by FESEM is similarly confirmed by AFM RMS value at 25 min.

The micro-textured reflection and absorption curves are presented in Figure. 3 (a) and (b) after being etched on c-Si surfaces at different etching durations. For comparison, planar c-Si reference of high surface reflection within 300-1100 nm wavelength region is used. It is noted that the high surface reflection associated with this untextured reference planar is due to poor light absorption of incident light in the substrate [31]. As compared to planar reference the WAR drops at 25 min of etching to 34.0 % with corresponding 31.0 % and 70 % of surface reflection and absorption at 600 nm of wavelength. The improved absorption as well as the reduction in wideband reflection is accredited to enhanced light scattering when the incident photons hit the pyramid structure on the wafer [35]. Further reduction in broadband reflection is obtained after 30 min of texturing with a calculated WAR of around 27.0 %. Since light scattering is enhanced more reflection reduction is likely because of the complete formation of pyramids on the whole areas of the wafer. The increased scattering presents enhanced light trapping with improved optical absorption into the absorber (c-Si) [36]. Moreover, a reflection of around 22.0 % is exhibited by the 30 minutes etched sample at 600 nm wavelength with a corresponding absorption of 78.0 %. After extending the texturing to 35 min, a broadband reflection profile analogous to the sample of 30 min texturing was obtained. An increased WAR of 27.2 % was achieved by this sample (35 min texturing) demonstrating the beginning of the occurrence of over-etching pyramids on the sample surface. At 40 minutes of texturing, severe over-etching was observed. However, a marginally higher WAR value of 27.5 % with an absorption curve comparable to the preceding sample with 35 min texturing was obtained.

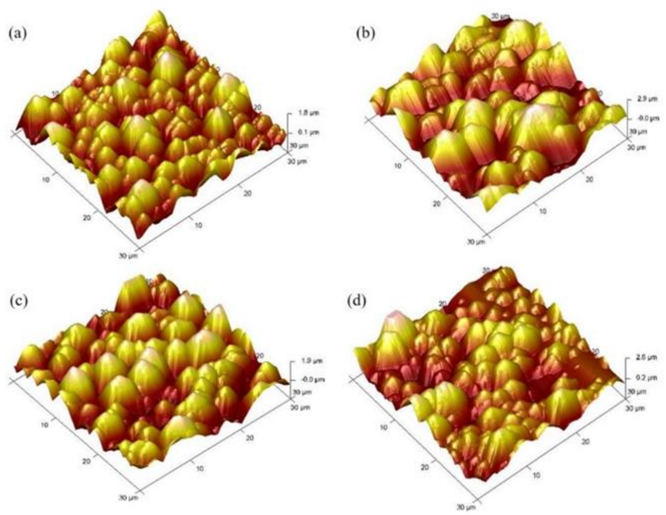

Figure 2. AFM images at etching time of (a) 25 minutes; (b) 30 minutes; (c) 35 minutes; and (d) 40 minutes.

Moreover, a hybrid micro/nano textures of b-Si nanowires on micro-texture pyramids prepared with different sizes by one-step $AgNO_3$-based MACE is shown in Figure. 4. [31]. 80 s of optimized MACE etching was adopted. From the figure, it is seen that for 25 min and 80s textured wafers (Figure. 4 (a) and (b)), non-uniform distributed nanowires on the pyramids as well as on the bare areas of c-Si were observed. For this sample, the appearance of the b-Si nanowires on the pyramids may be due to the etching away of the pyramid apexes and edges because of the smaller nature of the pyramid's size formed by 25 min texturing.The pyramid facets appear to possess less coverage of the nanowires as well. This is also due to the small sized nature of the pyramids owned by this sample which causes nanowires to begin collapsing because of their elongated length on the pyramids after the MACE process. This results in large voids and trenches around the apexes of the micro-pyramids as seen in Figure. 4 (a). B-Si nanowires are seen to finely and completely cover the pyramids for 30 min and 80 s and 35 min and 80 s wafers with ~ 300 nm average length over the side walls and the apexes with around 830 nm average length nm (Figure. 4. C; d; and e; f). This is because, for these samples, the pyramid sizes are optimal with between 3-7 μm and 3-10 μm heights and base widths respectively. For 40 min and 80 s wafers with completely over-etched pyramids, the nanowires (b-Si) seem to start etching down the pyramid's apex like what is seen in the sample with 25 min micro-textured (Figure. 4. g; and h) as similarly reported by Singh et al. [37]. This behavior further affirms the over-etching pyramids (40 min micro-textured).

Generally, the over-etching of the apex and edges seen for samples in Figure. 4 (a) and (b) and Figure. 4 (g) and (h) falls on Ag NPs faster deposition rate at the apex and the edges of the micro pyramids than in their facets and valleys during the one-step $AgNO_3$-based MACE. This represents at these sites, a faster etching rate due to the presence of higher surface free energy (SFE) as reported in the literature [26]. Because of this, electrons in these regions become highly active due to the higher SFE. This will make the Ag+ ions capture additional electrons from these sites and get deposited in a special way, covering firstly the apexes and edges and then other areas on the pyramids during the one-step $AgNO_3$-based MACE.

This preferential Ag^+ deposition at the apexes and edges generally at these regions yields self-selective surface etching of the pyramidal surfaces. As the etching time is prolonged within 0-80 s, the nanowires' depth becomes more pronounced, and differences in etching between the apexes, edges, and facets as well as the valley areas of the pyramid become more significantly dependent on the sizes of the micro-textures. Thus, for small sizes feature micro pyramids (Figure. 4 (a) and Figure. 4 (g)), the apexes and edges are etched away significantly faster compared to facet and valley regions, as reported by other works while studying the effect of $AgNO_3$ concentration on the one-step $AgNO_3$-based MACE process for nanowires formation on micro-textured surfaces [24]. The occurrence information of comprehensive self-assembled redox reactions of nanowire formation during the one-step MACE process on micro pyramids using one-step $AgNO_3$-based MACE can be obtained in the related literatures [26, 38].

Total reflectance and absorption in the percentage of hybrid textures pyramids covered with b-Si nanowires prepared using a one-step $AgNo_3$-based MACE process is shown in Figure. 5. From the figure, the pyramid sizes on c-Si show only a slight effect on the optical absorption of the hybrid micro/nanotextured wafers. In both reflectance and absorption curves aspects, surface reflection suppression (broadband) is achieved. A gradual decrease in the reflection curves (Figure. 5a) was observed from ultraviolet to near-infrared region with 30 min and 80s and 35 min and 80s samples showing the highest decreasing impact. This trend was reflected in the corresponding absorption curves as similarly obtained in the reference planar C-Si samples. Noting that 10.4%, 9.0%, 12.6 %, and 13.0% of calculated WAR values corresponding to 25 min and 80 s, 30 min and 80 s, 35 min and 80 s, and 40 min and 80 s samples were obtained respectively, compared to c-Si planar reference with 40.0% WAR value. A 30 min and 80 s sample textured pyramids with 3-7 μm heights and 3-10 μm base widths exhibited the lowest WAR (9.0%) as well as 92.0 % corresponding to optical absorption at 600 nm.

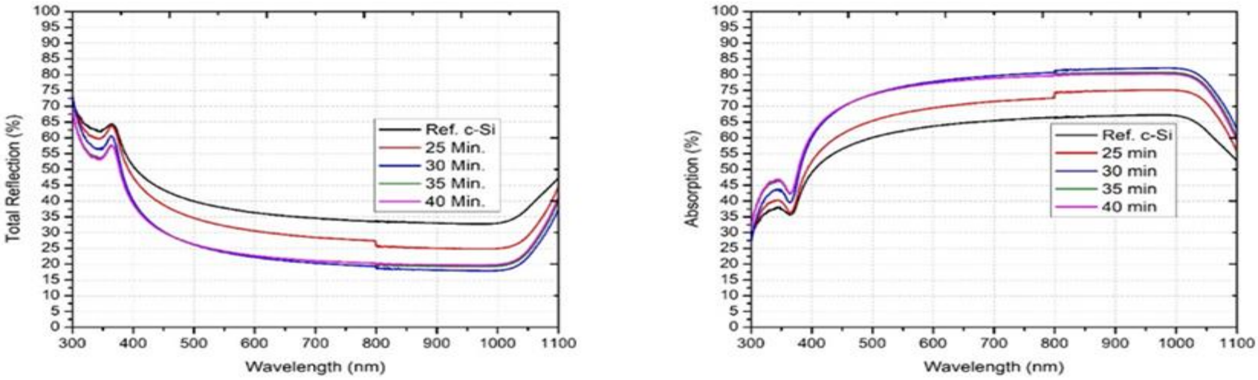

Figure 3. (a) Total reflection in percentage and (b) Absorption in percentage etched wafers at different time durations (25-40 minutes). Planar c-Si is used for comparison (as a reference).

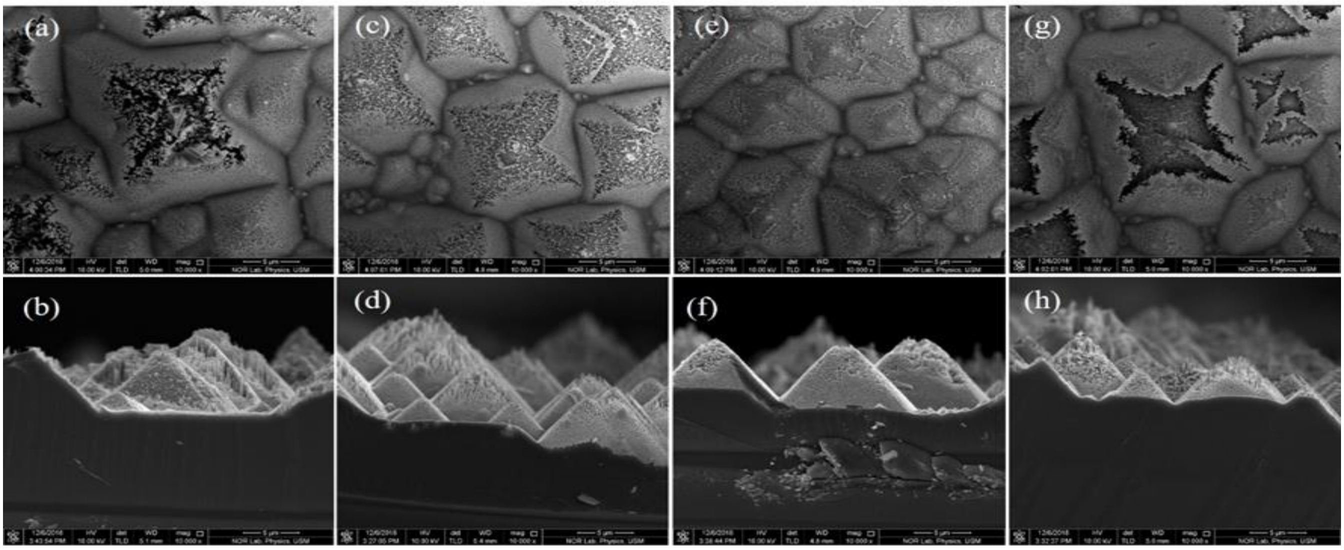

Figure 4. FESEM Images of hybrid textures of NaOH etched (25-40 minutes) and one-step MACE at 80s samples; (a), and (b) 25 minutes; (c), and (d) 30 minutes; (e), and (f) 35 minutes and (g), and (h) 40 minutes for top view and cross-section view respectively. For the entire images (NaOH etched and one-step MACE samples respectively), a 4 µm length scale bar is adopted.

The NaOH etched samples (35 min and 80 s and 40 min and 80 s) prior to the formation of b-Si nanowires exhibit about 88.0% absorption each at 600 nm wavelength. A minor high surface reflection is obtained in these samples at 300-700 nm with 40 min and 80 s samples showing as well a higher value compared to 30 min and 80 s and 25 min and 80 s samples at 300-400 nm region after the one-step $AgNO_3$-based MACE. It is observed that the enhanced optical absorption can be accredited to combined improvement in light coupling through refractive index grading from b-Si nanowires formation and underlying base pyramids light scattering which is in agreement with FESEM hybrid textures findings [39, 40]. The light trapping mechanism for the hybrid micro/nanotextured surfaces is due to both light scattering and refractive index (n) grading effects as the incident light photons hit the hybrid micro/nanotextured surfaces. As this happens, the light goes via a homogeneous medium with n increasing steadily while traversing from air to b-Si nanowires on top of the pyramids. At the initial stage, no light scattering will be expected since the dimension of the nanostructures is lower than the incident light wavelength. In this regard, suppression of surface reflection will be greatly achieved which in turn enhances the light coupling into the c-Si material [35].

Table 1 presents the calculated maximum potential J_{sc} for micro-textured and hybrid micro/nano-textured respectively. Similarly, enhancement in the maximum potential J_{sc} on micro pyramids after nanowires incorporation is included in the table. The table also captured, the WAR results (shown in bracket) obtained from Figure. 3 and Figure. 5 respectively for reference. 26.3 mA/cm^2 maximum potential J_{sc} was noted for the Flat reference c-Si wafer. For 25 min and 80 s samples, there is an increase of 4.6 mA/cm^2 in maximum potential J_{sc} to 30.9 mA/cm^2 as compared to the reference c-Si maximum potential J_{sc} (26.3 mA/cm^2). The enhancement in maximum potential J_{sc} is attributed to the lower broadband reflection backed by the increased light scattering at the pyramid surface due to enhanced grain size (as indicated by FESEM and AFM results) produced by 25 min etching in NaOH solution. Maximum potential J_{sc} increased to 38.0 mA/cm^2 with the presence of nanowires on the micro pyramids. This indicates a 22.9% improvement or about 7.1 mA/cm^2 increase in the feasible short circuit current density. The improvement is attributed to the enhanced light trapping of incident photons produced by the nanowires. Maximum potential J_{sc} of 34.1 mA/cm^2 at 30 min as well as 33.4 mA/cm^2 at 35 minutes of micro texturing respectively are seen for the microtextured wafers.

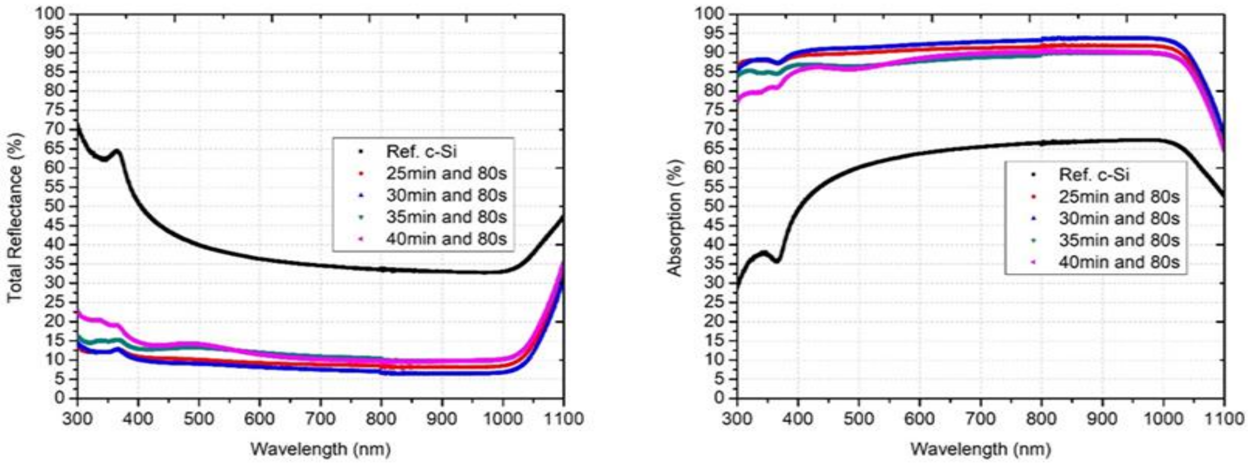

Figure 5. Hybrid textures curves for different NaOH etching time of 25-40 minutes and a fixed optimized 80 s etching (one-step MACE): (a) Reflection and (b) absorption. In both curves, planar c-Si is used as a reference.

With the presence of nanowires on these samples (i.e., 30 min and 80 s and 35 min and 80 s samples), the maximum potential J_{sc} increased for both samples to 38.9 mA/cm^2 and 37.2 mA/cm^2 representing 14.0 % and 11.4% improvement respectively. In this study, the maximum potential J_{sc} for the 30 min and 80 s sample signifies the peak potential photocurrent realized, with WAR of 9.0%, due to the higher broadband optical absorption produced by the hybrid micro/nano-textures on the surface of c-Si. Maximum potential J_{sc} reduces to 33.1 mA/cm^2 for samples with pyramids produced by 40 min of NaOH texturing.

Table 1 Maximum potential J_{sc} (calculated) of pyramid micro-textured samples at different etching (texturing) durations (25-40 minutes) and hybrid (pyramids and nanowires) realized by one-step MACE. The enhancement in maximum potential J_{sc} is the difference between maximum short circuit potential for pyramids (before) and after hybrid development. Similarly, calculated WAR is captured for all samples (indicated in the bracket).

S/N	Wafer	Pyramids (maximum potential J_{sc}, measured in mA/cm^2 unit)	Pyramids/nanowires (maximum potential J_{sc}, measured in mA/cm^2 unit)	Maximum potential J_{sc} improvement (in percentage)
1	c-Si reference	26.3 (WAR=40.0%)	---------------	--------------
2	25 min and 80 s	30.9 (WAR=34.0%)	38.0 (WAR=10.4%)	22.9
3	30 min and 80 s	34.1 (WAR=27.0%)	38.9 (WAR=9.0%)	14.1
4	35 min and 80 s	33.4 (WAR=27.2%)	37.2 (WAR=12.6%)	11.4
5	40 min and 80 s	33.1 (WAR=27.5%)	37.1 (WAR=13.0%)	12.0

This may be accredited to the over-etching effect as discussed earlier in the FESEM observations. With the presence of nanowires, the calculated maximum potential J_{sc} shows an enhanced value of 37.1 mA/cm^2 (12.0% improvement) compared to only the pyramids sample. Regardless of the realized outstanding enhancement in optical absorption for hybrid micro/nano-textured surfaces, it is worth noting that for practical application in photovoltaics, the challenge is to translate the obtained enhanced optical absorption into good electrical results.

This is because the surface recombination of photogenerated carriers on the surfaces of the textured c-Si remains a serious challenge [41]. This implies a trade-off between electrical and optical results. To overcome this issue excellent deposition of surface passivation layers like aluminum oxide (Al_2O_3) or SiO_2 onto the hybrid micro/nano-textures is required [42-44].

4. CONCLUSION

Hybrid-textured (micro/nano-structures) surfaces were fabricated in this work to improve wideband light absorption in c-Si material for solar cell application. Etching time for 25 minutes, 30 minutes, 35 minutes, and 40 minutes using IPA buffered solution of NaOH have been studied for microscale pyramid fabrication. Nanowires on the pyramids are formed by a one-step $AgNO_3$-based MACE process within 80 s. With 25 min NaOH etching, pyramids with small feature sizes (with some having heights of less than 1 µm) are fabricated on the surface of the c-Si absorber. At 30 min etching time, pyramids with heights and base widths between 3-7 µ m and 3-10 µm respectively are obtained. Similarly, at 35 min of etching, slightly over-etched pyramids are achieved with heights being reduced slightly due to the over-etching. Complete over-etched pyramids are obtained after 40 min of etching. It is noted that c-Si broadband reflection reduces with microscale pyramids formation through improved light scattering when light traverses from air to the micro pyramids on c-Si. As the etching duration increases, the WAR reduces from 40% (reference sample) to about 27.0% for the sample with a 30 minutes etching time. Because of pyramids over-etching, the WAR begins to slightly increase to 27.2% and 27.5% for 35 min and 40 min of NaOH texturing. Furthermore, the one-step Ag-based MACE process that followed after produced b-Si nanowires that are vertically aligned on the micro pyramids. For all the samples, the nanowires exhibited heights in the range of 300-830 nm with 40-50 nm lateral width. The WAR reduces significantly due to the formation of nanowires on the pyramids as observed in entire samples. This is due to the combined improved light trapping and increased light scattering by the nanowires and underlying pyramids respectively. It is noted that broadband light absorption is improved with the presence of both mechanisms. The lowest broadband reflection (9.0% WAR) is demonstrated by 30 min and 80 s samples in this study. Nanowires' presence on the pyramids led to the increased maximum potential J_{sc} to 38.9 mA/cm^2 (the highest potential photocurrent in this study) representing a 14.1% improvement compared to the maximum potential J_{sc} of the sample with pyramids only. The results showed that a hybrid micro/nano-textured surface in a c-Si-based device is a favorable approach to improve broadband light absorption as well as potential photocurrent for application in photovoltaic devices. It is suggested that a more systematic and comprehensive optimization of the parameters for the micro-textured pyramid formation should be considered in future studies.

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