Influence of metal assisted chemical etching time on mesoporous structure in as-cut upgraded metallurgical grade silicon for solar cell application

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Abstract:

In this work, upgraded metallurgical grade silicon (UMG-Si) wafer was used to fabricate mesoporous nanostructures, as an effective antireflection layer for solar photovoltaic cells. The length of the vertical Si nanostructure (SiNS) arrays was altered by varying the etching time during metal assisted chemical etching (MACE) process, using a silver catalyst. The optical, structural, morphological changes and the antireflection properties of Si nanostructures formed on ultra-metallurgical grade silicon wafer were analysed. Morphological studies indicate formation of Si nanocrystals on the vertical nanowires. The pore size depends on the Ag nanoparticle size distribution. All the samples demonstrated a luminescence band centred around 2.2 eV. From the optical results, samples etched for 45 minutes show strong absorption in the visible spectrum. The minimum and maximum surface reflectance in the visible region was observed for 15 minutes and 60 minutes etched SiNS. Based on the observed results, 15 minutes etched Si with a uniform porous structure has minimum reflectance across the entire silicon UV-visible absorption spectrum, making it worth further investigation as a candidate as an antireflection layer in silicon based solar cells.

Keywords: optical studies, mesoporous silicon, Raman spectroscopy, phonon confinement model, metal assisted chemical etching, upgraded metallurgical grade silicon, Photoluminescence

1. Introduction:

Silicon (Si) is the most widely used semiconductor in the field of electronics, energy conversion and energy storage. In addition, Si nanostructures exhibit superior performance in many applications in comparison with their bulk counterpart. Currently, extensive research is focussed on low-cost methods for controllable fabrication of Si nanostructures. Various methods have been developed to fabricate Si nanostructures such as metal-assisted chemical etching (MACE) [1-4] is one of the promising methods because of its simplicity, cost-effectiveness and versatility. Various Si nanostructures, for example, Si nanowires (SiNWs), porous Si, and mesoporous Si, have been successfully fabricated by this method, with specific control over their morphological features [5]. Various Si nanostructures have been fabricated to obtain superior antireflection properties and applied in various functional nanoscale devices such as high-performance solar photovoltaic (PV) cells [6], high-sensitivity sensors [7] and surface emitting devices [8]. Anti-reflection (AR) technology is an excellent method, which have been widely used to reduce reflection property of the surface of PV devices [9]. Furthermore, AR technology exhibits robust mechanical stability, especially when the device is based on silicon etching [10] and the method can enormously suppress the reflection losses over a long range of wavelengths by gradually changing refractive indices moving from that of the incident medium to that of the substrate [11]. Unfortunately, the fabrication of low-cost and large-scale anti-reflection structures is challenging. Importantly, nanostructures that enhance the optical properties also introduce new recombination channels causing severe deterioration in the electrical performance, which outweighs the gain in optics [12]. In recent years, Si nanostructured arrays with a shorter dimension according to the wavelength of visible light and recombination mechanisms in high-surface-area nanostructures have been intensively investigated. Si nanostructures, which exhibit better light trapping effects and a high photoelectric conversion, are successfully applied to many functional nanoscale devices [13, 14]. Oh et al., demonstrated 18.2 % efficient nanostructured ‘black-silicon’ cell without AR coating layer(s), while conventional solar cells normally require AR coatings to achieve similar efficiency levels [15]. Savin et al. demonstrated efficiencies above 22% with an interdigitated back-contacted Si solar cell, where carrier transport is very sensitive to front surface passivation [16]. These latter results were obtained with cryogenic reactive ion etching, which is more challenging to scale-up to the manufacturing level [17] as compared to MACE.

Importantly, the PV industry is targeting continuing cost-reduction of PV modules. Upgraded metallurgical grade (UMG) silicon is an alternative method of producing low-cost solar grade silicon by means of directional solidification [18]. Whereas, traditional purification processes which produce solar-grade silicon via the Siemens process result in higher purity, but a relatively more expensive product. A solar cell efficiency of 19.8 % was demonstrated utilizing 40% polycrystalline UMG-Silicon against 19.5 % utilizing 100% polycrystalline commercial Si under similar solar cell fabrication processes [19]. To target higher performances observed with dry etching while using the less expensive MACE process, here we report on a systematic study of mesoporous structure formation in upgraded metallurgical grade (UMG) silicon wafers for antireflection coatings towards solar cell applications. Specifically, the length of the vertical Si nanostructure arrays is altered by varying the etching time to analysis the optical, structural, morphological changes and the antireflection properties of Si nanostructures formed on UMG silicon wafer.

2. Materials and method:

Unpolished p-type upgraded metallurgical grade (UMG) 500 μm thick silicon wafers (100) with 1-10 $\Omega\text{-cm}$ resistivity (Elkem Solar) were used. As-received silicon wafers were cut into 1 cm x 1 cm squares, then standard chemical polishing (CP5) [20] was performed at room temperature with a 2:10:5 volume ratio of hydrogen fluoride, nitric acid and acetic acid ($\text{HF}(40\%):\text{HNO}_3(69\%):\text{CH}_3\text{COOH}(99\%)$) mixture for 20 mins. The CP5 polished UMG Si wafer was used as reference for all measurements. Then, wafers were subjected to piranha solution of sulphuric acid and hydrogen peroxide ($\text{H}_2\text{SO}_4(98\%):\text{H}_2\text{O}_2(50\%)$) in a volume ratio of 3:1 at 0°C for 10 minutes. Before the etching process, the oxide layer was removed by dipping the sample in diluted hydrogen fluoride solution with the volume ratio of ($\text{H}_2\text{O}:\text{HF}$) 10:1 for 3 min. at room temperature. Then silver nanoparticles (Ag NPs) were deposited on the freshly cleaned Si wafers by immersing in a 3.6 ml of HF with 28mg of silver nitrate (AgNO_3) aqueous solution (60 ml) for one minute. Excess Ag^+ ions on the surface were washed away using distilled water, then samples were immersed in etching solution comprises 3.6 ml of HF in 20 ml of H_2O and 0.6 ml of H_2O_2 for different etching time 15 min., 30 min., 45 min., 60 min. and 75 mins. The residual Ag NPs on the sample surface and in the pores of the Si were removed by immersing the samples in diluted nitric acid ($\text{H}_2\text{O}:\text{HNO}_3$) (3:1) for 60 minutes. Finally, the prepared samples were washed with distilled water and dried in nitrogen (N_2).

The resultant samples were characterized using scanning electron microscopy (SEM) VEGA TESCAN 3 model with tungsten filament to analyse the morphology of the silicon surface. Micro-Raman spectra were recorded at room temperature using a HORIBA Jobin Yvon LabRam HR 800 spectrometer with a thermo-electrically cooled charge coupled detector (CCD) with a spectral resolution was 0.3 cm^{-1} . Calibration was performed using the 521 cm^{-1} band of a pure Si wafer. A 17 mW He-Ne laser (633 nm) focused with a 100X objective to a $1\text{ }\mu\text{m}$ spot diameter was used to excite the silicon. The Raman scattering spectra of silicon/quartz were measured from 200 to 800 cm^{-1} wavenumbers. All the measurements were performed in the geometry of back scattering. The photoluminescence properties of the silicon nanostructures were measured in a range from 350 nm to 1000 nm using an Ocean Optics USB 4000-VIS-NIR detector and 375 nm laser (5 mW) operating in continuous wave (CW) mode as excitation source. Diffuse reflectance spectra (DRS) was measured with coaxial fibre optics cable with incidence/reflected angle of 45 degrees normal to the sample surface, in a range from 220 to 890 nm using an Ocean Optics USB 4000-UV-VIS detector and balanced deuterium- halogen light source (HP-2000-BAL Ocean Optics). Finally, the diffuse and specular reflectance properties of the silicon nanostructures were measured in a range from 200 nm to 800 nm using an integrating sphere with 8° incidence angle (JASCO V-650 UV-VIS spectrophotometer) for anti-reflection coating properties.

3. Result and Discussion:

3.1 Structural properties of Ag nanoparticles (AgNPs)

Graded mesoporous Si nanostructures has reduced recombination losses compared to Si nanowires (SiNWs) [12]. Based on our earlier work, optimized conditions were utilized to obtain mesoporous Si, more detail on the effect of silver loading on the nanostructure morphology can be found elsewhere [21]. Figure 1(a) shows the morphology and surface coverage of Ag nanoparticles (AgNPs) on CP5 polished-reference sample. The white spots on the SEM image are AgNPs randomly distributed on the silicon surface; only isolated Ag islands with irregular shapes are present. For comparison, morphology of electrochemically deposited AgNPs on as-received UMG silicon wafer under similar conditions is shown in Fig. 1(b).

Fig. 1: Morphology of AgNPs deposited on the surface of (a) CP5 polished and (b) as-received UMG silicon wafer

3.2. Structural properties of Si nanostructures:

Figures 2 and 3 show the top view and cross section of the porous silicon sample with different etching time by MACE process. Considering the top-view image of mesoporous Si layer in Fig. 2 (a), different pore sizes (represented by black spots/regions) were observed for 15 min. sample. Since Ag metal acts as the catalyst and reactive site for the etching of Si, smaller pores with random arrangement of larger pores are observed correlating to the size of the AgNP islands on the surface (see Fig. 1(a)). Increase in the etching time widens the pore size resulting in mesoporous Si nanostructures. The surface morphologies of the mesoporous Si layers in Figs. 2(b)-(e) have similar shapes and only the pore diameters were increased and the pore walls were widened, which led to the decreased observation of black spots/regions, in other terms, decreased number of pores on the Si surface. The surface particle density decreases and accordingly the surface porosity increases significantly from 54% to 84% upon increasing the etching time from 15 min. to 75 min., estimated from image analysis with imageJ software. The Si nanostructure arrays of different heights can be obtained by controlling the etching times

Fig. 2: Top view of the SEM image of the porous silicon samples of different etching time a) 15 min., b) 30 min., c) 45 min., d) 60 min. and e) 75 min.

Figure 3 shows SEM cross-section of the mesoporous Si layers at different etching time. The 11 μm to 30 μm thick mesoporous Si layer can be easily distinguished for different etching times from 15 min. to 75 min. It can be observed that, in all the samples the MACE process has created vertical nanostructures. However, porous/defect structures were also formed on these vertical nanowires. Li et al., investigated the MACE process of metallurgical grade and solar grade silicon wafers and observed formation of porous/defect structures on the vertical nanowires depending on the metal impurity content in the silicon wafer [22]. Importantly, under similar etching conditions, no porous/defect structures on the nanowires were formed utilizing high purity electronic grade Si wafer [23]. In addition, for 45 min. and 60 min. etched samples (Figs. 3c and 3d), extended vertical etched regions can be observed between the mesoporous layer and the bulk Si substrate. Further, increasing the etching time to 75 min. (Fig. 3e) resulted in both vertical and horizontal etched structures between the porous Si layer and the bulk Si. The AgNPs did not sink homogeneously on the silicon surface. Another major obstacle in the etching experiment is the formation of gas bubbles, which interfere with the fabrication of homogeneous porous silicon layers. From the results obtained, we observe that during the MACE process, the Ag catalyst morphology has

significant influence on the formation of porous silicon. The formation of porous Si layers was not uniform because of the non-homogeneous formation of AgNPs on the Si surface. The extended etched regions were formed, where the AgNPs sizes were larger continued the etching process. However, it should be noted that the irregular distribution of the pores could enhance photo conversion.

Fig. 3: Cross section SEM image of the porous silicon samples of different etching time a) 15 min., b) 30 min., c) 45 min., d) 60 min. e) 75 min and f) pore depth with etching time

3.2. Raman Analysis

The intensity of the Raman peak is sensitive to the structure of the crystals; thus, significant information can be obtained from intensity measurements. Generally visible light absorption is reduced in porous silicon compared to crystalline silicon. The formation of pores in silicon is an obvious reason for the increase in light penetration in porous silicon. The Raman spectra of the porous silicon samples of different etching times, prepared from CP5 polished UMG Si wafers are shown in Fig. 4. The spectrum corresponding to the CP5 polished UMG silicon is also plotted as a reference. The Raman scattering intensity enhancement of porous silicon is observed for different etching time. In general, the Raman scattering intensity is proportional to the equilibrium population and inelastic scattering

cross-section of phonons. The peak intensity of the Raman scattering signal from porous silicon is enhanced with the increase of the interaction area [23]. In comparison with the reference crystalline silicon substrate, the porous silicon surface possesses a dramatically different light absorption and scattering properties that could influence the inelastic scattering cross-section of phonon generated. With increasing surface area, the Raman scattering intensity of porous silicon also increases more than that of crystalline silicon.

Fig. 4: Raman Spectra for the porous Si samples of different etching time a) 15 min., b) 30 min., c) 45 min., d) 60 min., and e) 75 min. including CP5 polished UMG Si wafer (ref).

A tendency of decreasing in the peak intensity and peak shift towards lower wavenumber was observed for increasing the etching time from 15 min. to 45 min. Increasing the etching time above 45 min., shifts the peaks towards a higher wavenumber with increase in peak intensity. However, the peak intensity increases for all the etched samples compared to the CP5 polished UMG Si wafer. This effect is due to the quantum confinement of optical phonons in the electronic wave function of the Si nanocrystals [24]. The phonon confinement model may be used to tune the energy of the emitted light in nanoscale optical devices based on the nanoparticle size and shape. When the size of the particle reduces to the nanometer order, the wave function of optical phonons will no longer be a plane wave. The localization of wave function leads to a relaxation in the selection rule of wave vector conservation.

Porous silicon typically forms in a columnar structure on the (100) face of the silicon substrate. This represents a typical two-dimensional quantum confinement. There are silicon nanostructures with a wide distribution of columnar diameters in which the length of the column is not confined. The average size of the confined structures can be determined by the phonon confinement model. For nanocrystals, momentum conservation is no longer valid, since the optical phonons are localized. Importantly, for 45 min. etched sample, a broad peak at 518 cm^{-1} and an asymmetry was observed, while symmetric peaks were observed for all other etched samples. The asymmetry in the peak results from non-uniform pores and the peak shift to lower wavenumber indicates smaller nanoparticles [25]. Based on the result it may be proposed that initial etching conditions results in well-defined pores, which then results in non-uniform distribution of smaller nanoparticles. Further increase in etching time, consumes these smaller particles/structures, which tends to form uniform porous nanostructures.

According to the phonon confinement model [26], the estimated average crystalline size, L , is approximately 40 to 60 nm (see Fig. 5b). Using this phonon confinement model, it was determined that crystallite in porous silicon is found to be mesoporous in nature, whose diameter ranges from 10 to 80 nm [26, 27]. The compressive stress is induced by the lattice mismatch between Si substrate and the base of porous silicon pillars. This could also be due to the numerous lattice mismatches introduced during the fabrication process of porous silicon and the differences in the elastic constant and the thermal expansion coefficients. The characteristic symmetric broadenings of the Raman lines, the phonon peak position, full width at half maximum (FWHM) and peak shift for all porous silicon samples relative to the reference are summarized in Table 1 using Lorentz fit to all the samples is shown in Fig. 6.

Fig. 5: (a) Raman Spectra for the porous silicon samples of different particle size from 10 nm to 60 nm calculated from the phonon confinement model. **(b)** Normalized Raman Spectra for the porous silicon samples for different etching time; including CP5 polished UMG Si wafer as reference and 50 nm particle size simulated peak.

Table 1: Lorentz fit results of porous silicon with different etching times.

Sample	Wavenumber (cm ⁻¹)	Area (a.u)	FWHM (ω)(cm ⁻¹)	$\Delta\omega$ (cm ⁻¹)
Reference	520.8	40218.36	2.83	0
15 min.	520.5	312580.25	3.59	0.76
30 min.	520.3	326399.68	4.42	1.59
45 min.	518.7	349708.19	7.12	4.29
60 min.	519.9	305618.23	4.41	1.58
75 min.	520.2	298946.45	4.39	1.56

Fig. 6: Lorentz fitted Raman spectra for the porous silicon samples of different etching time a) 15 min., b) 30 min., c) 45 min., d) 60 min. and e) 75 min. including CP5 polished UMG Si wafer as Ref.

3.3. Photoluminescence Spectroscopy Analysis:

The photoluminescence (PL) spectra of the mesoporous silicon with different etching times are shown in Fig. 7. The PL spectra can be deconvoluted into three peaks centred

around 550, 590 and 660 nm. Efficient red luminescence, often referred as S-band was first reported from free standing Si quantum wires and attributed to 2-dimensional (2-D) quantum confinement of carriers widening the Si band gap. Later, a weak luminescence band in the blue spectral range (F-band) was observed in aged porous Si and was attributed to Γ - Γ transitions in Si nanocrystals. Similar observations were made in Si oxidized at high temperature, photoanodized Si, etc [28]. Several models have been proposed to understand the efficient luminescence from porous Si. Deleure et.al, calculated the electronic and optical properties of Si crystallites and wires with sizes between 0 and 4.5 nm and found agreement with the photon energies observed in luminescence. However, high PL efficiency of porous Si was attributed to the small probability of finding a non-radiative recombination centre in Si nanocrystallites from radiative decay life time measurements [29]. Wolkin et al., demonstrated that PL can be tuned from 1.5 eV to 3.1 eV when the surface is passivated with Si-H bonds. After oxidation, the blue PL was observed to red- shift by 1 eV and attributed to new electronic states in the band gap of the smaller quantum dots, when a Si-O bond is formed [30].

Fig. 7: Photoluminescence Spectra for the porous Si samples of different etching time a) 15 min., b) 30 min., c) 45 min., d) 60 min., and e) 75 min with simulated peak for 15 min sample

Generally, a PL signature in a semiconductor consists of near-band-edge emission and defects related luminescence. Near-band-edge emission results from recombination between free electrons (holes) with bound holes (electrons), known as free-to bound (FB) transitions. The defects related PL occurs from recombination between (i) electrons bound in donors and holes bound in acceptors, known as DAP, (ii) electrons from conduction band to holes bound in acceptors and (iii) electrons from donors to valance band. Yu et al., discriminated the observed PL band from porous silicon around 3.5 eV as Γ - Γ transition and 1.9 eV as DAP-defect related emission via excitation density-dependent and time-resolved PL [31]. Ghosh et al., fabricated Si nanowires (SiNW) with self-grown Si nanocrystals (SiNC) on their surface by MACE. Combining Raman, PL, X-ray photoelectron spectroscopy (XPS) and TEM analysis, showed that the visible luminescence band at 2.6 eV from quantum size effects in SiNCs and NIR band at 1.6 eV from phonon assisted recombination of intrinsic carriers of the electron–hole plasma (EHP) phase in oxidized SiNWs [27]. SiNCs embedded in silicon oxide (SiO₂) matrix was investigated by de Boer et.al [32]. From PL studies, they identified there dominant processes, (i) blue emission from oxygen-related recombination, (ii) green emission from Γ - Γ transition and (iii) NIR emission from Γ - X excitonic transition. However, the hot PL (Γ - Γ transition) was found to red-shift with decrease in SiNC size, white the excitonic PL (Γ - X transition) blue shifts with decrease in size. Moreover, the hot PL intensity was dependant on excitation intensity.

Table 2: Photoluminescence results of porous silicon with different etching times.

Etching time	Energy (eV)	Wavelength (nm)
15 min	2.26	548.74
	2.10	589.87
	1.91	650.45
30 min	2.23	556.19
	2.05	605.01
	1.87	663.01
45 min	2.22	556.57
	2.09	594.06
	1.93	642.70
60 min	2.29	540.64
	2.15	576.28
	1.99	622.39
75 min	2.30	539.17
	2.16	573.52
	2.00	619.68

In the present work, mesoporous structure consists of vertical nanostructures decorated with SiNCs. The PL signatures at 2.26 eV and 1.91 eV are attributed to the hot PL and the excitonic recombination in SiNCs on vertical nanostructures, while the band at 2 eV is attributed to SiNCs on the surface.

3.4. UV-Vis Spectroscopy Analysis:

Fig. 8: (a) Diffuse reflectance spectra of the porous silicon samples of different with etching time (b) Absorption spectra translated from diffuse reflectance by Kubelka-Munk function $F(R)$ (c) Graphical representation of modified $F(R)$ for direct band gap and (d) Graphical representation of modified $F(R)$ for indirect band gap

Figure 8(a) shows the diffuse reflectance spectra of the mesoporous Si fabricated using different etching time. The absorption coefficient (k) can be related to reflectance (R) by the Kubelka-Munk function (K-M or $F(R)$) [33], given by

$$F(R) = \frac{(1-R)^2}{2R} = \frac{k}{s} \quad (1)$$

Where s is the scattering coefficient. If $s \rightarrow 0$ (no scattering), all the light will be transmitted or absorbed, while $k \rightarrow 0$ (no absorption), all the light will be reflected. The absorption spectra translated from diffuse reflectance using Kubelka-Munk function $F(R)$ is shown in fig. 8(b). The as-cut wafer shows no absorption in the visible region, while the mesoporous structures demonstrate absorption in the visible spectrum. Increasing the etching time from 15 to 45 min blue shifts the absorption spectra, further increasing the etching time red shifts the absorption spectra. The observation correlates with Raman and SEM analysis as the particle size decreases initially with etching time and then increases. The modulation of the absorption spectra is the effect of the quantum size effects. A modified Kubelka–Munk function can be utilized to determine the band gap, E_g of the mesoporous structures. Band gap can be obtained by multiplying the $F(R)$ function by $h\nu$, using the corresponding coefficient (n) associated with an electronic transition as follows; $(F(R) \cdot h\nu)^n$, where $n = 2$ for direct allowed band gap and $n = 0.5$ for indirect band gap transitions [34]. The direct and indirect band gaps of the mesoporous structures are plotted in figs. 8(c) and 8(d).

The anti-reflection properties of the prepared Si mesoporous structures were studied using the total surface reflectance (specular and diffuse) method. Figure 9 shows the reflectance spectra for porous silicon fabricated using different etching time. The measured reflectance of the porous silicon sample varies from 15% in longer wavelengths (800 nm) and gradually decreases to below 5% at shorter wavelengths (200 nm) for a, b and c samples. The reflectance increases further up to 25% for d and e samples near longer wavelength (800 nm). On the other hand, the reference Si surface has reflectance from 35% to 25% in the UV and around 20% to 15 % visible region. The average surface reflectance of the Si substrate in the measured range decreased dramatically from 35% for the reference to less than 5% in the lower wave length region for all samples throughout the UV wavelength range. In the present work, all the etched porous silicon samples exhibit reflectance $<5\%$ in 200–400 nm wavelength. The increase in the reflectance to 25% in 60 min. and 75 min. etched samples compared to the reference sample is attributed to the residual AgNPs at the bottom of the etched surface. Arguably, the increase in reflectance in 45 min. etched sample compared to 15 min. sample is attributed to presence of fraction of AgNPs, which can be removed after prolonged etching diluted nitric acid ($H_2O:HNO_3$) (3:1).

Fig. 9: Reflectance spectra of the porous silicon samples of different etching time a) 15 min., b) 30 min., c) 45 min., d) 60 min. and e) 75 min. including as-cut UMG Si wafer (Ref) without CP5 polishing.

These results are promising compared to those in MACE studies showing a nanostructured diamond wire sawn single crystal and microcrystalline silicon solar cells, which did not obtain as low reflectance, but did go on to produce photovoltaic (PV) cells of 18.7% and 19.4% efficiency, respectively [35]. Future work is needed further optimize the MACE procedure used in this work and fabricate passivated layers for completed PV devices.

4. Conclusions:

The surface and cross-sectional morphological properties of Si nanostructures (SiNS) fabricated by metal assisted chemical etching results in formation of mesoporous nanostructure. The surface pore size depends on the silver nanoparticle size distribution and etching time. The depth of the SiNS increases monotonically from 11 to 30 microns with increasing etching time from 15 min. to 75 min., as revealed by cross sectional SEM images. In addition, porous/defect structures were formed on the vertical nanowires. The average crystalline size of the SiNS was found to vary from 40 nm to 60 nm from Raman analysis.

Raman studies also indicate formation of uniform porous structure except for 45 minute etched sample, which exhibits non-uniform mesoporous structure with crystallite size ranging from 10 to 80 nm. All the samples, show luminescence band around 2.2 eV. Three dominant PL peaks were identified originating from SiNC from the surface and SiNC decorated on vertical nanostructures. From the optical analysis, 45 mins etched sample demonstrated strong absorption in the visible spectrum, while all other samples demonstrate absorption near the yellow-red spectral region. The minimum and maximum surface reflectance in the visible region was observed for 15 min. and 60 min. etched SiNS, respectively. Based on the observed results, 15 min. etched sample exhibit the minimum reflectance across the entire UV-visible region. However, 45 min. etched Si with non-uniform mesoporous structure containing residual AgNPs exhibit minimum reflectance in 200 -500 nm spectral region; upon removing the residual AgNPs, 45 min. etched sample can be a viable candidate as an antireflection layer in silicon based solar cells. MACE is a simple and low-cost approach to enhancing the absorption properties of Si and improves the solar cell efficiencies.

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