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Citation: Journal of Applied Physics 116, 113503 (2014); doi: 10.1063/1.4895694
View online: http://dx.doi.org/10.1063/1.4895694
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/116/11?ver=pdfcov
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Suppressing light reflection from polycrystalline silicon thin films through surface texturing and silver nanostructures

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(Received 30 July 2014; accepted 3 September 2014; published online 17 September 2014)

This work demonstrates a novel method combining ion implantation and silver nanostructures for suppressing light reflection from polycrystalline silicon thin films. Samples were implanted with 20-keV hydrogen ions to a dose of 10\textsuperscript{17} /cm\textsuperscript{2}, and some of them received an additional argon ion implant to a dose of 5 \times 10\textsuperscript{15} /cm\textsuperscript{2} at an energy between 30 and 300 keV. Compared to the case with a single H implant, the processing involved both H and Ar implants and post-implantation annealing has created a much higher degree of surface texturing, leading to a more dramatic reduction of light reflection from polycrystalline Si films over a broadband range between 300 and 1200 nm, e.g., optical reflection from the air/Si interface in the AM1.5 sunlight condition decreasing from \sim 30\% with an untextured surface to below 5\% for a highly textured surface after post-implantation annealing at 1000 °C. Formation of Ag nanostructures on these ion beam processed surfaces further reduces light reflection, and surface texturing is expected to have the benefit of diminishing light absorption losses within large-size (>100 nm) Ag nanoparticles, yielding an increased light trapping efficiency within Si as opposed to the case with Ag nanostructures on a smooth surface. A discussion of the effects of surface textures and Ag nanoparticles on light trapping within Si thin films is also presented with the aid of computer simulations. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4895694]

I. INTRODUCTION

With the growing demand for affordable solar energy, low-cost polycrystalline silicon (poly-Si) is being increasingly used for fabrication of solar cells. To further lower the cost of solar cells, the thickness of Si cells should be as small as possible. According to theory,\textsuperscript{1–3} a Si thickness of 10–20 \textmu m is sufficient for achieving the typical high cell efficiency, provided the illuminated sunlight is fully absorbed within such thin-film Si cells. Unfortunately, Si materials are not a good light absorber and the Si thickness required for optical absorption in the low-energy portion of the solar spectrum, e.g., photon energy close to the Si band gap value, is typically beyond tens of microns. Therefore, the particular issue related to light trapping within Si cells becomes extremely important as Si thin films of thickness approaching tens of microns are adopted in photovoltaic actions.

An antireflection coating like a quarter-wavelength thin film alone on a planar Si surface cannot ensure the required high absorbance of light within the cells, since such optical thin films rely on optical interference to suppress light reflection from the Si surface, and are only effective for a narrow range of the solar spectrum and illuminating angles.\textsuperscript{4} Antireflection can be also achieved by depositing multi-layer structures of graded refractive index. This sophisticated materials processing is normally constrained by the selection of deposited materials of a desired refractive index, compounded with problems of increased optical absorption within the deposited materials.\textsuperscript{5} Surface texturing prior to antireflection coating is crucial to enhance light trapping in Si cells, particularly when the cell thickness needs to decrease in the range of a few tens of microns. In the case of single-crystal Si, surface texturing is normally realized by taking advantage of the anisotropic etching of Si crystalline planes in a chemical solution.\textsuperscript{6–8} This well-established anisotropic etching scheme is not applicable for surface texturing of poly-Si due to the presence of crystallites with various orientations. Furthermore, surface texturing via chemical etching requires the removal of the material by a thickness approaching \sim 10 \textmu m to be effective for light trapping, which is unacceptable in the case of a thin film with comparable thickness.\textsuperscript{2} Si surface texturing is possible with other techniques based on reactive ion bombardment or ultrafast laser irradiation. Light trapping within thin films can also be achieved by forming periodic gratings and back reflectors.\textsuperscript{9,10} But these methods require multiple materials processing steps involving lithography, masking, and thin film deposition, which are neither adequate for large-volume production nor economically viable.

On the other hand, the method based on the formation of noble metal nanoparticles on the surface for enhanced light trapping has gained much attention in recent years. These metal nanoparticles are believed to act as scattering centers increasing forward scattering of illuminated light into the solar cell material\textsuperscript{11} particularly for light with energy matching the surface plasmon energy of those nanoparticles. The surface plasmon energy is strongly influenced by the nanoparticle geometries (size, shape, and density), which are dictated by material deposition and post-deposition processing.
conditions. So metal nanoparticles formed at a certain growth condition may decrease light reflection from the material only in a limited range of the solar spectrum.

Our group has recently developed an approach using co-implantation of hydrogen and argon ions followed by thermal annealing to create textured surface structures in single-crystal Si. The approach can reduce the reflectance of Si over a broad spectral range to below 5%,12 and equally importantly, the resultant texture structures are only in the submicron range. Due to the advantage of ion implantation in scalable device fabrication, our research may help develop innovative manufacturing methods for high-volume production and processing of Si solar cells. In this work, we evaluate the applicability of this method to produce highly textured surfaces in poly-Si thin films for suppressed light reflection. Our results indicate that co-implantation of H and Ar in conjunction with thermal annealing can create a high density of textured surface structures in poly-Si thin films, limiting light reflection from the air/Si interface below ~5% following annealing at 1100 °C, a factor of four reduction in light reflection as opposed to the unprocessed poly-Si film. Our work also shows that deposition of an Ag thin film on such textured surfaces results in lower light reflection and smaller-size Ag nanostructures as opposed to the case with a flat untextured surface. In addition, we have performed computer simulations to aid in our understanding of the effects of surface textures and Ag nanostructures on light trapping within poly-Si films.

II. EXPERIMENTS

The poly-Si thin films used for this work were prepared by solid phase crystallization (SPC) of a 1.6-μm thick amorphous silicon (a-Si) layer, deposited via electron beam evaporation on a Si substrate with 1.0-μm SiO2 on the top, at a substrate temperature of 200 °C. This SPC process is known to result in a typical grain size of 1–2 μm in the films.13 Figure 1 shows the x-ray diffraction (XRD) (Scintag XDS 2000) scans of the poly-Si films grown after annealing the amorphous layer at various temperatures between 600 and 1050 °C for 48 h in nitrogen ambient. The XRD curve for the a-Si sample is featureless, and after annealing, four main peaks appear, corresponding to diffraction from the (111), (220), (311), and (400) silicon crystallographic planes, respectively. The SPC material tends to show a (111) preferential orientation, which has been attributed to the anisotropic crystallization.14 The full width at half maximum (FWHM) for the (111) peak decreases with increasing temperatures (inset Fig. 1), implying an increase in grain size with temperature.

These poly-Si samples were divided into two groups, one implanted with 20-keV hydrogen ions to a dose of 10¹⁷/cm², and the other receiving an additional implant with 90-keV argon ions to a dose of 5 × 10¹⁵/cm². According to TRIM (Transport of Ions in Matter), the ion peak range is ~270 nm for 20-keV H ions and ~100 nm for 90-keV Ar ions in Si. The implanted samples were annealed in Ar ambient in the temperature range of 400–1100 °C for 1 h. Following such materials processing, the surface morphologies of the poly-Si films were imaged using an optical microscope (Wild Heerbrugg Switzerland model M20–68544), and the optical reflectance from the samples were measured over the wavelength range 400–1100 nm at normal incidence with an UV/Vis spectrometer (Ocean Optics).

Silver nanoparticles were formed on the flat or textured surface via the thermal dewetting method. An Ag thin film of nominal thickness 20 nm was first deposited on the poly-Si surface via e-beam evaporation, and thermal annealing was performed at 200 °C and 300 °C for 60 min in nitrogen ambient. Finally, secondary electron microscopy (SEM) was employed to evaluate the size and density of the resultant Ag nanostructures.

III. RESULTS AND DISCUSSION

A. Surface texturing by ion implantation

Surface blistering in H-implanted single-crystal Si is a well-known phenomenon.15,16 With a large H concentration present in Si, H platelets are formed and act as the nucleation sites for the generation of gaseous H2 during thermal annealing, which could result in cracking or removal of Si materials as a result of an internal pressure buildup. Figure 2 shows the optical microscope images for the poly-Si samples following post-implantation annealing. The number of blisters/craters is determined by taking average of three regions of 20 × 20 μm² size for each post-implantation temperature. For the samples implanted with H only, micron-sized surface blisters at a density of ~10⁶–10⁷/cm² start to appear as the annealing temperature rises above 700 °C, while for the samples co-implanted with H and Ar, surface blistering occurs even at a temperature as low as 400 °C. The dual implants also result in a higher density and a smaller size of surface blisters, compared to the case with only the H implant. Similar behaviors have been observed for single-crystal Si;12 and we believe that the same mechanism is also operative in poly-Si. The marked differences in surface morphology between the H-only implant and the H + Ar implant may reflect differences in the density and distribution of defects created in these two situations. For the latter, there exist a large number of structural defects, which could readily trap
H atoms to form a high density of small H platelets, leading to densely packed surface structures. In contrast, for the samples implanted with H only, the number of H platelets is much smaller due to a smaller number of defects available for H trapping; and on the average, each H platelet should contain more H atoms and thus have a larger size. Upon annealing, these large platelets would rapidly expand and even coalesce with neighboring platelets, yielding well separated surface structures of a small density.

The degree of surface texturing increases with post-implantation annealing temperatures. Following the 1100°C anneal, a large portion of the poly-Si films receiving only H implant are found to exfoliate, but the poly-Si films with dual implants are highly textured in the surface without a significant rupture in the films. It is interesting to notice that the density of surface textures also depends on the annealing temperatures for solid phase crystallization of a-Si. Particularly, the poly-Si sample prepared by SPC at 600°C shows the highest density of textured structures, being a factor of ~2–8 as opposed to those poly-Si films grown at higher temperatures. At low SPC temperatures, the grain size is small but the crystalline grain density increases. Our observation implies that H induced exfoliation of poly-Si may occur within individual crystallites.

The additional implantation of 90 keV Ar ion is believed to produce an amorphous layer extending from the surface to the H-implanted layer, which helps shift the location of maximum stress to a depth below the H-implanted region. As a consequence, eruption of Si occurs at a depth beyond the projected range of implanted H ions (~270 nm), resulting in deep texture structures in the surface. In addition, the Ar implantation creates more defects for H trapping, yielding a higher density of textured structures. We have examined the effects of implanted Ar ion energy on the formation of surface textured structures. By varying the energy for Ar ions, we have produced different a-Si layers with thickness either much less or larger than the implanted H ion range, but these Ar implants do not yield the desired surface textures as seen above. This is because the location for the maximum stress is too close to the surface in the case of lower Ar ion energies, or the resultant amorphous Si layer is too thick containing the entire profile of implanted H ions and inhibiting the growth of H platelets large enough for accumulation of molecular hydrogen, in the case of higher Ar ion energies.

B. Optical reflection of textured surfaces

Figure 3 shows the examples of light reflection as a function of wavelengths from ion beam processed poly-Si samples. The oscillatory features in the spectra are caused by optical interference of the multilayer stack of p-Si/SiO2/Si, as confirmed by our computer simulations. From these reflectance data, we have calculated the integrated reflectivity (Figure 4) in the standard air mass 1.5 (AM1.5) sunlight condition by weighing the photon flux over the corresponding solar spectrum. The unprocessed, smooth poly-Si samples are

FIG. 2. (a) Optical microscope images of surface morphologies at post-implantation annealing temperatures (1000 and 1100°C) for two poly-Si samples grown at SPC temperatures 600 and 1050°C, respectively. The scale bars on the images are equivalent to 10 μm. Top images: H ion implantation only; Bottom images: H and Ar ion implantation; (b) Surface texture density as functions of post-implantation annealing temperatures for poly-Si samples prepared at various SPC temperatures.

FIG. 3. Optical reflectance spectra for poly-Si samples implanted with (a) H ions only; and (b) both H and Ar ions at different post implantation annealing (texturing) temperatures. The reflectivity is measured with respect to a Si control.
highly reflective with the standard 1.5 AM reflectance \(\sim 36\%-42\%\), slightly varying with the SPC temperatures and/or surface conditions. The poly-Si samples implanted with only H ions do not show any reduction in light reflection until the post-implantation annealing temperature is raised to 1100°C, where the reflectivity decreases to \(\sim 20\%\), about half of that for the untextured films.

The optical reflectance spectra for the poly-Si implanted with both H and Ar ions are much different even at low post-implantation annealing temperatures (400–600°C). Compared to the unprocessed poly-Si control, there is a shift in the wavelength position for optical interference, which seems to increase with the degree of surface texturing (or post-implantation annealing temperatures). Such shift in wavelength positions may reflect the phase difference incurred as the incident light bounces between facets of textured structures on its way into the sample. With a highly textured surface, light would be reflected between textured structures many times, increasing its travel distance before entering into the sample bulk and thus possessing a large phase shift.

The optical reflectivity values for these surface-textured samples decrease with increasing post-implantation annealing temperatures, and reach the minimum values of \(\sim 10\%\). It should be pointed out that our optical reflection measurements include the contributions of light reflection from several interfaces between air and poly-Si, between poly-Si and SiO\(_2\), and between SiO\(_2\) and Si. The textured poly-Si surface layer could be considered as a graded-index layer where the refractive index gradually increase from 1.0 at the top to 3.5 (refractive index for poly-Si) at the bottom of the textured layer. For simplicity, one may assume replacing the textured surface with a single smooth ultrathin layer of an effective refractive index that would yield the same level of light reflection from the textured surface. Based on this model and our data, we can estimate the reflection coefficient \(R_1\) at the air/poly-Si interface after applying the Fresnel equation to determine the reflection/transmission coefficients at the poly-Si/SiO\(_2\) and SiO\(_2\)/Si interfaces, as shown in Fig. 5. Therefore, the measured minimum reflectivity value of \(\sim 10\%\) indicates that the optical reflectivity at the air/poly-Si interface is below \(5\%\). This low level of light reflection is comparable to the results achieved either relying on metal nanoparticle masking and chemical wet etching (\(\sim 3\%\) reflectivity),\(^17\) or based on reactive ion etching (\(\sim 2\%\) reflection)\(^18\) to form texture structures in poly-Si surfaces.

The optical reflection data are indeed found to correlate with the density of textured structures created in the sample surfaces. Co-implantation of H and Ar ions, followed by annealing at high temperatures, can produce a high density of textured surface structures, e.g., \(\sim 10^7/cm^2\) following post-implantation at 1100°C, thus being more effective in suppressing light reflection from the poly-Si surfaces than the case of single H implantation. As mentioned above, the formation of surface textured structures in the samples with dual implants is strongly influenced by the Ar ion energy, which determines the location of maximum stress in Si. If this location is too much shallower or deeper than the H-implanted region, surface textured structures with large heights, do not appear in a good quantity. Consequently, such surfaces are not effective in suppressing light reflection, as confirmed by the light reflection measurements from the H and Ar co-implanted samples with an Ar ion energy too lower or higher than 90 keV.

C. Formation of Ag nanostructures on textured surfaces

Here, we compare the formation of silver nanostructures on ion implantation textured surfaces and untextured flat surfaces, as well as their respective effects on light reflection. As shown in Figure 6, the morphologies of the resultant Ag nanostructures could be different between the cases with a textured or untextured flat surface, even though the conditions for metal deposition and post-deposition annealing are the same. For annealing at 200°C after deposition, the surface pre-texturing leads to the formation of Ag nanostructures with a larger size (average area: \(\sim 1.6 \times 10^5\) nm\(^2\)) and a density (\(\sim 2.7 \times 10^9/cm^2\)) as opposed to the case starting with an untextured surface (average area: \(\sim 6.2 \times 10^4\) nm\(^2\); density: \(\sim 3.6 \times 10^5/cm^2\)). As the post-deposition annealing

![Fig. 4](image1.png)

**Fig. 4.** Integrated reflectance for poly-Si samples over the 1.5AM spectrum for different post-implantation annealing temperatures. Also included are the 1.5AM reflectance data for the cases with an Ag thin film deposited on the textured/untextured poly-Si surfaces and annealed. The data for the cases with an untextured surface correspond to those of the texturing temperature 300°C.

![Fig. 5](image2.png)

**Fig. 5.** Schematic for the multilayer sample structure used to estimate the reflectivity at the air-poly-Si interface. The arrows indicate the reflected and transmitted light beams at each interface and the symbols \(R\) and \(T\) represent the reflection and transmission coefficients, respectively.
However, the effects of surface texturing become much weaker at 300 °C. Ag nanostructures of a relatively large size.

Implantation also creates structural defects in the poly-Si surface. Ion implantation also creates structural defects in the poly-Si surface, which are distorted or dangling bonds typically acting as trapping sites for atomic diffusion, consequently leading to a smaller mobility of Ag atoms on the surface and thus the formation of Ag nanostructures of a relatively large size. However, the effects of surface texturing become much weaker at 300 °C, due to greatly enhanced diffusion of Ag atoms and partially recovery of surface structures at such temperature.

D. Effects of Ag nanostructures on optical reflection

Fig. 7 shows the effects of Ag nanostructures on optical reflectance from the untextured control and poly-Si samples with varied levels of texturing, achieved by H and Ar co-implantation followed by annealing. The oscillatory features remain in the reflectance spectra for the sample with Ag nanostructures, and a slight shift in the wavelength positions for constructive/destructive optical interference is detected, which we conjecture is caused by a possible phase shift as the incident light scatters off the Ag nanostructures. More noticeable is the change in the reflected light intensity. For the untextured surface, the as-deposited Ag thin film behaves like a good optical mirror, causing a dramatic increase in light reflection by a factor of ~3. After annealing the film at 200 °C, the light reflectivity drops by a factor of ~1.5, but is still above the level without Ag thin film deposition. Once the post-deposition annealing temperature is raised to 300 °C, the light reflectivity becomes much lower than before, e.g., only a half of the original values over the wavelength range of 450–600 nm.

This characteristic can be correlated with the morphology of Ag structures resulting from different post-deposition annealing temperatures. At 200 °C, the deposited Ag film is ruptured at various locations due to the dewetting process, resulting in a network of large domains, which possess bulk-like characteristics when interacting with light. Bulk silver has a plasmon energy 3.78 eV (≈328 nm) and is thus highly reflective for light with energy smaller than this plasmon energy. This explains why light reflection from the surface is increased after annealing the deposited Ag film at 200 °C. In contrast, the 300 °C anneal coverts the deposited Ag film to an array of well separated nanoscale Ag islands. Due to the size constrain of these Ag nanostructures, bulk-like characteristics are lost during their interaction with light. The surface plasmon energy for a spherical Ag nanoparticle of 150 nm radius in air is estimated to be around 2.75 eV (450 nm wavelength) and would be red-shifted if being
placed on a material surface. Additionally, when factoring in the contribution of multipoles which have energies typically higher than the surface plasmon energy for electric dipoles, it seems reasonable to expect a significant reduction of light reflection over a broad spectrum for wavelength above 450 nm, as seen in our reflectance spectra.

Similar effects of post-Ag-deposition temperature on optical reflection have been observed for the samples with pre-textured surfaces. Ag nanoparticles grown by annealing the deposited Ag film at 200°C, light reflection from the sample increases by a factor of ~30%–100%. The situation is reversed for those Ag nanostructures formed by post-deposition annealing at 300°C, i.e., a decrease by a factor two in light reflectivity in the wavelength range between 450 and 700 nm. But depending on the level of texturing and the initial poly-Si grain size, both two post-deposition annealing temperatures can decrease the light reflectivity below the level corresponding to the case without Ag deposition. This implies that there could be an intricate interplay among Si grain structures, ion beam processing, and post-metal-deposition annealing in the formation of Ag nanostructures on poly-Si surfaces.

The AM1.5 reflectivity data for the samples with Ag nanostructures formed in different surface conditions are included in Fig. 4. Forming Ag nanostructures on a pre-textured surface has yielded lower light reflection than the case with Ag nanostructures on a flat untextured surface. However, for post-Ag-deposition annealing at 300°C, the amount of reduction in light reflection induced by Ag nanostructures, relative to the respective samples without Ag deposition, is found to be comparable in both situations. A comparable level of reduction in light reflection suggests that the total areas covered by Ag nanostructures in both situations should be similar to each other. This is indeed confirmed by our SEM observations, for example, the average filling factor of Ag nanostructures on a flat or a textured surface being ~30%. The weakening or lack of Ag nanostructure effects on light reflection is observed for highly textured surfaces, i.e., formed at a post-implantation temperature greater than 900°C. This is because the highly textured surfaces in our samples may have satisfied the Lambertian reflection condition, and further scattering off the Ag nanoparticles is of little importance, statistically speaking, in affecting the pathways of the incident light before it enters into the poly-Si bulk.

E. Computer simulations

Computer simulations based on the finite difference time domain (FDTD) method have been conducted to help better understand the effects of surface textures and Ag nanostructures on optical reflection from poly-Si. The Lorentz-Drude model is used for the optical constant of silver, and a constant index of 3.45 over the detected wavelength range is assumed for poly-Si.

Our simulation results (Fig. 8) show an overall decrease in the light reflection over the entire solar spectrum once the poly-Si surface is textured. For example, a density of ~3 × 10^9/cm^2 of hemisphere-like surface textures of 0.5–0.65 μm in size yields a reduction of light reflection or an increase of light transmission within Si, both on the level ~10%–15% in the entire simulated spectral range (300–1450 nm wavelength). In our highly textured samples, the light reflection decreases by more than a factor of two with the texture density less than ~10^7 textures per cm^2 surface area. This quantitative difference in light reflection between our experimental observations and simulation results may arise from a lack of the knowledge about the geometry of textured surfaces in our poly-Si samples. Compared to the experiment, the simulated reflectance curve exhibits a smaller numbers of interference fringes. This results from our choice of a very thin Si layer in the simulation in order to reduce the computing time.

Adding Ag nanoparticles on top of a poly-Si surface can have different results, depending on the number/size of

![Fig. 8. Computer simulation showing the light reflectance and transmission spectra for thin-film Si with smooth and textured surfaces. Also included are the simulated spectra for Si with Ag nanoparticles (high density: ~5 × 10^9/cm^2; low density: ~2.5 × 10^9/cm^2) on a textured surface. A schematic for the sample structure in simulation is shown on the right hand side.](image-url)
nanoparticles. At a large density (>5 × 10^9/cm^2) of Ag particles of size 150–250 nm randomly dispersed on the Si surface, light reflection from such sample is much greater than that without any Ag. Size dependent effects manifest themselves as the Ag particle density is lowered. For example, with a density of ~2.5 × 10^9/cm^2 Ag particles with 150–250 nm radius on a poly-Si surface, light reflection decreases below the level for the original Si, particularly in the long wavelength range, e.g., at 1.0 μm, R ~ 25% for Ag particles on Si and R ~ 33% for Si without Ag particles.

At a fixed density, the particle size is another important factor affecting the characteristics of light reflection and transmission. The particle size effects may be readily inferred from the electrostatics approximations. Considering the contribution of electric dipoles, the scattering (C_{sca}) and absorption (C_{abs}) cross sections for a metal particles of diameter a can be expressed as:

\[ C_{sca} = \frac{4(2\pi)^3}{3\lambda} \left| \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m} \right|^2, \]
\[ C_{abs} = \frac{8(\pi a)^3}{\lambda} \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m} \]

where \( \varepsilon \) and \( \varepsilon_m \) are the dielectric function of the metal nanoparticle and the surrounding medium, respectively, and \( \lambda \) the light wavelength. As seen in an example shown in Fig. 9, when the nanoparticle size increases, light scattering due to its electric dipoles becomes increasingly more dominant than light absorption, but large-sized particles tend to absorb more light power than small-sized particles. This conclusion is also expected when the contributions of higher order multipoles are included.

Fig. 10 compares the simulated spectra of light reflectance and transmittance for a poly-Si sample with Ag nanoparticles of two size distributions on the surface: one with radius between 50–100 nm and the other between 150–250 nm. With 50-nm Ag nanoparticles on top of the poly-Si surface, the dipole-related surface plasmon resonance occurs around the 1400 nm wavelength. A red shift toward greater wavelengths is expected for surface plasmon resonance as the Ag nanoparticle size increases. Thus the light scattering and absorption in the simulated range are mainly due to the effects of nanoparticle’s higher order multipoles. In addition, interference between scattered light from the nanoparticle and reflected/transmitted light at the Si/air interface may take place depending on their phase difference or their pathways, as suggested by oscillations in the simulated spectra.

Despite these complicated features, our simulation results confirm that large-size Ag nanoparticles indeed can cause higher reflection or lower transmission of light, due to their strong ability for light absorption/scattering. Fig. 9(c) shows the optical absorption spectra calculated by subtracting the scattered and transmitted intensities from the total incident intensity. In the simulated spectral range, light absorption by the large-size (radius 150–250 nm) Ag nanoparticles is more than twice that of the small-sized (radius 50–100 nm) nanoparticles. For a poly-Si sample with large-size Ag nanoparticles on top of its surface, about 5%–10% of the illuminating near-infrared light (800–1200 nm wavelength) and more than 30% of the blue and green light are lost as heat in the Ag nanoparticles. Such strong light absorption within large-sized Ag nanoparticles has posed a limiting factor to the efficiency for light trapping in Si, as suggested by previous work as well. Depending on the spectral range of interest, there could be an optimal range of nanoparticle size for achieving a high efficiency of light trapping in Si. From our simulations for the cases with a fixed density of Ag nanoparticles on the Si surface, small-size (50–100 nm) particles give rise to a higher trapping efficiency (~65–75% vs. 56–64%) in the visible spectral range, compared to medium-size (100–150 nm) particles. But the efficiency (>80%) in the near-infrared range for the latter is greater than that (<75%) for the former. As the Ag particle size exceeds 150 nm, light trapping efficiencies drop in both the visible and near-infrared ranges, due to the increased metallic volume causing a significant optical loss within Ag particles.

Our simulations (Fig. 10) also show the distinct effects of a pre-textured or flat surface on light trapping within poly-Si.
With Ag nanoparticles of a density of $2.5 \times 10^{8}/\text{cm}^2$, light reflection decreases over most of the solar spectrum once the underlying surface is switched from an untextured/flat to a textured one. Interestingly, under the same conditions of Ag particle size and density, smaller optical absorption losses at short wavelengths ($<650$ nm) are detected when large-size ($>100$ nm) Ag nanoparticles are placed on a pre-textured surface. In this spectral range, the optical absorption exceeds 30% in the case of a flat surface, but falls to ~28% in the case of a textured surface.

We speculate that the decreased optical loss within large-sized Ag nanoparticles in the presence of a textured surface may be related to multiple reflection of light from the facets of the existing surface textures. When a particle is on a flat surface, the incident light or the light forward scattered off the particle could enter into the nanoparticle following its reflection from the surface. In contrast, the incident light and the forward scattered light would have a decreased chance to bounce back to the particle, when the underlying surface is textured. The modified optical paths due to the textured surface may also change the conditions for interference between the scattered light and reflected light, as implied by the variations in the peak positions and amplitudes compared to the flat surface case. Furthermore, our simulations indicate that the spectral variations caused by the underlying surface conditions (i.e., textured vs. untextured surface) become more pronounced in the case with large-size Ag nanoparticles. This is understandable since large particles tend to scatter more light and the increased particle volume enhances light absorption within metal nanoparticles.

IV. CONCLUSIONS

In conclusion, we have experimentally studied the behaviors for light reflection from ion implantation induced surface textures of poly-Si thin films. Compared to single H ion implantation, dual implants of H and Ar ions can yield a much higher density of surface textures, thus a more reduction in light reflection or a greater light trapping efficiency within poly-Si. The method is able to decrease under the AM1.5 condition light reflection at the air/poly-Si interface from ~30% for an untextured surface to less than 5% in the case of a highly textured surface created by dual implants. We have also evaluated the growth of Ag nanoparticles on the textured poly-Si surface as well as their effects on light reflection. Experimentally, the combination of nanoparticle growth and surface texturing can further decrease light reflection from poly-Si, which according to our computer simulations, would result in an increased efficiency for light trapping within the poly-Si. The suppressed light reflection due to the presence of a textured surface also helps reduce light absorption within large-size (>100 nm) Ag nanoparticles. In addition, our simulations suggest that there would be an optimal range in the size/density of Ag nanoparticles, beyond which Ag nanostructures may have an adverse effect on light trapping within textured/untextured poly-Si films due to increased optical losses in reflection and absorption.

ACKNOWLEDGMENTS

We would like to express our gratitude to Arthur Haberl and Wayne Skala at the Ion Beam Laboratory of the University at Albany for their efforts in maintaining the accelerator facilities. We are indebted to Dr. Changwoo Lee for preparing amorphous Si films for this work. Access to Dr. Michael Carpenter’s UV/Vis spectrometer is also greatly appreciated.

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