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Influence of Laser Texturing on the Formation of Multiscale Textures for Broadband Light Absorption Enhancement in a-Si Thin film for Solar cells

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Abstract

A light-trapping scheme, such as the textures, is required for the efficient collection of light in thin film solar cells to achieve high light conversion efficiencies. Light trapping is important for thin film solar cells where a single light-pass through the absorber is not sufficient to capture the weakly absorbed red and near-infrared photons. The amount of light absorbed depends on the optical path length and the absorption coefficient. In the present work, influence of laser fluence and different ambience on surface texturing is studied to improve the light-trapping characteristics. Laser texturing with a nanosecond pulsed Nd^{3+}:YAG laser in air and water is used to create surface textures in a-Si thin films that enhances light-trapping along with simultaneous crystallization and hydrogenation. The light-trapping characteristics of textures are analyzed by optical reflectance measurements. The reflectance values across the whole spectra reduced by 20% to 35% compared to untreated sample indicating an improvement in light trapping via multiple reflections due to the textured surface. Theoretical simulation shows the increase in absorption in the long wavelength region with the multiscale textures compared to uniform textures.

Keywords: Laser texturing, Light trapping, Amorphous silicon, Solar cells, thin films.

1. INTRODUCTION

Thin-film solar cells have advantages such as reduced semiconductor material consumption and the ability to deposit thin films over large areas. The thinner active layer can also minimize the carrier collection length as well as the bulk recombination. Thin-film solar cells based on amorphous silicon (a-Si:H) have gained considerable attention for tandem junctions with strong light absorption and low processing temperature, allowing it to be deposited in large areas on low cost substrates like plastics or polymers[1]. However, the thin nature of the absorber limits the optical absorption of the cells. The typical film thickness is around 1μm for effective light absorption in a-Si:H thin film solar cells, which is ~2 orders of magnitude thinner than that in single crystalline Si. Also, the reflectivity of flat a-Si surfaces is high in the range between~30% (for longer wavelength) and ~50% (for shorter wavelength). Light trapping via multiple reflections is considered an important mechanism that allows the reduction of reflection losses with an increase in the optical path length of incident light in photovoltaic devices. Texturing using wet chemical etching is not applicable for amorphous materials or thin films. Another method is reactive ion etching [2], but the cost is very high compared to wet etching.

A number of different light-trapping methods have been explored, including plasmonic nanoparticles and photonic structures. However, absorption is is often limited to narrow wavelength intervals [3]. It is also reported that a broad-band absorption enhancement requires light trapping structures with a certain amount of randomness. So, random multiscale textures are promising way for enhanced light trapping [4].

Laser surface texturing technique has the advantage of noncontact processing and recently, pulsed lasers are used for texturing of a-Si films. Femtosecond laser assisted texturing along with hyper doping of sulphur on Si wafers has resulted in "black Silicon" improving absorption in UV-Visible-Infra red range [5]. Alternatively, nano-second laser texturing of a-Si thin films without laser ablation can also be considered. The laser-assisted melting and re-solidification approach induces the texture formation via capillary action in molten silicon without ablating the material. Nano-second pulsed laser texturing results in a small order of multi scale conical but random structures, because of the slight variation of fluences and temperatures during the experimental process [6].

In this work, experimental and theoretical studies are performed to generate textured surface on a-Si film and analyze the influence of texture on light trapping characteristics. The finite element method (FEM), a frequency-based optical modeling method that solves for the electric and magnetic field strengths throughout the spatial computational domain is used. The dependence of absorption properties on surface textures are also analyzed with periodic and random surface textures. Surface interactions and light propagation inside the textured film for a discrete set of wavelengths are simulated.

2. EXPERIMENTAL DETAILS

Laser texturing was performed using solid state pulsed $Nd^{3+:}$YAG laser (Brilliant b, Quantel) (532 nm) with a pulsed duration of 6 ns (FWHM) was used. 10 mm × 10 mm samples were scanned with the laser with different percentage of spot overlapping such as 30%, 50% and 90% to analyze the

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formation of textures. 1μm and 400nm thick a-Si thin film deposited on c- Si substrates were used in the experiments. The laser beam was focussed to a spot of 2 mm by using 200 mm focal length lens. Experiments were conducted in different medium like air and water to identify the suitable processing conditions for annealing and texturing. To investigate the influence of the laser fluence on annealing and texturing processes, the a-Si films were treated with different fluence values by altering the laser beam energy. Pulsed laser treated samples were analyzed by a scanning electron microscope (SEM) (Quanta 200) and atomic force microscopy (AFM) (Bruker, Dimension edge) to investigate the effect of laser fluence and spot overlap on the surface morphology of textured thin-films. The effect of textures on light trapping characteristics was analyzed using a broadband light source and a monochromator system (Bentham PVE 300).

3. RESULTS AND DISCUSSIONS

3.1 Surface Morphology Analysis

Figure 1 shows SEM images of untreated and laser textured samples with the fluence of 300 mJ/cm^2 in air and flat-top beam profile. Samples were scanned with 90% spot overlapping. The untreated a-Si/ c-Si show no trace of surface modification (Fig. 1(a)). Surface change was observed on the laser treated samples with 532 nm wavelength as shown in Fig. 1 (b). This is attributed to modification of the surface state that was heated to a temperature greater than the melting temperature. With the laser irradiation, a liquid-solid interface is formed. As the thermal conductivity at the liquid-solid interface is larger than at the liquid-air interface, nanocrystalline Si grains start to nucleate and the size of the grain increases. A ridge structure is expected to form due to the density change between the solid and the liquid phases of Si films, due to the creation of capillary wave [7]. For lower fluence values, spherical bead-like structures were noticed. When the laser fluence was further increased, the size of the bead-like structure increased, which was an indication of complete melting.

Laser induced texture formation was analyzed with AFM and the texture dimensions were derived from the analysis. Figure 2 shows textured a-Si surface with laser fluence of 200 mJ/cm^2 for 50% of laser spot overlap. The AFM image shows the formation of conical structures. The rms roughness of each surface morphology was obtained from 3-D AFM images (scan area: 50 μm × 50 μm). As the fluence values increased from 200 mJ/cm^2 to 400 mJ/cm^2, the flat surface of the a-Si thin film's surface morphology changed from flat to largely textured.

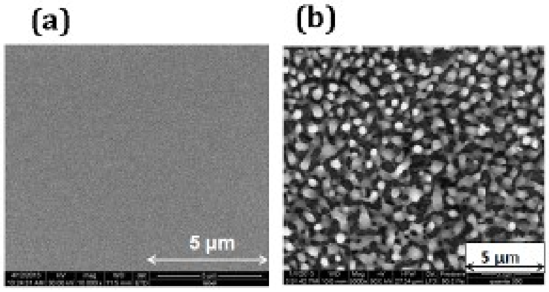

Fig. 1 SEM micrograph of a-Si/c-Si samples (a) untreated and (b) treated with ns-laser at 532 nm with fluence value of (b) 300 mJ/cm^2 with 90% spot overlapping in air with flat-top beam profile.

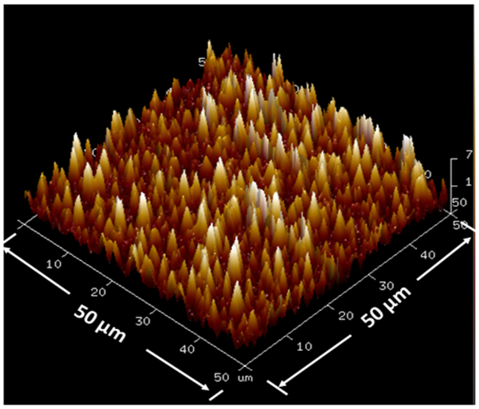

Fig. 2 AFM images of laser treated sample in air with 50% of laser spot overap with a fluence of 200 mJ/ cm^2.

The texture height increases as the laser fluence was increased. The roughness of the surface treated with Gaussian beam was more compared to flat-top beam. As the laser spot overlap increased from 30% to 90%, the conical textures sharpen and the height increases due to repeated incidence of laser pulses. Underwater annealing produced smaller base diameter and high density structures compared to annealing in air environment. This smaller size formation in water might be due to the

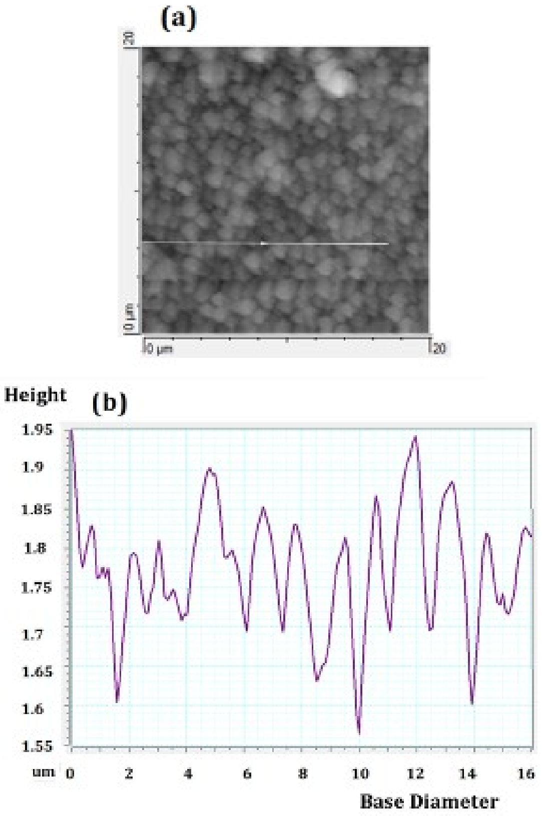

Fig. 3. AFM image of a-Si/c-Si sample treated with ns-laser at 532 nm with 90% spot overlap and 200 mJ/cm^2 (a) 2D image and (c) its roughness profile along the line shown in (a).

reduction in capillary wavelength in water ambience [8].

The texture dimensions were derived based on the experimental observations and it was clear that the ns-laser induced textures were conical in shape. Laser induced textures were found to be slightly randomized and having the nano cones with different sizes as shown in Fig. 3. Figure 3 (a) shows 2D AFM image of a-Si/c-Si sample treated with ns-laser at 532 nm with 90% spot overlap and 200 mJ/cm^2 and 3 (b) shows the roughness profile along the line shown in (a). Based on the AFM analysis, it was found that naturally formed nano cones with laser treatment were found to be having the height ranging from 100 to 700 nm, base diameter ranging from 1000 to 2500 nm (1000 to 2000 nm for samples treated in water and 1500 to 2500 nm for air treated samples) for the fluence varying from 200 mJ/cm^2 to 400 mJ/cm^2 depending on the treatment conditions and laser parameters.

3.2 Optical Characteristics

Optical reflectance measurements using a broadband light source and a monochromator with an integrating sphere were used to confirm the light trapping effect due to these textures on solar cell. Figure 4 shows the integrated values of optical reflectance spectra of the thin-film surface integrated over the wavelength region of 300 to 1100 nm. The reflectance values reduced to ~14% to 19% compared to untreated sample (~41%) indicating an improvement in light trapping via multiple reflections due to the textured surface. Reduction in reflection was found to be more for water treated samples compared to air treated samples, which might be due to increase in multiple reflections with the high dense textures found in water treated samples [8]. The experimental results show that minimum reflectance is reached with the roughness (Rq) of ~150 to 300 nm and above.

4 THEORETICAL INVESTIGATIONS

Influence of textured surface on light trapping was analyzed using Maxwell's equations in two dimensions to analyze wave propagation within thin-film. The finite element method (FEM) is a frequency-based optical modeling method that solves for the electric and magnetic field strengths throughout the spatial computational domain. Using this, parameters such as reflectance, transmittance, and absorptance of the film that has surface textures were calculated. Surface interactions and light propagation inside the textured film for a discrete set of wavelengths were simulated. In this method, the Faraday and Ampere–Maxwell laws of the frequency domain are combined together to yield a single vector wave equation in terms of the electric field E or, alternatively, the magnetic field H, as follows:

$$\nabla \times \mu_r^{-1} (\nabla \times E) - K_0^2 (\varepsilon_r - (j\sigma/\omega\varepsilon_0))E = 0 \qquad (1)$$

In Eq. (1), j is the current density; ε_r and μ_r denote the relative permittivity and magnetic permeability of the medium respectively and $K_0 = \omega\sqrt{\mu_0\varepsilon_0}$ is the propagation constant. The electromagnetic (EM) filed is obtained via resolving these Maxwell equations and the spatial distribution of energy flux, and thus the optical characteristics are achieved by integrating the EM field. From this, the reflectance $R(\lambda)$ and transmittance $T(\lambda)$ of the simulated cell are calculated using the scattering parameters. Then, the absorptance spectrum $A(\lambda)$ is readily obtained from the relation $A(\lambda) = 1-R(\lambda)-T(\lambda)$.

Numerical analysis was performed using a Comsol Multiphysics module v. 5.2. Both the flat and textured thin films were modeled with a 2D geometry as shown in Fig. 5 to simulate the interaction between the incident light and the textured film, which is realized by infinitely extending the structural unit using periodic boundary conditions. Experimentally derived texture dimensions with the base diameter ranging from 1000 nm to 2500 nm and height from 100 nm to 700 nm were used as a reference. Since the laser induced textures are random in nature with varying dimensions, the superiority of these multiscale textures were analyzed by comparing them with uniform textures. Since the non uniform structure produced by laser texturing was difficult to reproduce or realize *via* simulation method, geometry with textures of varying dimensions such as the height of the cone and the diameter at the base were assigned randomly making sure they fall within experimental results as shown in Fig. 5 (b). As shown in Fig. 5 (c) and (d), the flat a-Si has low reflectance and high absorption only in a narrow wavelength range up to 800 nm, while textured thin films (both uniform and multiscale ones) have excellent light absorption over a broad wavelength. Moreover, the absorption spectrum of the multi scale nano-cones textured a-Si is much smoother and higher than that of the periodic one in the long wavelength range. Experimentally measured optical reflectance of the laser induced multiscale textures shown in Fig. 6 is smoother in longer wavelength region compared to simulated results. This is attributed to the high order of randomness in the experimental samples which is difficult to realize with simulation. When the dimensions of the textures are smaller than the light wavelength, the texture acts as an inhomogeneous medium with an effective refractive index gradually increasing from air to silicon and ease the mismatch between the two refractive indexes. Thus light will ignore the existence of the texture and can easily pass through it, which reduce the reflection on the top and promote the absorption greatly. Because of the suppressed reflection, the absorption is greatly improved over a large range of wavelengths and angles of incidence. When the light wavelength is much shorter than the texture size, multiple reflections among the textures assist in enhanced light trapping. When the size of the Si nano-cones are comparable to light wavelength, scattering of light dominates in enhancing the absorption characteristics [9]. Therefore, while for the periodic structure coupling of light into cell is only possible at particular wavelengths, the random textures are able to couple light at any wavelength.

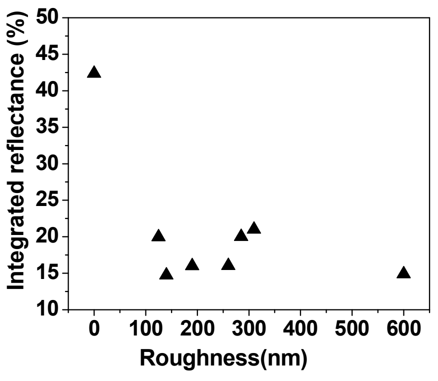

Fig. 4 The reflectance values integrated over wavelength of the laser treated samples for different roughness values

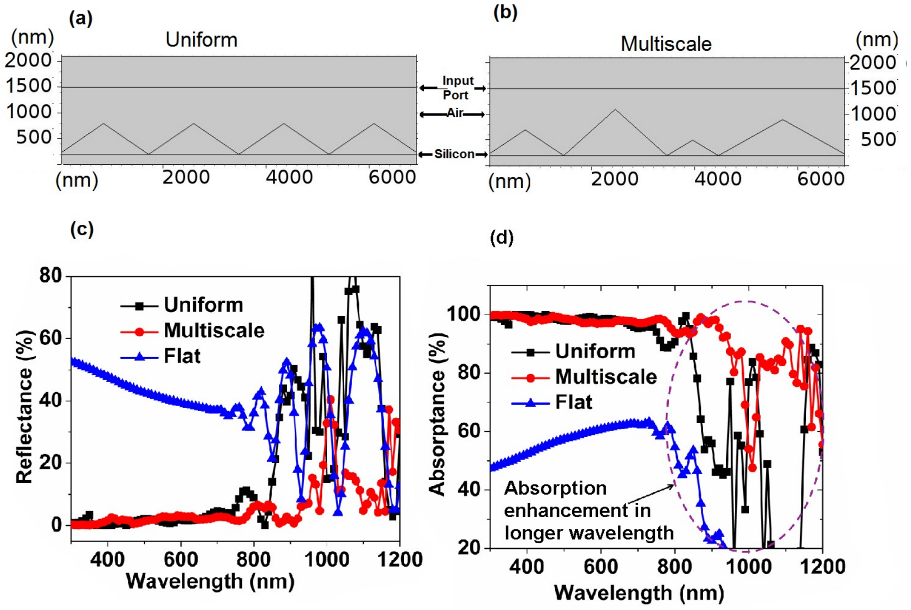

Fig. 5 Simulated geometry of (a) Uniform and (b) Multiscale textures and their spectral (c) reflectance and (d) absorptance showing absorption enhancement in longer wavelength region for multiscale textures compared to uniform textures.

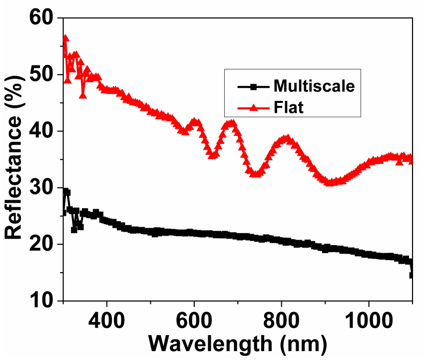

Fig. 6 Experimental optical reflectance spectra of the untreated and laser treated multiscale, textured a-Si/c-Si sample.

5 CONCLUSIONS

Nanosecond pulsed Nd^{3+}:YAG laser is used to create surface textures in a-Si thin films in air and water medium to enhance light-trapping. Laser induced textures were found to be conical in shape with varying dimensions. The reflectance values reduced to ~14% to 19% compared to untreated sample (~41%) indicating an improvement in light trapping. With theoretical analysis it was found that the random Si nano-cones facilitate achieving higher light trapping, performing far better than the planar surface and also better than the periodic ones. Therefore, the random Si nano-cones formed by the laser texturing provides opportunity to enhance the light absorption of a-Si solar cells along with crystallization and defects passivation.

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