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Optical properties of silicon light trapping structures for photovoltaics

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ABSTRACT

Light trapping structures in photovoltaics are essential to suppress reflection losses and increase conversion efficiency. For wafer silicon (Si) solar cells, this is commonly achieved by chemical texturing and the application of an antireflection coating. Such surfaces still show significant reflection losses that are ~10%. Hence, for further reduction in reflection, new methods for light trapping need to be explored, which are effective for a broad solar spectral and angular range. In this paper, we explore an ultrafast laser texturing method that successfully reduces the reflection below 5% over a broad spectral and angular range and more importantly, is applicable to crystalline, multi-crystalline, thin film silicon and other materials. The optical properties of ultrafast laser textured silicon surfaces produced in a sulfur hexafluoride (SF_6) gas ambient are evaluated by total reflection including scattering as a function of wavelength and angle of incidence. The optical results are further compared with other texturing schemes. This study also investigates the silicon bandgap modification induced by ultrafast texturing method. Finally, a comparison is made for the photovoltaic parameters of solar cells made of ultrafast laser textured surfaces, chemically textured surfaces, porous silicon surfaces, and etched silicon surfaces that result in nanowires for light trapping to understand impact of surface texturing on photovoltaic device performance.

1. Introduction

For photovoltaic applications, near zero reflection over a broad spectral and angular range is desired to increase conversion efficiency. Surface texturing greatly enhances the optical path length of the incident light and reduces surface reflection and has become indispensable for solar cells. For silicon solar cells, surface texturing is conventionally obtained by chemical (anisotropic and isotropic) etching [1,2]. Chemical etching techniques produce randomly distributed structures on the silicon surface. Antireflection coatings (ARC) like titanium dioxide, silicon nitride (SiN_x), etc. are used for further reduction of reflection. Even with ARC, chemically textured surfaces still show reflection losses of about 5–10% [3–5]. Furthermore, these techniques are inapplicable to thin film silicon solar cells and are less effective for multi-crystalline silicon wafers, which are more widely used. Hence, it becomes essential to explore new surfaces texturing methods that are suitable to next-generation ultrathin (<100 μm) wafers (crystalline and multi-crystalline) and thin film (<5 μm) silicon solar cells. Density graded (porous) silicon surfaces, silicon nanowires, nanoholes, laser texturing and plasmonics for thin films are some of the promising alternatives that have been recently reported [6–15] out of which laser-induced surface texturing is fast emerging to be an attractive alternative. Currently, laser processing plays an important role in photovoltaic manufacturing [16–22] and is showing immense potential for new applications like doping, back fired contacts, etc. [23–33], which is a great motivation to explore laser surface texturing.

Laser surface texturing has been achieved using lasers with pulse widths in the nanosecond and femtosecond regime [11,34,35]. Depending on the pulse width, wavelength and laser fluence, surface texturing is obtained either by (a) ablation-induced surface grooving [10,34] or (b) laser-induced self-assembled semi-periodic light trapping structures [29,36–38]. The ablation-induced surface grooving technique creates 50 μm deep craters to reduce reflection losses with significant material lost during etching of the laser-damaged region. Short wavelength ($\lambda = 248$ and 532 nm) nanosecond laser irradiation can create self-assembled conical pillars that very effectively trap light, but the height of these pillars are over 20 μm. This makes the process unsuitable for next-generation ultrathin wafers, where the texture size approaches the thickness of the wafer. Ultrafast (fs and ps) lasers on the other hand are able to create similar conical structures that are about 3–10 μm high with similar light trapping properties [39–41]. The high density or decreased periodicity of these structures relaxes the pillar height thus providing excellent light trapping. The other advantage of ultrafast laser (femtosecond pulses) over pulsed (nanosecond pulses) laser processing is that the heat-affected zone and laser-induced damage can be greatly minimized [40]. Hence, ultrafast laser processing is seen to be a very promising technology for surface texturing.

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In this paper, we report results of total integrated light scattering (TIS), which is inclusive of reflection, scattering and transmission, as a function of angle and wavelength for femtosecond laser textured silicon surfaces prepared in a SF_6 gas ambient. We further compare it with graded density porous surfaces and chemically textured surfaces, which are very effective light trapping schemes. Through this optical study, we also investigated the role of sulfur incorporation in silicon during the ultrafast laser texturing process, which creates an intermediate band within the silicon bandgap. Lastly, we compare the photovoltaic device parameters of ultrafast laser textured silicon solar cells fabricated in our laboratory and compare it with other texturing schemes discussed in the literature to fully understand the implications of surface texturing on photovoltaic device performance. The goal of this work is to study the optical properties of femtosecond laser-induced light trapping structures, its control and highlight its role as an alternative method for texturing of single crystal silicon, multi-crystalline silicon and thin film silicon for photovoltaics applications.

2. Experimental

Ultrafast laser texturing is achieved by exposing float zone (FZ) Si (1 0 0) wafers of thickness 280 μm and resistivity of 1 Ω cm to a train of femtosecond (130 fs) pulses from a Spectra Physics Ti–sapphire laser system (1 mJ pulse energy; frequency 1 kHz) having a wavelength of 800 nm. The experiments are carried out in 800 mbar pressure of SF_6 gas. Large area texturing is obtained by scanning the sample under the laser beam using a computer controlled precision x–y stage. Samples with different texture heights are prepared by varying the average number of laser pulses impinging on the silicon surface. The average numbers of laser pulses are controlled by varying the velocity at which the samples are scanned under the laser beam. Further details describing the processing of the samples is described in Ref [35]. One of the ultrafast laser textured silicon samples also undergoes a thermal annealing step in the presence of oxygen at 1100 °C for 7 h. Next, chemically textured (CT) silicon surfaces are obtained by anisotropic etching in a mixture of sodium hydroxide, isopropyl alcohol and de-ionized water [42]. After chemical texturing, 70 nm of silicon nitride is deposited using a plasma enhanced chemical vapor deposition (PECVD) system to serve as an antireflection coating. Lastly, density graded porous silicon surfaces (PS) are obtained by a technique described in reference [8] investigated for photovoltaic applications. This is very similar to the nanoporous surfaces reported by NREL [43]. The morphology of the textured surfaces is investigated using a Zeiss SUPRA 40 scanning electron microscope.

Total integrating scattering (sum of specular reflection, scattering and transmission) values are obtained using a 6 in. integrating sphere (Model#RTC-060-SF from Labsphere Inc.) with spectraflect coating. Individual lasers of different wavelengths (405–1550 nm) are used as the light sources. The textured samples are mounted in the center of the sphere using a jaw and clip type center mount holder. This enables the measurement of total integrated scattering as a function of angle. Total integrated scattering is calculated by measuring the signal from the sample and normalizing it with a calibrated reflectance standard. Next, angular scattering measurements are made by having the incident light normal to the textured surface and detecting the scattered light at different detection angles (θ_d) with respect to the normal. A silicon detector (model#818-SL) and a germanium detector (model#818-IR-L) with a power meter (model#1830-C), all from Newport Corp., are used to measure the incident and reflected powers. Specular reflection and transmission are measured using a Film Metrics reflectometer and an absorption spectrophotometer (Perkin Elmer Lambda EZ201).

Lastly, solar cells (active area = 1 cm^2) on ultrafast laser textured FZ-silicon surfaces are fabricated to assess the performance of texturing method. These results are then compared with solar cells having different texturing schemes found in the literature. Ultrafast laser textured silicon solar cell fabrication steps include, (a) laser damage removal by chemical etching, (b) thermal defect annealing at 1050 °C for 60 min, (c) emitter doping by the spin on doping method, (d) surface passivation with 10 thermal oxide and 70 nm PECVD silicon nitride, (e) formation of a back surface field and contact using a Ferro 53-038 aluminum paste, (f) photolithography for front electrode patterning (g) e-beam evaporation of Ti (100 nm)/Pd (50 nm)/Ag (1000 nm) followed by 3 μm Ag electroplating and (h) forming gas annealing at 400 °C for 20 min. Devices are characterized for total efficiency and quantum efficiency. Further details on the device fabrication steps and characterization can be found in Ref. [38,44].

3. Results and discussion

Fig. 1 shows the scanning electron microscope images of the three types of textured surfaces used in this work.

Fig. 2 shows the total integrated scattering (TIS), which includes reflection, scattering and transmission measurements as a function of angle for different wavelengths for ultrafast laser textured silicon. These measurements are further compared with chemically textured silicon having SiN_x as ARC and for a porous silicon surface. Fig. 2 also includes an ultrafast laser textured silicon sample that is thermally annealed in a dry oxygen environment at 1100 °C for a period of 7 h in a tube furnace. The thickness of the resulting thermal oxide on a planar control surface is measured to be ~250 nm.

The comparison of these four types of textured structures is indeed very interesting because the mechanism of light trapping for each one is different. Light trapping for the ultrafast laser textured surface and the conventional chemically textured surface is governed by multiple reflections [45]. Ultrafast laser textured silicon surfaces processed in SF_6 gas ambient have about 1 at% of sulfur incorporated in the silicon surface. Such a high concentration of sulfur in silicon creates an intermediate band within the bandgap of silicon. This enables silicon to absorb photons with energies smaller than its bandgap. This means that light absorption for the ultrafast laser textured silicon occurs by multiple light reflections and sulfur mediated absorption. For the porous silicon case, light trapping is obtained by the gradual modulation of the effective refractive index that tends to be close to unity as suggested by Refs. [7,46].

As seen in Fig. 2, the porous silicon surface is the most effective medium to reduce reflection. It is also seen that the porous silicon surface has little or no angular dependence as seen in Fig. 2(a)–(d). However, we can clearly see a weak angular dependence for all other textured surfaces. It is also apparent that the chemically textured surface with ARC displays an angular dependence that is similar to the laser textured sample. We have also carried out Monte Carlo based ray tracing (TracePro from Lambda Research Corp.) to simulate the optical characteristics of thermally annealed ultrafast laser textured silicon surfaces. The simulation results are included in Fig. 2(b). It can be seen that the simulation results closely match the experimentally measured values. The small deviation of the simulated results from the experimental values can be attributed to surface roughness, feature size variation, etc. in our samples, which have not been included in the simulations. Thus, it is clear that light trapping in the ultrafast