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Photovoltaic enhancement of Si micro- and nanostructure solar cells via ultrafast laser texturing

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Abstract: The purpose of the present study was to achieve laser-microtextured Si structures, the material used as silicon wafers, with a thickness of 330 μm for a fast laser texturing technique, in order to produce micro-/nanosurface textures by means of a UV femtosecond laser. A textured silicon surface was prepared that has the capability to trap light, thereby greatly reducing the visible light reflection for photovoltaic cells. The textured surface was measured by scanning electron microscope. The results showed a photocurrent increase of about 25% in the laser-textured zones.

Key words: Ultrafast laser-microtextured, Si structures, solar cell

1. Introduction

Silicon thin films are used in many devices in various fields of applications such as optics, opto-electronics, and microelectronics [1]. A bandgap of silicon 1.12 eV leads to efficient detection of visible light and conversion of sunlight into electricity. There is a wide range of interest in improving the responsivity of silicon detectors in the visible and the near-infrared (near-IR) regions of the electromagnetic spectrum [2]. In order to increase the efficiency of actual solar cells, many different ways are currently being developed by researchers, through focus on the nano- and microstructurization of the surface [3]. Nanostructured solar cells offer several advantages including: (1) the ability to exceed a single junction solar cell efficiency by implementing new concepts; (2) the ability to overcome practical limitations in existing devices, such as tailoring the material properties of existing materials or using nanostructures to overcome constraints related to lattice matching; and (3) the potential for low cost solar cell structures using self-assembled nanostructures [4]. Pulsed lasers are promising tools for machining with submicrometer precision due to reduced heat diffusion related to fast laser–matter interaction [5,6]. The use of ultrafast laser texturing offers many benefits compared to standard wet chemical texturing techniques, and is now an economically attractive process for the solar industry due to continued improvements in laser power and reduction in laser costs [7]. Moreover, lasers are unique energy sources that could texture surfaces by selectively removing materials via ablation. Since laser ablation is an isotropic process, texturing could be achieved irrespective of the crystallographic orientation of the material surface. Several groups have demonstrated that lasers could be used to texture the surface by creating grooves [8]. To create such types of textures, usually lasers with pulse widths of tens of nanoseconds are used [9]. Other important advantages of ultrafast laser-textured surfaces are (a) high reproducibility; (b) good uniformity of micro/nanostructures; and (c) applicability to c-Si and mc-Si, as well as thin films. Lasers are increasingly adopted in the PV

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industry at various process steps, such as edge isolation, groove formation, and soldering [10]. There are 3 different kinds of texturization techniques for multicrystalline silicon solar cells: acid texturization, reactive ion etching, and mechanical texturization [11]. Surface texturing can be achieved by both femtosecond and long-pulse lasers, but femtosecond lasers are better suited for precise micromachining due to their extremely high peak power and ultrashort pulse duration, which leads to greatly reduced thermal energy diffusion and heat-affected zone and allows for precise control over the texturing process; therefore, for texturing films of limited thickness, femtosecond laser processing is more desirable [12]. The first work about the use of ultrafast laser processing of surface texturing of crystalline bulk silicon was reported by Mazur et al. [13,14]. The beneficial effect of the microtexturized Si obtained by femtosecond laser was demonstrated by Halbwax et al. [15]; it showed a photocurrent intensity increment of more than 30% in the laser-treated regions. Mwenifumbo et al. [16] investigated laser microtextured titanium coating on the surface of silicon. Specimens were irradiated by nanosecond laser pulses. To improve the material quality and thus device performance, thermal annealing and chemical etching after ultrafast texturing were performed on Si [17,18].

In the present work, we improved the method used to enhance the absorption efficiency of silicon solar cells by using a UV femtosecond laser in air, and the formation of surface texturing was observed and its feature characteristics were studied by scanning electron microscope (SEM).

2. Experimental

The samples were n-type silicon (100) doped with a phosphorus concentration of up to 10^{12} cm^{-3} and cleaned by the conventional RCA treatment. The prepared samples had the following parameters: thickness 330 μm, resistivity 1 Ω.cm, and area 2 $\times$ 2 cm. In order to increase the efficiency of the actual solar cells, the front surface of the cell was textured. The optical set-up that was used to deliver the laser beam to the sample surface is presented in Figure 1. Femtosecond laser texturing was carried out using a commercial Ti:sapphire oscillator regenerative amplifier system (Hurricane model, Spectra-Physics) at 800 nm, of linear polarized light at 1 kHz repetition rate, and a laser pulse duration of 130 fs. The sample was mounted on a 3-axis translation stage and irradiated by laser pulses focused by a 50-mm focal-length lens. The output beam from the system had a laser power of 3 W in the Gaussian mode with a diameter of 7 mm. The laser energy that was delivered to the sample surface could be attenuated by a diffractive optic attenuator and its frequency was doubled by a BBO crystal, generating fs laser irradiation at 400 nm wavelength, and completed by a set of neutral density filters (NDFs) placed between the reflection mirrors. The laser beam was passing through 2 UV mirrors to reduce the residual IR radiation. The laser beam was focused to $\sim$8 μm diameter by a 20$\times$ Nikon microscope objective with a 0.45 numerical aperture (NA), 10 mm focal length, and long working distance of 8 mm. A PC controlled the analyzer rotation, the opening and closing of the shutter placed in front of the polarizer, and xyz stages (ANT-25LV) of 2.5 mm resolution. The fabrication results were monitored by a charge-couple device (CCD) camera. The surface texture morphology of the samples was observed by SEM. The scanning was adjusted such that laser lines overlapped suitably to generate a uniform surface texture over the silicon surface.

3. Results and discussion

Laser processing is a very good technique for texturing silicon structures due to the contactless treatment. Moreover, textures of different patterns can easily be implemented on the treated surface without any additional masking. We have developed a method of laser texturing as a possible solution to the problem of surface textured silicon. Surface texture ensures that incident light meets the cell surface at least twice; transmission of light into the cell is thus considerably increased (Figure 2). The surface texture has many properties simultaneously, including very low reflectance at all incidence angles, and good light trapping that increases the optical path length inside the solar cell.

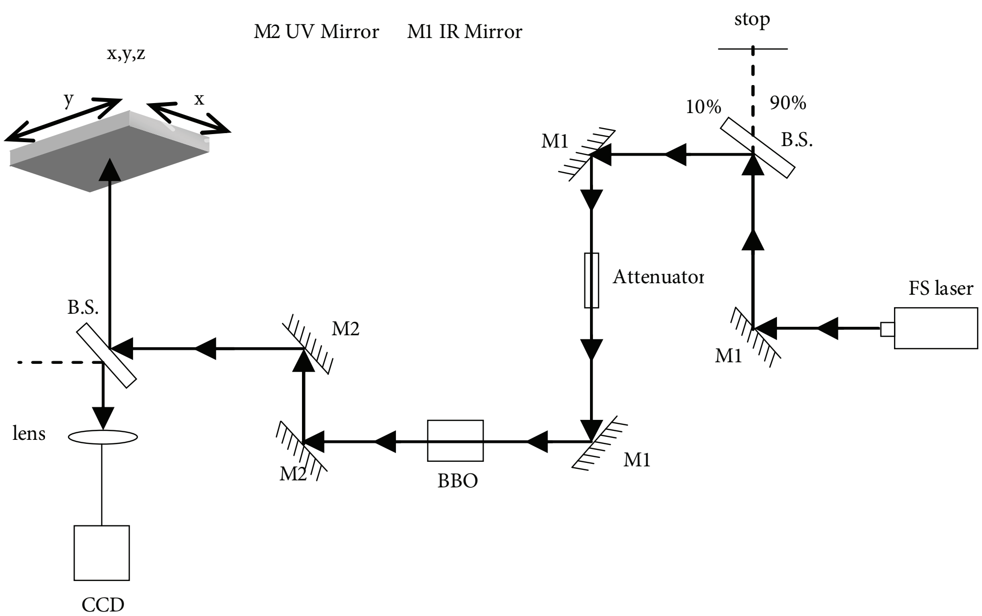

Figure 1. Diagram of femtosecond laser experimental set-up.

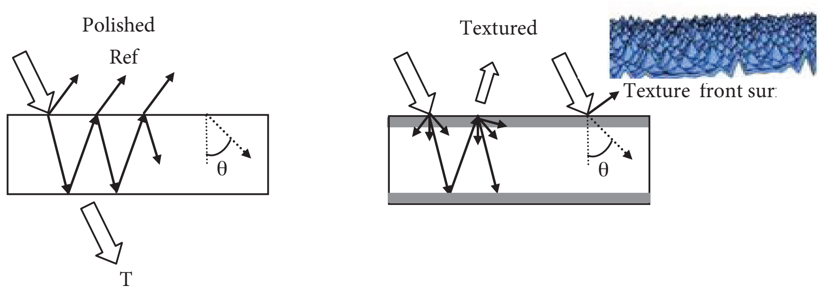

Figure 2. Texture decreases front surface reflectance for all wavelengths.

The periodic structure on the Si (100) surface was formed using double exposure by 2 line mapping directions, with the direction of the sample for the duration of exposure and time of drilling chosen so that the samples under study are similar to the islands of the image located periodically. The form of hillocks was close to cylindrical and therefore has great benefit in terms of increasing the absorption of the light path in the cell. The change in the electrical properties is characterized by a change in the short circuit current density (JSC) and the open-circuit voltage (VOC), fill factor (FF), and efficiency (η) as shown in Table 1. It is shown that the electrical properties and the photovoltaic efficiency are changed after femtosecond laser irradiation. The improvement in JSC from a smooth to a textured surface is very distinct; the gain due to enhanced absorption is around 30%. The solar cells exhibit a strong increase in efficiency as a result of an increase in fill factor and open-circuit voltage with increasing irradiation pulses.

Table. Comparison of solar cell parameters for nontextured and laser texturing.

Corresponding solar cell	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)
Nontextured	40.6	580	68	10
Laser textured	45	655	74	12.5

When observed optically, the surface of the processed Si structure is much darker than the original, which shows that the textured surface has the capability to trap light, which greatly reduces the visible light reflection. Figures 3a, 3b, and 3c show the SEM images. We observed a semiperiodic structure known as grooves in the microstructure after laser irradiation. Figure 3d shows the optical microscope image of a laser surface texture with a different path. The motion direction was controlled by a scanner to obtain a contour path. A nonsmooth surface can be seen that can enhance the absorbed efficiency of light. It can be concluded that a surface texture for Si has greater absorbance while being more economical than bulk silicon and may be ideal for solar cell fabrication.

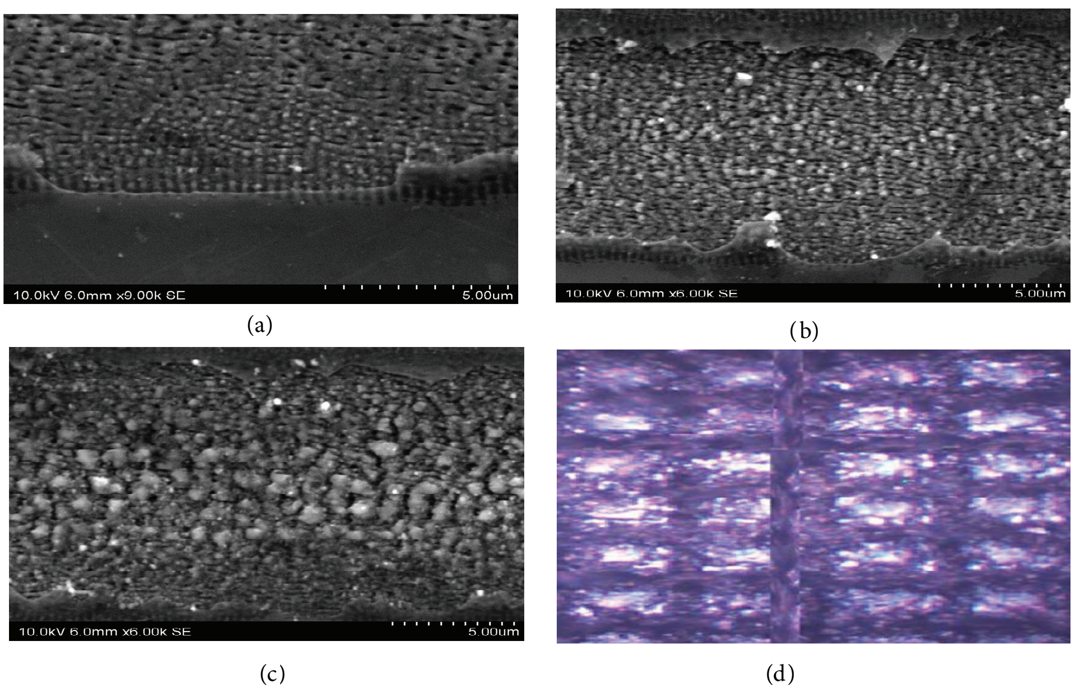

Figure 3. SEM images of laser surface texture (a, b, and c), and optical microscope image (d) of surface texture with different path.

Figure 4 illustrates the light beam induced current (LBIC) scan, in which the beneficial effect of the texturizations is demonstrated. The scan shows that the photocurrent intensity is clearly increased in the laser-treated regions. The real photocurrent of the nonlaser treated surface was close to 20 nA and therefore the gain becomes higher. Additional measurements will give better quantitative results.

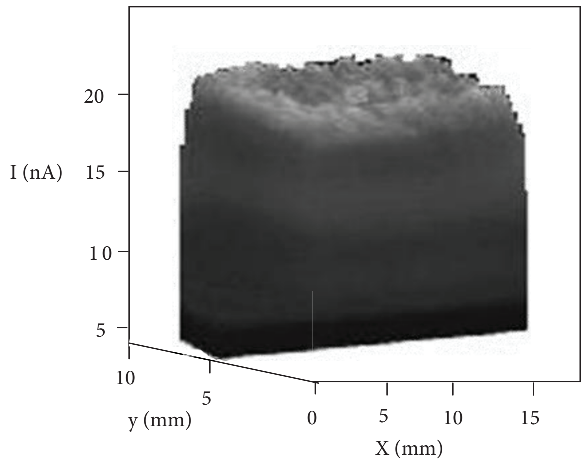

Figure 4. LBIC scan for the laser-treated zones.

4. Conclusions

In this paper, we have prepared a laser-microtextured Si structure that reduces the reflection of a Si surface. Laser surface texturing was achieved on a Si solar cell by UV femtosecond laser. The microstructure of the texture was observed by SEM and optical microscope. A relatively significant efficiency improvement of 3% (absolute) for laser-textured cells was observed. The resulting photocurrent was analyzed by LBIC and shows improvements of 25% using the laser texture. As a result, this approach leads to enhanced Si cell efficiency. The current method is much cheaper and simpler than reactive-ion etching (RIE).

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