Two dimensional grating and efficiency enhancement of Si photovoltaic cells by surface texturing using UV femtosecond laser pulses

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Abstract

A fast laser texturing technique has been utilized to produce micro/nano surface textures in Silicon by means of UV femtosecond laser. We have prepared good absorber surface for photovoltaic cells. The textured Silicon surface absorbs the incident light greater than the non-textured surface. The results show a photovoltaic current increase about 21.3% for photovoltaic cell with two-dimensional pattern as compared to the same cell without texturing.

Key words

Texturing, femtosecond, Silicon

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تشكيل المحزز الثنائي الابعاد و تعزيز كفاءة الخلايا الفوتوفولتائية بتركيب السطح باستخدام نبضات الأشعة الليزرية فائقة القصر للمنطقة فوق البنفسجية

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الخلاصة:

استخدمت تقنية التركيب لانتاج تشكيلات سطحية بأبعاد المايكرو/النانومترية وذلك بتشعيع السلبكون بنبضات ليزية فائقة القصر (فيمتوثانية) وبطول موجي قصير يقع ضمن المنطقة فوق البنفسجية. وقد تم اعداد سطوح ممتصة جيدة لخلايا فوتوفولتائية. السطوح المركبة لخلايا السيليكون تمتص الضوء الساقط اكثر من السطوح الغير مركبة. واظهرت النتائج ان هناك زيادة بقيمة التيار الفوتوفولتائي بحوالي ٢١,٣% للسطوح المركبة بأبعاد ثنائية عنها بالسطوح الغير مركبة

Introduction

Lasers find widespread application in materials processing. They are successfully applied in industrial processes including welding, cutting, drilling, ablation deposition and surface treatment [1, 2]. The interaction of a high power laser beam with material has many applications including chemical analysis, micromachining and pulsed laser deposition of thin films. The laser-material interaction involves complex processes of heating, melting, vaporization, ejection of atoms, ions and molecules, shock waves, plasma initiation and plasma expansion. The resulting crater and laser material interaction are dependent on the laser beam parameters (pulse duration, energy, and wavelength), the solid target properties and the surrounding environment's condition [3.]

Silicon is the most commonly used semiconductor in optoelectronic devices and silicon photodiodes are often used in industrial applications as reliable devices for light to electricity conversion. Silicon photodiodes are manufactured according to their spectral responsivity. These features are especially important in the field of optical radiometry in which measurements of photometric and radiometric quantities have to be done with a high level accuracy. The description of high accuracy interpolation of quantum yield of Silicon photodiode detectors in the near UV is presented by Kubarsepp et al [4]. The results of the of the quantum yield calculations and of measurements obtained by use of a Silicon trap detector are presented. Carey et al [5] investigated the I-V characteristics and responsivity of photodiodes fabricated with silicon that was micro structured by use of femtosecond laser pulses in a Sulfur-containing atmosphere. The Silicon surfaces irradiated with high intensity nanosecond laser pulses in the presence of Sulfur-containing gases have near unity absorption from near UV (250nm) to NIR (2500nm) at photon energies well below the bandgap of ordinary Silicon[6].

Microstructures develop spontaneously on Silicon surface under the cumulative short laser pulses irradiated in different ambient atmospheres [7,8]. The texturization of Silicon by ultrashort laser pulses enhances the absorption of light through the following phenomena [9-12]: 1) incoming light rays that are reflected from one tilted (by texturing) surface may strike another surface resulting in an increased probability of absorption, and therefore reduced reflection, 2) the light rays refracted within the silicon propagate at an angle, causing them to be absorbed closer to the junction than this process could occur in the case of planar surface which is especially relevant in material with diffusion lengths comparable to or less than the cell thickness, 3) photons which are reflected from the rear surface coming back to the front can encounter a tilted silicon surface, improving the chance of being internally reflected, either at the silicon interface or at the glass surface, and providing next chance for absorption. The third phenomenon is referred to as light-trapping, and gives an improved response especially to infrared light[13].

The silicon substrate is the most costly component in the solar cell. Reducing the wafer thickness drives down the cost as does the replacement of monocrystalline silicon with lower cost poly-silicon or mc-Si, which is made from a less energy intensive process. However, this cost efficiency comes with a price. Reducing wafer thickness risks lower strength, difficulties in handling, thermal breakage and lower light trapping capability. Mc-Si has higher metals contamination and material variability, generally poorer electrical performance, poorer structural integrity, and lower thermal stability [14]. One of the most technological methods of formation of periodically structured resistive mask is recording the interference pattern from two coherent light beams on the substrate with photoresist. Using this method, it is possible to fabricate a mask with apertures that looks like parallel strips with a period of submicrometer to a few micrometers (holographic diffraction grating). If we carry out the double exposure for two mutually perpendicular orientations of the substrate, we shall obtain a two dimensional grating, *i.e.* mask as periodically located holes or islands (depending on conditions of exposure time and etching). This technological method has been named as interferential lithography. Interferential lithography has been lately used for fabrication of one-dimensional nanostructures [15], production of the master mold for nanoimprinting lithography [16,17].

In our previous work, we have demonstrated how we can create sub-microstructures in photovoltaic cell by irradiating the sample with NIR femtosecond laser pulses. The responsivity and the conversion efficiency of the photovoltaic cell are enhanced by this technique [18].

The paper presents results on the development of surface texturing by means of laser processing and investigation of the influence of laser texturization on the operational properties of the photovoltaic cells in order to enhance the absorption efficiency of the Silicon solar cells.

Experimental part

A commercial Silicon samples (SM36-18al type) had the following parameters: thickness ~ 330μm and resistivity 1 Ωcm. In order to decrease light reflection coefficient, front surface of the cell has been textured. The texture in the form of perpendicular grooves has been produced by means of Coherent Legend Ti: Sapphire laser facility generated horizontal linear polarized light, pulsed at a 1-kHz repetition rate, with pulse duration of 130-fs at a central wavelength of 800 nm. The output beam from the system had a laser power of ~3W in the Gaussian mode with a diameter of ~7mm. The schematic of the experimental setup is shown in Fig.1. The laser beam was attenuated by a diffractive optic attenuator and its frequency was doubled by a Beta-Barium Borate (BBO) crystal, generating fs laser irradiation at 400nm wavelength. A smaller integrated fluence is created by neutral density (ND) filter placed between the reflection mirrors. The laser beam passed through two UV mirrors to reduce the residuals IR radiation. The laser beam was focused to ~8μm diameter by a 20X Nikon microscope objective with a 0.45 numerical aperture (NA), 10 mm focal length and long working distance of 8 mm. The sample under study is mounted on a PC controlled Aerotech x-y-z translation stage (ANT-25LV) of 2.5nm resolution and the fabrication process was viewed by a CCD Camera. The experiments were performed by translating the sample along the x-direction so that the laser beam scribed parallel structures, line by line along x axis.

The experiments using Si samples involved, the structural dimension created at different spacing with the fixed laser pulse energy while the translation speed is constant in all irradiation processes. The two-dimensional periodic structures with different spacing periodicities (10μm, 20 μm and 40 μm) on Si (100) surface were formed using the single exposure by two directions line mapping (irradiation), with the orientation of Si sample for two exposures differed by 90º.

Results and discussion

Silicon captures incident light with each pass through the bulk. As the industry manufacturers point of view, moves to thinner substrates, capture efficiency drops. To overcome this bottleneck, the structure is modified to generate a longer internal light path and to prevent the incident light from exiting the cell. A textured surface has good light capture properties to allow the light to enter the cell. The rear surface reflects internal light back into the cell substrate (Fig.2). The texture on the front bounces internally reflected light back into the cell. In addition some cell designs will relocate the front contact to further enhance the light collection area.

The sample surface roughness shows a noticeable correlation between the texture and surface reflectivity in the visible and NIR region (Fig.3). The reflectivity in damped by increasing the grating period spacing. The reduction of the surface reflection is due to the fact that texturing offers angled surfaces making some light rays bounce from one surface to another enlarging the incident photons optical path length and increasing their internal reflection. This enlarged optical path, found in textured surfaces, provides a change in the angle of incidence allowing the refracted photons to be absorbed closer to the p-n junction of the cell. This oblique coupling of light will produce an increase in the generated current. The texturing processes are commonly used to suppress optical losses, but they are optimized to absorb only at a limited wavelength range. The samples under study looked like periodically located islands of photoresist (the structure period in two mutually perpendicular directions makes 9 μm), Fig.4. The form of hillocks was close to cylindrical. Vary spaced or close structures reduce reflectivity, so that spacing could be varied in this study is an advantageous condition.

A standard method used to measure the efficiency of the solar cell via the measurements of the I-V characteristics at the dark and light using a 1000W/m2 sun simulator.

A more profound understanding of such light trapping mechanism is needed. Table 1 shows a comparison of the electrical properties of the Si cells (open circuit voltage V_{oc}, short circuit current I_{sc}, and efficiency E_{ff}). As it is seen, samples even utilizing low cost technique, show increased efficiency for one dimension and two dimensions texturing.

Scanning Electron Microscope (SEM) images of the sample surface structure obtained in air environment show semi periodic structures known as ripples or grooves, were found after laser irradiation, see Fig. 4. One line scan was performed at a fixed scan speed. A periodic structure (lines) was formed and observed in sub-micrometer (nanometer) range. The surface modification was inferred from the measurement of the first-order diffraction efficiency calculating by measuring the beam intensity in the first order diffraction spot with a CCD camera were 0.57, 0.52, 0,49 for 10μm, 20μm and 40μm respectively (Fig. 5).

As a conclusion, we believe that the use of this approach leads to enhance Si cell efficiency. The low intensities defining the laser irradiation drastically change the scale of the surface reshaping process, promoting the formation of nanostructures and the interaction between surface roughness and/or smoothness lead to increase the number of pulses contributing certainly to rapid nanochannels formation with vary spacing. The irradiation process provides formation of micrometer periodic structures on substrates with a large area using single or double exposition. Thus, inexpensive technology using femtosecond laser pulses allows forming high-quality Si cells. This method is much cheaper and simpler than the electron beam lithography.

Table 2. The voltage- current parameters of the Si cell before and after irradiation process, the filling factor is 47%.

No	Cell	I_{sc}(mA)	V_{oc}(mV0)	E_{ff}
1	Without irradiation	650	580	11.05
2	1 dimensional irradiated sample, 10μm spacing	690	605	12.1
3	2 dimensional irradiated sample, 10μmX10μm spacing	730	610	13.06
4	2 dimensional irradiated sample, 20μmX20μm spacing	715	600	12.43
5	2 dimensional irradiated sample, 40μmX40μm spacing	710	597	12.28

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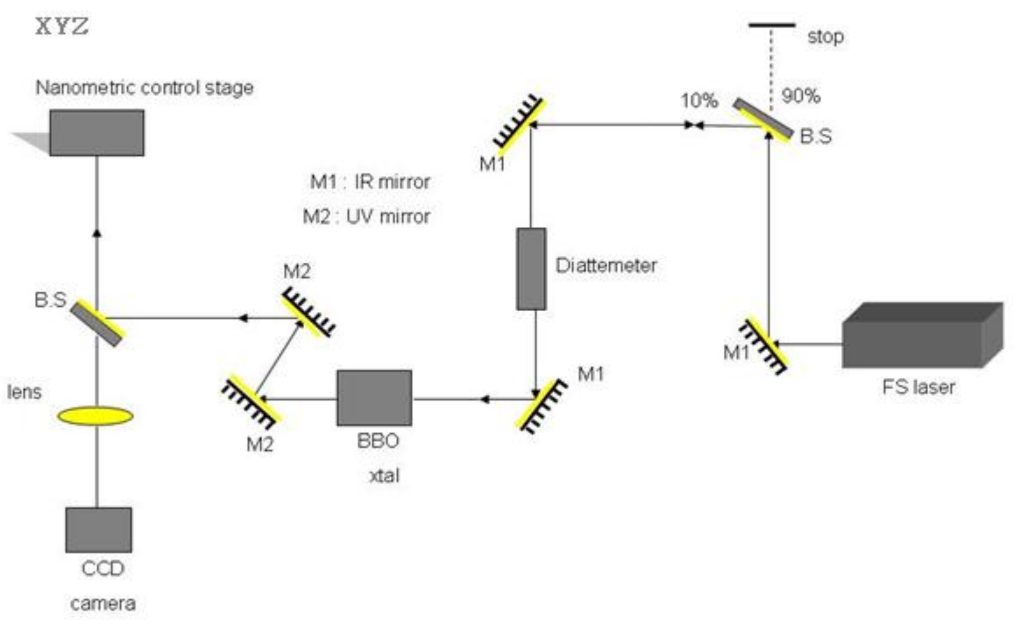

Fig.1. Sample irradiation set-up (FS femtosecond pulse laser source, BS beam splitter, M1 IR mirrors, M2 UV mirrors, BBO nonlinear crystal)

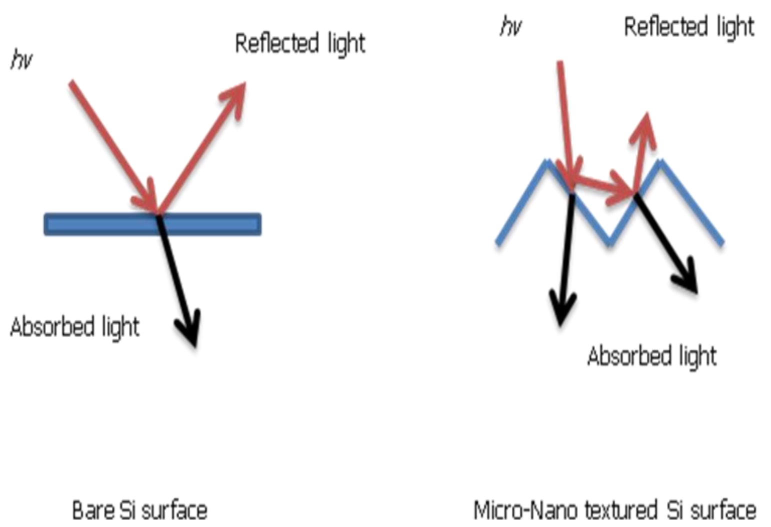

Fig.2. Texturing effect on the light reflection and absorption

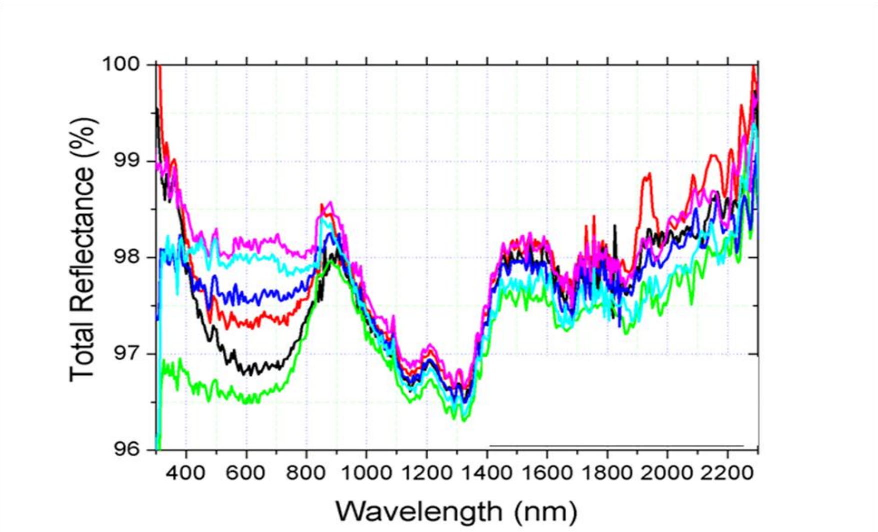

Fig.3. The spectral reflectivity of the 10µm X 10 µm (green), 20 µm X20 µm (black), 40 µmX40 µm(red) two dimensional and one dimensional 10 µm(blue) gratings. The upper two (blue, pink) curves are for non irradiated samples.

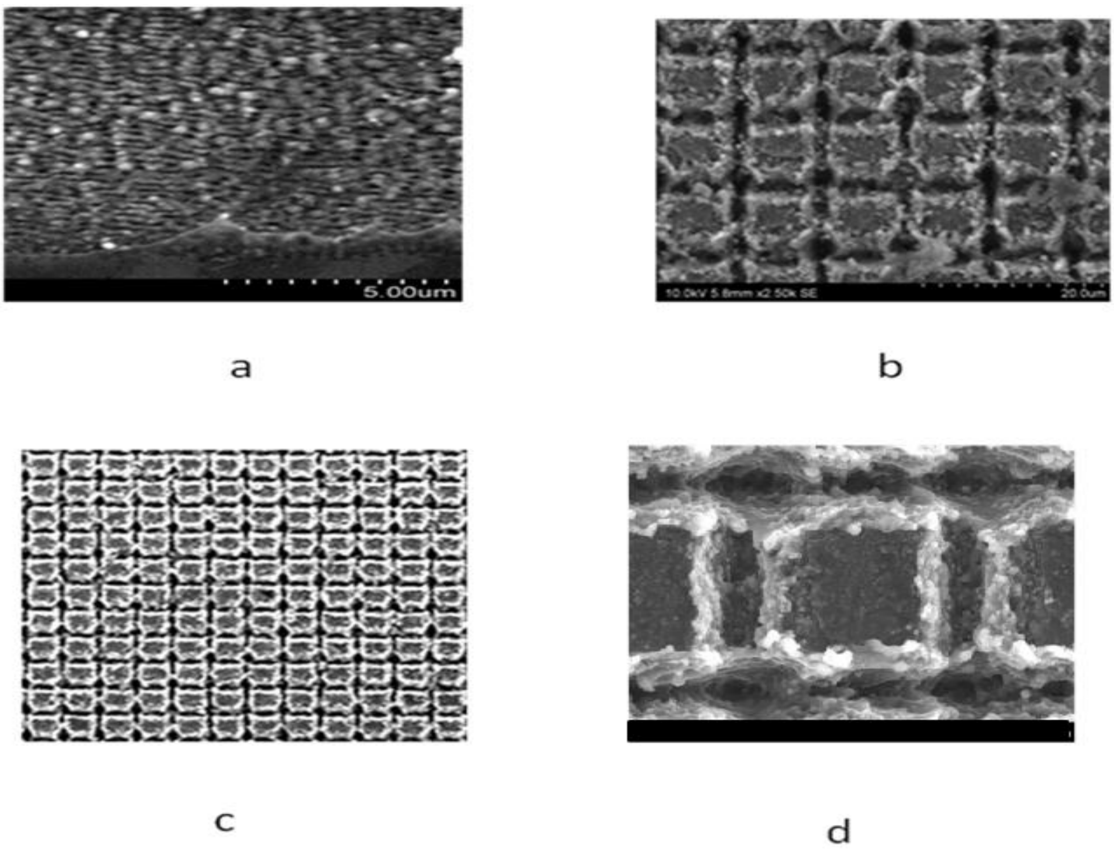

Fig.4. SEM images for 10 µm one dimensional irradiated sample (a), b, c and d for two dimensional 20 µm irradiated sample (d). The operating microscope voltage is 10kV