Optical absorption enhancement of thin-film amorphous silicon induced by femtosecond laser pulses for solar cell fabrication

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ABSTRACT

In this paper, we present a new method for direct-write laser fabrication of thin-film amorphous silicon (a-Si) on crystalline silicon substrate induced by femtosecond laser irradiation. Using megahertz frequency femtosecond laser pulses makes it possible to control laser fluence in the amorphization range of silicon under ambient condition. Finally, a thin-film of amorphous silicon is generated on the silicon substrate. It was observed a significant drop in light reflectance of the irradiated area (a-Si) in the visible range. This method can lead to promising solutions for solar cell fabrication techniques based on amorphorized silicon. In comparison with previous methods, our approach is single-step and both processing time and cost of fabrication are reduced.

A Scanning Electron Microscope (SEM), a Micro-Raman, Energy Dispersive X-ray (EDX) spectroscopy and an optical spectrometer were used to investigate the properties of the amorphorized thin layer on Si-substrate.

Keywords: amorphous silicon, thin film solar cell, ultra fast laser, photothermal effect, laser materials processing

1 INTRODUCTION

Rising energy prices are making alternative energy sources increasingly attractive. Solar energy is one of the most important and reliable energy sources, which has attracted a lot attention these days. However, a major drawback of current solar cells is their low efficiency, which is unavoidable with semiconductor-based solar cells. This is because the incoming light photons must have energy equal to the band gap energy of semiconductor to knock out an electron. If the photon has less energy than the band gap energy then it will pass through. If it has more energy than the band gap, then that extra energy will be wasted as heat.

Silicon is an ideal material for optics, optoelectronics and solar cell fabrication, because of its excellent optical, electrical and mechanical properties. A serious limitation of bulk crystalline silicon is that it does not emit light due to its indirect band gap. During the last decade, many efforts have been focused on converting monocrystalline silicon into multicrystalline silicon and amorphous silicon in order to increase light absorption [1-6]. In contrast to conventional fabrication techniques, these methods have some advantages but still they suffer from one or more problems such as high cost of fabrication, low efficiency and surface damage [7-9].

In this paper, we present a new method for direct-write laser fabrication of thin-film amorphous silicon (a-Si) on crystalline silicon substrate induced by femtosecond laser irradiation. Using megahertz frequency femtosecond laser pulses makes it possible to control laser fluence in the amorphization range of silicon under ambient condition. Finally, a thin-film of amorphous silicon is generated on the silicon substrate. It was observed a significant drop in light reflectance of the irradiated area (a-Si) in the visible range. This is attributed to increases in the absorption of incident light that can be used in photovoltaic or other light energy conversion applications. In comparison with previous methods, our approach is single-step and both processing time and cost of fabrication are reduced. This method can lead to promising solutions for solar cell fabrication techniques based on amorphorized silicon.

A Scanning Electron Microscope (SEM), a Micro-Raman, Energy Dispersive X-ray (EDX) spectroscopy and an optical spectrometer were used to investigate the properties of the amorphorized thin layer on Si-substrate.

2 EXPERIMENTAL SETUP AND FABRICATION PROCESS

Figure 1 shows the fabrication process induced by femtosecond high repetition laser pulses. First, silicon samples with the crystalline orientation of <100> are rinsed with pure water and aceton then they were irradiated with femtosecond pulses with pulse energy well below the ablation threshold.

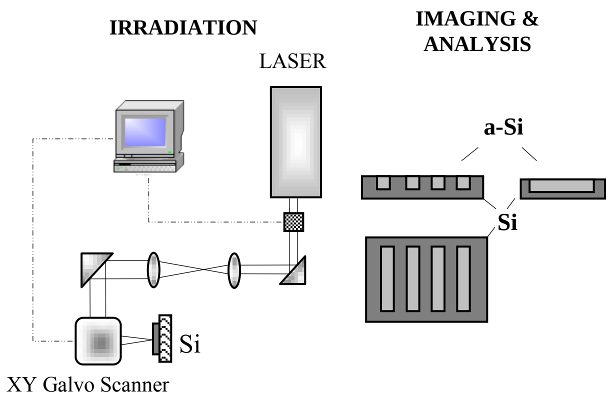

Fig. 1. Process of experiment and experimental setup.

The Femtosecond laser used in the study was a diode-pumped, Yb-doped laser system with the average output power of 11 W which emits laser pulses with a central wavelength of 1030 nm and frequency rate in the range between 200 kHz and 26 MHz. Laser pulses of 200 fs pulse duration are emited by this laser. The output beam diameter from the laser is 4.5 mm. By using a combination of a plano-convex (f=-100) and a plano-concave (f=200) lenses; the laser beam is expanded to9 mm; then the it is rotated to circular polarization by a quarter waveplate located in the beam path. Using an iris diaphragm the beam diameter is reduced to 8 mm right before entering into galvo scanner. A two-axis galvo-scanner was used for beam scanning since it has a high scanning speed (to 3000 mm/s). Due to focus the normal beam to the surface of silicon, scan lens with a focal length of 63.5 mm is used. The theoretical focused laser spot diameter (d_0) is approximately calculated from: $d_o \approx 1.27\ \lambda_o F/D$. [10] Where, F is the focal length of the scan lens, λ_o is the wavelength of the laser which is equal to 1030 nm and D is the laser beam diameter at the input of the galvo-scanner (8 mm). From this formula the theoretical spot size is 10.38 µm in diameter. During the experiment the spot size may change due to scatter and misalignment. The average laser power was measured to be 7-8.4 W at the repetition rate of 13 and 26 MHz. In this experiment the scanning speed of line features is in the range of 15-100 mm/s.

Irradiated Si samples were examined under a Scanning Electron Microscope (SEM), a Micro-Raman and Energy Dispersive X-ray (EDX) spectroscopy and an optical spectrometer to evaluate the optica/ and materials properties of irradiated area. Back scattering micro-Raman analysis was performed at room temperature using 532 nm line of Ar ion laser source.

3 RESULTS AND DISCUSSION

Using a high repetition laser pulses with the pulse duration in the range of 200 to 3500 femtosecond enables us to control the laser fluence in the amorphization range of silicon, and finally a thin film of amorphorized silicon of predetermined design is generated on silicon substrate (Fig. 2).

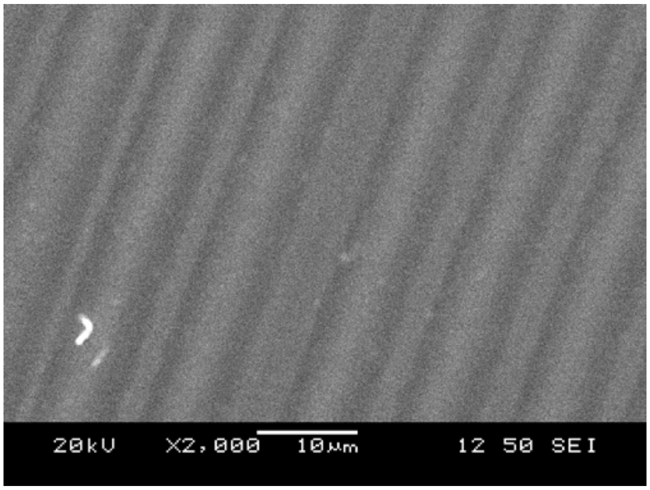

Fig.2. SEM image of irradiated area (a-Si)

After the laser excitement, the amorphous phase is formed on crystalline silicon substrate because of the rapid cooling, which is up to 10^{13} °C/s. [11]

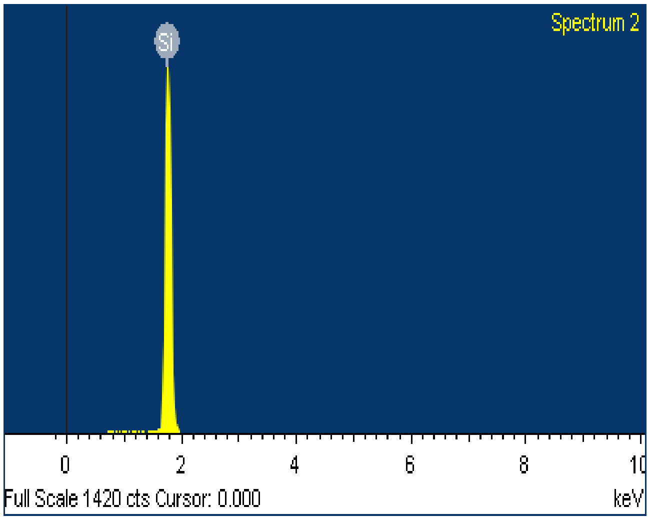

Fig. 3. EDX result of irradiated area

As shown in Fig.3, EDX analysis of the irradiated area excluded the possibility of any chemical compound formation such as silicon oxide or silicon nitride since no trace of oxygen or nitrogen is observed in the EDX results.

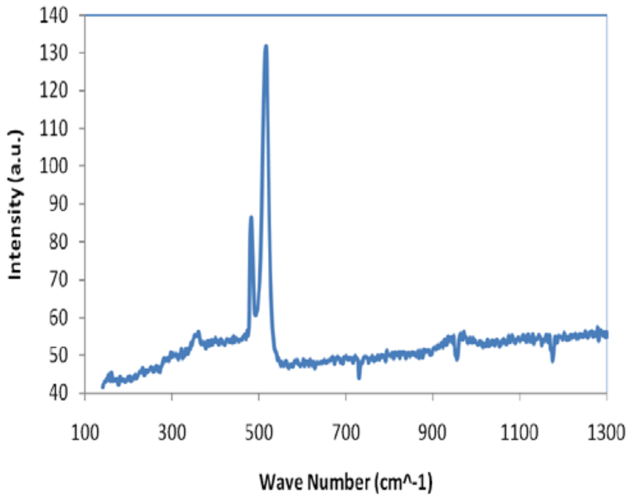

Fig. 4. micro-Raman spectroscopy graph of irradiated area

Figure 4, shows the micro-Raman spectroscopy results of the laser irradiated area which are believed to be made of amorphorized silicon.

Back scattering micro-Raman analysis was performed at room temperature using a laser source of 532 nm line of Ar ion. The Raman spectroscopic measurements on the processed samples show a sharp peak at the wavenumber of 519 cm^{-1}, which is the characteristic peak of silicon. Also, a secondary peak is observed at the wavenumber of 480 (cm^{-1}) which corresponds to amorphorized silicon [12].

Therefore, it can be concluded that the irradiated zone was converted from crystalline to amorphorized state.

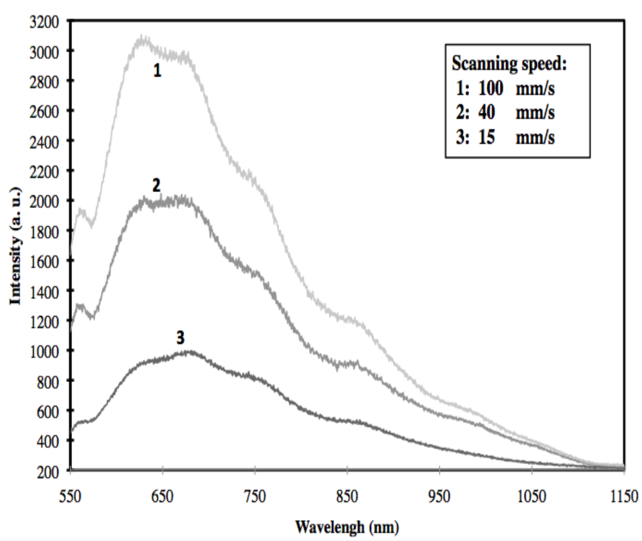

Fig. 5. Light spectroscopy of amorphorized area induced by laser pulses with different scanning speeds (15, 40 and 100 mm/s)

The optical properties of irradiated samples were investigated by measuring the reflection spectrums at different experimental condition using USB2000+RAD spectroradiometer (Ocean Optics, Dunedin, Florida, USA).

The light reflection was measured for wavelengths in the range of 550–1000 nm, with 1 nm increments. The resolution of the spectrometer is 0.35 nm and a full spectrum is captured and stored into memory every millisecond. As shown in Figure 5, the reflection of the amorphorized silicon surfaces using laser irradiation at wavelengths of 500–1000 nm is decreased by decreasing the scanning speed from 100 to 15 mm/s (increasing the pulse number)

As the incident pulse number increases more energy was deposited therefore the heat affected areas or volume become wider which results in increase of the amount of silicon converted from crystalline to amorphorized state [13].

Generally, amorphous structure has a higher absorption rate of light in comparison with the same material in crystalline state; it was reported in previous researches that amorphous silicon (a-Si) has a higher band-gap than silicon in crystalline state [14], thus amorphorized silicon can absorb the visible part of solar spectrum better than the crystalline silicon.

4 CONCLUSION

In this research, we propose a new method for single-step fabrication of thin film of amorphorized silicon on silicon substrate induced by high repetition femtosecond laser pulses under ambient condition which significantly reduce the reflectance of the surfaces and increase in the absorption of incident light that can be used in photovoltaic or other light energy conversion applications. Using high repetition laser pulses with the different pulse durations in the femtosecond range enabled us to control the laser fluence in the amorphization range and finally a thin film of amorphorized silicon could be fabricated on Si-substrate.

In comparison with previous methods proposed for a-Si thin-film solar cell, our proposed method is single step, there is no need for additive materials (and the amorphorized layer of silicon is grown from a Si wafer substrate) and finally, processing time and wafer damage are considerably reduced which lead to promising solutions for thin-film silicon solar cells fabrication.

Additionally, we investigatet the effect of the number of pulses on the heat affected area. It was found that by increasing the pulse number of laser pulses, the amorphorized volume become larger which leads to increase in light absorbtion.

Further studies in fabrication of thin-film solar cell based on amorphorized silicon will be focused on the generation of a combined oxide and amorphous surface with better optical properties (higher light absorbtion) by optimizing the laser parameters.

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