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The fabrication and characteristic investigation of microstructured silicon with different spike heights

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ABSTRACT

Microstructures with different spike heights are fabricated on the silicon surface by using femtosecond laser pulses. It is proved that the spike height of microstructured silicon has specific relations with fabrication parameters, including single pulse energy, pulse number, proportional relation between single pulse energy and pulse number under the same laser fluence, and ambient gas. Additionally, the light absorptions of microstructured silicon with different spike heights are compared. All these results are important for the optimal fabrication of surface-microstructure photovoltaic materials, such as solar cell, infrared sensor, etc.

1. Introduction

Microstructured silicon fabricated by femtosecond laser pulses can change the properties of single crystal silicon material dramatically [1,2]. Importantly, the light absorption property in a wide wavelength range (200–2500 nm) can be enhanced to more than 90% [3,4], which can be widely applied in solar cells [5], infrared sensors and optoelectronic detectors [6,7]. Therefore, many efforts have been devoted to the investigation of surface morphology and absorption property of microstructured silicon under different laser parameters and fabrication conditions, including the laser pulse duration [8,9], laser polarization [10], laser fluence [11], laser wavelength [12], gas medium and the gas pressure [13]. However, little investigations are about the evolution of spike height. According to the investigations before [14], the higher spike height can couple more incident light into the silicon, i.e., enhance the antireflection effect. Moreover, the multi-reflection of light between spikes are beneficial for improving the absorption from doping in the silicon substrate. Importantly, the geometric shape of spikes will not be changed during the later annealing processes, which is indispensable during the manufacture of solar cells or infrared sensors—such as ohmic contact, electrode preparation and passivation processes. This means that the capacity of antireflection and absorption contributed by spike height can be reserved well, which is important for the improvement of the photovoltaic material efficiency. Therefore, in this paper, we experimentally investigated the average spike height of microstructures as functions of single pulse energy, pulse number, proportional relation between single pulse energy and pulse number under the same laser fluence, and ambient gas.

2. Experimental setup and measuring method

We used a Ti:Sapphire laser system, typically 800 nm, 45 fs, 1 kHz, and the spatial profile of laser spot was nearly Gaussian. After focused by a convex lens ($f=100$ cm), the laser beam was delivered into the vacuum chamber through a 0.4 mm window. The base pressure of vacuum chamber was less than 10^{-4} Torr, and it can be backfilled with gas. The vacuum chamber was fixed on X and Z-axes translation stage to realize the two dimensional movement. The (100) silicon wafer (phosphor doped, 500 μm thickness, n type with resistivity between 0.01 and 0.02 Ω cm) in the vacuum chamber was put vertical to the incident direction of laser pulses and before the laser focal spot, in order to avoid the damage of high laser energy to window. Correspondingly, the spot of laser beam irradiated on the sample surface was monitored by a CCD camera (WinCamD-UCD12) and its diameter was set at ~300 μm in the entire experiment by changing the distance between the wafer and the lens. Furthermore, for the intensity adjustment, we used a quarter-wave plate and a polarization beamsplitter to provide linear and adjustable attenuation. A beam shutter (SH05, Thorlabs) was used to control the number of laser pulses. After irradiation, the average spike height of microstructure was measured by using a scanning electron microscope (SEM, Tescan,

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VEGA II). The height of spikes were read from the SEM pictures, and a factor of $\sqrt{2}$ was multiplied because the sample was titled 45° angle for the measurement. Each value of spike height was the average result of 5 points, and the measuring error was ~1 μm.

3. Experiments and discussions

3.1. Single pulse energy

In the experiments, with ambient gas of SF_6 at a pressure of 500 Torr, we investigated the dependence of average spike height

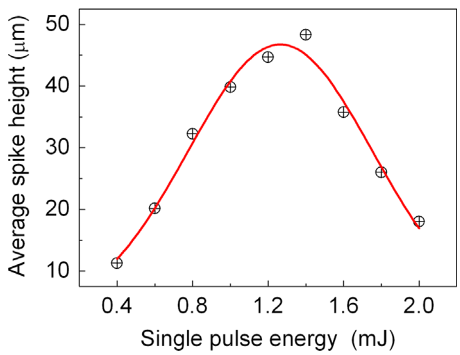

Fig. 1. The average height of spikes as a function of single pulse energy. The circles stand for the experimental data; solid line is the nonlinear fitting curve (Gauss function).

of microstructured silicon on the single pulse energy first. The pulse number was fixed at 1000. The corresponding results are shown in Figs. 1 and 2.

From Fig. 1 we can see that, as the single pulse energy increases from 0.4 to 2 mJ, the average spike height increases first and then decreases, in which the highest spike height can be obtained at the single pulse energy of 1.4 mJ. Usually, the higher the incident laser energy, the stronger the material ablation is. Therefore, it may be thought that the spike height increases with the increase of incident laser energy. However, our experimental results show that when the irradiated pulse number is fixed, there exists an optimal single pulse energy for the maximum of spike height.

For explanation, the entire process of microstructures formation should be considered firstly [15]: when laser beam irradiates on the silicon surface, part of light is scattered by the mirror surface of silicon wafer, which then interferences with the incident beam and results in inhomogeneous energy deposition. The deposited energy ablates and melts the silicon material at non-uniform depth, creating capillary waves. As the increase of ablation and melting time, these capillary waves gradually become ripple pattern, then quasi-periodic array of beads, and finally conical spikes. Therefore, the proper increase of single pulse energy can promote the material ablation and hence contribute to the increase of spike height.

During this process, the single pulse energy determines the ablation and volatilization degree of silicon material; the pulse number represents the interaction time between laser and silicon, which determines how much energy can be transmitted into the material interior. Therefore, when the pulse number is fixed,

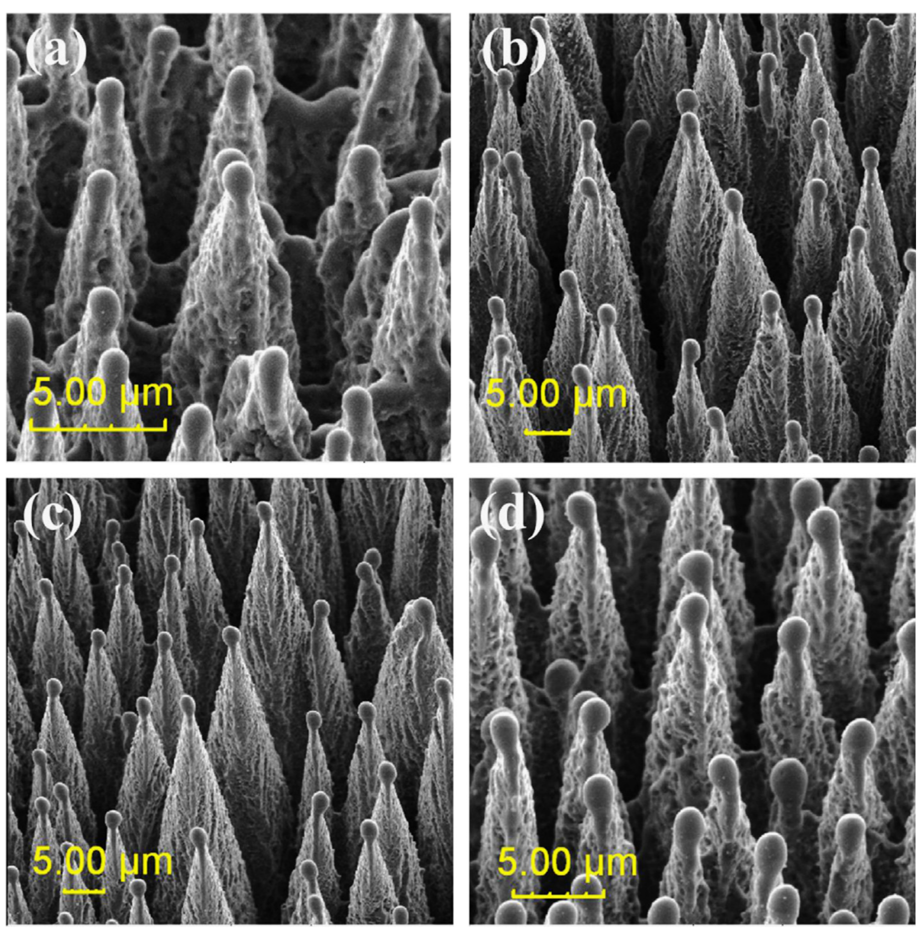

Fig. 2. SEM images of microstructured silicon fabricated with different single pulse energy: (a) 0.4 (b) 1.0 (c) 1.4 and (d) 2.0 mJ. Each SEM image is taken at a 45° angle to the surface normal.