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The effect of laser wavelength on the formation of surface-microstructured silicon

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ABSTRACT

We experimentally investigated the properties of the surface-microstructured silicon fabricated by 800 and 400 nm laser pulses. We found that as the increasing of pulse number, the average height of spikes fabricated by the 800 nm laser pulses increases more than that of the 400 nm laser pulses. This is due to that the formation of the conic spike structure is originated from the conical distribution of incident laser energy in the sample, and the height of cone is proportional to the penetration depth of the laser pulse. Additionally, by comparing the samples which have similar average height of spikes, we found that the denser interval of spikes fabricated by the 400 nm wavelength laser pulses has higher absorption coefficient than that of 800 nm laser pulses. These results are beneficial for the preparation of high absorption surface-microstructured silicon.

1. Introduction

Surface-microstructured silicon has attracted both experimental and theoretical interest for its high absorption efficiency in a wide wavelength range (0.2~2.5 μm) [1], which make it be a novel candidate structure for various applications, such as solar cells [2], terahertz emission [3], sensors and optoelectronic detectors [4,5] etc. It is found that its absorption property is strongly dependent on the morphologies formed on the silicon surface. Therefore, lots of efforts have been devoted to the fabrication of surface-microstructured silicon for obtaining different surface morphologies. In the past work, many experimental parameters including the laser fluence [6], pulse width [7], polarization [8], pulse number [9], gas medium [1], and gas pressure [10] have been adjusted to obtain the different surface-microstructured silicon, and the corresponding results present different absorption property. However, up to now, no investigation was focused on the detail relation between surface morphology and the laser wavelength. As the laser pulses with different wavelength have different penetration ability in silicon, therefore the surface-microstructure fabricated by different wavelength laser as well as their optical properties must be different.

In this paper, we focused our researches on the micro-spike structure fabrication on silicon substrates by using different wavelength laser pulses. The morphologies of the structures fabricated by different laser pulses were investigated by scanning electron microscope (SEM). The relationship between the structures and optical properties, such as reflection, absorption etc. also be discussed in detail.

2. Experiment

In the experiments, we used a Ti: Sapphire amplifier to produce 800 nm, 130 fs pulses at 1 kHz (*Coherent Inc.*). The laser beam was focused by a convex lens ($f = 100$ cm), and delivered into the vacuum chamber (the base pressure was less than 10^{-4} Torr). To generate the 400 nm laser pulse, a 0.2 mm-thick nonlinear optics crystal Beta-Barium Borate (BBO) was put after the lens. Several mirrors with the high-reflection coating at 400 nm and antireflection coating at 800 nm were used to obtain the pure 400 nm laser. Then, we can utilize the 800 or 400 nm laser pulse for the microstructure fabrication. The pulse duration of 400 and 800 nm laser pulses could be considered as the same due to the thickness of BBO crystal was very thin. The vacuum chamber was mounted on a three-axis translation stage. The (100) silicon wafer (*n* type with phosphor doped and resistivity between 0.01~0.02 Ω cm) in the vacuum chamber was put vertically to the incident direction of laser and the diameter of each laser spot focused on the sample surface was about 300 μm in the whole experiments. The ambient gas SF_6 was filled into the chamber until the pressure obtained 500 Torr. The pulse number injected on the sample was controlled by a beam shutter (SH05, *Thorlabs Inc.*). Finally, the fabricated sample was analyzed by a SEM (*Tescan*), and UV–VIS spectrum (Lambda 1050, *PerkinElmer*).

3. Results and discussion

In order to understand the effect of laser wavelength on the formation of surface-microstructured silicon, we firstly measured the height change of spikes as a function of pulse number. Due to the different characteristic of 800 and 400 nm laser, the incident energy of the 800 and 400 nm laser pulses were all chosen as 0.106 kJ/cm^2

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per pulse to make sure the microstructure can be both effectively formed and no defects appear on the sample surface during the whole change range of pulse number [11]. The corresponding results are shown in Fig. 1. We can see that the average height of spikes increases monotonically with the increasing of pulse number for both the 800 and 400 nm laser pulses. This is determined by the formation mechanism of the surface-microstructured silicon. We know that as the increasing of pulse number, the interaction time between laser and silicon increases and more energy can be transferred to the deep of silicon, which causes the melt of material under the surface, promoting the formation of conic spikes [12]. Therefore, the corresponding spike height increases monotonically. Furthermore, it can also be seen that the increasing rate of the spikes fabricated by 800 nm laser pulses is much quicker than that of the 400 nm laser pulse as the increasing of pulse number. From Ref. [13], we have known that when laser energy is absorbed by silicon material, the distributed energy per unit volume is inversely related to the laser wavelength. Then, for laser pulses with the shorter wavelength, its energy gathered in a smaller conical region, while for laser pulses with the longer wavelength, its energy can go deeper into the silicon and then distributes in a lager conical region. Therefore, when the conic spikes are well formed, every energy caused by every added pulse makes the average height of conic spikes fabricated by the 800 nm laser pulses is higher than that of 400 nm laser pulses. Finally, we can observe the higher increasing rate of spikes fabricated by the 800 nm laser pulses.

Additionally, it has been proved [14] that the spikes height of surface-microstructured silicon mainly determines its absorption coefficient. However, in our experiment, the conic spikes which fabricated by two different wavelength laser pulses show different results. In our experiments, we choose the samples which have similar spike height fabricated by the 800 and 400 nm laser pulses with the pulse number of 1000 respectively for the absorption evaluations (consistent with Fig. 1). The measurements were performed with a Lambda 1050 spectrophotometer, in which the absorptance (A = 1-R-T is determined by the transmittance (T) and reflectance (R). The corresponding results are shown in Fig. 2.

We can see clearly that the two samples both have a dramatically small reflectance and transmittance over the entire measured spectra. In addition, we noticed that although the average height of spikes fabricated by the 400 nm laser pulses is slightly lower than that of the 800 nm laser pulses (3.1 μm VS 3.4 μm), however, the absorptance of them are opposite (~95% VS ~90%). By comparing the surface morphology of the samples fabricated under both cases, it is found that the nanostructures distributed on these spikes are almost the same; the only difference is that the interval between spikes fabricated by the 400 nm laser pulses is denser than that of 800 nm laser pulses. Therefore, we presume that this phenomenon is mainly dependent on the different interval density of spikes. In order to prove this, we investigated

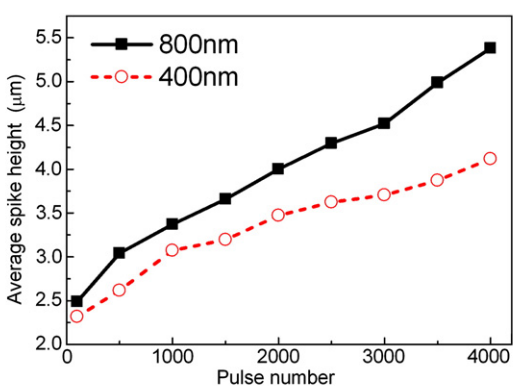

Fig. 1. (Color online) The average height change of spikes fabricated by the (a) 800 (b) 400 nm laser pulses as the function of pulse number. The incident laser energy was 0.106 kJ/cm^2 per pulse.

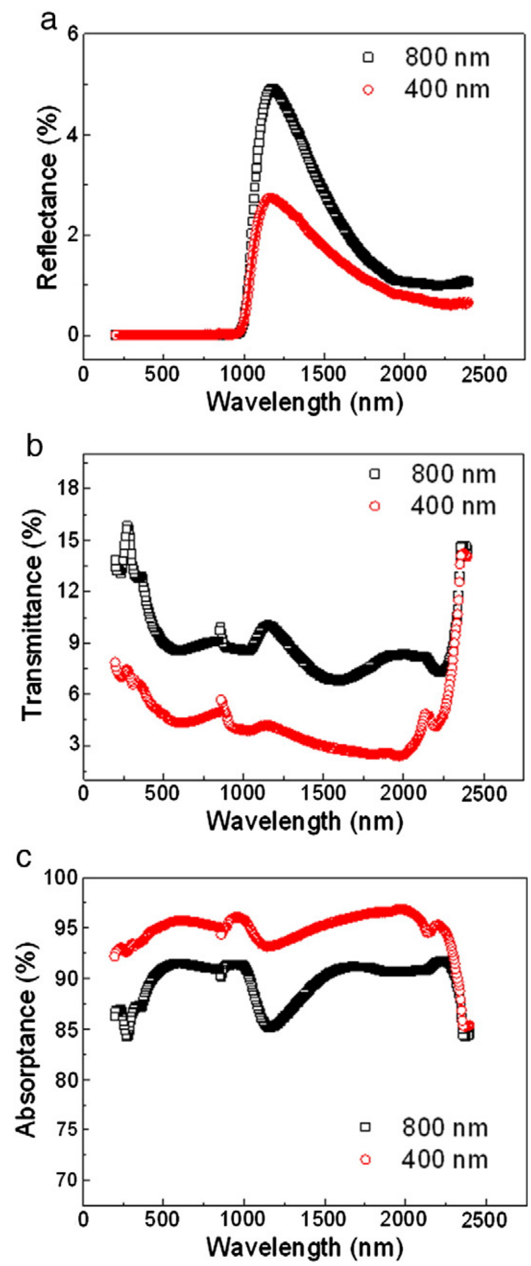

Fig. 2. (Color online) (a) Reflectance (b) transmittance and (c) absorptance of surface-microstructured silicon etched by the 800 and 400 nm laser pulses.

the corresponding interval change between spikes as the increasing of pulse number, as shown in Fig. 3.

We can see that the interval between spikes increases with the increasing of the incident pulse number under both cases. Furthermore, the increase rates of the interval for both fabricating lasers are almost the same, which is different from the increasing rates of the spike height under the same pulse number. From the process of microstructures formation [12] we know that: when laser beam irradiates on the silicon surface, the interference between the incident beam and light scattered by minor surface of silicon wafer results in inhomogeneous energy deposition. When the incident energy exceeds both the ablation and melting thresholds for silicon, ablation and melting occur at non-uniform depth, creating capillary waves with the period of laser wavelength. As the increase of ablation and melting time, these capillary waves gradually become the ripple pattern, then quasi-periodic array of beads, and finally the conical structures. Therefore, the interval between spikes is originated from the interval

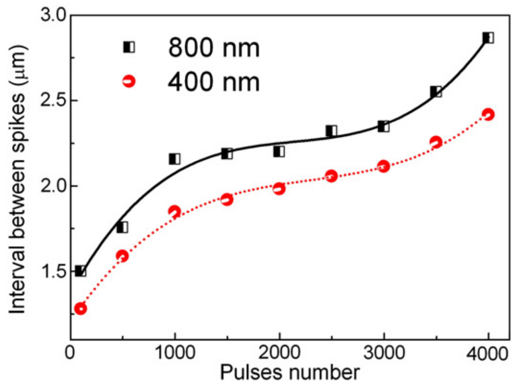

Fig. 3. (Color online) The interval change between spikes fabricated by the 800 and 400 nm laser pulses as the function of pulse number. The solid (800) and dashed (400) lines are the corresponding three-order polynomial fitting of experimental data.

of initial capillary waves, which is proportional to the wavelength of the incident laser. Then, the interval of original spikes increases with the continuous ablation and melting processes. Thus, the final interval between spikes depends on the driving laser wavelength and the pulse number. The longer wavelength as well as increasing pulse number produces the larger interval. On the other side, it is well known that the extremely high absorption ability of the surface-microstructured silicon mainly comes from the light trapping effect. The sample with denser spike interval should have higher light trapping ability, which causes the sample fabricated by 400 nm laser pulses has a higher absorptance than that of 800 nm laser pulses eventually.

4. Conclusions

In conclusion, we fabricated a micro spike structure on the n-type silicon surface by two different laser pulses and explained the formation mechanism. By varying the laser wavelength and pulse number, we can control morphology of spike structure successfully. We found that as the increasing of pulse number, the average height of spikes fabricated by 800 nm laser pulses increases quicker than that of the 400 nm laser pulses, which is caused by the different penetration depth of different wavelength laser. Furthermore, we also found that the absorption of spike-structured silicon is not only effected by the height of spikes, which is well known by the recently reports, the interval of the spikes plays an important role as well. By the precise control, a significant improvement (approximately 5% from 200 nm to 2000 nm) of absorptance was achieved. These results are promising and useful for promoting the development of solar cells, sensors, optoelectronic detectors and the interrelated interdisciplinary subjects.

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