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The evolution of ablation area induced by femtosecond laser

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Abstract

Surface damage morphologies were studied by irradiating with pulses (fluence of 1.13 J/cm^2) in succession. Investigation the dependence of the ablation regions on the number of the laser pulses, a silicon(100) plate was irradiated by the femtosecond laser in the range of 50 to 1000 pulse, with the fluence of 1.13J/cm^2. The ablation regions had been divided into several parts, which depend on the number of pulses. The formation of columnar structure was discussed also.

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Key words: Femtosecond laser; evolvement; Ripples;Columnar; Silicon

1. Introduction

The emergence of ultrashort laser pulses such as femtosecond laser has revolutionized the field of laser–matter interaction in recent years.[1] The laser processing of silicon has received significant attention because of its potential in a micromachining application. Silicon, as the most important material for the semi-conductor industry useful for MEMS/NEMS, microchannels, microholes, periodical submicron gratings and nanophotonics[2], presents some specific characteristics when irradiating with ultra-short laser pulses at low fluence. Laser-induced surface structuring on silicon has been extensively studied [3-5]. Comparing to long-pulse laser[6-8], ultra-short pulsed laser radiation had been shown to be highly effective for precision material processing and surface micromodification based on rapid creation of vapor and plasma phase, negligible heat conduction ,and the absence of liquid phase, in addition to these advantages, periodic nanostructures were self-organized in the femtosecond laser irradiated area [9-11]. Recently, the formation of microstructures (ripples, columns, and cones) on Si samples in case of multiple pulse irradiations on stationary samples has been reported by several research groups[12]. Laser-induced periodic

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surface structures (in general was LIPSSs) have been observed substantially near ablation threshold of material. Several mechanisms for formation of ripples had been proposed, such as the acoustic wave mechanism[13],the generation of second-harmonic[14], surface tension gradient[15], interference between the incident light/surface wave and the Boson condensation hypothesis[16,17].The theory of interference between the incident light/surface wave was the most popular mechanism which had been used to interpret the formation of the periodic ripple structures as usual[18]. Picosecond and femtosecond laser induced phase transitions in silicon had been studied during the last decades[19,20]. These phenomena with practical application, for example, in high density optical memory recording systems where the difference in optical reflectivity between the crystalline and amorphous phase of the same material was utilized.

At experiment, we perform the detailed study of the evolvement of ablation area by femtosecond laser on the surface of silicon.

2. Experimental

At experiment, we use an amplified Ti:sapphire laser system based on the chirped pulse amplification technique that generates 130 fs laser pulses at a 1kHz repetition rate and with central wavelength of 800nm. The laser was running at a repetition rate of f = 1kHz. The energy output was controled with an energy attenuator. With a power meter to measure the average power of the pulses generated. Take advantage of delay generator (Stanford Research, DG535) to control the interval time of femtosecond laser, then the number of pulses could be controlled accurately, here, we selected a predefined number (N) of pulses per spot (50,100,200,400,800,1000). The laser beam was focused on the surface of the sample which was mounted on a computer- controlled x–y translation stage with a fused silica lens with 200-mm focal length. The silicon (100) wafer, with a thickness of 400μm, was subjected to different pulse number at fixed pulse fluences. All experiments were performed in air with normal incidence. The morphology of the irradiation area was examined using a scanning electron microscope (SEM) which without further treatment. For a Gaussian spatial beam profile with a $1/e^2$ beam radius ω_0 was about 21.2μm which had reported previously[21], the maximum laser fluence at the cross-sectional surface ϕ_0 was proportional to the incident laser pulse energy E which could be obtained as follow equation $\phi_0 = 2E/\pi\omega_0^2$ .At this experiment, the pulse energy was about 155μJ , which accordance to the fluence was 1.13J/cm^2. Coyne et al.[22] analyzed the interaction of ultrashort pulses with wafer-grade silicon in air using an optical and electron microscope and suggested that the optimum fluence condition for precise and accurate machining of silicon was in the range of 0.8–1.5 J/cm^2.It was obviously that fluence of irradiation laser was near the threshold of the silicon.

3. Results and discussion

Fig.1 shows the microphotographs of structure on the irradiation area at the pulse number of 50,100,200 and 400 with a constant pulse fluence of 1.13J/cm^2. Images had been taken directly after processing without further cleaning. As shown in Fig.1, the irradiation area could be divided into five regions. Fig.1(b1) and (c1) were the center of irradiation area of Fig.1(b) and (c), respectively. Obviously, there was no periodic structure appearance. The confused raindrop-like nanostructure covered the whole region I, however, on the developed region II, the ripple-like structure was obtained with periodic of about 1.4μm as shown in Fig.1(e). The ripple structure was not like the classical ripple structures which had been extensively researched.[23] According to the widely used formation theory of ripple, the periodic was in the same order of the wavelength of irradiation laser pulse, here was about 800nm.In experiment, the broaden of the ripple was due to the combination of adjacent ripple structures when irradiation with the multiple pulses. The crack and melted on the region III was observed, this was due to the accumulation of multiple pulse radiation the same region repeat. Also, by the reflectivity, it was determined that region Ⅳ without any phase change. There was many scraps from region III sedimentation on the surface of region Ⅳ due to shock wave of radiation pulse and the gravitation. In the region Ⅴ, there was a phase change since there was a difference in reflectivity from SEM. With further increasing the number of pulse to 400, the region III was more evident as Fig.1(d) shows.

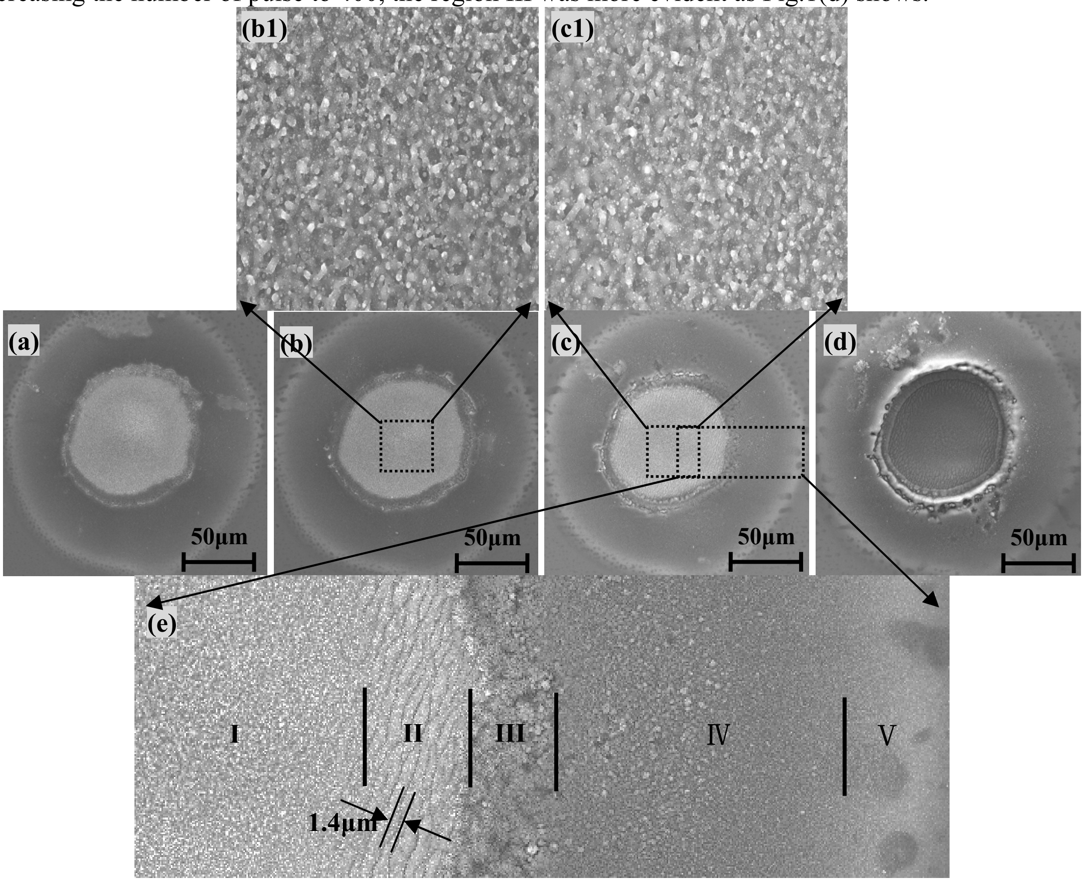

Fig.1 SEM micrographs of the irradiation area at the pulse fluence of 1.13J/cm^2 with different pulse number, (a) 50;(b)100;(c)200;(d)400;(e) the irradiation region plots of (c); (b1) the central area of (b);(c1) the central area of (c).

With increasing number of pulses at the same laser fluence created different surface damage morphologies on silicon, as seen in Fig.2. As show in Fig.2(c), the irradiation area was divided into six regions. It was obviously that the number of divided regions were increased with the increasing of the number of pulses. In additional, at higher number of pulses, the surface damage area became larger, see Fig.2(a) and Fig.2(b) after irradiation with 800 and 1000 pulse respectively. In the central area of region I, the columnar structure was formed with width was about 2.2μm which covered with many nanodots as shown in Fig.2(b1). Column formation in crystalline silicon had been observed in the past with different pulse duration, laser fluence, and the ambient environment. In a recent work[24] on fs laser with crystalline silicon, sharp spikes were observed when the material was irradiatied in SF_6 or Cl_2 environment but not in vacuum, N_2 or He. The chemical reactions were suggested to be essential for formation of sharp spikes. At this experiment the formation of the columnar structures was due to the accumulation of the multiple pulses. The previous pulse created nanostructures on the central of irradiation area as shown in Fig.1, which will increase the absorption and modulate the distribution of the pulse energy on the central area. So, the threshold of formation columnar structures was higher than that for ripple and other structures. In region II, the width of the ripple-like structures was about 1.9μm greater than that in the region II of Fig.1(e). Interesting, the ripple-like structures was covered with classical ripple structures with periodic width was about 800nm, which consistent to the theory as shown in Fig.2(b2). Further,with increase the pulse fluence, the melted and oxidation region was emergence as shown in region III and Ⅳ, respectively. With increasing of the pulse number, the area of no phase change region was reduced gradually, as shown in region Ⅴ of Fig.2(c). The next regions (the no phase change) could be similarly explained by the diffraction of the beam.

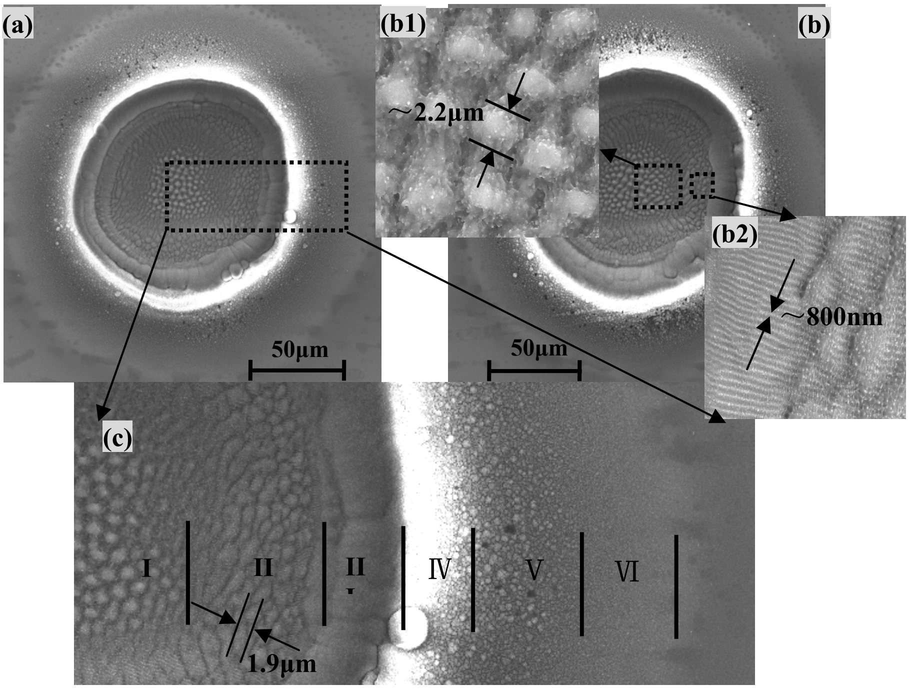

Fig.2 SEM micrographs of the irradiation area at the pulse fluence of 1.13J/cm^2 with different pulse number, (a) 800;(b)1000;(c) the irradiation region plots of (a); (b1) the columnar structure on central area of (b);(b2) the periodic ripple structures on the periphery of ablation area of (b).

4. Conclusion

At experiment, we investigated the femtosecond laser-produced microstructures on the silicon surface. The effection of pulse number on the evolvement of ablation area when the pulse fluence was kept consistent was presented. We had found several different types of surface damage morphologies. When pulse number at the range of 50 to 400, five regions were observed. With further increasing the pulse number above 800, the irradiation area could be divided into six regions, also, the pattern of columnar structure was formed in the central region of irradiation area. The phenomenon of evolvement of irradiation area with increasing the pulse number could been explain by the accumulation of multiply pulse radiation.

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