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Formation of periodic ripples through excitation of ∼1 μm spot using femtosecond-laser Bessel beam on c-Si

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ABSTRACT

We investigated the effect of periodic trenches (ripples) formed through sub-micrometer machining by focusing linearly polarized femtosecond laser pulses with conical axicons to a ∼1 μm spot on c-Si in vacuum. The machined patterns were compared with the fluence distribution in the Bessel zone observed with a CCD camera. A fluence well below the ablation threshold successively forms a modification pattern, periodic ripples, and a crater with increasing number of laser shots. The rippled zone covers an area larger than the expected domain of laser modification and extends along the polarization direction of the laser beam. In contrast, a circularly polarized laser beam forms a round hole with a clear edge and does not leave a ripple-like corrugation. In comparison with a laser beam with circular polarization, a laser beam with linear polarization having the same fluence forms a crater with less laser shots because of pre-formed ripples but at the expense of degrading the machining quality. These results suggest that the formation of ripples results from surface plasmon waves generated at the peak fluence point. The periodic ripples can potentially be applied in the fabrication of gratings and photonic crystals.

1. Introduction

Femtosecond laser machining has been successfully utilized for the micrometer-scale machining of solid materials over the past two decades, and it has now reached the range of sub-micrometers or tens of nanometers for semiconductors [1–4], metals [5,6], and dielectrics [7,8]. Our previous work showed that the sub-micrometer ablation of c-Si by linearly polarized femtosecond laser pulses focused with conical axicons is always associated with the formation of periodic trenches (ripples) [3] as the laser fluence is close to the ablation threshold. The periodic ripples formed with sub-micrometer machining deteriorate the machining performance; however, they are rather beneficial to form trenches of ∼100 nm width by scanning the laser beam in the direction perpendicular to the direction of laser polarization [9]. Potential applications for these periodic ripples include the fabrication of gratings and photonic crystals.

As sub-micrometer machining is performed with a laser fluence close to the ablation threshold, investigation of the solid-surface metamorphism induced by the laser irradiation is important. Some published works have reported detailed analyses of the solid surface exposed to a fluence below or close to the ablation threshold [10]. According to the results of those works, c-Si preserves the laser-affected zone formed by irradiation at a fluence well below the ablation threshold in the form of metamorphism and surface corrugations.

In the present work, we investigate the effect of ripple formation associated with sub-micrometer machining using a Bessel beam on the micromachining performance with a fluence less than the ablation threshold. Particular attention is paid to the morphology of the rippled zone in relation to the excitation intensity at a spot with a diameter of ∼1 μm, which is comparable to the period of the ripple, to gain insight into the origin of the periodic ripple patterns.

2. Experimental

The experimental setup of the present study was the same as that of our previous work on the femtosecond-laser sub-micrometer machining of Si [3]. A laser-beam-focusing optical system consisting of a tandem arrangement of two axicons and a convex lens forms a Bessel zone ∼40 mm away from the apex of the axicon, where the sample surface was placed. The sample, c-Si with a surface orientation of (1,0,0), was placed in a vacuum chamber at a residual pressure of 10^{-6} Torr. The laser was operated

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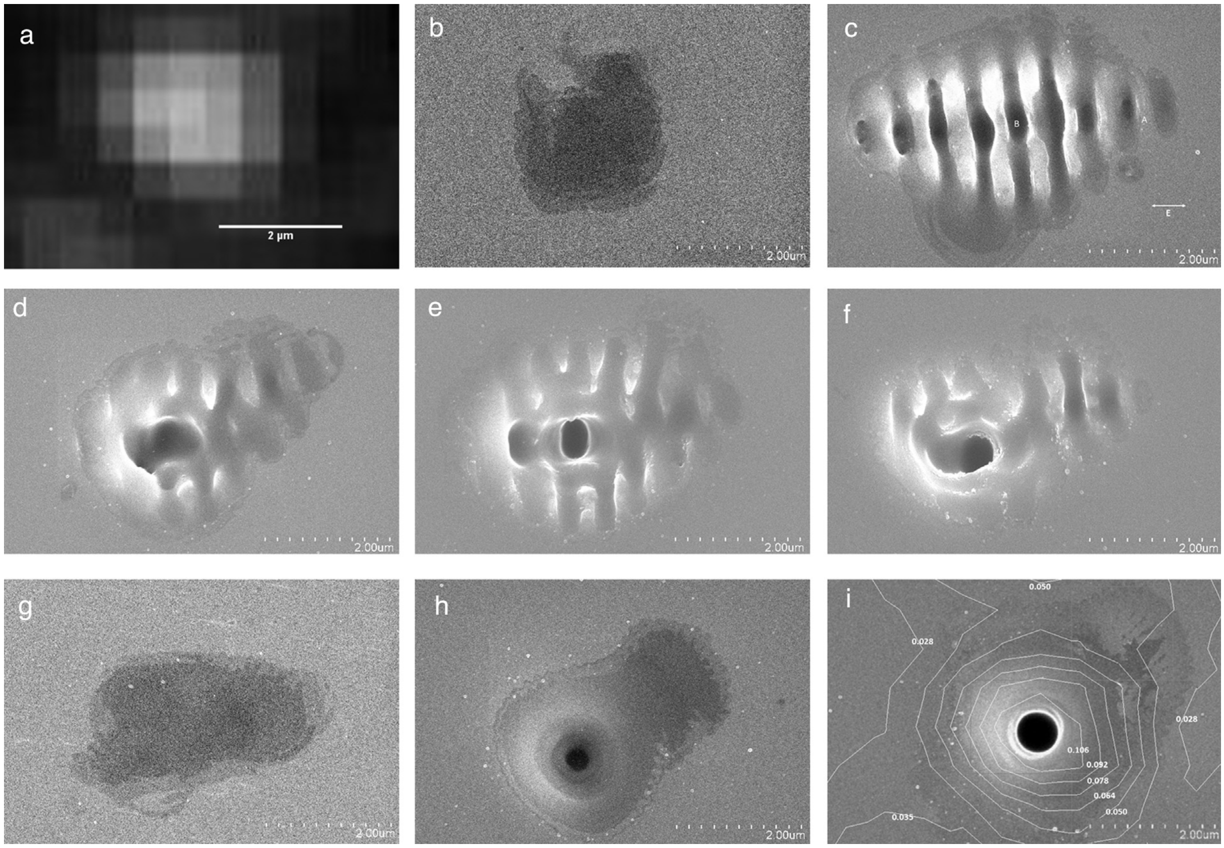

Fig. 1. (a) Central-spot pattern of the Bessel Gaussian beam. Laser-induced pattern formed by a peak fluence of 0.113 J/cm^2 at 786-nm wavelength at linear polarization after (b) 32 shots, (c) 60 shots, (d) 479 shots, (e) 958 shots, and (f) 1916 shots. Same as (b)–(f) but at circular polarization with (g) 32 shots, (h) 958 shots, and (i) 1916 shots.

at a repetition rate of 479 Hz with a wavelength of 786 nm and pulse duration of 160 fs. The polarization of the focused beam was changed from linear to circular by placing a $\lambda/4$ plate before the focusing optics to investigate the polarization-dependent features of the laser-irradiated surface. The ablated patterns were observed using a scanning electron microscope (SEM).

The fluence distribution on the sample surface was evaluated using a CCD camera to obtain a pattern of the Bessel zone with $\times$19 magnification. The sensitivity of the CCD camera was absolutely calibrated with a femtosecond mode-locked fiber laser (Femto Light, IMMURA America) to obtain the fluence distribution in the beam profile from the count rate at each pixel.

3. Results

Fig. 1(a) shows an image of the central spot of the Bessel beam pattern obtained using the CCD camera at a magnification of $\times$19. The square blocks in the pattern correspond to the optical intensity at each pixel. Owing to the non-uniform divergence of the laser beam, the intensity distribution in the spot is slightly oval. Fig. 1(b), (c), (d), (e), and (f) shows SEM images of the ablated patterns formed by the linearly polarized laser beam with a peak fluence of 0.113 J/cm^2 and the laser-shot numbers of 32, 60, 479, 958, and 1916, respectively. The laser-induced pattern in Fig. 1(b) appears as a stain, indicating that the metamorphism of c-Si has started. On increasing the number of laser shots, the laser-affected zone evolves into a ripple pattern, as shown in Fig. 1(c). Similar features were observed at 120 and 240 shots. The commencement of crater formation is observed in Fig. 1(d), and the opening and depth are further increased in Fig. 1(e) and (f). The crater is finally shaped with the oval opening. All these laser-induced features are limited within the central bright spot of Fig. 1(a). At circular laser polarization, a laser-induced stain-like pattern is formed with low shot numbers such as 32, as shown in Fig. 1(g), which covers an area larger than that obtained with linear polarization. A round dip starts forming with an increased number of laser shots, such as in Fig. 1(h) at 958 shots, and the dip is surrounded by the laser-induced pattern. Further increase in the number of laser shots to 1916 deepens the hole with a diameter of ~600 nm, as shown in Fig. 1(h) with equifluence contours.

The effect of laser irradiation with a smaller fluence is compared by reducing the peak fluence to 0.066 J/cm^2. Fig. 2(a) shows the beam pattern in this experiment, which exhibits an oval distribution of the fluence with the longer axis oriented vertically because of the uneven beam divergence. Fig. 2(b) and (c) shows the laser-induced patterns formed on the sample surface at linear polarization with cumulative shot numbers of 958 and 1916, respectively. Low numbers of laser shots such as 32, 60, 120, and 240 did not form recognizable laser-induced features. Equifluence contours are superposed on Fig. 2(c). The stain-like patterns of these results do not match the fluence distribution of the beam pattern; instead, a horizontally extending feature with a weak periodicity of ~930 nm surrounded with filamentary patches, as shown in Fig. 2(c), is characteristic. Fig. 2(e) shows the laser-induced pattern formed with 958 shots at circular polarization. The laser-induced pattern is rather vertically prolonged and oval, corresponding to the fluence distribution at the center of the beam profile, but with no periodic features.

4. Discussion

The evolution of laser-induced patterns at linear polarization with a peak fluence of 0.113 J/cm^2 for increasing number of laser