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SILICON SPALLING DESTRUCTION AND ABLATION IN AIR UNDER BICHROMATIC LASER RADIATION

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Abstract. The ablation of silicon in air under one- and two-pulse nanosecond laser irradiation with wavelengths of 355 and 532 nm is studied experimentally. The specific mass removal, the spectra of the near-surface plasma, and the microstructure of the surface of irradiated targets are investigated depending on the power density of the laser radiation and the time interval between laser pulses. The features of ablation and spalling destruction of irradiated silicon planar targets, as well as the formation of near-surface plasma, have been established.

1. INTRODUCTION

The laser effect on silicon wafers is being actively investigated to identify effective modes of their modification and processing due to the widespread use of silicon in microelectronics /see Yoo J.H. et al. 2000, Bonse J. et al. 2002, Bovatsek J.M. et al. 2010, Galasso G. et al. 2015/. Researchers associate the mass removal from the silicon surface under nanosecond laser action with the process of explosive boiling /see Yoo J.H. et al. 2000, Bovatsek J.M. et al. 2010, Galasso G. et al. 2015/. Femtosecond laser exposure to silicon revealed amorphization, melting, crystallization, evaporation, ablation and the formation of periodic structures /see Bonse J. et al. 2002/. It is shown that laser pulses shorter than 500 fs do not provide advantages for silicon processing. The results of laser exposure to materials depend on many parameters, including the wavelength of laser radiation. Therefore, the use of bichromatic laser radiation makes it possible to influence the efficiency of laser ablation of materials and the formation of near-surface plasma /see Chumakov A.N. et al. 2014/.

The purpose of this work was to determine the features of nanosecond bichromatic laser action on silicon in atmospheric air in a wide range of parameters and to identify the modes of effective specific mass removal and the formation of laser erosion plasma.

2. EXPERIMENTAL DETAILS

Experimental setup was based on two Nd:YAG lasers LH−2132 and LH−2137 (LOTIS TII, Belarus) and a synchronization system for generation of paired nanosecond laser pulses with wavelengths of 355 and 532 nm and durations of 18 and 15 ns, respectively. The sequence order and the time interval between pulses could be adjusted. The time profile of laser pulses was measured with a 11HSP-V2 (Standa) photodetector and a Teledyne Lecroy Wave Surfer 510R oscilloscope with a bandwidth of 1 GHz. The energy of laser pulses was monitored using an Ophir instrument with a PE25BF-DIF-V2 ROHS measurement probe. Emission spectra of laser-induced plasma were recorded using the SL40-2 spectrometer (SOL instruments, Belarus). A coaxial beam of radiation of both lasers was formed using a spectrum splitter and focused with an achromatic lens (f = 150 mm) on the surface of a silicon wafer. The diameter of spots of laser irradiation on the target was 200 μm for λ = 355 nm and 250 μm for λ = 532 nm. The surface of irradiated samples was examined with a TESCAN VEGA 3 (TESCAN, Czech Republic) scanning electron microscope. The profiles of laser craters on the surface of silicon were measured with an ACCRETECH Surfcom Crest DX-T profilometer with a resolution of 1 μm.

3. RESULTS AND ANALYSIS

In the case of bichromatic laser exposure, the specific mass removal of silicon and the intensity of the spectral lines of the near-surface plasma depend on the time interval between the pulses and the order of their sequence (Figures 1-2, negative values of the interval correspond to the advancing effect of radiation with λ=355 nm).

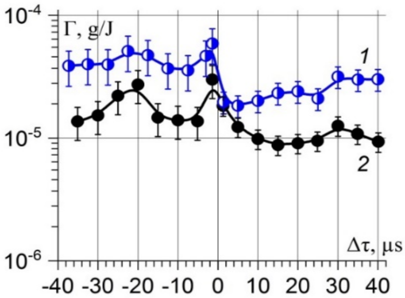

Figure 1: Dependences of the specific mass removal of silicon on the time interval within bichromatic laser pulses with power density q_{355} = 1.9 and q_{532} = 3.5 GW/cm^2 (1), q_{355} = 1.0 and q_{532} = 1.94 GW/cm^2 (2)

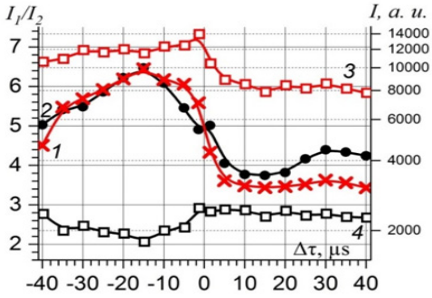

Figure 2: Ratio between the intensities of spectral lines Si II 412.9/N II 501.1 nm (1), Si II 412.9/Si I 288.2 nm (2), and dependences of the intensity of spectral line Si II 412.9 nm (3), N II 501.1 nm (4) on the time interval within bichromatic laser pulses with power density q_{355} = 1.9 and q_{532} = 3.5 GW/cm^2

Especially effective was the laser action with q_{355} = 1.9 GW/cm^2, q_{532} = 3.5 GW/cm^2 and q_{355} = 1 GW/cm^2, q_{532} = 1.94 GW/cm^2 (Figure 1). At the same time, the bichromatic laser effect was accompanied by a spalling destruction on the back side of the target /see Savenkov G.G. 2002/.

Local increasing of specific mass removal of silicon (Figure 1) at time intervals between laser pulses -20 µs, -3 µs and +30 µs correlated with an increase in the intensity ratio of the Si II spectral line (412.9 nm) to both the Si I atomic line (288.2 nm) and the nitrogen spectral line N II (501.1 nm). These data may indicate a significant heating of the destruction products from the first pulse by the second one, as well as an increase in the intensity of NII spectral lines in the region of positive intervals (Figure 2).

The experiments revealed that two pairs of bichromatic irradiating laser pulses did not induce spallation on the bottom side of the silicon wafer. Spallation in the indicated regime was observed only after irradiation with four or more pairs of bichromatic laser pulses.

Typical SEM images of ablation and spallation craters are shown in Fig. 3 for irradiation with four (Figs. 3, a and 3, b) and eight (Figs. 3, d and 3, e) pairs of pulses.

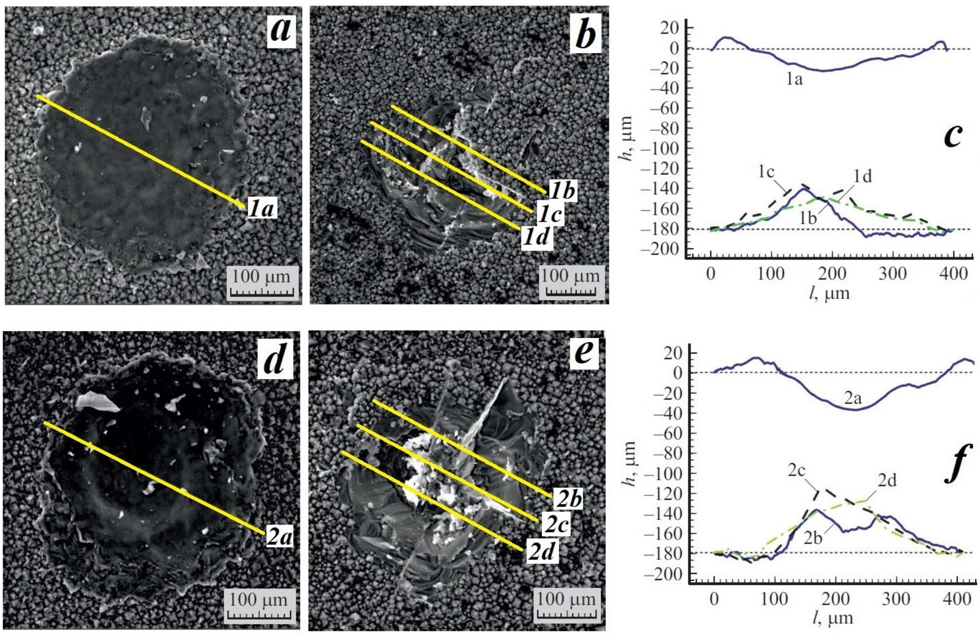

Figure 3: SEM images of ablation (a, d) and spallation (b, e) craters and the corresponding profiles (c, f), formed as a result of irradiation with four (a–c) and eight pairs (d–f) of laser pulses with wavelengths of 355 and 532 nm (treatment parameters: q_{355} = 1.9 GW/cm^2, q_{532} = 3.5 GW/cm^2, $\Delta\tau = -3$ µs).

The results of measurement of their profiles are also presented (Figure 3, c, f). The difference in shape between ablation and spallation craters stands out. The typical shape of ablation craters is that of a sphere segment, while spallation craters have an irregular shape (formed by several partial spalls) with a roughly triangular profile.

It should be noted that the maximum depth of spallation craters is 1.5−2 times higher than the maximum depth of ablation ones. This suggests that spallation produces a significant contribution to the specific mass removal in the process of drilling of through holes in the indicated treatment regimes.

The analysis of the profiles of laser ablation and spallation craters on the surfaces of silicon wafers (Figure 3) showed that the phenomenon of spalling destruction under bichromatic laser exposure occurs before the formation of a through hole, and the depth of the ablation and spallation craters increases with the number of pairs of impacting pulses.

Such phenomenon was not observed with monochromatic exposure of laser radiation with wavelength of 532 nm, but when exposed to radiation of 355 nm, the spalling destruction was observed only with a large number of acting laser pulses (more than 20).

4. CONCLUSIONS

Laser spalling destruction and ablation of silicon in air has been experimentally investigated and the nonlinear dependence of the specific mass and intensity of spectral lines of near-surface plasma on the laser radiation power density, time interval and sequence order of bichromatic nanosecond laser pulses with wavelengths of 355 and 532 nm and radiation power density from 0.2 to 3.5 GW/cm^2 has been revealed.

The features of ablative and spalling destruction of irradiated flat silicon targets, which are amplified by the action of paired bichromatic laser pulses on silicon, are established.

Acknowledgments

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