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FEATURES OF SILICON ABLATION IN AIR UNDER THE INFLUENCE OF ND:YAG LASER HARMONICS

A. N. CHUMAKOV, V. V. LYCHKOVSKY and I. S. NIKONCHUK

B.I. Stepanov Institute of Physics of the National Academy of Sciences of Belarus, 220072, Minsk, Independence ave., 68-2
E-mail a.chumakov@dragon.bas-net.by

Abstract. Ablation of silicon sample in air under irradiance of single and double laser pulses with wavelengths 355 and 532 nm was studied by means of optical and scanning electron microscopy, as well as video registration of plasma's plume radiation in time. Dependence of specific sample's material removal on laser fluence and time interval between coupled pulses of bichromatic laser irradiance was established.

1. INTRODUCTION

Since silicon is used widely in microelectronics, laser treatment of silicon wafers has been studied extensively in recent years to determine efficient treatment regimes. The absorption coefficient of silicon increases by three orders of magnitude as the irradiation wavelength decreases from 1064 to 266 nm. Therefore, laser treatment of silicon may be made more efficient if one uses the 2nd, 3rd, or 4th harmonics of radiation of a Nd : YAG laser / see Liu H.C. et al. 1999, Yoo J.H. et al. 2000, Panzner M. et al. 2002 /. The aim of the work was to determine the features of laser ablation of silicon in atmospheric air when it was irradiated with nanosecond pulses of monochromatic and bichromatic radiation with wavelengths of 355 and 532 nm in a wide range of parameters and to identify the modes of effective specific mass removal and the formation of erosive plasma.

The use of coupled LR pulses (especially those that differ in wavelength) with an adjustable time interval and sequence order should provide an opportunity to enhance considerably the efficiency of ablation of materials, heating of ablation plasma, and generation of shock waves / see Min'ko L.Ya. et al.: 1990, Chumakov A.N. et al.: 2014, 2017 /. Double-pulse bichromatic laser treatment offers more degrees of freedom for control over the process of laser ablation of materials differing in their thermophysical and optical characteristics. However, it still remains understudied. The aim of the present study is to determine the specific features of laser ablation of silicon in atmospheric air irradiated with nanosecond monochromatic and bichromatic (355 and 532 nm) LR pulses in a wide range of parameters and identify the regimes of efficient specific mass removal and production of near-surface plasma.

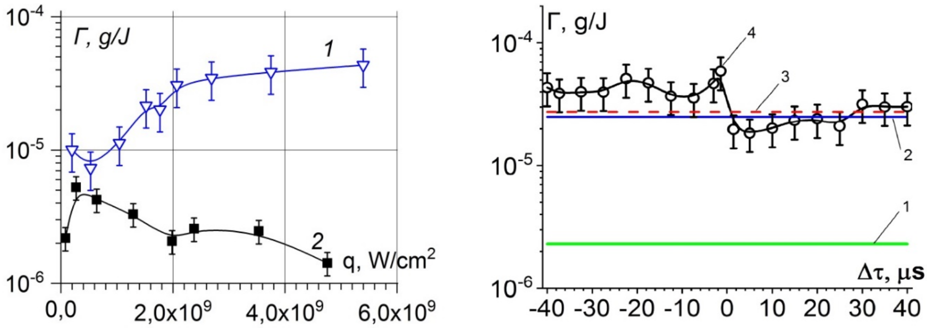
2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

The setup was constructed based on two Nd : YAG lasers LH−2132 and LH−2137 (OOO ”LOTIS TII“, Minsk) and a synchronization system for generation of paired nanosecond LR 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 shape of the laser pulses was measured with a 11HSP-V2 (Standa) photodetector and Wave Surfer 510R digital oscilloscope. The energy of laser pulses was monitored using an Ophir instrument with a PE25BF-DIF-V2 ROHS measurement head. 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 into a spot with diameter of ~200 microns. The targets were (111) silicon wafers with a thickness of 180 μm.

The specific mass removal was determined experimentally based on the volume of a through hole in a silicon wafer with a thickness of 180 μm, which was made by a countable number of laser pulses, with the known density of silicon (2.33 g/cm^3) and the measured total energy of laser pulses taken into account. In the case of doublepulse bichromatic treatment, the specific mass removal was determined at different time intervals between laser pulses falling within the range from −40 to +40 μs (negative intervals correspond to pulse sequences in which the shortwave laser pulse came first). The surface of irradiated samples was examined with a TESCAN VEGA 3 (TESCAN, Czech Republic) scanning electron microscope. The ablation laser plume was recorded with a video camera / see Nikonchuk I.S. et al: 2016 / featuring an ICX415AL CCD sensor. Emission spectra of laser-induced plasma were recorded using the SL40-2 spectrometer (SOL instruments).

3. RESULTS AND DISCUSSION

It should be noted that silicon ablation was observed at the following threshold values of LR power density: Q_{355} ~ 1.7 J/cm^2 for 355 nm and Q_{532} ~ 2.5 J/cm^2 for 532 nm. The results of examination of the specific mass removal of silicon in different regimes of monochromatic LR treatment and irradiation with paired bichromatic radiation pulses with wavelengths of 532 and 355 nm are presented in Fig. 1. The obtained results revealed the nonlinear nature of dependences of the specific mass removal of silicon on the power density of the irradiating monochromatic LR with wavelengths of 532 and 355 nm within the interval from 0.1 to 5 GW/cm^2 (Fig. 1, *a*). The nonlinear nature of the experimental dependences of the specific mass removal on the radiation intensity q at both wavelengths indicates a change in the mechanism of silicon ablation. Thus, at q_{355} ~ 1 GW/cm^2 (curve 1, λ = 355 nm,), the decline in the efficiency of specific mass removal is replaced by its sharp increase with subsequent saturation. At the same time, the formation of a through hole in a silicon wafer was characterized by the signs of brittle fracture with spallation of individual fragments on its back side.



a b

Figure 1: Dependences of the specific mass removal of silicon: *a* – on the power density of LR with wavelengths of 355 (*1*) and 532 nm (*2*); *b* – on the time interval within bichromatic LR pulses with power density q_{355} = 1.9 and q_{532} = 3.5 GW/cm^2 (*1* – λ = 532, *2* – λ = 355, *3* – estimate of the overall effect of LR at both wavelengths; *4* – irradiation with bichromatic LR pulses (negative time intervals correspond to pulse sequences in which the 355-nm pulse came first))

A similar pattern was observed under the influence of LI 532 nm (curve 2), while the transition from a decline to a local increase in mass removal occurred at q_{532} = 2 GW/cm^2. Probably, in the first sections of the curves (up to the intensities of 1 and 2 GW/cm2 for λ = 355 and 532 nm, respectively), the melting-evaporation mode is implemented, and at q > 2 GW/cm^2, brittle fracture with spallation is added.

The specific mass removal was also examined under irradiation of silicon in air with paired bichromactic LR pulses with wavelengths of 355 and 532 nm. The dependence of mass removal on the time interval between paired pulses and their sequence order was studied for a number of regimes. A typical dependence of this kind is presented in Fig. 1, *b*. This dependence is also nonlinear. If the shortwave LR pulse came first (i.e, the time interval is negative), specific mass removal *4* is 2−3 times higher than overall removal *3* in the case of monochromatic irradiation at both wavelengths. The maximum values of specific mass removal are achieved at interpulse intervals $\Delta\tau = -20$ and -1.3 μs. In the region of positive time intervals between laser pulses, specific mass removal *4* generally remains lower than overall removal *3* and exceeds it somewhat only at intervals from +30 to +40 μs.

The identified differences between the dependences of specific mass removal of silicon on the power density of incident radiation at the examined wavelengths correspond to the observed features of dynamics of the plasma plume (Figs. 2).

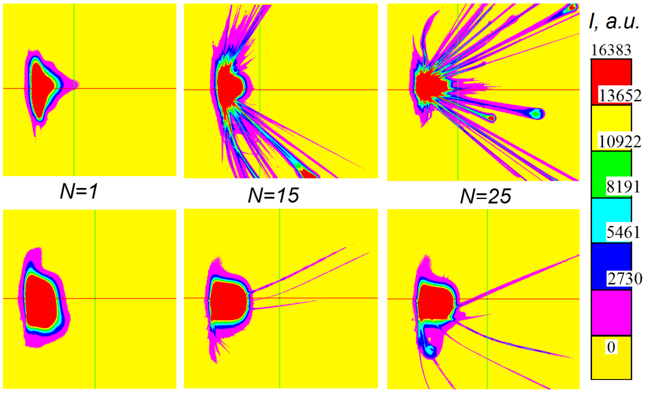


Figure 2: Individual still images of the plasma plume corresponding to the irradiation of silicon in air with the 1st, the 15th, and the 25th laser pulses in a series with a wavelength of 355 (*a*) and 532 nm (*b*)

Specifically, intense ejection of particles of the condensed phase, which continues well after the disintegration of the plasma plume, is observed on exposure of silicon to LR with λ = 355 nm, while LR with λ = 532 nm produces a glowing plasma plume with weakly pronounced ejection of particles of the condensed phase.

4. CONCLUSIONS

The nonlinear dependence of the specific mass removal of silicon on the power density of the acting laser radiation, the time interval and sequence order of bichromatic nanosecond laser pulses with wavelengths of 355 and 532 nm and a power density from 0.2 to 5 GW/cm2 has been revealed. An increase in the efficiency of silicon ablation under the influence of bichromatic laser pulses has been established.

Acknowledgments

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