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FORMATION AND HEATING OF SILICON PLASMA IN AIR UNDER PULSED BICHROMATIC LASER IRRADIATION

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Abstract. The formation and heating of laser plasma under the irradiation of silicon in air by pulsed laser radiation with wavelengths of 355 and 532 nm at radiation power density of up to 5 GW/cm^2 has been investigated. An increased efficiency of the formation and heating of erosion plasma under bichromatic irradiation of silicon with advanced action of nanosecond pulses with wavelength of 355 nm has been established.

1. INTRODUCTION.

The efficiency of materials laser ablation in gases and formation of near-surface plasma depends on variety of parameters including intensity, laser radiation (LR) wavelength, laser pulse duration, repetition rate and order in which they follow (see Min’ko et. al. 1990, Pershin 2009, Khalin 2013). Increase in power density of LR lead to formation of near-surface plasma that start to shield sample’s surface, which from one hand limits laser ablation and from other greatly contributes to newly formed surface plasma. In order to increase efficiency of materials laser ablation and heating of near-surface plasma a pulsed bichromatic laser irradiation with controlled time parameters can be used (see Chumakov et. al. 2014, Chumakov, Bosak et. al. 2014).

The goal of current work is to establish the features of formation and heating of silicon plasma in air ablated by nanosecond laser pulses of bichromatic laser irradiance with wavelengths 355 and 532 nm, controlled time interval and order in which pulses follow.

2. EXPERIMENTAL.

The installation is based on two Nd:YAG lasers and synchronization system which provide generation of paired nanosecond laser pulses with wavelengths 355 and 532 nm and duration of 18 and 15 ns respectively. Pulses follow in controlled order and time interval between them. The coaxial beam from both lasers was formed with spectral splitter and focused on 180 μm thick silicon plate's surface in 200 μm (λ = 355 nm) and 250 μm (λ = 532 nm) diameter spot by achromatic lens (*f* = 150 mm).

Pictures of laser induced plume were taken with video camera based on ICX415AL matrix (time exposition ~ 3 ms) (see Nikonchuk et. al. 2016). Spatial resolved integral spectra of plume light were taken using diffraction spectrometer and digital video camera. Spectra were calibrated utilizing reference lines of LR with wavelengths of 532 and 632,8 nm. The emission spectra of laser plasma were registered by SL40-2 spectrometer based on TCD 1304 photodetectors within LR power density range of 0,9–5 GW/sm^2 (time exposition ~7 ms). Form of laser pulses was registered by 11HSP-V2 photodetector and Wave Surfer 510R digital oscilloscope (bandwidth 1 GHz). Laser pulse energy was measured with Ophir device by PE25BF-DIF-V2 detector.

3. RESULTS AND DISCUSSION.

Analysis of plasma's plume video pictures show that laser irradiance of silicon with wavelength 355 nm leads to ejection of vast number of condensed phase particles, which is much weaker in case of laser irradiance with λ = 532 nm (fig.1 a-b). Bichromatic irradiance with leading laser pulses of λ = 355 nm provides much more intensive plasma formation and weaker particles ejection (fig. 1, c-d).

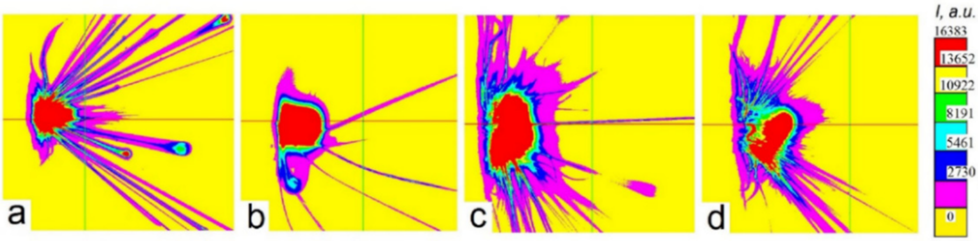

Fig. 1. – Video pictures of plasma plume induced by monochromatic (a, b) and bichromatic (c, d) laser irradiation on silicon: a – q_{355}=1,9 GW/sm^2, b – q_{532}=3,5 GW/sm^2;
c – bichromatic λ_1=355 + λ_2=532 nm, interval between pulses Δτ = –20 мкс, d – bichromatic λ_1=532 + λ_2=355 nm, interval between pulses Δτ=+30 мкс (negative time interval corresponds with leading action of 355 nm laser pulse)

The spectra obtained with 355 nm monochromatic laser irradiance of silicon contains strongly broadened atomic (Si I 288,2 and 390,5 nm) and ionic silicon lines (Si II 385,6 and 413,1 nm) with traces of double ions (Si III 308,6 nm) and high intensity of continuous radiation (fig. 2, spectrum *1*). Bichromatic 355 + 532 nm laser irradiation of silicon initiate spectra with lowered level of continuous radiation and significant number of atomic and ionic silicon lines with traces of triple exited ions (Si IV 408,8 nm) as well as ionic N II 501,1 nitrogen line (fig. 2, spectrum 2). This indicates heating of plasma at temperature of ~20 000 K. Change of laser pulses order to 532+355 nm leads to weaker heating of ablated plasma and to stronger ejection of particles what confirmed by weakening of double ions Si III spectral lines and absence of triple ions traces (fig. 3).

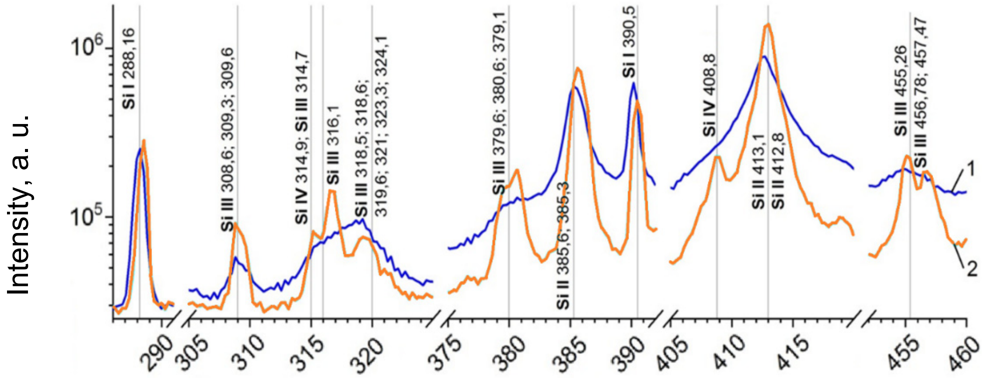

Fig. 2. – Spectra of surface plasma induced by monochromatic LI with λ=355 nm and q_{355}=4,6 GW/sm^2 (*1*) and birchromatic LI with q_{355}=1,9 GW/sm^2 + q_{532}=3,5 GW/sm^2 (Δτ=–1,4 μs) (*2*) on silicon sample in air

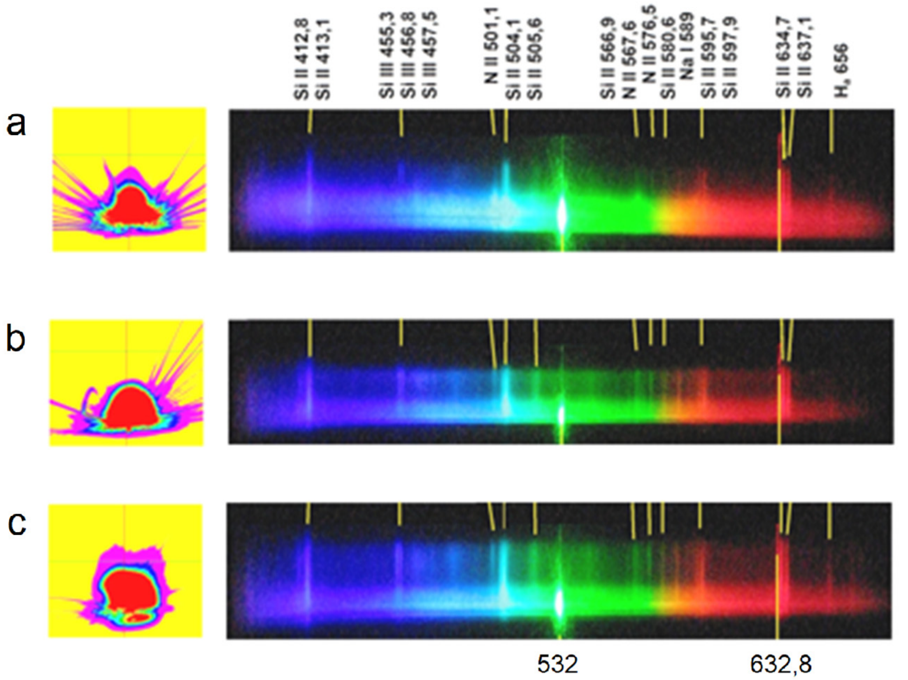

Fig. 3. – Video pictures of plasma plume and their corresponding spectra induced by bichromatic LI with q_{355}=1,9 GW/sm^2 and q_{532}=3,5 GW/sm^2 and interval between pulses Δτ=–5,5 μs (*a*), –1,3 μs (*b*) and +15 μs (*c*).

The influence of time interval from -40 to +40 μs and order of bichromatic pair of pulses on plasma parameters was evaluated based on silicon Si III 380,6 / Si II

385,6 / Si I 390,5 nm and nitrogen N II 501,1 nm spectral line's intensities ratio (fig. 4). Also, it was considered that Si II 385,6 / Si I 390,5 nm and Si III 380,6 / Si II 385,6 nm line's intensities ratio represent plasma temperature to some extent.

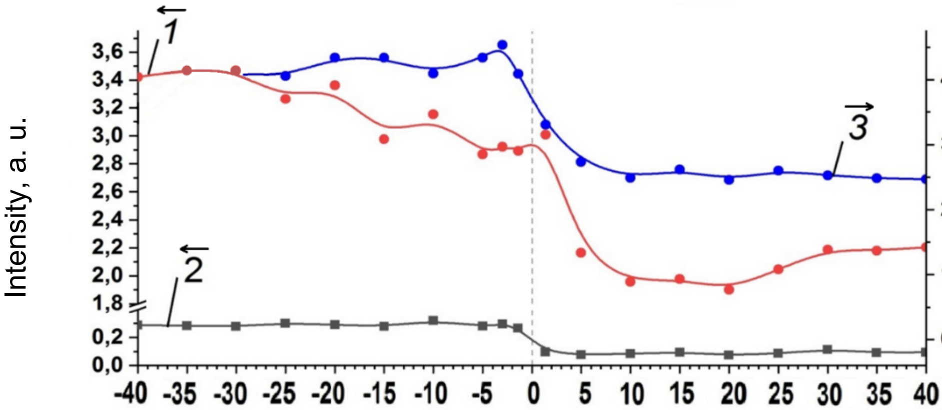

Fig. 4. – Dependence of line's intensity ratio Si II 385,6 / Si I 390,5 (*1*), Si III 380,6 / Si II 385,6 (*2*), Si II 385,6 / N II 501,1 (*3*) on time interval and order of laser pulses with wavelengths of 355 and 532 nm in silicon plasma

Analysis of dependencies *1* and *2* in fig. 4 shows comparability of Si III 380,6 nm and Si II 385,6 nm line's intensities which point on range of plasma's temperature from 11000 to 19000 K (range of "normal" temperatures for Si II and Si III spectral lines). Maximum values of dependencies *1* and *2* are reached with leading action of 355 nm laser pulse, that point on peak heating of silicon plasma with current conditions. With change of pulses order to 532 + 355 nm a raise in nitrogen's N II 501,1 nm line intensity is observed followed by decreasing of Si II 385,6 / N II 501,1 line's intensity ratio (dependence *3*, fig. 4).

4. CONCLUSION.

Formation and heating of surface plasma induced by pulsed laser irradiation of silicon with power density up to 5 GW/sm^2 in air was studied. Increase in formation and heating effectiveness of erosive plasma induced by bichromatic irradiation on silicon with leading action of 355 nm laser pulses was established.

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