Energy Spectrum and Charge Composition of Laser Plasma Ions

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Abstract. A mass spectrometric study of the spectra of multi-charged ions Al, Cu, depending on the frequency \( \nu = 1, 3, 5, 10, 12 \text{ Hz} \) and at \( q = 10^{11} \text{ W/ cm}^2 \). It has been proved that with increasing \( q \) of laser radiation, the energy spectrum of ions expands towards high energies, and the energy spectrum also has several maxima, the number of which increases with increasing \( q \) of laser radiation. It has been experimentally proven that silicon ions with a charge \( Z > 6 \) recorded in a plasma formed from a \( \gamma \)-irradiated target under study are characterized by a lower minimum energy than an unirradiated target.

1. Introduction

At present, a large number of experimental and theoretical works are devoted to the study of the interaction of a single laser pulse on the surface of a mono and multicomponent target. Methods of using repetitively pulsed radiation in laser processing of metals, as well as in the creation of high-temperature superconducting materials in which the frequency of pulse studies varies in a wide range from several Hz to kHz, are investigated [1]-[3]. In addition to these, new approaches such as stochastic models are studied [4] and techniques from machine learning is applied [5], [6]. It is known that, with an increase in the pulse repetition rate, the process of interaction of a laser pulse with the target surface becomes much more complicated and depends on the preceding radiation pulses. The time during which the preceding pulse affects the subsequent one is determined both by the heat conduction inside the target and by processes near the surface, for example, by the scattering of target ions ejected from its surface and ionization, recombination processes by the generated plasma.

2. Methodology

As is known, the formation of the charge and energy spectra of the ions of the laser plasma is determined from the ionization, recombination and acceleration processes occurring in the laser plasma. However, in this case, such laser parameters as power density, wavelength, angle of incidence, focusing conditions, multichannel laser radiation play an important role [7], [8]. Especially, multi-charged ions formed by one, two and many-channel laser radiation significantly differ in the charge, energy and quantitative characteristics of the ions. In this case, the role of repetitively pulsed laser radiation on the formation of the spectra of multiply charged ions in laser plasma remains open. It is characteristic that with a change in the frequency of the repetitively pulsed laser radiation at the perpendicular incidence of radiation on the target surface, it becomes possible to control elementary plasma processes near the target surface and the efficiency of formation of the spectra of multiply charged ions of the laser plasma.
This assumption is based on the following. It is known [2] that when a solid is exposed to light fluxes with such a power density, the target evaporates, the intensity of which is determined by the binding energy [3]. Gamma irradiation of the studied Si with large doses (high-dose irradiation) leads to the formation of defects in the crystal lattice associated with the breaking of bonds and displacement of atoms to the interstitial site [8]. The probability of formation of such defects in silicon and their coagulation into large areas of destruction is determined by the type and dose of radiation [5]. In addition, under γ-irradiation, energy-intensive defects are formed in semiconductors, as a result of which the internal energy of the sample increases.

It is well-known, the ability of a semiconductor to conduct heat is the sum of the electronic and phonon thermal conductivity. Measurement of the electrical conductivity of the sample under study showed that with an increase in the dose of γ-irradiation, its resistance increases. This circumstance means that the electronic thermal conductivity of silicon due to free electrons decreases. The formation of structural defects during high-dose irradiation of silicon leads to a deterioration in the lattice thermal conductivity, since thermal phonons are scattered by them like photons in a turbid medium. Naturally, the deterioration of the thermal conductivity of the target and the existence of regions with a lower binding energy in it not only brings the time of the onset of evaporation closer, but also increases the intensity of this process [9]. In this case, in the unloading wave flowing in the target when the shock wave reaches the surface, the sample also tends to get rid of the tension arising in it during the formation of structural defects. All these factors increase the power of the thermal explosion that occurs on the surface of γ-irradiated silicon.

3. Result and Discussion

The purpose of this work is a mass spectrometric study of the spectra of multiply charged ions A1, Cu, depending on the frequency ν = 1, 3, 5, 10, 12 Hz and at q = 10^{11} W / cm^2. It has been experimentally established that with an increase in laser ν, the intensities of singly charged A1^{1+} ions change nonlinearly, while the intensities and energies of multiply charged Al and Cu ions (Z>1) increase due to additional thermal and ionization processes at the target surface, as well as an enhancement of the effect. 'quenching' the ionization state of ions in plasma. In Figure 1 shows the energy spectra of Si ions obtained under the action of laser radiation with different power densities on an unirradiated monoelement target. The figure describes the following:

a. With increasing q of laser radiation, the energy spectrum of ions expands towards high energies.

b. The energy spectrum has several maxima, the number of which increases with increasing q of laser radiation.

A comparison of the energy spectra of ions emitted from the initial and γ-irradiated silicon in Figure 2 shows the following different concentration of gamma-induced defects, when radiation defects appear in the target and their concentration increases, the first maximum is shifted. For example, if the energy of the first maximum of Si^{6+} ions formed from an unirradiated target is less than 2.2 keV, in the case of gamma irradiation of Si up to 10^6 P it is about 2.5 keV, then at 10^8 P it is 3.0 keV.

![Figure 1. Energy spectra of Si ions recorded in the plasma formed when exposed to laser radiation with q = 10^{11} W / cm^2](image-url)
As can be seen from this regularity, obtained at \( D = 10^9 \) \( \text{P} \), the energy of this maximum lies in the region of 3.5 keV, and the spectrum picture indicates that the formation of the energy spectrum is not yet complete, since ions with higher charges are present in the plasma.

![Figure 2](image)

**Figure 2.** The energy spectra of Si\(^{3+} \) ions (1-3) and (4-6) recorded in the plasma formed from multielement silicon in different states: 1, 4 - before irradiation, 2, 3, 5, 6 - after \( \gamma \)-irradiation before \( 10^6 \) \( \text{P} \).

It has been experimentally established that silicon ions with a charge \( Z>6 \) recorded in a plasma formed from a \( \gamma \)-irradiated target under study are characterized by a lower minimum energy than an unirradiated target. Moreover, the greater the concentration of radiation defects (the greater the degree of radiation damage to the target), the more the minimum energy decreases. So, for example, if for Si\(^{7+} \) ions formed from an unirradiated target the value of \( E_{\text{min}} \) was 2.0 keV, then after \( \gamma \)-irradiation of the target to \( 10^6 \) and \( 10^9 \) \( \text{P} \), the value of the minimum ion energy decreased to 1.2 and 1.0 keV, respectively. The following is characteristic of the plasma generated by the action of laser radiation on a \( \gamma \)-irradiated target: with an increase in the concentration of radiation defects in the target, ions with a relative energy \( E / Z < 500 \text{ eV per unit charge} \) increase the charge multiplicity; for ions with a relative energy \( E / Z > 500 \text{ eV per charge} \) (re-combined ions) with an increase in the irradiation dose, the multiplicity of the ion charge decreases. Graphical display of the regularity connecting the relative energy \( E / Z \) and the maximum multiplicity of the ion charge depending on the radiation dose.

Similar dependences were obtained for all values of \( q \) of laser radiation. If we associate it with the processes occurring in the laser plasma, it becomes obvious that in the case of \( \gamma \)-irradiation of Si with certain doses, a higher-temperature plasma can be formed. However, with significant radiation damage to the target, an increase in the density of the plasma bunch contributes to an increase in the efficiency of recombination processes.

It was experimentally proven that when intense laser radiation is exposed to \( \gamma \)-irradiated silicon to certain doses, a more dense plasma is formed compared to the pre-irradiated (initial) state. This is confirmed by the results of studies of the absorption of probe laser radiation with \( \lambda = 1.06 \mu \text{m} \) by the plasma. As a result of an increase in the density of the ejected substance, the shielding time of the target surface from the acting light flux decreases. This leads to an increase in the fraction of the luminous flux used for ionization and heating of the plasma bunch.
Figure 3. Energy spectra of Si ions with Z = 1-6, registered in the plasma formed when irradiated silicon is exposed to laser radiation

The study of the energy spectra of multiply charged Si ions formed when the samples are exposed to light fluxes of identical power showed that ions with a charge greater than +6 emitted from a target irradiated with doses of $D > 10^6 \text{ P}$ need less energy to cover a distance of 360 cm than an ion with the same charge, but generated from the original target. Moreover, the larger the dose, the lower the value of $E_{\text{min}}$. For example, in the interaction of laser radiation with $q = 10^{10} \text{ W/cm}^2$ with Si irradiated to $10^6$ and $10^9 \text{ P}$, $E_{\text{min}}$ for $\text{Si}^{7+}$ ions was 1.2 and 1.0 keV, respectively. Under identical experimental conditions for the same ions produced in the case of unirradiated silicon, it is 2.0 keV. Based on the above discussion of the reasons for the increase in the size of the crater, it is reasonable to relate the decrease in $E_{\text{min}}$ of the multiply charged ion scattering in the plasma formed under the action of laser radiation on radiation-damaged silicon with an increase in the plasma bunch pressure due to the unloading of a strained target in the unloading wave and an increase in the amount of ejected matter in Figure 3.

4. Conclusion

Based on experiments, we conclude that it is quite obvious that when such a plasma bunch expands into vacuum, the charged particles acquire a greater hydrodynamic acceleration. Significant radiation damage to the target, which occurs at $D > 10^9 \text{ P}$, leads to the formation of plasma with such a density that the efficiency of recombination processes in it increases. Similar dependences were obtained for all values of $q$ of laser radiation. If we associate it with the processes occurring in the laser plasma, it becomes obvious that in the case of $\gamma$-irradiation of Si with certain doses, a higher-temperature plasma can be formed.

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