Resonance laser-induced breakdown at the surface of a metal

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A resonance lowering of the plasma formation threshold in vapors of the surface of a metal target (a sodium wafer) bombarded by a laser has been observed for the first time. The techniques of erosion plasma diagnostics are described and the characteristics of the resonance curves are discussed.

In the breakdown of a medium by laser radiation there is the particularly interesting situation in which the energy of the quantum corresponds to the resonance energy for some transition in the atomic or molecular system. In a number of experimental studies devoted to the bombardment of stationary vapors of alkali or alkali-earth metals of density $N \simeq 10^{13}$–10^{17} cm^{-3} (see the review article of Ref. 1 and the literature cited there), it has been shown that under resonance conditions for a relatively low intensity $I \simeq 10^5$–10^7 W/cm^2 and radiation pulse duration $\tau \leqslant 1$ μsec, nearly complete ionization of the medium can be attained. A theory of the effect was first proposed by R. Measures,[2] who suggested that the high density of excited atoms at resonance is the source of the energy transferred to free electrons in quenching collisions. A more general explanation of this effect was given by V. A. Kas'yanov and A. N. Starostin,[1,3] who studied the process of induced bremsstrahlung absorption in the scattering of an electron on the field-induced atomic dipole moment and found that under resonance conditions the energy accumulation rate of the electrons is sharply increased, leading to an abrupt falloff of the breakdown threshold.

A similar effect must also occur in laser interactions with the surface of a solid. As far as we know, the present study is the first to report the observation of a resonance decrease of the plasma formation threshold in vapors of the surface of a metal target bombarded by a laser, the target in this case being a sodium wafer.

The experimental setup consisted of an LZhI-501 dye laser tunable in the vicinity of the resonance transitions in the Na atom ($3^2S_{1/2} - 3^2P_{1/2}$, $\lambda \simeq 589.6$ nm and $3^2S_{1/2} - 3^2P_{3/2}$, $\lambda \simeq 589.0$ nm) with half-width of the radiation spectrum excited by the second harmonic of the laser on the crystal YAG:Nd^{3+} equal to 0.05 nm, together with the interaction chambers. The energy of the laser pulse was varied in the range 0–5 mJ, and its duration was 20 nsec at half-height. The radiation was focused on the sample under study, located in a chamber evacuated to a pressure of 10^{-4} Torr with a spot size 0.1 mm in diameter. An erosion flare diagnostics system allowed us to record the density of the ionic component of the plasma N_i at a distance $r = 8$–12 cm from the target by a plasma probe operating in the saturation regime and the plasma emission into the continuum in the range 350–400 nm, and also to measure the electron density from the Stark broadening of the 568.2- and 568.8-nm lines of the Na atom (Ref. 4) for $r \simeq 0.1$ mm with adjustable delay τ_3 relative to the start of the laser pulse.

The plasma formation threshold was determined for each wavelength by the method[5] of extrapolating to zero the dependences of the amplitude of the probe signal and the continuum emission on the radiation intensity (Fig. 1). It follows from our data that the curves for the two methods converge to a single point, which determines the threshold intensity I_{th} for a given wavelength. We note that the spread in the threshold did not exceed 15–20%. In Fig. 2 we show the dependence of the threshold intensity on the wavelength in the range 575–610 nm. In the graph we clearly see the decrease of I_{th} in the vicinity of resonance $3S-3P$ transitions with the width of the distribution at half-height $\Delta\lambda$ of order 8 nm. The dependence of the electron density N_e, determined from the Stark broadening for constant intensity of the incident radiation equal to 56 and 250 MW/cm^2 (Fig. 3), also displays a pronounced resonance behavior with $\Delta\lambda \simeq 5$ and 8 nm.

The smearing out of the resonance curves is apparently determined by the field broadening which is related to saturation of the transition. For the vapor density $N \sim N_e \sim 3\times10^{16}$ cm^{-3} the width of the unsaturated absorption line is $\Delta\lambda_0 \simeq 3\times10^{-3}$ nm (assuming that the broadening is mainly related to resonance collisions[6]), and the intensity of the saturation at the center of the line is $I_s \simeq 2$ W/cm^2. Then for $I \simeq 5\times10^7$ W/cm^2 the broadening is $\Delta\lambda \simeq \Delta\lambda_0(1+I/I_s)^{1/2} \simeq 15$ nm, whose order of magnitude is close to the measured value. Here $\Delta\lambda$ increases slowly with

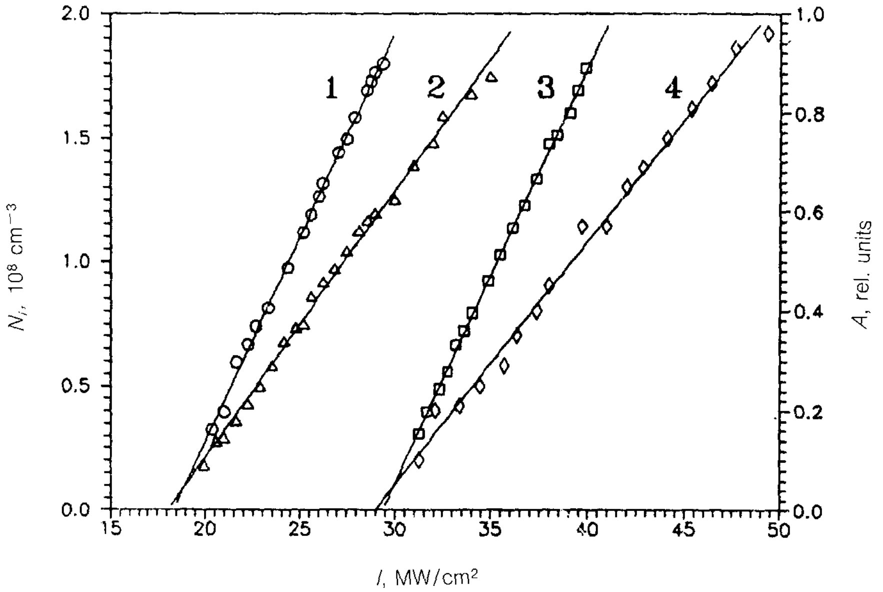

FIG. 1. Dependence of the ion density N_i (1,3) ($r=8$ cm) and amplitude A of the plasma radiation signal in the continuum (2,4) on the intensity of radiation with wavelength 588.9 nm (1,2) and 592.6 nm (3,4).

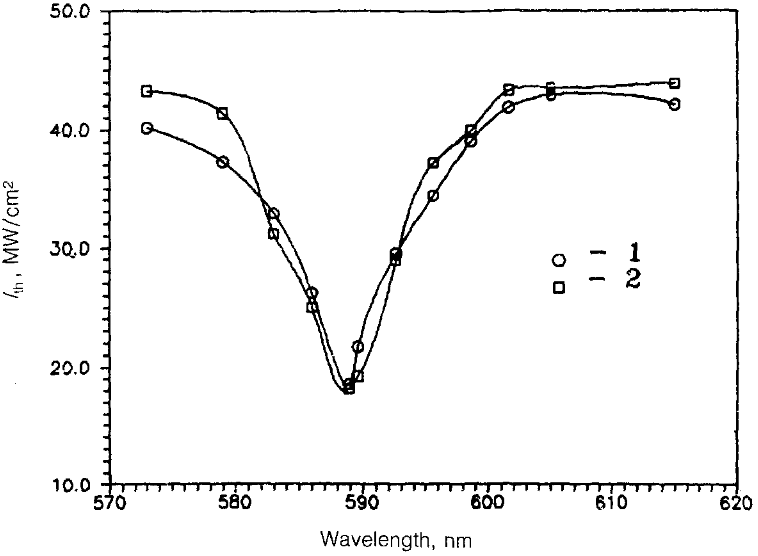

FIG. 2. Dependence of the plasma formation threshold (1—from the probe data, 2—from continuum radiation) on the wavelength of the laser radiation.

increasing intensity of the incident radiation, which was also observed in the experiment (Fig. 3). We note that this estimate apparently gives too large a value of the width of the resonance curve, since the ionization has an explicit nonlinear dependence on the population of the excited level.

It should be noted that the measured ratio ξ of the threshold intensities and the electron densities for the resonance and the nonresonance cases is relatively small ($\sim$2–3). Meanwhile, it follows from the results of Refs. 1 and 3 that under our conditions ξ must be of order 10^2–10^3, the same order of magnitude as the ratio of the plasma densities determined in stationary vapors.[7] This can most likely be explained in the following manner. In the heat-conduction mode the temperature T of the surface and the vapor is proportional to the intensity, while $N \propto \exp(-1/T)$ and depends strongly on I. Since the ionization time $\propto N^{-1}$, to attain breakdown after the same time τ_{th} determined by the duration of the laser pulse, in the nonresonance case it is necessary to increase I by only several factors, since the abrupt growth by several orders of magnitude of the vapor density cancels the falloff of the electron energy collection rate and the corresponding falloff of the ionization constant compared to the resonance case. It should also be borne in mind that it is possible to have significant self-absorption of the laser pulse near the resonance when it propagates in the cloud of vapor expanding toward the beam.

We have shown that, as noted earlier,[8] resonance lowering of the threshold can be important in the interaction between an aluminum surface and a XeCl laser whose wavelength ($\lambda = 308$ nm) is close to that of the $3P - 3D$ transition in the Al atom.

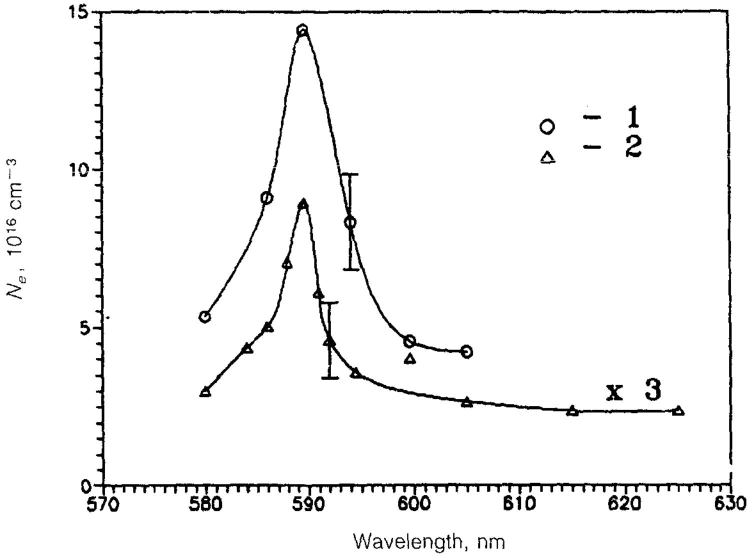

FIG. 3. Dependence of the electron density on the wavelength of the laser radiation ($r \simeq 0.1$ mm, $\tau_3 = 80$ nsec): (1) $I = 250$ MW/cm^2, (2) $I = 56$ MW/cm^2.

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