EXPANSION MECHANISM IN A LASER-PRODUCED SPARK

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Time-resolved Schlieren studies of the expansion of a laser-produced spark during the rising portion of the initiating laser pulse have been carried out in neon, argon, nitrogen, and air. The results obtained are not compatible with the radiation-supported shock-wave model, nor can they be explained in terms of a radiation transport wave or a simple breakdown wave. A satisfactory explanation involving a traveling ionization-breakdown wave is proposed.

Since the discovery that a laser-induced spark moves into the incident laser beam at a velocity in excess of 10^7 cm/sec,[1] at least three theoretical models have been proposed to account for this phenomenon.[2] Of these, the mechanism most favored to date is that of the radiation-supported shock wave first suggested by Ramsden and Savic,[3] and subsequently supported by experimental evidence obtained by a number of workers. Mandel'shtam et al.[4] have shown that spark velocities increase as $W^{1/3}$ (where W is the laser power) and measurements of the electron temperature[4,5] give values in reasonable agreement with the radiation-supported shock-wave model. In a recent paper[6] Daiber and Thomson have reported measurements of distance versus time and values of absolute velocity which are in close agreement with the predictions of the theory.

Nevertheless, no extensive study of different gases at different pressures and varying laser powers has been presented to give a convincing and unified picture. For this reason we have carried out experiments in four gases (argon, neon, nitrogen, and air) at pressures between 60 and 1520 Torr, with laser pulses having rise times between 14 and 24 nsec and with peak powers ranging from 35 to 300 MW.

The experimental arrangement, which has been described in detail elsewhere,[7] involved the use of two lasers. The beam from a Pockels-cell Q-spoiled ruby laser was focused with a 3.5-cm focal-length lens within a pressure cell to produce the spark, while a mode-locked neodymium glass laser was used as a light source for time-resolved Schlieren photography of the plasma. Both the incident laser power and the power transmitted through the spark were monitored by photodetectors, thus providing measurements of the breakdown time and instantaneous power absorption.

From the time-resolved Schlieren records, the motion of the ionization front along the axis of the laser beam could be observed and comparison with streak photographs of the luminous front showed fair agreement over the time range considered here, i.e., during the rising portion of the laser pulse. However, the results obtained were found to be incompatible with the radiation-supported shock-wave theory. In the case of air, in which measurements were made with constant peak powers of 110 and 300 MW, 24-nsec rise time, and at pressures ranging from 100 to 760 Torr, it was found that the initial velocity increased with pressure very nearly as $v \propto p^{1/2}$. We have been unable to find any simple model based upon the radiation-supported shock-wave theory which can explain such a high positive value of the exponent of p. Furthermore, measurements of velocity and power absorption failed to show any simple relationship between their instantaneous values despite the fact that such a relationship is fundamental to the mechanism.

The radiation transport-wave mechanism suggested by Raizer[2] shares the weakness of the shock-wave mechanism already discussed. The theory requires a relationship between instantaneous velocity and instantaneous power absorption. No such relationship has been found.

Raizer[2] has also suggested a breakdown wave mechanism which predicts a constant wave velocity during the rising portion of an approximately triangular laser pulse. No such constancy has been observed.

However, our results can be explained in terms of a traveling ionization-breakdown wave. As originally proposed, the breakdown wave mechanism requires the presence of initiating electrons throughout the gas; however, such an assumption cannot reasonably be accepted.[8]

We have assumed that electrons are produced ahead of the breakdown wave. One mechanism which could account for this is the effect of precursor radiation from the spark itself. If electrons appear at point x at time t_1, and the wave arrives at time t_2, then following Raizer,

$$\int_{t_1}^{t_2}\frac{dt}{\tau}=\int_{t_1}^{t_2}BIdt=\ln\frac{n_{ec}}{n_{e0}}\simeq\text{const},\qquad(1)$$

where τ is the e-folding time of a cascade ionization process, B is approximately a constant, n_{ec} is the critical electron density for breakdown, and n_{e0} is the number of initiating electrons.

The laser pulse shape has been approximated by a triangle, and the rising portion of the pulse only has been considered. Thus the instantaneous beam intensity at point x is given by

$$I=W_0t/\pi t_{\max}(r_0+x\tan\alpha)^2,$$

where W_0 is the peak laser power and $t_{\max}$ the time-to-peak power. An electron is assumed to be produced at the focus at close to time zero by the laser beam, and an initial radius r_0 is taken from which the spark expands. Taking the time t_2-t_1 as a constant ($=t_b$, the time to breakdown), it can then be shown that

$$(r_0+x\tan\alpha)^2=(r_0^2/t_b)(2t_2-t_b)\cdots,\qquad(2)$$

where x is the distance traveled by the wave front from time zero, 2α is the angle subtended by the laser beam at the focus, and t_b accounts for variations in wave velocity with gas, pressure, peak power, and pulse length.[9] Although no theoretical justification has been found for the assumption $t_2-t_1=t_b$, it appears to be borne out by the experimental results.

Equation (2) requires that a plot of $(2t_2-t_b)/t_b$ vs $(r_0+x\tan\alpha)^2$ result in a straight line passing through the origin and having a slope $1/r_0^2$. A fairly wide range of values of r_0 and $\tan\alpha$ yields a straight line, but the slope is extremely sensitive to the values employed; and it was found that for a value of $r_0\approx0.007$ cm, the required value of $\tan\alpha$ was 0.043. Using these two values, all the experimental data for the growth of sparks, obtained over the wide range of conditions we have employed, can be plotted as shown in Fig. 1.

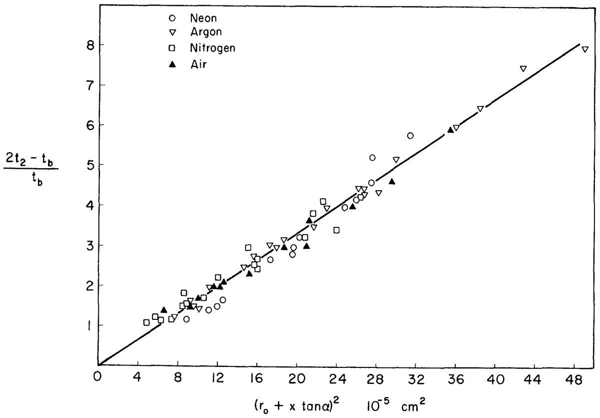

FIG. 1. Plot of experimental points in terms of Eq. (2). Values of r_0 assumed: neon, 0.008 cm; argon, 0.007 cm; nitrogen and air, 0.006 cm. Value of r_0 derived from mean slope and Eq. (2) is 0.007 cm. The gas pressures used were as follows: air and nitrogen, 60 to 760 Torr; argon, 60 to 1520 Torr; and neon, 760 to 1520 Torr; with intermediate values separated by steps of 200 Torr or less.

Estimates of r_0 and $\tan\alpha$ from the Schlieren records yield values of 0.007 ± 0.002 cm and 0.07 ± 0.02, respectively, which are not greatly at variance with the values used in Fig. 1. However, the concept of a single $\tan\alpha$ invariant in time is undoubtedly an oversimplification of the true situation, and it has only been adopted here because of the difficulty of determining the true spatial and temporal dependence of the power density with our present techniques; in fact, time-resolved studies of the laser near-field pattern revealed a filamentary structure varying in time. On the other hand, some justification for the use of a single value of $\tan\alpha$ is obtained from the Schlieren records, which show that the spark expansion occurs in a cone of roughly constant angle. In any event, the remarkable agreement between theory and experiment, exhibited in Fig. 1, is far superior to that obtained using the alternative theories discussed above. Nevertheless, it is possible that one or more of the other mechanisms may predominate with different experimental parameters.

Additional studies are being carried out and complete experimental data, accompanied by a more detailed discussion of the theory, will be presented in a later paper.

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INELASTIC SCATTERING OF TUNNELING ELECTRONS BY LOCALIZED VIBRATIONAL MODES IN PbTe p-n JUNCTIONS[*]

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Liquid-helium-temperature tunneling data for PbTe indium-doped p-n junctions exhibit a series of sharp conductance increments with ~5-mV spacing as well as the "zero-bias conductance minimum" and the LO-phonon shoulder at ~13.8 mV. Indium-gallium alloyed junctions exhibit also a second series with ~6.5-mV spacing. This periodic structure is attributed to the "inelastic scattering" of tunneling electrons by localized vibrational modes of the indium and gallium impurity atoms in the tunneling junction.

In the course of an investigation of the "zero-bias conductance anomaly" in PbTe indium-alloyed p-n tunnel junctions,[1] we have observed a sharp periodic structure, with approximately 5-mV spacing, in the curves of dI/dV vs V and d^2I/dV^2 vs V in the voltage range $|V| < 30$ mV. When indium-gallium mixtures were used as the alloying material, an additional periodic structure was observed with approximately 6.5-mV spacing. The sharp periodic structure is attributed to an "inelastic scattering" of tunneling electrons by localized vibrational modes of indium and gallium substitutional "impurity" atoms in the transition region of the p-n junctions. The observed spacing is consistent with the excitation energies of the localized modes, which are calculated from the mass-defect parameter and the LO-phonon energy, for indium ($\hbar\omega_{\text{loc}} \approx 5$ meV) and for gallium ($\hbar\omega_{\text{loc}} \approx 6$ meV).

The diodes, which were formed by alloying 0.003-in.-diam indium (and indium-gallium) spheres into degenerate p-type PbTe ($n_p \approx 5 \times 10^{17}$ cm^{-3}), exhibit a "zero-bias conductance minimum"[2] and a conductance rise at eV $\approx \hbar\omega_{\text{LO}} \approx 13.8$ meV corresponding to the LO-phonon energy. The narrow conductance minima in alloyed p-n junctions in the III-V compound semiconductors[3-5] and in the IV-VI compound semiconductors[6-8] have been attributed to polaron effects[3,6] and, more recently, to impurity-induced inelastic scattering by acoustic phonons.[9] Rediker and Calawa have observed that the minima for PbTe p-n junctions disappeared at relatively low magnetic fields, whereas the minima for III-V compound p-n junctions were magnetic field independent up to fields of the order of 100 kG.[10] It was these observations which led us to undertake a detailed investigation of the zero-bias conductance anomaly in PbTe. In the present experiments, the conductance minima were studied in the temperature range 1.1°K$<T<$10°K and in magnetic fields up to 20 kG.

Our data show that the minima have the form of an energy gap characteristic of tunneling involving a superconductor. We find that the shape of the conductance minimum[11] and its temperature and magnetic field dependence,[12] shown in Fig. 1, are qualitatively the same as those of the curve for dI/dV vs V of a superconductor-insulator-metal tunneling junction. This indicates that the minimum is associated with superconductor tunneling through a Schottky barrier at the metal-semiconductor contact. The width of the minimum indicates an energy gap of $2\Delta \sim 2$ meV. Furthermore, the observed disappearance of the minimum by $T \lesssim 7$°K and the observed temperature dependence of the width indicates a transition temperature $T_c \lesssim 7$°K. These values are consistent with the value obtained from the BCS relation $2\Delta = 3.5kT_c$. The energy gap is believed