Microwave breakdown of ionic crystals initiated by a secondary-emission discharge

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A new type of breakdown has been observed in single microwave pulses. This breakdown takes the form of a contracted discharge along the surface of the crystal, accompanied by a pronounced (up to 100%) absorption of the radiation, evaporation of the material of the test sample, and ionization of this material. The breakdown is preceded by a nonresonant secondary-emission discharge. The electron density in the conduction band of the crystal is estimated to reach 10^{21} cm^{-3} in the course of the breakdown. It is suggested that the breakdown is due to the buildup of a high concentration of time-varying color centers during the discharge.

High levels of electronic excitation achieved in solids by one method or another have made it possible to observe some new physical phenomena and entities over the past several decades. Examples are lasing, electron–hole droplets, and a plasma resonance involving nonequilibrium charge carriers in semiconductors. A fundamental plasma luminescence and a high-energy conductivity have been observed in ionic crystals.[1] In this letter we are reporting surface microwave breakdown of an insulating crystal in vacuum during excitation of the surface layer of the crystal by electrons from a secondary-emission discharge.

A specific type of electron discharge—a nonresonant secondary-emission discharge—occurs at the surface of an insulator in a microwave field in vacuum.[2] The onset of this discharge has been attributed to a breeding of electrons as they bombard the surface. The condition for the onset of a nonresonant secondary-emission discharge is that the electron oscillation energy $\mathcal{E}_\sim = e^2E_0^2/2m\omega_0^2$ be greater than the electron energy $\mathcal{E}_1$ at which the secondary-emission yield of the insulator is equal to one (e and m are the specific charge and mass of an electron, ω_0 is the angular frequency of the field, and E_0 is the field amplitude). Although the microwave absorption coefficient (per unit area of the target) in a secondary-emission discharge is low, $\eta \sim eE_0/m\omega_0 c \sim 10^{-2}$, the high current densities ($\sim$1 A/cm^2) and small electron-penetration depths ($\sim 10^{-6}$–10^{-5} cm at $\mathcal{E}_\sim \approx 100$ eV) lead to a high density of electronic excitations in the crystal ($\sim 10^{21}$ cm^{-3}) over the duration of the radiation pulse, $\sim 10^{-5}$ s. Under these conditions we have managed to observe a surface breakdown of ionic crystals in fields two orders of magnitude weaker than the fields involved in laser breakdown or in breakdown in quasistatic fields.

Figure 1 shows the experimental layout. Cleaved or polished crystals of lithium fluoride or sodium chloride with dimensions of 70×10×5 mm are positioned through a cutoff section at the electric-field maximum of a standing TE_{10} wave of a rectangular waveguide with a cross section of 12×5.7 cm^2. The waveguide is evacuated by titanium

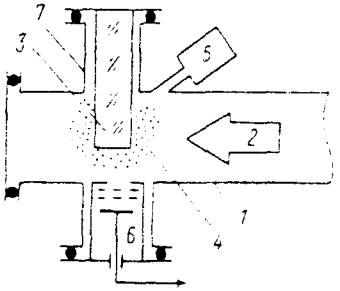

FIG. 1. Experimental layout. 1—Waveguide; 2—microwave radiation; 3—LiF crystal; 4—microwave discharge; 5—FÉU-79 photomultiplier; 6—multigrid electrostatic analyzer; 7—cutoff section with a diameter of 24 mm.

pumps to a pressure of 10^{-6} torr. A microwave pulse with a length τ from 1 to 60 μs and a power P_0 up to 5 MW is delivered from the magnetron to the vacuum section along a microwave line. The magnetron is decoupled from the section by ferrite isolators. The wavelength in the waveguide is $\lambda_g = 20$ cm. The pulse repetition frequency is varied from single pulses (0.1 Hz and less) to 2 Hz. A multigrid analyzer detects the current of electrons emitted from the surface of the crystal (in the stage of the secondary-emission discharge) or from the region of the plasma-burst discharge which arises because of microwave breakdown of the crystal. The emission from the crystal or plasma is detected by an FÉU-79 photomultiplier. The signals representing the incident and reflected microwave power are detected with the help of directional couplers.

The secondary-emission discharge arises when the threshold power is exceeded. The onset of the discharge is detected from the appearance of signals representing emission by the crystal and of an electron current at the collector of the multigrid analyzer (Fig. 2a). Under these conditions the threshold fields correspond to the condition for the onset of a nonresonant secondary-emission discharge.[2] These threshold fields are about 2 kV/cm. In this stage of the discharge, one can visually see a weak luminescence due to electrons of the secondary-emission discharge. This luminescence is uniform over the crystal surface. An increase in the length τ or power P_0 of the pulse results in breakdown of the crystal and the formation of a plasma burst. The breakdown delay time $\Delta\tau \leqslant \tau$ obeys the empirical law $(S_0 - S_{\min}) \cdot \Delta\tau = \text{const}$, where $S_{\min}$ is the threshold intensity for the onset of the secondary-emission discharge (which is inversely proportional to the square of the microwave wavelength). The value of the constant is determined by the nature of the crystal.

The breakdown is accompanied by a pronounced absorption of microwave energy with a time scale $\delta\tau \sim 0.1$ μs, an intense flash of light, and a burst of electron and ion currents to the collector of the multigrid analyzer (Fig. 2b). Visually, one sees a brightly emitting contracted discharge on the crystal surface. This discharge is stretched out along the electric field vector of the wave (Fig. 3). The optical emission from the discharge is detected by two FÉU-79 photomultipliers. The collimator slits of these photomultipliers are oriented across the crystal. These slits are spatially separated along the crystal. We found that the emission propagation velocity during the formation of the channel is 5×10^8 cm/s. This figure is an order of magnitude greater than the maximum velocity of development of surface breakdown of insulators in static electric fields.

Each breakdown event resulted in evaporation of material of the test sample. Ero-

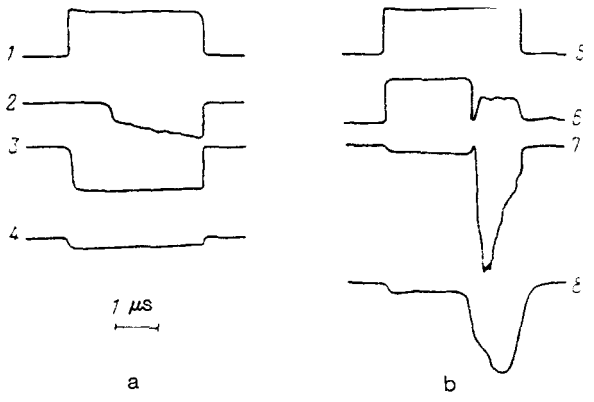

FIG. 2. Typical oscilloscope traces of the signals during the microwave discharge at the surface of a LiF crystal. a: Secondary-emission discharge. 1—Incident microwave power; 2—electron current from the discharge region near the threshold for the onset of the secondary-emission discharge ($P_0=45$ kW, $E_0=2.3$ kV/cm); 3,4—electron current and emission from the discharge region when the threshold for a secondary-emission discharge is exceeded by a factor of 6 ($P_0=280$ kW, $E_0=5.7$ kV/cm). b: Plasma-burst discharge. 5,6—Power of the incident and reflected microwave radiation; 7,8—electron current and emission from the discharge region near the threshold for microwave breakdown and the transition from a secondary-emission discharge to a plasma-burst discharge ($P_0=300$ kW, $E_0=5.9$ kV/cm). The gain levels for traces 2, 3, and 7 form the ratios 260:13:1, respectively.

sion channels a few microns in diameter formed at the surface of the crystal. Precise weighing of the samples after 10^4 pulses showed that 10^{17}–10^{18} atoms/cm^2 were evaporated per pulse, on the average. After the application of 10^4 pulses of secondary-emission discharge to the sample, no significant erosion was observed, but we did find an intense surface coloring of the crystal, due to the formation of F and F_2 color centers.[3]

We can use the pronounced absorption of microwave power during the formation of the breakdown channel to estimate the heating of the material in the channel and its electrical conductivity σ. It is easy to see that the energy per lattice site in the discharge channel is ~ 6 eV, if we determine the channel radius a from the thermal conductivity of the crystal and the duration of the breakdown. This high specific energy deposition means that evaporation, dissociation, and intense ionization of the material occur in the breakdown channel. However, the emission from the discharge channel precedes the onset of a strong absorption of energy. While the absorption coefficient is 1% in this early stage of the development of the breakdown channel, the energy per lattice site is only 0.06 eV, i.e., on the order of the energy of an optical phonon. Accordingly, the crystal can still be regarded to be in a solid state. Under these conditions we can easily estimate the channel admittance Y; from the latter we can estimate the conductivity σ, working from the relation[4]

$$Y/Y_0=\sigma(16\pi\lambda_g/\omega_0 b_1)(\pi a/\lambda)^2\sim 10^{-2}.$$

We can furthermore estimate the electron density in the conduction band from $n_e=m\sigma\nu_e/e^2$. Here Y_0 is the characteristic admittance of the waveguide, λ_g is the wavelength in the waveguide, $2b_1$ is the width of the waveguide, and ν_e is the rate at

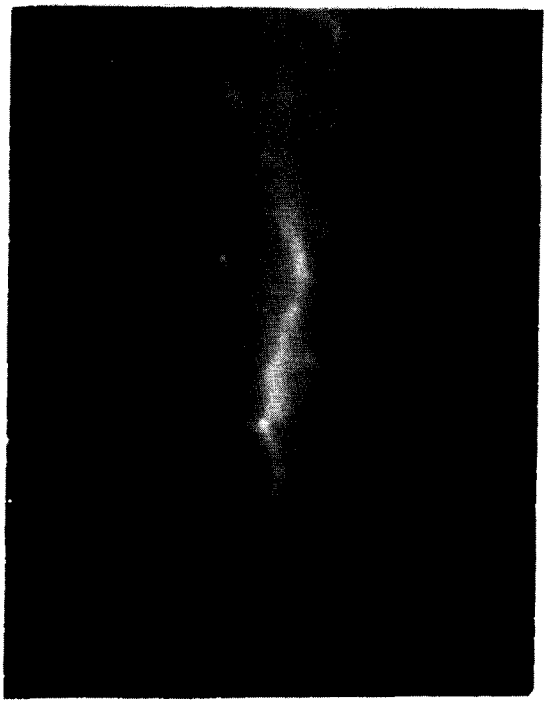

FIG. 3. Photograph of a contracted discharge during the breakdown of a LiF crystal.

which electrons are scattered by longitudinal optical phonons. With $a = 10^{-4}$ cm and $\nu_e = 10^{14}$ s^{-1} (Ref. 5) we find $\sigma = 5 \times 10^{15}$ s^{-1} and $n_e = 2 \times 10^{21}$ cm^{-3}.

The mechanism for reaching such high electron densities cannot be an accumulation of electron–hole pairs over the duration of the secondary-emission discharge, because of the high rate at which these pairs recombine[1] ($\sim 10^{12}$ s^{-1}), although the density of electronic excitations during the secondary-emission discharge is $\sim 10^{21}$ cm^{-3}. One might suggest that F, H, V, and I centers undergo a slower relaxation ($\sim 10^{-6}$ s) at room temperature. The energy of electron–hole pairs and excitons is expended primarily on the generation of these centers.[6] In this case the buildup of color centers and the subsequent recombination of these centers leading to the formation of electrons will cause an increase in the electron density.[6] As soon as the electron density reaches a level at which the imaginary part of the permittivity is one ($\omega_{Le}^2 > \omega_0 \nu_e$, where ω_{Le} is the electron plasma frequency or Langmuir frequency), regions of a local field intensification arise near inhomogeneities in the electron density. The result is a sharp local increase in the electron density, due to an increase in the electron temperature and a decrease in the rate of recombination of electron–hole pairs. A microwave "streamer," stretched out along the electric field vector, arises in a surface layer of the crystal. The increase in the energy of the electrons in this streamer due to the local field intensification causes a heating of the lattice in this region, followed by an explosive recombination of color centers and the formation of a breakdown channel. The "seed" electron density in the conduction band required to initiate this process is $n_e \sim 10^{15}$ cm^{-3}. A concentration of time-varying F

color centers on the order of 10^{17} cm^{-3} is sufficient here; this concentration is clearly reached in our case.[3]

As an alternative mechanism for the breakdown of the insulators we considered microwave breakdown in gas evolved from the surface of the crystals due to electron-stimulated desorption in the stage of the secondary-electron discharge. Experimental results and estimates show that for this mechanism to operate the intensity of the microwave radiation would have to be three orders of magnitude higher than that used in these experiments. The breakdown of the crystals in microwave fields two orders of magnitude weaker than the static breakdown fields is thus due to the formation of an electron–hole plasma with a high carrier density (10^{19}–10^{21} cm^{-3}). This plasma appears because of a relaxation of a metastable state of the ensemble of nonequilibrium lattice defects which induce the secondary-emission discharge.

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