Phonon jets: streamer-breakdown channels in crystals

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The acousto-electronic mechanism for the directiveness of incomplete electrical breakdown in crystals is examined. This mechanism is based on the formation of a region with a strong streamer electric field along the direction of the jet-like flow of generated phonons, which slow down fast current carriers.

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Incomplete breakdown of dielectrics and semiconductors has recently been attracting attention due to the fact that intense lasing was discovered in this process.[1,2] Conducting channels (streamers), growing into the bulk of the crystal, propagate along well-defined crystallographic directions. However, this directiveness remains a puzzle: existing theories do not give a unique description of the effect,[1–4] in spite of the fact that such spark-breakdown channels have been observed since 1887.[3]

In this paper, we propose a model of streamer formation, which shows that the directiveness of the breakdown can be explained by retardation of fast nonequilibrium current carrier excited by acoustical phonons in the direction of phonon "focusing."[5] A wide range of experimental data for different crystals can be explained with this model.[1–4]

We describe the initiation of the streamer by the following system of equations:

$$\frac{\partial n}{\partial t} = \frac{1}{e}\operatorname{div}\mathbf{j} + W(E), \tag{1}$$

$$\frac{\partial}{\partial t}\operatorname{div}\mathbf{E} = -\frac{4\pi}{\epsilon}\operatorname{div}\mathbf{j}, \tag{2}$$

$$\mathbf{j} \cong e n \mathbf{v}_0 + n\mu'\mathbf{f}, \tag{3}$$

in which the usual approximation are adopted (we ignore carrier diffusion and assume that the carrier drift velocity and mobility are equal to their limiting values in a strong field v_0 and μ' [1]), the only difference being that the current (3) includes the force **f**, which is attributable to the acoustical phonon flux S (Ref. 6),

$$\mathbf{f} = -AS, \quad A \cong 2\gamma_s / n v_s . \tag{4}$$

This force opposes supersonic drift of carriers created at a rate $W(E)$ in a strong electric field E due to impact ionization or the tunneling effect.[1] The coefficient A is estimated from the equation for the acousto-electric force,[7] where γ_s and v_s are the electronic increment and the velocity of sound. The field of a "point" source (tip of an electrode, electron or laser pulse[1,2]) excites elastic oscillations in the crystal, due to striction or the piezoelectric effect[7]: longitudinal (L) and fast transverse (FT) and slow transverse (ST) phonons with a wide range of orientations of the wave vector **q**. Because the group velocity tilts away from the phase velocity, the phonons form intense fluxes in the crystal along the "focusing" directions $\mathbf{r}_f^s$.[5] For this reason, the force (4) can be represented approximately in the form

$$f=\begin{cases} f_s(r,t)\,\mathbf{r}_f^s, & \text{when } \mathbf{r}\parallel \mathbf{r}_f^s,\ (s=L, FT, ST); \\ 0, & \mathbf{r}\nparallel \mathbf{r}_f^s,\ (\mathbf{r} - \text{distance from source}). \end{cases} \tag{4a}$$

From Eqs. (2)–(4a) and (1), where we assume that, as in Ref. 1, the density distribution n is one-dimensional along r, we obtain

$$n=n_i+\int_0^t W(\mathbf{r}-\tilde{\mathbf{v}}_0\tau,\tau)\,d\tau\,;\ \tilde{\mathbf{v}}_0=\mathbf{v}_0-\mu'\mathbf{E}_s,\ E_s=-\frac{f_s}{e},\ W_{\text{tun}}\sim E^{10/3}e^{-E_i/E}\ {}^{1}, \tag{5}$$

where n_i is the equilibrium electron density and, for simplicity, we assume that f_s is constant and $v_0 \gg \mu' E_s$. Since the streamer directions do not coincide with the field of the source, we view it as a metallic hemisphere with radius $r_0 \sim \mu$m impregnated on the surface of the crystal.[1–4] In this case, the solution of Eq. (2) has the form

$$E(\mathbf{r},t)\cong\frac{4\pi}{\epsilon}\,\frac{j_s t}{(r+r_0)^2}-e\tilde{v}_0(\mathbf{r})\int_0^t n(\mathbf{r},\tau)\,d\tau,\quad (\mathbf{E}\parallel\mathbf{r}). \tag{6}$$

Here $j_s = Cr_0\epsilon/4\pi$, and C is the linear growth rate of the potential U on the hemisphere. Equations (5) and (6) describe the evolution of the streamer (see Fig. 1).

In the absence of phonons ($f_s = 0$), the field is spherically symmetrical. The region with the strong field breaks away from the hemisphere at the time τ_0, determined

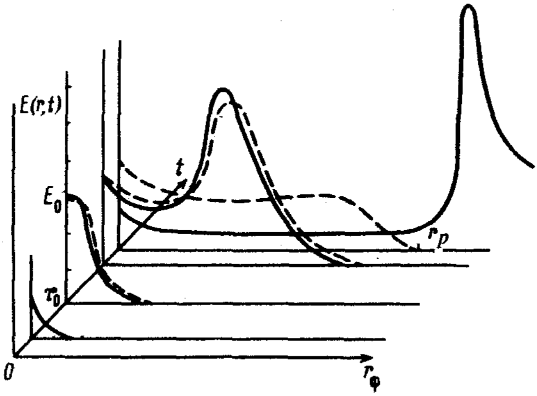

FIG. 1. Creation of a region with a strong streamer field [$E(r,t)$ according to Eq. (6)]: a) without phonons (dashed lines); b) with a retarding acoustical wind in the direction of phonon "focusing" (solid lines).

from the equation $\partial E/\partial r_{r=0,t=\tau_0}=0$, and rapidly attains velocities $v \sim v_0$ (for CdS $\tau_0=10^{-9}$ s with $C=10^{12}$ V/s, $E_0=E(0,\tau_0)=3\times10^6$ V/cm, $n_0=n(0,\tau_0)=10^{16}$ cm^{-3}; $v_0=10^7$ cm/s at $T=80$ K[1]). The peak in the field at first increases and then decreases as $1/r^2$, and its velocity also decreases, nearly disappearing at a distance $r_p=\sqrt{j_s/en_iv_0}$. Thus, in spite of the increase in voltage $U=Ct$, the spherical streamer fades at distances from the source that are shorter the higher n_i and v_0, which explains the absence of breakdown in crystals with high conductivity,[1-4] when $r_i \lesssim r_0$.

The influence of the phonons is manifested at the stage of creation of the streamer $t \gtrsim \tau_0$. At this time, the electric field of the source, still weakly screened by the carriers, resonantly excites elastic oscillations near the hemisphere with frequency $\omega \gtrsim \tau_0^{-1}$ and wavelength $2\pi/q \lesssim r_0$, i.e., under the condition that

$$\frac{dU}{dt} \sim \frac{U(\tau_0)}{\tau_0} \cong \frac{E_0 r_0}{\tau_0} \geqslant E_0 v_s = C^s . \tag{7}$$

From here, for the existence of breakdown, we obtain a lower bound on the increase in voltage: $(dU/dt)_{\min}=C^s$. Thus, for CdS, with the generation of transverse phonons $(v_T=2\times10^5$ cm/s), we obtain $C^T=6\times10^{11}$ V/s, which agrees with experiment[1] and is two orders of magnitude lower than the estimate $C_{\min}{}^1=E_0^l v_0$, where $E_0^l \gtrsim E_0$ corresponds to the field required for the laser effect. The electric potential wells, which form due to the inverse piezoelectric effect with maximum depth along the directions of phonon "focusing," slow down the fast excited carriers with $t \sim \tau_0$, which leads to an increase in the maximum of the field along $\mathbf{r}_f^s$:$E_{\mathrm{M}} \cong E_{\mathrm{M}}(\mathbf{r} \neq \mathbf{r}_f^s)+E_s$ in (6). From expression (4), we obtain an estimate of the field $E_s=2\gamma S/en_0v_s \sim 10^5$ V/cm with $S \sim \eta^2 v_s E_0^2 \sim 10^4$ W/cm^2 for the CdS crystal, where the piezoelectric constant $\eta^2 \sim 10^{-2}$ and $\gamma \sim \gamma_{\max}=\eta^2 q/8$ with $qv_0 \sim en_0\mu'$ and $q \sim 10^5$ cm^{-1}. The exponential dependence $W(E)$ in (5) results in rapid growth in carrier density and pushes the regions with strong field along r_f^s. Thus a needle-shaped streamer forms (Fig. 1). Its further motion with a velocity determined by the creation of carriers $v_W \gg v_0, v_s$ ($v_W^{\mathrm{CdS}} \sim 10^8$ cm/s) is described by the model,[1] in which the phonons excited by the "point" source are ignored.

It follows from condition (7) that the quantity dU/dt can be used to control the direction of the streamer.1) Thus, with $v_s<(dU/dt)E_0<v_T$, the streamer can proceed only along the focusing direction of surface phonons $\mathbf{r}_f^s$; when $v_T<(dU/dt)/E_0<v_L$, the streamer proceeds along the direction $\mathbf{r}_f^T$; and, for $dU/dt>E_0v_L$, it proceeds along the focusing directions of longitudinal phonons inside the crystal. Thus, in NaCl, the ratio of the increase in breakdown voltage in different directions[4] $0.94_{[111]}:1.00_{[110]}:1.43_{[100]} \cong v_{ST}:v_{FT}:v_L$ coincides with the ratio of the velocities of phonons "focused" in the same directions.[5]

In the crystals with an inversion center NaCl, LiF, KBr, and other,[3,4] breakdown proceeds essentially along the directions of phonon focusing with $E=0$. In crystals lacking an inversion center, the piezoelectric effect in high electric fields appreciably alters the elastic properties with a lowering of symmetry due to the nonlinear terms $e_{i,\alpha\beta}$.[8] Thus the hexagonal CdS crystal becomes trigonal: in a field $E_2 \sim 10^6$ V/cm, a new modulus of elasticity appears $c_{14}=e_{2,14}E_2 \sim 10^9$ N/m^2, $e_{2,14} \sim 10$ C/m^2.[8] Cones of phonon focusing[9] transform into jets, for example, $r_f^{ST}=(\phi=0°, \theta_{ST} \cong 40°$ and $135°)$;

$r_f^L(\phi = 30^\circ \theta_L \cong 80^\circ$ with $E_2 > 0$ and $\theta_L \cong 100^\circ$ with $E_2 < 0$, i.e., with a change in the polarity of the voltage at the tip), which coincides with the directions of streamers in CdS($\theta = \measuredangle \mathbf{r}_f^s, \mathbf{z}$).

There also exists a thermal source of "focused" phonons, arising due to Joule heating by the current carriers. It not only helps to create the streamer but it can also increase the index of refraction of light N in its conducting channel (for $dN/dT > 0$) and can lead to wave-guide trapping of laser radiation, which could be the reason for the afterglow of the channel.[1]

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[1)] With $dU/dt = \text{const}$, contact of the streamer with the region of inhomogeneity, in which $E_0^H > E_0$ (for example, due to a larger forbidden band $W_H(E) < W(E)$, can slow down the streamer and excite breakdown due to a new "point" source with a different streamer direction, corresponding to "focusing" of phonons with lower velocity (for example, $v_T \cong v_L/2$).

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