Field-even current in the ferroelectric SbSI

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A field-even current has been observed in a ferroelectric material for the first time. The mechanism responsible for this current may be a ballistic mechanism consisting of a scattering of carriers by charged centers which comprise an injected space charge.

Kazlauskas and Levinson[1] foresaw some time ago the possibility that a field-even current could exist in a crystal lacking a symmetry center[1]:

$$j_k = \alpha_{ijk} E_i E_j \ . \tag{1}$$

The first experimental observation of a field-even current was achieved by Tkachenko and Ivanov[2] in the piezoelectric p-InSb. Ivchenko and Pikus[3] calculated a field-even current (1) for the same case, p-InSb, under the assumption of streaming and a displacement mechanism.

In this letter we report the first experimental observation of a field-even current in a ferroelectric near the phase transition. The ferroelectric SbSI is of point group $mm2(C_{2v})$, so that the field-even current can be written in the following form, in accordance with (1):

$$j_3 = \alpha_{31} E_1^2 \qquad (2)$$

Here the external field E_1 is applied along the [100] direction, and j_3 is a current which is quadratic in the field and which is flowing in the spontaneous-polarization direction. We studied modified SbSI crystals grown by the Bridgman method with[4,5] $T_C = +60\,^\circ\mathrm{C}$. Aquadag electrodes are deposited on (100) faces, and a longitudinal field E_1 ($E_1 = 50$–1200 V/cm) is applied to these electrodes. The transverse current j_3 is measured with the help of aquadag electrodes deposited on faces perpendicular to the [001] direction.

The experimental results can be summarized as follows. A space-charge-limited current $j_1 \simeq V_1^2/L^3$ flows in the longitudinal direction, along [100] (V_1 is the voltage applied in the longitudinal direction, and L is the distance between the electrodes in the longitudinal direction). In the transverse direction we measure the current j_3; according to (1), we should have $j_3 \sim V_1^2$. The effect is observed in the ferroelectric phase; the transverse current j_3 disappears at the transition to the centrally symmetric paraelectric phase. When the ferroelectric undergoes a 180° polarization reversal, the transverse current j_3 changes direction. In a polydomain crystal, there is no field-even current j_3. The direction of the field-even current j_3 thus depends on the direction of the spontaneous polarization. Comparison of the experimental results with (1) yields $\alpha_{31} \simeq 10^{-14}$–$10^{-15}$ A/V^2. The component α_{31} turns out to be several orders of magnitude below the corresponding component of the photovoltaic tensor, $\alpha_{31}^{\mathrm{ph}}$, in SbSI (Ref. 5). With an open transverse circuit we observe a voltage $\sim$20 V which is quadratic in the field; this figure is an order of magnitude greater than the band gap of the crystal. The results show that the voltage which is quadratic in the field is limited solely by the electrical conductivity of the crystal. A transverse current j_3 which is quadratic in the field is observed only when a space-charge-limited current j_1 flows in the [100] longitudinal direction. When the current-voltage characteristic for j_1 is linearized, the transverse current j_3 vanishes.

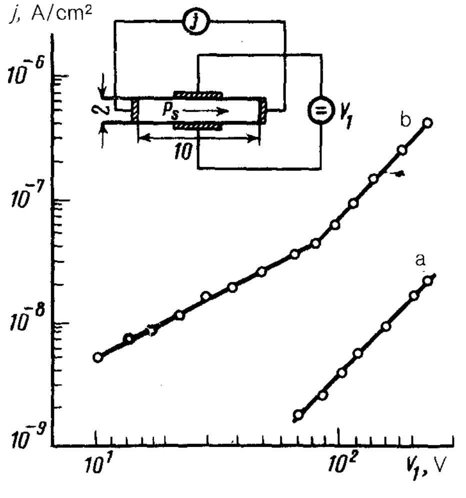

FIG. 1. Current-voltage characteristics of (a) the transverse current j_3 and (b) the longitudinal current j_1. $T = 300$ K. The sample is a parallelepiped 10 mm long (the [001] direction), 2 mm high ([100]), and 5 mm wide ([010]). The longitudinal electrode has an area of 4×5 mm^2.

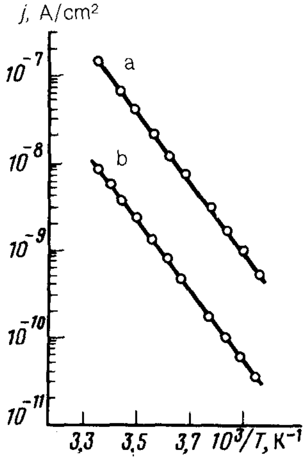

FIG. 2. Temperature dependence of (a) the transverse current j_3 and (b) the longitudinal current j_1. $E_1 = 1200$ V/cm.

Figure 1 shows I–V characteristics $j_1(V_1)$ and $j_3(V_1)$. In a field $E_1 = 400$–1200 V/cm the ratio j_3/j_1 reaches 6%. Figure 2 shows the temperature dependence of j_1 and j_3; we see that we have $j_1, j_3 \sim \exp(-U/kT)$, where the activation energy is $U \simeq 0.8$ eV. The temperature dependence of the field-even current in SbSI is thus the inverse of that found for streaming in Ref. 3. Illumination with red light with an energy of 0.8 eV causes j_1 and j_3 to increase. Illumination in the intrinsic region causes j_1 to increase as a result of the photoconductivity; the I–V characteristic of the photocurrent becomes linear; and the transverse current j_3 disappears.

The temperature dependence of j_1 and j_3 and the relationship between the field-even current j_3 and carrier injection along the [100] direction can be explained on the basis that the longitudinal current j_1 is limited by space charge, while the transverse current j_3 is associated with an asymmetric scattering of electrons by charged trapping centers which form a space charge. Let us assume that the space charge which is formed through the injection of electrons in the longitudinal direction (the current j_1) consists of free electrons with a density n and electrons which have been trapped at trapping centers, with a density N and an activation energy U. If the filling of the trapping centers is only slight, the relationship between n and N is

$$n = k_2^T N/\beta M, \tag{3}$$

where M is the density of trapping centers, β is their capture cross section, $k_2^T = \beta N_c \exp(-U/kT)$, N_c is the state density, and $n \ll N$. The equations and boundary conditions for a space-charge-limited longitudinal current j_1 are

$$j_1 = q\mu n E_1; \qquad \frac{dE_1}{dx} = \frac{4\pi}{\epsilon} Nq; \qquad \frac{dj_1}{dx} = 0 \tag{4}$$

$$E(x=0) = 0; \quad E(x=L) = E_1^0; \quad E_1^0 = \frac{V_1}{L}. \tag{5}$$

The solution of (4),(5) is the well-known current-voltage characteristic for j_1:

$$j_1 = \frac{\mu k_2^T \epsilon}{8\pi\beta M} \frac{V_1^2}{L^3} . \tag{6}$$

If the current j_3 is a consequence of an asymmetric scattering of electrons by charged trapping centers, we have

$$\mathbf{j}_3 \sim j_1 < l > \mathbf{P}_0 , \tag{7}$$

where $\mathbf{P}_0$ is the spontaneous polarization, and $\langle l \rangle$ is the mean displacement of an electron in the transverse direction. In (6) and (7) we see directly the temperature dependence of j_1 and j_3 and the effect of red illumination.

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[1] P.-A. V. Kazlauskas and I. B. Levinson, Fiz. Tverd. Tela (Leningrad) **6**, 3192 (1964) [Sov. Phys. Solid State **6**, 2552 (1964)].

[2] A. Yu. Tkachenko and Yu. L. Ivanov, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 270 (1984) [JETP Lett. **39**, 323 (1984)].

[3] E. L. Ivchenko and G. E. Pikus, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 268 (1984) [JETP Lett. **39**, 320 (1984)].

[4] L. M. Belyaev, A. A. Grekov, L. N. Syrkin, L. N. Tatarenko, and N. P. Protsenko, Akust. Zh. **23**, 810 (1977) [Sov. Phys. Acoust. **23**, 463 (1977)].

[5] E. I. Gerzanich and V. M. Fridkin, Segnetoélektriki tipa $A^{V}B^{VI}C^{VII}$ (V-VI-VII Ferroelectrics), Nauka, Moscow, 1982.

Translated by Dave Parsons