CARRIER HEATING IN FERROELECTRIC SEMICONDUCTORS

V. L. Bonch-Bruevich

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The carriers in ferroelectric semiconductors are acted upon not only by applied external electric fields, but also by an internal electric field. The latter is localized in surface layers with thicknesess on the order of the screening radius r_0. This field has an intensity of the order of $\frac{4\pi}{a}\mathcal{P}$, where $\mathcal{P}$ is the absolute value of the polarization vector, a is a constant that depends on the geometry of the specimen (it may also contain ε, the permittivity of the ferroelectric in the direction perpendicular to the surface, as a multiplier).

In itself, of course, the internal field does not cause nonequilibrium processes, because the drift current is fully compensated by the diffusion current in the absence of the external field. But when even a weak external field E" is applied, these currents are "unbalanced," and the internal field contributes to heating. In this respect, the situation here is the same as in any other spatially inhomogeneous system*. It is easily verified by solving the system of kinetic equations for the symmetric and antisymmetric parts of the distribution function (f_s and f_a) by iterations that

$$f_s = f_0 + \hat{L}_1[E''_\alpha E''_\beta f_0] + \hat{L}_2[E'_\alpha E''_\beta f_0] + \hat{L}_3\left[\frac{\partial E''_\beta}{\partial x_\alpha} f_0\right] + \dots . \tag{1}$$

$$\begin{aligned} f_a = {} & \hat{K}_1[E''_\alpha v_\alpha f_0] + \hat{K}_2[E'_\alpha E''_\beta E''_\gamma v_\gamma f_0] + \\ & + \hat{K}_3\left[\frac{\partial}{\partial x_\gamma}(E'_\alpha E''_\beta) v_\gamma f_0\right] + \hat{K}_4[E'_\alpha E''_\beta E'_\gamma v_\gamma f_0] + \\ & + \hat{K}_5\left[v_\gamma (E'_\gamma + E''_\gamma)\frac{\partial E''_\beta}{\partial x_\alpha}\right] + \dots . \end{aligned} \tag{2}$$

Here $\hat{L}_i$ $(i=1, 2, 3)$ and $\hat{K}_i$ $(i=1, \dots, 5)$ are integral operators, α, β, γ are vector indices, $f_0 = \exp\left(\frac{F - W - e\varphi}{kT}\right)$ is the equilibrium distribution function, $E' = -\nabla\varphi$ and E" are the intensities of the internal and external electric fields, respectively, W is the energy of the electron at $\varphi = 0$, F is the Fermi level, v is the velocity of the electron, and the dots indicate terms of higher order in E". We note that f_0 can also be understood as the Fermi function.

The final expressions obtained from (1) and (2) for the current density and the other physical variables will naturally contain not the field E' itself, but the only independent vector (other than E") in the problem—the polarization vector $\mathcal{P}$. Here it must be remembered that the contribution from the terms that contain E' in (1) and (2) is due solely to the surface layers of the specimen.

Thus, the expression for the current density in a weak external field should have the form

$$\begin{aligned} j_\alpha = {} & \sigma_{\alpha\beta} E''_\beta + \sigma_{\alpha\beta\gamma\delta} E''_\beta E''_\gamma E'_\delta + \sigma'_{\alpha\beta\gamma\delta} E''_\beta \mathcal{P}_\gamma \mathcal{P}_\delta + \\ & + \sigma''_{\alpha\beta\gamma\delta} E''_\beta E''_\gamma \mathcal{P}_\delta + \dots . \end{aligned} \tag{3}$$

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*See V. L. Bonch-Bruevich, I. P. Zvyagin, and A. G. Mironov, Electrical Domain Instability in Semiconductors [in Russian], Moscow, 1972.

Here $\sigma_{\alpha\beta}$, etc. are material tensors with obvious symmetry properties. Strictly speaking, they should be regarded as integral operators, but for what follows nonlocal effects will not be of fundamental importance.

According to the above, the components of the tensors $\sigma''_{\alpha\beta\gamma\delta}$ and $\sigma'_{\alpha\beta\gamma\delta}$ are small compared to $\sigma_{\alpha\beta\gamma\delta}$, as $\frac{4\pi}{a} r_0/L$ is compared to $\left(\frac{4\pi}{a}\frac{r_0}{L}\right)^2$ (L is the linear dimension of the specimen in the direction perpendicular to the surface). They can be overdetermined in such a way that all tensors of equal rank will have the same order of magnitude if the true value of $\mathcal{P}$ is replaced by the effective value

$$\mathcal{P}_{\text{eff}} = \xi\mathcal{P}, \quad \text{where} \quad \xi \sim \frac{4\pi}{a}\cdot\frac{r_0}{L}.$$

The third and fourth terms in the right-hand side of (3) will obviously be more important than the second term in weak enough external fields. Hence it follows that not only the detailed form, but also the type of the specimen's volt-ampere characteristic may depend both on $\mathcal{P}$ and on the relative orientation of the vectors P and E" and the axes of the crystal; the explicit form of the corresponding angular dependence follows immediately from (3) with consideration of the symmetry relations for the specific crystal involved.

An analogous expression for the electron temperature T (understood as a measure of the average carrier energy) corresponds to (3). Using the continuity equation for the energy, we obtain

$$T - T_0 = A_{\alpha\beta} E''_\alpha E''_\beta + A'_{\alpha\beta} E''_\alpha \mathcal{P}_\beta + \cdots \qquad (4)$$

Here T_0 is the lattice temperature and $A_{\alpha\beta}$, etc. are material tensors that are related in obvious fashion to $\sigma_{\alpha\beta}$, etc., and to the energy relaxation time.

We see that, depending on the relative orientation of the vectors E" and P and the axes of the crystal, it is possible in principle to obtain either heating or cooling of the carrier gas during passage of current (the latter possibility results from the need to perform work against the internal field).

The conclusions drawn above from relations (3) and (4) do not depend on whether we take the local approximation or treat $\sigma_{\alpha\beta}$, $A_{\alpha\beta}$, etc., as integral operators. Actually, it is easily verified that nonlocal effects in (4) can be neglected if

$$\frac{\tau j}{enr_0} = \frac{\tau v_d}{r_0} \ll 1. \qquad (5)$$

Here τ, n, and v_d are the energy relaxation time, the free-carrier concentration, and the drift velocity of the free carriers.

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