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Electric fields and currents due to excess charges and dipoles in insulators—A comment

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A general expression is derived for the motion of the zero-field plane in a dielectric with persistent polarization containing an arbitrary space-charge distribution.

Most investigations of time-dependent polarization of dielectrics have considered either space-charge effects due to the transport and trapping of charge carriers or effects due to the existence of a component of dielectric polarization out of phase with the electric field (persistent polarization). Recently some general relations were established which are valid when both effects are present and interact with each other.[1] A main point was the discussion of the equation

$$J(t) = j(z_0, t) - \frac{dz_0}{dt}\rho(z_0, t), \quad (1)$$

which gives the total current density J in terms of the conduction current density j and the motion of a plane where the electric field is zero, z_0 being its position and ρ is the value of the space charge in this plane at time t. The equation applies to plane-parallel geometry. A relation of this type was first stated by Lindmayer[2] and subsequently derived from first principles for short-circuit conditions by Gross and Perlman.[3] It has been shown in Ref. 1 that it also applies in open circuit (e.g., $J=0$) with or without electrodes in contact with the dielectric, and for arbitrary applied voltage, provided only that a zero-field plane does exist. Contrary to what was surmised in Ref. 1, it does not apply in the presence of heterocharges and persistent polarization $P(z,t)$. This can easily be seen if one assumes that the dielectric does not contain any excess space charge, so that $\rho(z,t)=0$. Then $J(t)=j(z_0,t)$, which in the absence of diffusion reduces to $J(t)=0$. Such a relation would rule out the generation of thermally activated depolarization currents connected with frozen-in dipoles which have been successfully used in measurements of electret polarization[4] and dipole structure.[5,6]

It is, however, easy to generalize Eq. (1) to include persistent-polarization effects. Inside the dielectric the displacement D is given by

$$D(z,t) = \epsilon E(z,t) + P(z,t), \quad (2)$$

where ϵ is the "instantaneous" dielectric constant, E is the field, and $0<z<d$, d being the thickness of the dielectric. The total current density is the sum of the conduction and displacement current,

$$J(t) = j(z,t) + \frac{\partial D(z,t)}{\partial t}, \quad (3)$$

while from Poisson's equation

$$\frac{\partial D(z,t)}{\partial z} = \rho(z,t). \quad (4)$$

By integrating relation (4) one obtains

$$D(z,t) = D(z_0,t) + \int_{z_0}^{z} \rho(z,t)\,dz. \quad (5)$$

But

$$D(z_0,t) = \epsilon E(z_0,t) + P(z_0,t).$$

Since $E(z_0,t)=0$, relation (5) becomes

$$D(z,t) = P(z_0,t) + \int_{z_0}^{z} \rho(z,t)\,dz. \quad (6)$$

Consequently, the total current density can be written

$$J(t) = j(z,t) - \frac{dz_0}{dt}\rho(z_0,t) + \int_{z_0}^{z} \frac{\partial\rho(u,t)}{\partial t}\,du + \frac{dP(z_0(t),t)}{dt}.$$

The time variation of ρ is related to the conduction-current densities by

$$\int_{z_0}^{z} \frac{\partial\rho(u,t)}{\partial t}\,du = j(z_0,t) - j(z,t).$$

This leads to the expression of the total current density:

$$J(t) = j(z_0,t) + \frac{dP(z_0,t)}{dt} - \frac{dz_0}{dt}\rho(z_0(t),t). \quad (7)$$

In the absence of diffusion $j(z_0(t),t)=0$ and

$$J(t) = \frac{dP(z_0,t)}{dt} - \rho(z_0(t),t)\frac{dz_0}{dt}. \quad (8)$$

No assumptions have been made about initial and boundary conditions. Therefore this relation applies for any operation, i.e., current or voltage modes. The terms containing P in Eq. (8) contain the contribution of the heterocharge polarization.

A particular case is the operation in short-circuit conditions. If the dielectric contains no space-charge distribution one has $\rho(z, t) = 0$. If, in addition, the dipole polarization is uniform, one has $P = P(t)$ and $E = 0$ for any value $0 < z < d$. Then any point inside the dielectric can be taken as a zero-field plane and Eq. (8) reduces to the well-known relation $J = \partial P/\partial t$, which is the basis of most thermally activated investigations.

If, however, $P = 0$ and the dielectric is kept in open circuit, one has $J = 0$ and $dz_0/dt = 0$. The zero-field plane, therefore, remains stationary.

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[1]G. Dreyfus and J. Lewiner, Phys. Rev. B 8, 3032 (1973).

[2]J. Lindmayer, J. Appl. Phys. 36, 196 (1965).

[3]B. Gross and M. M. Perlman, J. Appl. Phys. 38, 853 (1972).

[4]B. Gross and R. J. de Moraes, J. Chem. Phys. 34, 2061 (1962).

[5]C. Bucci, R. Fieschi, and G. Guidi, Phys. Rev. 148, 816 (1966); C. Bucci and R. Fieschi, Phys. Rev. Lett. 12, 16 (1964).

[6]S. Mascarenhas, Radiat. Eff. 4, 263 (1970).