SOME EFFECTS DUE TO ELECTRON-PHONON INTERACTION IN PHASE TRANSITIONS OCCURRING IN A SEMICONDUCTOR FERROELECTRIC

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Submitted 3 February 1966
ZhETF Pis'ma 3, No. 6, 252-255, 15 March 1966

The first report of the discovery of ferroelectric properties in single-crystal SbSI was published in 1962 [1]. Soon afterwards it was established that other $A_V B_{VI} C_{VII}$ semiconductors also exhibit ferroelectric phase transitions [2]. The simultaneous presence in these compounds of a relatively narrow forbidden band (~2 eV), photoconductivity, and ferroelectric properties has made it possible to investigate for the first time the behavior of the intrinsic absorption edge in the region of the ferroelectric phase transition [3,4], the associated anomalies in the behavior of the lifetime of the nonequilibrium carriers [5], and the quantum yield of the photocurrent.

The presence of a relatively high density of nonequilibrium carriers in semiconductor ferroelectrics makes it necessary to take into account the free energy of the electronic subsystem in the expansion of the crystal free energy in the parameter P (P = spontaneous polarization). We shall show below that this leads in turn to several new effects, which constitute noticeable features of the behavior of a semiconductor ferroelectric in the phase-transition region. Near the Curie point the total free energy of the crystal can be expressed in the form [6]

$$F = F_0 + \alpha P^2 + \frac{\beta}{2}P^4 + \ldots + nE_g(P), \qquad (1)$$

where α and β are the known coefficients of the Landau expansion, n the density of the nonequilibrium carriers causing the photoconductivity, and E_g the width of the forbidden band. According to [7] the term nE_g includes the change in the electronic-subsystem free energy due to the electron-phonon interaction. Using the first three terms of the expansion

$$E_g \simeq E_{go} + aP^2 \qquad (2)$$

and substituting (2) in (1), we transform (1) to

$$F = F_{01} + \alpha_1 P^2 + \frac{\beta}{2}P^4 + \ldots, \qquad (3)$$

$$F_{01} = F_0 + nE_{go}, \qquad (4)$$

$$\alpha_1 = \alpha + an. \qquad (5)$$

Using the conditions for the minimum of the free energy [6], we obtain from (5)

$$\theta_1 = \theta - a\frac{n}{\alpha'_\theta}, \qquad (6)$$

where θ and θ_1 are the Curie temperatures in the absence and presence of nonequilibrium carriers, respectively, n the concentration of the nonequilibrium carriers, α'_θ is the reciprocal of the Curie constant [6], and a is the coefficient characterizing the electron-phonon coupling in the expansion (2). According to (6), when a sufficiently high density of non-equilibrium carriers is produced in a semiconductor ferroelectric the Curie point experiences a shift whose magnitude and sign are determined respectively by the magnitude and sign of the constant a. The latter can be determined from (2) by investigating the anomalies of E_g or of the temperature coefficient dE_g/dT in the phase transition region. These anomalies are best considered separately for the case of a second-order phase transition and for the case of a second-order phase transition close to the critical Curie point [6].

In the first case (second-order phase transition), by substituting in (2) the well known expression for the square of the spontaneous polarization [6]:

$$P^2 = \frac{\alpha'_\theta}{\beta} (\theta - T), \tag{7}$$

we arrive at the following relations:

$$\Delta\left(\frac{\partial E_g}{\partial T}\right)_p = a \frac{\alpha'_\theta}{\beta} = a \frac{\Delta C_\theta}{\theta \alpha'_\theta}, \tag{8}$$

$$\Delta\left(\frac{\partial E_g}{\partial p}\right)_T = -a \frac{\alpha'_\theta}{\beta} \frac{d\theta}{dp}, \tag{9}$$

$$\frac{\Delta\left(\frac{\partial E_g}{\partial p}\right)_T}{\Delta\left(\frac{\partial E_g}{\partial T}\right)_p} = -\frac{d\theta}{dp}. \tag{10}$$

Here $\Delta(\partial E_g/\partial T)_p$ and $\Delta(\partial E_g/\partial p)_T$ are the independently-measured jumps in the values of the corresponding coefficients on going over from the paraelectric to the ferroelectric region, ΔC_θ is the jump in the specific heat, and $d\theta/dp$ is a constant characterizing the shift of the Curie point with change in pressure. Thus, in a second-order phase transition the co-efficients of the temperature and pressure variations of the width of the forbidden band experience finite discontinuities whose signs and magnitudes are determined respectively by the sign and magnitude of the constant a.

In the second case (second-order phase transition close to the critical Curie point), it is necessary to take into account the term $(\gamma/6)p^6$ in expansion (1) [6]. Substituting in (2) the corresponding expression for the square of the spontaneous polarization corresponding to this case [6], we arrive at the relations

$$\left(\frac{\partial E_g}{\partial T}\right)_p = \left(\frac{\partial E_{go}}{\partial T}\right)_p - a \frac{\alpha'_\theta}{(2\gamma\alpha'_\theta)^{1/2}} (\theta - T)^{-1/2}, \tag{11}$$

$$\left(\frac{\partial E_g}{\partial p}\right)_T = \left(\frac{\partial E_{go}}{\partial p}\right)_T + a \frac{\alpha'_\theta}{(2\gamma\alpha'_\theta)^{1/2}} \frac{d\theta}{dp} (\theta - T)^{-1/2}. \tag{12}$$

Thus, near the critical Curie point the coefficients $(\partial E_g/\partial T)_p$ and $(\partial E_g/\partial p)_T$ become infinite like $(\theta - T)^{-1/2}$, and the signs of these coefficients near the Curie point are determined by the sign of the constant a.

As shown in [8], the phase transition in SbSI is close to the critical Curie point. Accordingly, anomalously large values of $\partial E_g/\partial T$ and $(\partial E_g/\partial p)_T$ were observed in [3,4], with signs corresponding to positive a ($d\theta/dp < 0$ for SbSI). Unfortunately, the constant a was not estimated numerically from these measurements, since the values of γ were unknown.

I am grateful to I. M. Lifshitz for reviewing the manuscript and for a discussion, and also to R. A. Suris and A. P. Levanyuk for a discussion and numerous remarks.

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INFLUENCE OF MAGNETIC-FIELD CONFIGURATION ON THE HEATING AND CONTAINMENT OF A PLASMA IN A MIRROR TRAP ("PROBKOTRON")

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Submitted 6 February 1966
ZhETF Pis'ma 3, No. 6, 255-258, 15 March 1966

It was observed earlier [1], that heating of a plasma by an electron beam in a mirror trap increases strongly with increasing mirror ratio. Further experiments have shown that heating and containment of the plasma depend strongly on the distribution of the magnetic field along the trap axis. The experiment was carried out with the installation of [1], which made it possible to operate with two different configurations of the magnetic field (Fig. 1).

The mirror ratio and the field in the center remained unchanged in both cases.

The plasma with initial density 10^{12} cm^{-3} was prepared with a titanium injector. A pulsed beam of electrons with current strength 1 A, energy 10 kV, and duration 500 μsec was injected into this plasma.

The heating and decay of the plasma were investigated by measuring the time variation of the energy content (nT) and of the density n.

It is seen from Fig. 2 that on going over from a field configuration with local mirrors