Photovoltaic displacement current in the piezoelectric semiconductor $Bi_{12}GeO_{20}$

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The displacement component of the bulk photovoltaic current was detected experimentally for the first time by measuring its Hall component in the magnetic field. The temperature and spectral dependences of the mobility of nonthermalized electrons in the piezoelectric semiconductor $Bi_{12}GeO_{20}$ were measured.

The bulk photovoltaic current[1] which is seen as a result of uniform exposure to light of a homogeneous crystal without a symmetry center is given by[2,3]

$$J_i = \alpha_{ijk} E_j E_k^* + i\gamma_{ij} (\mathbf{E} \times \mathbf{E}^*)_j, \tag{1}$$

where E_j and E_k are the components of the electric field of a light wave, and $i(\mathbf{E}\times\mathbf{E}^*)$ determines the degree of circular polarization of light, σ, in accordance with the relation

$$i(\mathbf{E} \times \mathbf{E}^*) = \sigma \frac{\mathbf{q}}{|\mathbf{q}|} I, \tag{2}$$

where $\mathbf{q}$ is the photon wave vector, and I is the light intensity. The first term on the right side of (1) describes the bulk photovoltaic current for linearly polarized light [linear bulk photovoltaic current (BPC) J_i^l] and the second term describes the circular BPC J_i^c. The tensors α_{ijk} and γ_{ij} are nonvanishing for the piezoelectric and optically active crystals, respectively. In a magnetic field $\mathbf{B}$, the linear and circular BPC are expressed in terms of the tensors S_{ijkl} and Q_{ijk}, respectively:

$$J_i^{B_j} = S_{ijkl} B_j E_k E_l^* + iQ_{ijk} B_j (\mathbf{E} \times \mathbf{E}^*)_k . \tag{3}$$

In bismuth germanate piezoelectric crystals (symmetry group 23) the nonzero components of the linear and circular BPC tensors are α_{14}; γ_{33}; $S_{3311} = -S_{3322} = S_1$, $S_{3131} = -S_{3232} = S_2$; $Q_{312} = Q_{321} = Q$. Equations (1) and (3) for $Bi_{12}GeO_{20}$ can therefore be written

$$J_z = \frac{1}{2} \alpha_{14} I \sin 2\beta + \gamma_{33} I \sigma, \tag{1'}$$

$$J_x^{B_y} = \frac{1}{2} S_2 I B_y \sin 2\beta + Q I B_y \sigma. \tag{3'}$$

The x, y, and z axes coincide with the axes of (2), z is the direction of illumination of the crystal, β is the angle between the polarization plane of light and the x axis, and B_y is the strength of the magnetic field directed along the y axis. The current $J_x^{B_y}$ is the

Hall component of the current J_x if the magnetically induced effects are ignored. The mobility of the nonthermalized carriers can be determined from (1) and (3) (Refs. 4–6):

$$\mu = \frac{1}{B} \frac{J_x^{B_y}}{J_z} . \tag{4}$$

The mobility (4) determined in this manner differs fundamentally from the ordinary (thermalized) Hall mobility, since BPC is affected only by nonthermalized carriers.

The linear BPC in a crystal without an inversion center is based on two microscopic mechanisms. The first mechanism, a ballistic mechanism, is associated with the asymmetry of the momentum distribution of nonthermalized electrons in the zone.[2,3] The second mechanism, a displacement mechanism, involves a displacement of the center of mass of the wave packet of electrons as a result of their photoexcitation.[7–10] In this case of self-excitation, these mechanisms account for approximately equal currents and the linear bulk photovoltaic current is the sum of the ballistic and displacement BPC. The following features of the displacement and ballistic components of BC can be used to distinguish one component from the other. First, the circular BPC is a purely ballistic current.[10] Secondly, the displacement current in a magnetic field does not affect the Hall component (if the magnetically induced effects are ignored). Thirdly, it can justifiably be assumed that the impurity BPC is primarily a ballistic current.[10]

We will attempt to draw a distinction here between the ballistic BPC mechanism and the displacement BPC mechanism in piezoelectric bismuth germanate crystals. For this purpose, we have measured the linear BPC J_z^l and circular BPC J_z^c and their Hall component in a magnetic field in the region of intrinsic absorption and impurity absorption. We used a modulation method of measuring the BPC and its Hall compo-

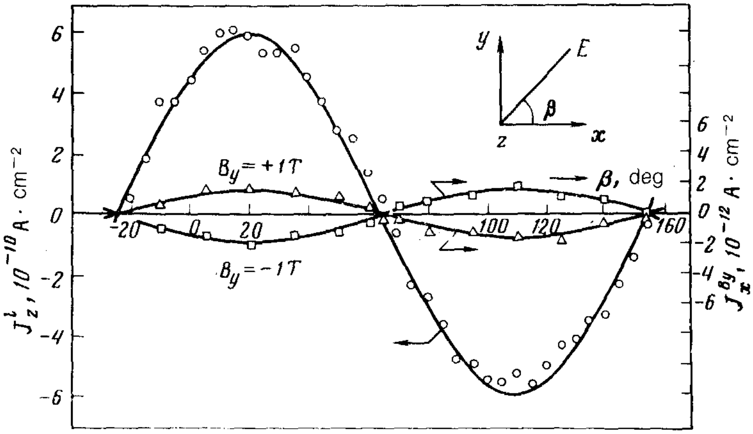

FIG. 1. Angular diagram of the linear bulk photovoltaic current (BPC) $J_z^l(\beta)$ and of its Hall component $J_x^{B_y}(\beta)$ in a magnetic field $B_y = \pm 1$ at $T = 300$ K and $\lambda = 0.44$ μm.

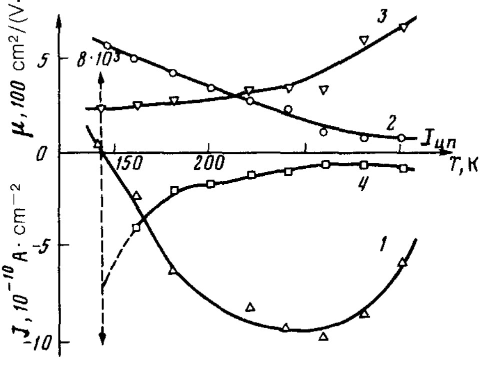

FIG. 2. Temperature dependences of the linear BPC J_z^l (1) and circular BPC J_z^c (2) and of the mobilities μ_c (3) and μ_l (4); $\lambda = 0.44\ \mu$m.

nent in a magnetic field,[6] $B_y \lesssim 1$ T. As the light sources we used a He-Cd laser ($\lambda = 0.44\ \mu$m) and Ar laser lines.

Figure 1 shows the angular diagrams of the linear BPC J_z^l and of its Hall component $J_x^{B_y}$. These diagrams, measured at $T = 300$ K and $\lambda = 0.44\ \mu$m, are consistent with (1) and (3) for $\alpha_{14} = 1.6\times 10^{-9}$ A·cm·(W)$^{-1}$. The component $\gamma_{33} = 2.1\times 10^{-10}$ A·cm·(W)$^{-1}$ was determined from the measurements of the circular BPC J_z^l under the same conditions. The values of α_{14} and γ_{33} are in agreement with the measurements carried out previously.[11]

Figure 2 shows the temperature dependences of the linear BPC J_z^l and circular BPC J_z^c and of the mobilities μ_l and μ_c calculated according to (4) for the linear and circular BPC, respectively. We see from Fig. 2 that J_z^c and μ_c vary only slightly with the temperature. In contrast, the linear BPC J_z^l and μ_l are strongly temperature dependent, and μ_l and μ_c have opposite signs over the entire temperature interval, while J_z^l changes sign at nitrogen temperature. The electrons are the carriers of the circular BPC J_z^c, consistent with the data on the phototransit measurements of $Bi_{12}GeO_{20}$.

The ballistic component of the linear BPC can be distinguished from the displacement component of BPC by using the results shown in Fig. 2. Assuming that the circular current is a ballistic current $J_z^c \equiv J_{\rm bal}^c$, the linear current J_z^l is the sum of the ballistic component $J_{\rm bal}^l$ and the displacement component $J_{\rm sinh}^l$, and keeping in mind that the Hall component of the linear BPC is governed by its ballistic component, we write the expressions for the mobilities μ_c and μ_l

$$\mu_c = \frac{1}{B}\,\frac{J_{x,c}^{B_y}}{J_z^c} \equiv \frac{1}{B}\,\frac{J_{x,l}^{B_y}}{J_{z,bal}^l}, \quad (5)$$

$$\mu_l = \frac{1}{B}\,\frac{J_{x,l}^{B_y}}{J_z^l}, \quad (6)$$

$$J_z^l = J_{z,\,bal}^l + J_{z,\,\rm sinh}^l. \quad (7)$$

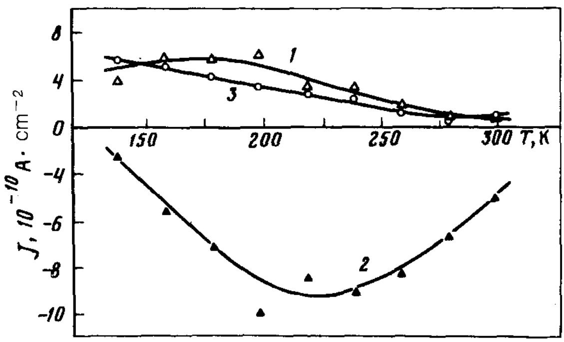

FIG. 3. Temperture dependences of the ballistic component of the linear BPC (1), of the displacement component of the linear BPC (2), and of the circular BPC (3); $\lambda = 0.44\ \mu$m.

We then find the expressions for the displacement component $J^l_{z,\text{sinh}}$ and the ballistic component $J^l_{z,\text{bal}}$ of the linear BPC:

$$J^l_{z,\,bal} = \frac{1}{B}\,\frac{J^{B_y}_{x,l}}{\mu_c}\,, \tag{8}$$

$$J^l_{z,\,\text{sinh}} = J^l_z - \frac{1}{B}\,\frac{J^{B_y}_{x,l}}{\mu_c}\,, \tag{9}$$

Substituting in (8) and (9) the experimentally measured values of J^l_z (curve 1 in Fig. 2), of the Hall component of the linear BPC $J^{B_y}_{x,l}$, and of the mobility μ_c (curve 3 in Fig. 2), we find the ballistic and displacement components of the linear BPC. The temperature dependences of these components are shown in Fig. 3 (curves 1 and 2). J^l_{bal} and J^l_{sinh} run in opposite directions over the entire temperature interval. The sign of the linear BPC (curve 1 in Fig. 2) thus changes because of the dominance of the ballistic component at low temperatures. The difference in the signs, the values, and the temperature dependences of μ_c and μ_l is attributed to the displacement component of the linear BPC and to its temperature dependence. At $T = 300$ K the mobility of the nonthermalized electrons is $\mu \cong 600$ cm^2/(V·s). The thermalized mobility in bismuth germanate is $\mu \ll 1$ cm^2/(V·s), according to the data on phototransit measurements.

Special measurements showed that the displacement component of the linear BPC decreases sharply as the intrinsic absorption changes to impurity absorption ($\lambda \cong 0.51\ \mu$m). Accordingly, in the impurity band μ_c and μ_l have the same sign and are approximately equal in value.

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