New photogalvanic effect in gyrotropic crystals

E. L. Ivchenko and G. E. Pikus

A. F. Ioffe Physicotechnical Institute, USSR Academy of Sciences

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It is shown that in gyrotropic crystals illuminated by circularly polarized light there is produced a photocurrent whose direction changes with changing sign of the polarization. The value of this current is calculated for tellurium in the case of interband and intraband light absorption.

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It is known that the photogalvanic effect can be caused by inhomogeneous illumination (for example, the Dember effect) of by sample inhomogeneity (barrier photoemf). In homogeneous crystals under stationary homogeneous illumination, the photoemf can be due to dragging of the electrons by the photons,[1-3] to optical rectification,[4] or to excitation or scattering anisotropy due to the asymmetry of the impurity

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potential.[5] In the study of these effects it is customary to consider the case of unpolarized or linearly polarized light.

It is shown in the present paper that in gyrotropic crystals illuminated by circularly polarized light, a photocurrent is produced in a direction that varies with changing sign of the polarization. This effect is described by the second-rank tensor

$$j_\alpha = I\gamma_{\alpha\beta}\kappa_\beta \, , \tag{1}$$

where $\boldsymbol{\kappa}=i[\mathbf{e}\times\mathbf{e}^*]$, $\mathbf{e}$ is the polarization vector, and I is the intensity of the light. The tensor γ differs from zero only in gyrotropic crystals in which the components of the polar and axial vectors are transformed in accordance with equivalent representations, and is analogous to the gyration tensor $\mathbf{g}$ that determines the natural optical activity.

Relation (1) is invariant to time reversal. Therefore the considered effect is not connected in principle with dissipative processes, in contrast to the effects investigated in[4] and[5], which are described by the tensor

$$\vec{\lambda}: \; j'_\alpha = I\lambda_{\alpha\beta\gamma}[(e_\beta e^*_\gamma + e_\gamma e^*_\beta)/2]$$

We have calculated the tensor γ for tellurium crystals (symmetry D_3), whose band structure is shown in Fig. 1. The conduction band of Te is doubly degenerate at the point M, while in the valence band the degeneracy is completely lifted and the electron and hole spectra are of the form[6,7]

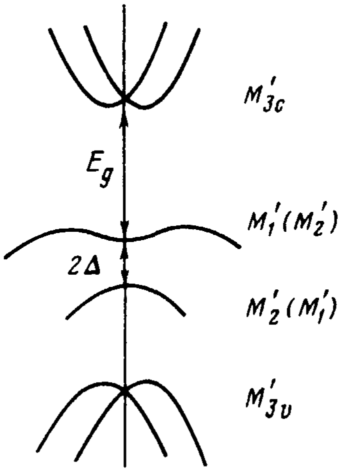

FIG. 1. Structure of energy bands of tellurium near the extrema of $M(P)$.

$$\epsilon_c(\mathbf{k}) = A_c k_z^2 + B_c k_\perp^2 \pm \beta_c k_z \, ,$$

$$\epsilon_v(\mathbf{k}) = A k_z^2 + B k_\perp^2 - (E - \Delta), \; E = (\Delta^2 + \beta^2 k_z^2)^{1/2}. \tag{2}$$

The $\pm$ sign corresponds to the two branches of the conduction band with angular-momentum projections $m_z = \pm 1/2$. The wave function of the holes is a superposition of states with $m_z = \pm 3/2$

$$\psi_v = C_{3/2}|3/2> - C_{-3/2}|-3/2>, \; C_{\pm 3/2} = \left(\frac{E \mp \beta k_z}{2E}\right)^{1/2}. \tag{3}$$

When the light propagates along the principal axis z, a longitudinal photocurrent

$$j_z = I\gamma_{zz}\kappa_z \equiv I\gamma_{zz}\mathscr{P}_{\text{circ}}, \tag{4}$$

is produced in Te, where $\mathscr{P}_{\text{circ}}$ is the degree of circular polarization of the radiation (in this case $j'_z = 0$, inasmuch as $\lambda_{z\alpha\beta} \equiv 0$).

Interband transitions. Upon excitation with circularly polarized light with $\hbar\omega > E_g$, depending on the sign of the polarization, the generated electrons either have only $m_z = 1/2$ at $\mathscr{P}_{\text{circ}} = -1$ or $m_z = -1/2$ at $\mathscr{P}_{\text{circ}} = 1$. The transition probability is proportional in this case to $C^2_{-3/2}$ or $C^2_{3/2}$, respectively. Thus, the angular momentum of the photon is transferred to the electron and hole. Owing to the singularities of the spin-orbit interaction, the electron and hole spin orientation is accompanied by directional motion, i.e., the carriers generated by the light acquire average velocities $\bar{v}^e_z$ and $\bar{v}^h_z$, and this in fact is the cause of the photocurrent. In this case

$$\gamma_{zz} = eK(-\bar{v}^e_z\tau^e_p + \bar{v}^h_z\tau^h_p), \tag{5}$$

where K is the absorption coefficient and τ^e_p and τ^h_p are the carrier momentum relaxation times.

If terms linear in **k** are taken into account in the conduction band only (i.e., at $\beta = 0$), the quantities $\bar{v}^{e,h}_z$ do not depend on the frequency of the exciting light

$$\bar{v}^e_z = \bar{v}^h_z = -\frac{\beta_c}{\hbar}\frac{A}{A_c + A}\mathscr{P}_{\text{circ}}. \tag{6}$$

However, the main contribution should be made by the valence-band terms linear in **k**, since $\beta \gg \beta_c$.[8] At $\beta_c = 0$, the values of $\bar{v}^e_z$ and $\bar{v}^h_z$ are determined by the expressions ($\mathscr{P}_{\text{circ}} = 1$)

$$\bar{v}^e_z = v_0\frac{A_c}{A}\frac{a}{2}F_1(\eta_M), \quad \bar{v}^h_z = v_0\left[-\frac{a}{2}F_1(\eta_M) + F_2(\eta_M)\right]. \tag{7}$$

Here $F_1(\eta) = [\sqrt{1+\eta^2} - \eta^{-1}\ln(\eta + \sqrt{1+\eta^2})]$, $F_2(\eta) = 1 - \eta^{-1}\arctan\eta$, $\eta = \beta k_z/\Delta$, $v_0 = \beta/\hbar = 4\times10^7$ cm/sec, $a = 2A\Delta/\beta^2 = 0.765$,[6] and η_M is the maximum value of $|\eta|$ and is defined by the condition ($k_\perp = 0$)

$$E_g + \epsilon_c(\eta_M) + \epsilon_v(\eta_M) = \hbar\omega.$$

Figure 2 shows the dependence of $\bar{v}^{eh}_z(\omega)$ calculated from (7) at $A = 0.363\times10^{-14}$ eV-cm^2 and $A_c/A = 1$.

Estimates show that in interband transitions the considered effect greatly exceeds the dragging effect, and the ratio of the emf that depends on the sign of $\mathscr{P}_{\text{circ}}$ to the Dember emf is of the order of $(v_0/\bar{v}_e)\sqrt{\tau_p^e/\tau_0}$, where v_e is the average thermal velocity of the photoelectrons and r_0 is their lifetime.

Intraband transitions. In the frequency region $\hbar\omega < E_g$, the absorption of light is connected with transitions of holes inside the valence band. Calculation show that a considered effect does not occur in direct optical transitions between the nearest branches M_1' and M_2' of the valence band (Fig. 1). It does appear, however, in indirect transitions (within a single branch or between branches) with simultaneous scattering of the holes by the phonon or impurity centers, if one takes into account as virtual states in such transitions the states in the band of symmetry M_3' (in particular, in the conduction band M_{3c}'). Estimates show that both in excitation by light of frequency $\omega > \omega_{\text{opt}}$, when the scattering is predominantly with participation of optical phonons (ω_{opt} is the frequency of the optical phonon), and at $\omega < \omega_{\text{opt}}$, when the scattering is by acoustic phonons, the photocurrent (4) is comparable in magnitude with the dragging current.

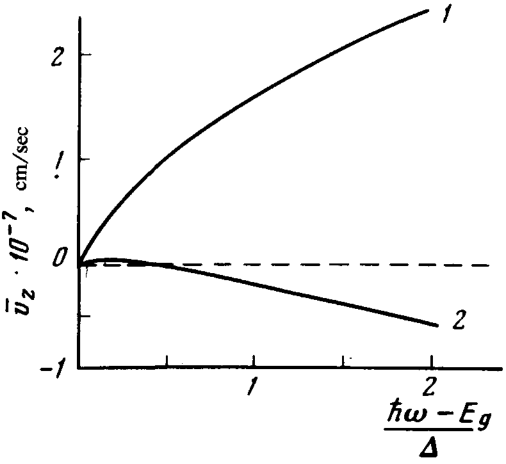

FIG. 2. Frequency dependence of the average velocities of the electrons (curve 1) and holes (curve 2) generated in interband absorption of circularly polarized light.

We note that a photocurrent with a sign that depends on the sign of the field is produced in gyrotropic crystals illuminated by unpolarized light in a longitudinal magnetic field H_z. For tellurium, however, this effect is smaller than the effect considered above to the extent that the parameter $g_1\mu_0 H_z/\Delta$ is small, where g_1 is the g-factor of the holes and determines the relative shift of the extrema of the band M_1' in the magnetic field.[6]

Inverse effect. In gyrotropic crystals it is possible also to have an inverse effect, wherein passage of current leads only to partial orientation of the free carriers, as a result of which the recombination radiation in interband excitation by unpolarized light should have a partial circular polarization. Calculation shows that in Te crystals the degree of polarization $\mathscr{P}_{\text{circ}} \sim v_{\text{dr}}/v_0$, where v_{dr} is the drift velocity of the holes. In this case the plane or polarization of linearly polarized light should also experience a rotation proportional to the current density.

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