Optical activity in tellurium induced by a current

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We observed a change in the rotation rate of the plane of polarization of light propagated in a Te crystal along the major axis C_3 as a result of transmission of an electric current through the crystal. The angle of complementary rotation, which is proportional to the current, reverses its sign as a result of change in the current direction. The results of calculation are in satisfactory agreement with the experimental data.

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A transmission of current through gyrotropic crystals changes their optical activity linearly with respect to the current. This effect is described by a third rank tensor $\vec{\theta}$:

$$\delta \epsilon^a_{\alpha\beta} = i\,\theta_{\alpha\beta\gamma} j_\gamma , \tag{1}$$

where **j** is the current density and $\delta\epsilon^a_{\alpha\beta}$ is the corresponding variation of the antisymmetric component $\epsilon^a_{\alpha\beta}$ of the dielectric constant tensor $\epsilon_{\alpha\beta}(\epsilon^a_{\alpha\beta} = -\epsilon^a_{\alpha\beta})$. As follows from the invariance of the relation (1) under time reversal, the variation of $\epsilon^a_{\alpha\beta}$ is caused by the flow of current **j**, regardless of the external source of this current.

The current-induced optical activity is not connected with spatial dispersion, in contrast to electro-optical activity or electrogyration, which is caused by the electric field E and is described by a fourth rank tensor[1-3]

$$\delta \epsilon^a_{\alpha\beta} = i\,\kappa_{\alpha\beta\gamma\delta} E_\gamma q_\delta , \tag{2}$$

where **q** is the wave vector of light in the crystal. For tellurium, in the geometry of our

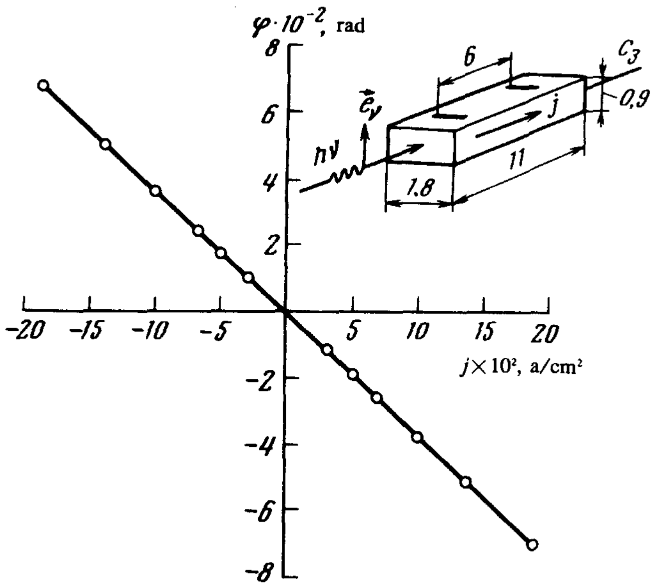

FIG. 1. Dependence of the angle of rotation ϕ on the current density for a sample with $p = 1.5\times10^{17}$ cm^{-1} at $T = 77$ K.

experiment ($\mathbf{j},\mathbf{q}\|C_3$), electrogyration does not occur, since the components $\kappa_{\alpha\beta zz} = 0$ in crystals of D_3 symmetry.

Baranova *et al.*[4] were first to indicate the possibility of changing the rotation angle of the plane of polarization of light as a result of transmission of current, which they called the electrical analog of the Faraday effect. They also calculated the θ_{xyz} constant for the gyrotropic liquid. Ivchenko and Pikus[5] reported the possibility of observing this effect in Te. A current-induced optical activity heretofore has not been observed experimentally. The experimental data and the results of a theoretical calculation given below show that the effect in tellurium is five orders of magnitude larger than that predicted by Baranova *et al.*[4] for the gyrotropic fluid.

Experiment. A plane-polarized focused light from a 0.1–0.3-W CO_2 laser ($\lambda = 10.6\,\mu$m) operating in a continuous mode was transmitted through the tellurium sample along the C_3 axis. Current pulses of 5 μsec duration were simultaneously transmitted through the sample in the same direction. The shape of the sample and the arrangement of the electrodes are shown in Fig. 1. The concentration of holes at $T = 77$ K was $p = 1.5\times10^{17}$ cm^{-3}. Using a Cd Hg Te photodetector, we measured a current-induced variation of the intensity of light transmitted through an analyzer $I(\chi)$ as a function of the rotation angle of the analyzer χ. In general, this dependence has the form

$$I(\chi) = \frac{1}{2} I\,[1 + P_{\rm lin} \quad \cos 2(\chi - \psi)\,], \tag{3}$$

where I is the intensity, $P_{\rm lin}$ is the degree of linear polarization of light at the exit from the crystal, and ψ is the rotation of the polarization plane in the crystal. For the investigated sample $P_{\rm lin}$ was 0.83. This depolarization, which apparently was caused by the scattering of light on the surface of the sample, is not connected with the circular dichroism, which, as the estimates show, is negligible.

The current-induced variation of the intensity of light at the exit is

$$\Delta I(\chi) = I\cdot P_{\text{lin}} \sin 2\left(\chi - \psi_0 - \frac{\phi}{2}\right)\sin\phi \approx \phi I P_{\text{lin}} \sin 2\left(\chi - \psi_0 - \frac{\phi}{2}\right), \tag{4}$$

where ψ_0 is the rotation of the plane of polarization due to the natural optical activity (NOA) at $j = 0$ and ϕ is the rotation induced by the current ($\phi \ll 1$). The value of ϕ was determined from $\Delta I(\chi)$ in the maximum at $\chi = \psi_0 + (\phi/2) \pm (\pi/4)$ for different values of the current. Figure 1 shows the dependence of the angle of rotation ϕ on the current density. It can be seen that the $\phi(j_z)$ dependence is linear and at $j = 700$ A/cm^2 $\phi = -2.5\times 10^{-2}$ rad.

Theory. The angle of rotation per unit length is determined by [6]

$$\phi = \frac{\omega}{2c}\left[n(\sigma_-) - n(\sigma_+)\right] = -i\,\frac{\omega}{2cn_\perp}\,\mathrm{Re}\,(\epsilon^a_{xy}), \tag{5}$$

where $n(\sigma_+)$ and $n(\sigma_-)$ are refractive indices of the clockwise- and counter-colckwise-polarized light waves, respectively [which are associated with the values $n_\pm$ introduced in Ref. 6 by the relation $n(\sigma_\pm) = n_\mp$]. It follows from the general expression for the $\hat{\epsilon}$ tensor (see, for example, Ref. 7) that $\delta\epsilon^a_{xy}$ in Eq. (1) can be written in the form

$$\delta\epsilon^a_{xy} = i\,\frac{4\pi}{\hbar\omega V}\left(\frac{e}{m_0}\right)^2 \sum_{lk} f_h(-\mathbf{k})\,\frac{|p^-_{lv}(\mathbf{k})|^2 - |p^+_{lv}(\mathbf{k})|^2}{\omega^2_{lv} - \omega^2}. \tag{6}$$

Here $f_h(\mathbf{k})$ is the distribution function of the holes, $p^\pm_{lv}$ are the interband matrix elements of the momentum operator, $p^\pm = (p_x \pm ip_y)/\sqrt{2}$, $\hbar\omega_{lv} = \mathscr{E}_l(\mathbf{k}) - \mathscr{E}_v(\mathbf{k})$, and $\mathscr{E}_r(\mathbf{k})$ is the energy of the electron in the state $(r,\mathbf{k})$.

We calculated the contribution to $\delta\epsilon^a_{xy}$ of the virtual transitions from the valence band to the conduction band of tellurium. As the calculation[8] and experimental data[9] show, these transitions determine the NOA in the Te crystals.

The current-induced optical activity is caused by the variation of the interband transition probabilities due to the variation of the distribution function of the holes. The upper valence band of tellurium is nondegenerate and at $k_z > 0$ the states with the projection of the momentum $m_z = 3/2$ predominate to the wave function of the electrons and at $k_z < 0$ the state with $m_z = -3/2$ predominate.[8] Therefore, the interband transition probability of the clockwise- and counterclockwise-polarized light greatly depends on k_z[8]

$$W^\pm_{\mathbf{k}} \sim f_h(-\mathbf{k})\sum_c |p^\pm_{cv}(\mathbf{k})|^2 \sim f_h(-\mathbf{k})\,\frac{\mathcal{E} \mp \beta k_z}{2\mathcal{E}}, \text{ where } \mathcal{E}^2 = \Delta^2 + \beta^2 k_z^2. \tag{7}$$

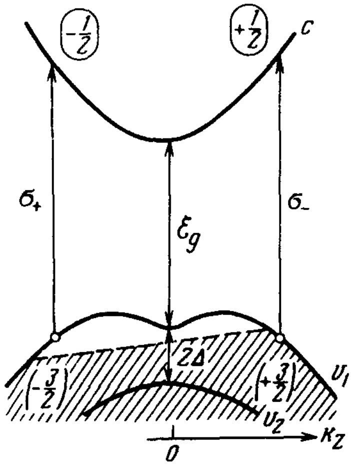

FIG. 2. Variation of the probability of interband transitions in Te due to current transmission (for clearness, we show the case of degenerate holes).

During the flow of current, when the states of the holes with $k_{z,h} = -k_z > 0$ are largely occupied, as seen in Fig. 2, the absorption coefficient of light $\alpha(\sigma_-)$ exceeds $\alpha(\sigma_+)$ (when $\beta > 0$).

The calculation shows that when $(\mathcal{E}_g - \hbar\omega) \gg k_B T$

$$\gamma = \frac{\phi}{j_z L} = \frac{2\pi e}{c n_\perp \Delta} \frac{m_{\parallel}^v}{m^*} \frac{\omega_g v_0}{\omega_g^2 - \omega^2} Q, \tag{8}$$

where $\mathcal{E}_g = \hbar\omega_g$ is the width of the forbidden band and $v_0 = \beta/\hbar$ (the other notations are the same as those in Ref. 5. The coefficient Q in Eq. (8) depends on the distribution function $f_h(\mathbf{k})$ and in the simpler case when

$$f_h(\mathbf{k}) = f_0(\mathcal{E}_h)\left[1 + \frac{eE_z}{k_B T} v_z(\mathbf{k})\,\tau(\mathcal{E}_h)\right] \text{ and } \tau(\mathcal{E}_h) \sim \mathcal{E}_h^n,$$

where $f_0(\mathcal{E}_h)$ is the equilibrium Boltzmann function, $\mathcal{E}_h(\mathbf{k}) = -\mathcal{E}_v(-\mathbf{k})$ is the kinetic energy of the hole, and $v_z = \partial\mathcal{E}_h/\partial(\hbar k_z)$ is the momentum relaxation time of the holes, we have

$$Q = a\int_0^\infty dx \frac{\sqrt{x}}{1+x} \times (a\sqrt{1+x}-1)\Gamma(n+1,\xi) \Big/ \int_0^\infty dx \frac{\sqrt{x}}{1+x}(a\sqrt{1+x}-1)^2\Gamma(n+1,\xi), \tag{9}$$

where $\Gamma(n+1,\xi)$ is an incomplete gamma function

$$\xi = \frac{\Delta}{k_B T}\left(\frac{a}{2} x - \sqrt{1+x} + 1 \right),$$

and $a = \hbar^2 \Delta / m_{\parallel}^{v} \beta^2$. The Q coefficient is weakly dependent on the index n. At $n = 0$, $\alpha = 0.765$, $\Delta = 63$ MeV, and $T = 77$ K this coefficient is $Q = 1.66$. Consequently, at $m^* = 0.1\, m_0$, $\mathscr{E}_g = 0.34$ eV, $\beta = \pm 2.44 \times 10^{-8}$ eV·cm, $\lambda = 10.6\,\mu$m, and $n_\perp = 4.8$, we obtain

$$\gamma = \pm 2\pi \times 1.45 \times 10^{-5} \text{ rad} \cdot \text{A}^{-1} \cdot \text{cm},$$

which is close to the experimental value $\gamma = -6 \times 10^{-5}$ rad·A^{-1} cm.

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