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PHOTOCURRENT INDUCED BY OPTICAL ORIENTATION OF FREE CARRIERS IN OPTICALLY ACTIVE CRYSTALS

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A photocurrent induced by optical orientation of free carriers has been investigated under interband and intraband absorption of the light in Te. The photocurrent was found to be proportional to the degree of circular polarization of the light and reverses the polarity as the sign of the circular polarization is changed.

I. Introduction

It has been found that the optical orientation of free carriers can be accompanied by their drift in optically active crystals [1-4]. Absorption of the circular polarized radiation in such a medium induces a photocurrent which reverses the polarity as the sign of the circular polarization is changed. The effect hereafter referred to as a circular photogalvanic effect (CPGE) is phenomenologically described by the relation [1,4]

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

Here $\vec{j}$ is the induced current density, I is the light intensity, $\vec{\varkappa} = i[\vec{e} \times \vec{e}^*]$, $\vec{e}$ is the polarization unit vector. In cubic crystals or in uniaxial crystals for the light propagating along the C axis, $\vec{\varkappa} = \mathcal{P}\,\vec{e}_q$, where $\vec{e}_q$ is the unit vector in the light propagation direction and $\mathcal{P}$ is the degree of the circular polarization. The tensor γ is non-zero only for optically active crystals in which case there are components of polar and axial vectors belonging to equivalent representations of the crystal point group.

It has been pointed out [1] that the circular photocurrent can be generated in Te both under direct interband and under indirect intraband transitions. In the latter case, the two-step virtual transitions via intermediate states in other bands give rise to the CPGE. The effect was first investigated under free-carrier absorption of the CO_2 -laser radiation in Te [2,3].

In this paper we report the first observation of the interband CPGE. We also present here the results of further studies of the intraband CPGE which show the existence of other mechanisms of the effect besides that described in [1-3].

II. Interband transitions

The band structure of Te is shown in Fig. 1(a). Due to spin-orbit splitting the spin degeneracy of the valence band is lifted at the extremum $M(P)$. The electron wave function ψ_i (i=1,2), in the valence subbands M_1 and M_2 is a linear combination of the states $|\pm 3/2\rangle$ with the angular momentum $J_z = \pm 3/2$ [5,6]

$$\psi_i = e^{i\vec{k}\vec{r}}\left[C^{(i)}_{3/2}(k_z)\,|3/2\rangle + C^{(i)}_{-3/2}(k_z)\,|-3/2\rangle\right] \tag{2}$$
,

where $$C^{(1)}_{\pm 3/2} = \mp C^{(2)}_{\mp 3/2} = \left(\frac{1 \pm \eta}{2} \right)^{1/2}, \quad \eta = \frac{\beta K_z}{(\Delta^2 + \beta^2 K_z^2)^{1/2}}.$$

Further we assume $\beta > 0$. It follows then that for $K_z > 0$ the contribution from the state $|3/2\rangle$ prevails in the function Ψ_1 while for $K_z < 0$ the state $|-3/2\rangle$ is dominant.

Under optical pumping by the σ_+ polarized light propagating along the C axis, the $|-3/2\rangle \rightarrow |-1/2\rangle$ transition is allowed only. Hence for the transitions from the valence subband M_1' the electrons with $K_z < 0$ and holes with $K_z > 0$ are excited predominantly in the sample and as a result a photocurrent appears along the crystal C axis. The corresponding component of the tensor γ can be written as

$$\gamma_{zz} = \gamma^e_{zz} + \gamma^h_{zz} = \frac{eK}{\hbar\omega} \left(-\bar{v}_{ze} \tau^e_p + \bar{v}_{zh} \tau^h_p \right). \quad (3)$$

Here K is the absorption coefficient, τ^e_p and τ^h_p are the momentum relaxation times of the photoexcited electrons and holes respectively, $\bar{v}_{ze}$ and $\bar{v}_{zh}$ are the average velocities of the photocarriers before the momentum relaxation. According to [1] $\bar{v}_{ze}$ and $\bar{v}_{zh}$ increase with increasing the photon energy and are of the order of $v_0 = \beta/\hbar = 4\times10^7$ cm/sec for $\hbar\omega \approx E_g + 2\Delta$. For the photon energy, $\hbar\omega > E_g + 2\Delta$ the transitions from the split-off valence subband M_2' begin. These transitions induce the photocurrent of the opposite polarity and $\bar{v}_{ze}$, $\bar{v}_{zh}$ decrease.

Because of the large value of the absorption coefficient, the direct measurements of the e.m.f. due to the CPGE are complicated. However, the effect may be measured readily at a transverse magnetic field $H \parallel x$. Assuming for simplicity that the momentum relaxation times τ^e_p and τ^h_p are independent on the wave vector we obtain for transverse e.m.f., V_y, in the case of $\ell \gg d \gg K^{-1}$ (see Fig. 2)

$$V_y = -\frac{H_x \ell I e^2}{c\, d\, \sigma_{\parallel} \hbar\omega} \left(\frac{\bar{v}_{ze}}{m^h_{\parallel}} + \frac{\bar{v}_{zh}}{m^e_{\parallel}} \right) \tau^e_p \tau^h_p \quad (4)$$

$m^{e,h}_{\parallel}$ being the longitudinal effective masses for electrons and holes and $\sigma_{\parallel}$ being the longitudinal conductivity.

The measurements of the interband CPGE were performed in undoped samples of Te with $N_a = 5\times10^{14}$ cm^{-3} of residual acceptores. The samples were intrinsic at room temperature ($n_i \approx 5\times10^{15}$ cm^{-3}). They were prepared in a form of a plate, the crystal C axis being perpendicular to the illuminated surface. The samples were irradiated by 3.39μm line of a continuous He-Ne laser with power of up to 5 mW, so that only the electron transitions from the M_1' subband took place. The linearly polarized laser light was first passed through a rotating quarter wave plate. The degree of circular polarization of the light incident on the crystal varied with time as $\sin 2\varphi = \sin 4\pi\nu t$, where φ is the angle between the optical axis of the quarter wave plate and the polarization plane of the laser light. The photovoltage V_y was measured by means of lock in. To obtain the dependence V_y on degree of polarization the plate rotated slowly and the sygnal was registered at frequency of the laser light chopping. For the measurements of the absolute magnitude of the voltage a speedly rotated plate was used and the registration was at the double frequency of the rotation.

The magnetic fields were up to H_x =10 kG. The transverse signal V_y was found to depend linearly on H_x. Fig. 2 shows the experimental dependence $V_y(\varphi)$. The signal variation is described by the formula

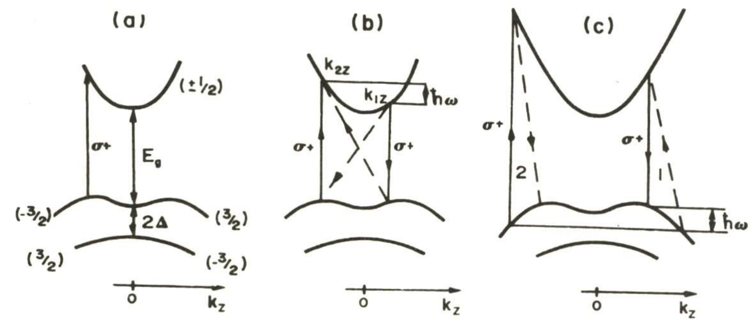

Fig.1 The band structure of Te near the extremum point M: (a) Direct transition. (b) Indirect transition for electron absorption. (c) Indirect transition for hole absorption. Direct optical transition are shown by solid lines and phonon-induced interband transition by dashed lines

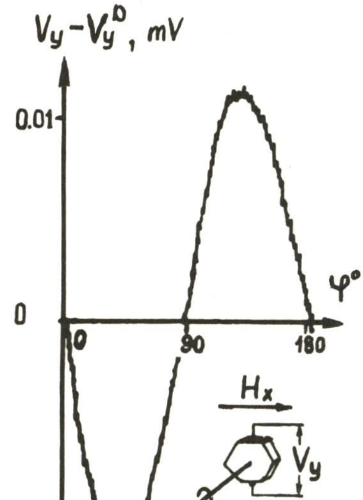

Fig.2 The e.m.f. induced by 3.39μm irradiation of a Te sample as a function of the angle φ of quarter wave plate at T=300 K

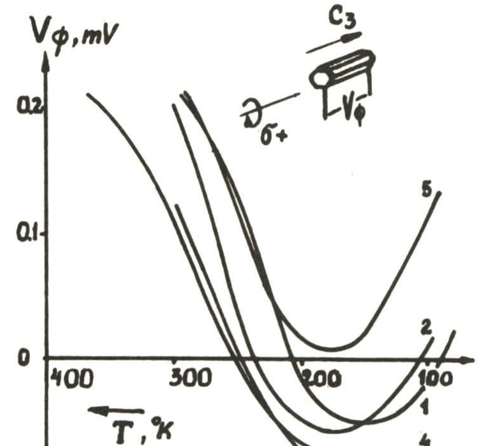

Fig.3 Temperature dependence of the CPGE voltage in the case of intraband transition for Te crystals with different concentrations of the acceptor impurity: 1. $N_a = 5\cdot 10^{14}$ cm^{-3}; 2. $N_a = 2\cdot 10^{15}$ cm^{-3}; 3. $N_a = 1.3\cdot 10^{16}$ cm^{-3}; 4. $N_a = 1.6\cdot 10^{17}$ cm^{-3} 5. pure crystal with mechanical defects. The size of the samples is 10 mm^2 x 1 cm

$$V_y(\varphi) = V_y^b + V_y^o \sin 2\varphi \quad . \tag{5}$$

The constant contribution V_y^D is due to the Dember effect. The ratio V_y^o/V_y^D was approximately 0.05 in agreement with the theoretical estimation

$$\frac{V_y^o}{V_y^b} = \frac{m_{\parallel}^e}{m_{\parallel}^h} \frac{\bar{\vartheta}_{ze}}{\bar{\vartheta}_{zh}} \sqrt{\frac{\tau_p^h}{\tau_o}} \quad , \tag{6}$$

which is valid if $\bar{v}_{ze} > \bar{v}_{zh}$. Here $\bar{v}_{zh}$ is the thermal velocity of holes and τ_0 is the hole lifetime.

III. Free-carrier absorption

In addition to our previous works [],2] we measured the intraband CPGE in doped Te crystals in a wide temperature range. The photovoltage was induced by the radiation of Q-switched CO_2 pulse laser producing 100 nsec pulses with a peak power about 8 KW and operating at the frequency 500 Hz. The samples were prepared as in [3]. The geometrical arrangement is shown in Fig.3.

Fig. 3 shows the temperature dependence of the longitudinal signal V_φ for a series of samples with different impurity concentrations. In lightly dpoed samples ($N_a < 2 \times 10^{15}$ cm^{-3}) the sign reversal of the CPGE occurs at the temperature where the Hall coefficient reverses the sign, i.e. in the region of the transition from p-type donductivity to intrinsic conductivity. This is consistent with the mechanism due to the virtual optical-phonon-assisted transitions proposed in [2,3] (Fig.1(b,c)).

In contrast with the undpoed crystals, for samples containing more than 10^{16} cm^{-3} acceptors the sign reversal of V_φ occurs in the extrinsic region. Moreover, the temperature corresponding to $V_\varphi = 0$ does not depend on N_a and at higher temperatures V_φ is a linear function of T . We conclude that at high temperatures another mechanism contributes to the CPGE. This mechanism may be due to two-phonon-assisted intraband transitions [7].

A number of Te crystals show an additional sign change near the liquid introgen temperature. The low-temperature reversal of V_φ was observed to be associated with the mechanical defects in the samples. This was confirmed by the measurement of CPGE on the samples with roughly ground surface. In this case the temperature region of negative V_φ vanished and the CPGE showed a constant sign (Fig.3, curve 5).

It should be noted in conclusion that at present CPGE has been observed also in some other crystals with different symmetry (the point group T) [8].

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