

Circular photon drag effect in bulk semiconductors

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Abstract. We report on the observation of the circular photon drag effect in a bulk semiconductor. The photocurrent caused by a transfer of both linear and angular momenta of photons to charge carriers is detected in tellurium. Dependencies of the photocurrent on the light polarization and on the incidence angle agree with the symmetry analysis of the circular photon drag effect. Experimental spectral data on the photocurrent in mid-infrared range qualitatively agree with a microscopic model of the circular photon drag effect considering intersubband optical transitions of holes in tellurium.

1. Introduction

Circular photon drag effect (CPDE) represents an electrical current arising in medium under optical excitation due to simultaneous transfer of both linear and angular momenta from photons to free charge carriers. This photocurrent is sensitive to the light helicity and reverses its direction on switching from right- to left-circular polarization of light. In contrast to the intensively studied photon drag currents insensitive to the circular polarization (for review see [1]), the history of CPDE is rather short. While CPDE was predicted theoretically in 1980s [2, 3], it was demonstrated experimentally only in 2006 by studying quantum wells [4]. Further experiments also dealt exclusively with 2D systems such as photonic crystal slabs [5], graphene [6–8], metamaterials [9] and quantum well structures [10]. However, CPDE has not been observed so far in any bulk (3D) material. The reason is that CPDE is forbidden by symmetry in cubic crystals like III–V semiconductors, or it is masked by other effects in those media where it is allowed.

In this work, we report on the observation of CPDE in a bulk semiconductor demonstrating that the photon drag current sensitive to the light helicity is possible in 3D crystals. For investigations we choose tellurium, because it demonstrates a few related phenomena, namely, electric-current-induced optical activity, the linear photon drag effect, and linear and circular photogalvanic effects [1, 11]. In contrast to 2D systems [4, 6–8], for tellurium we can choose a particular geometry where CPDE is not hidden by any other effect. We show experimentally that the values of CPDE current in tellurium are two orders of magnitude higher than in quantum well structures. The phenomenological model of CPDE is developed on the base of symmetry arguments accounting for birefringence of tellurium. Microscopic mechanism of the observed effect is discussed.

2. Phenomenological description of CPDE

In order to choose a proper geometry for observation of the CPDE current we perform the symmetry analysis of helicity-dependent photocurrents in tellurium. The point symmetry group of tellurium



is D_3 . In the plane perpendicular to the optical axis z , there are three rotation axes C_2 . We denote one of them as x and also denote a perpendicular axis in the same plane as y (see inset in figure 1). We consider a radiation incident in the plane xz . Performing a symmetry analysis, we obtain the photocurrent which reverses its direction under switching from right-hand- to left-hand-polarized radiation. The density of this photocurrent j_{circ} proportional to the circular polarization degree of light P_{circ} is given by

$$j_z^{\text{circ}} = \gamma P_{\text{circ}} \frac{q_z}{q} E^2, \quad (1)$$

$$j_x^{\text{circ}} = \tilde{\gamma} P_{\text{circ}} \frac{q_x}{q} E^2 + \tilde{T} P_{\text{circ}} \frac{q_x^2}{q} E^2, \quad (2)$$

$$j_y^{\text{circ}} = T P_{\text{circ}} \frac{q_x q_z}{q} E^2. \quad (3)$$

Here \mathbf{q} and \mathbf{E} are the radiation wave vector and electric field, respectively. The constants γ and $\tilde{\gamma}$ describe the circular photogalvanic effect caused solely by transfer of an angular momentum of photons to free carriers but not accompanied by a linear momentum transfer. The longitudinal CPDE current described by the constant \tilde{T} is present due to a trigonal symmetry of tellurium. The transverse CPDE described by the constant T is caused by a nonequivalence of the z direction and the directions in the perpendicular plane xy , i.e., due to uniaxiality of tellurium. This CPDE current is odd in the incidence angle θ_0 . Equations (1)–(3) demonstrate that the current j_y^{circ} transverse to the incidence plane xz is caused solely by the CPDE, in contrast to two other photocurrent components. Therefore in the experiments aimed at observation of CPDE we focus on the photocurrent j_y^{circ} .

To derive the dependence of j_y^{circ} on the incidence angle it is necessary to take into account that tellurium is a birefringent crystal. Since the ordinary and extraordinary beams propagate with different velocities, the CPDE current oscillates in space along the propagation direction. To obtain the resultant CPDE current density j_L^{CPDE} in a sample of thickness L , one can integrate j_y^{circ} over the L . As it was shown in our paper [12], the resultant CPDE current density depends on θ_0 as follows

$$j_L^{\text{CPDE}}(\theta_0) = T \frac{\omega}{c} P_{\text{circ}}^0 E_0^2 \tau_{ps}(\theta_0) \sin \theta_0 \frac{\sin[2\pi L / d(\theta_0)]}{2\pi L / d(\theta_0)}, \quad (4)$$

where the transmission coefficient $\tau_{ps}(\theta_0)$ and oscillation period $d(\theta_0)$ are determined in [12].

3. Experimental observation of CPDE and discussion of its microscopic mechanism

Experiments were performed on a p -Te single crystal (hole concentration $7 \cdot 10^{16} \text{ cm}^{-3}$) at room temperature. The lateral surface of the samples was a natural facet of the crystal, and the end faces were subjected to optical polishing. The crystal under investigation exhibited a natural optical activity and was levorotatory. The thickness of the sample in z -direction was $L = 0.8 \text{ mm}$. To measure the photocurrent J_y , two contacts were located at the lateral surface of the sample (see inset in figure 1). We applied pulsed radiation of a Q -switched CO_2 laser operating in the spectral range from 114 to 135 meV. The radiation was focused on a spot of 0.5 mm diameter. The photocurrent was measured by means of a storage oscilloscope. The sample was illuminated by a laser beam under incidence angle θ_0 . The laser radiation was linearly polarized. By applying a Fresnel $\lambda/4$ rhomb we modified the radiation polarization from linear to elliptical. The circular polarization degree of the light at the Fresnel rhomb output P_{circ}^0 is changed according to $P_{\text{circ}}^0 = \sin 2\varphi$ where φ is the azimuth of the Fresnel rhomb.

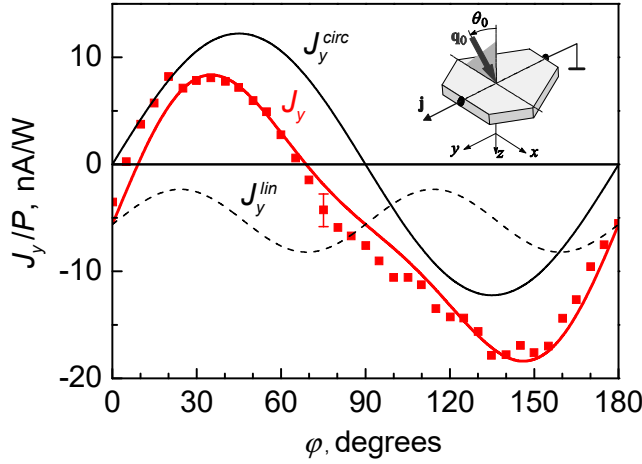


Figure 1. Dependence of the transverse photocurrent on the Fresnel rhomb azimuth at the photon energy $\hbar\omega = 134$ meV. Curves $J_y^{circ} \propto \sin 2\phi$ and J_y^{lin} represent the circular and linear photocurrents, respectively. Inset shows the experimental geometry.

The photocurrent at each azimuthal angle ϕ depends linearly on the laser power P . Figure 1 shows the typical dependence of the transverse photocurrent normalized to the laser power (J_y/P) on the Fresnel rhomb azimuth (ϕ) under oblique incidence of the laser beam (at $\theta_0 = -15^\circ$). The experimental data are well described by the following phenomenological expression:

$$J_y / P = C \sin 2\phi + L_1 \sin 4\phi + L_2, \quad (5)$$

where the first term is proportional to P_{circ}^0 and corresponds to the “circular” photocurrent $J_y^{circ} \propto \sin 2\phi$ which we are interested in. Two other terms represent the “linear” photocurrent J_y^{lin} which appears under elliptically polarized excitation. The linear photocurrent is insensitive to the radiation helicity.

We analyzed the ϕ -dependencies of the transverse photocurrent J_y at various incidence angles θ_0 and revealed the dependence of the circular photocurrent amplitude C on the incidence angle. It is presented in figure 2(a) by circles. One can see that the circular photocurrent is mainly an odd function of θ_0 with an admixture of a small even contribution. According to the phenomenological arguments (see section 2), the CPDE current is an odd function of the incidence angle. Therefore we continued our analysis studying the odd in θ_0 part of C . It is defined as follows: $C_{odd}(\theta_0) = (C(\theta_0) - C(-\theta_0))/2$. Experimental data on $C_{odd}(\theta_0)$ are shown in figure 2(a) by squares. They are fitted well by the average CPDE current density $j_L^{CPDE}(\theta_0)$ given by equation (4). This finding confirms that the dominating odd in θ_0 contribution to the circular photocurrent is due to the CPDE. We note that the CPDE current detected in tellurium exceeds by two orders of magnitude the current observed in quantum-well structures [4].

We performed the same measurements and analysis at three other photon energies. The obtained dependence of $|C_{odd}|$ on the photon energy is shown in figure 2(b). In the spectral range of 116–134 meV, absolute value of the observed CPDE current decreases with the photon energy. Such a behavior qualitatively agree with a microscopic model considering intersubband optical transitions of holes in tellurium for the photon energies exceeding the intersubband gap [12]. In the framework of this model, CPDE current is estimated simulating shifts of carriers in real space occurring at photon absorption. Simulation gives $j_L^{CPDE} / I \approx 50$ nA/W at $\hbar\omega = 130$ meV and $\theta_0 = 10^\circ$ (I is the radiation intensity). This is the same order of magnitude as that of the experimental data (see figure 2). Slightly smaller values of the current (~ 10 nA/W) are detected in the experiment because not all current generated in the laser spot area reaches the contacts. Part of the current is closed in the nonilluminated part of the sample.

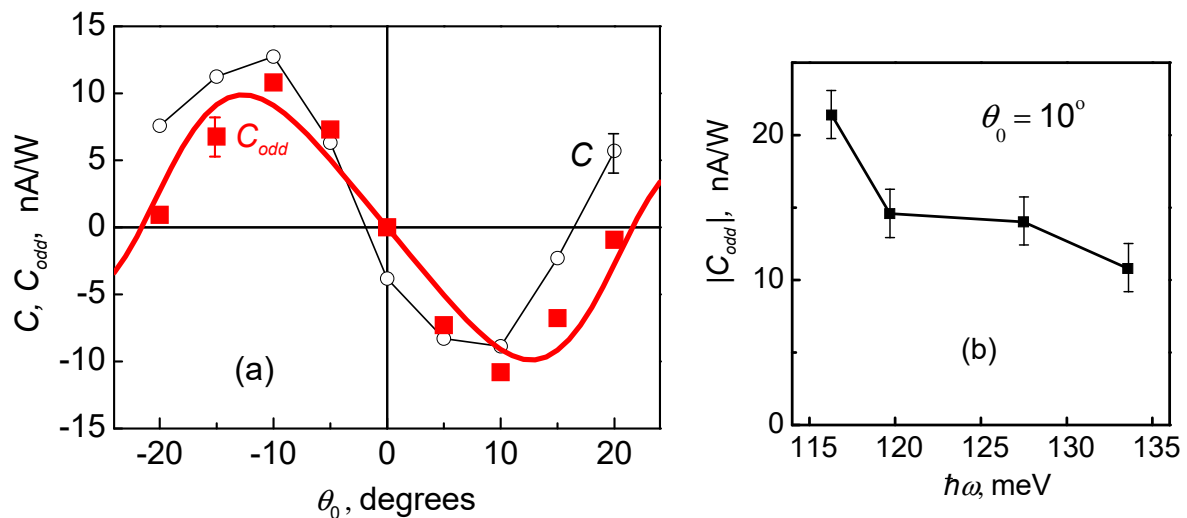


Figure 2. (a) Incidence angle dependence of the circular photocurrent amplitude C (circles) and its odd in θ_0 component C_{odd} (squares) at $\hbar\omega = 134$ meV. Thick line is a fit of C_{odd} by $j_L^{\text{CPDE}}(\theta_0)$ given by equation (4). (b) Dependence of the CPDE amplitude $|C_{\text{odd}}|$ on the photon energy.

4. Conclusions

The helicity-dependent photocurrent transverse to the light incidence plane was detected in bulk tellurium. The above analysis of the polarization state, incidence angle, and photon energy dependencies of the photocurrent confirms the observation of the CPDE. The CPDE current is shown to be an odd function of the incidence angle. The phenomenological model of CPDE was developed based on symmetry arguments accounting for birefringence of tellurium. Experimental spectral data on the photocurrent qualitatively agree with a microscopic model of the circular photon drag effect considering intersubband optical transitions of holes in tellurium. Due to the high sensitivity of CPDE, tellurium can be used for helicity-dependent photodetectors in mid-infrared range.

Acknowledgements

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