Circular Photon Drag Effect in Quantum Wells

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***Abstract*—We report on experimental observation of the circular photon drag effect, i.e., the photon drag current which reverses its direction upon switching the light helicity. In our experiments, the circular photon drag current was excited at intersubband transitions in (110)-oriented n-doped GaAs/AlGaAs quantum well structures. The experimental data are described by an analytical expression derived from a phenomenological theory. A microscopic model for the circular photon drag effect is developed demonstrating that the generated current has spin dependent origin.**

I. Introduction

In this paper, we present both experimental and theoretical investigations of circular photocurrents excited by intersubband optical transitions in n-doped (110)-grown quantum well (QW) structures. We report on observation of the circular photogalvanic effect (CPGE) [1] and a new effect caused by simultaneous transfer of both linear and angular momenta of photons to free carriers. This effect, referred to as the circular photon drag effect, was theoretically predicted two decades ago [2], [3] but so far not observed. All the previous investigations dealt with the linear photon drag effect where the inversion of the light helicity does not affect the sign and magnitude of the current [4], [5]. The circular photon drag effect, in contrast, represents the photon drag current that reverses its direction by inversion of the light helicity from left-handed to right-handed and vice versa.

II. Experimental technique

The experiments have been carried out at room temperature on asymmetrical (110)-oriented GaAs/AlGaAs molecular beam epitaxy grown heterostructures containing 100 QWs of 8.2 nm width separated by 40 nm barriers. The sample edges are oriented along $x \parallel [1\bar{1}0]$ and $y \parallel [00\bar{1}]$ in the QW plane, and the z axis points parallel to the structure growth direction. To measure electric currents ohmic contacts were prepared in the center of each sample edge. The measurements of photocurrents are carried out under excitation of the samples with infrared or terahertz radiation at normal and oblique incidence. The source of infrared radiation is a Q-switch CO_2 laser with an operating spectral range ($9.2 - 10.8$ μm) corresponding to intersubband transitions between the lowest and the first excited subbands of the investigated QWs. Pulsed THz radiation, which causes the intrasubband (Drude-like) absorption, is obtained by applying an optically pumped pulsed molecular laser [1]. The geometry of the experiment is sketched in the inset of Fig. 1. The photocurrent is measured

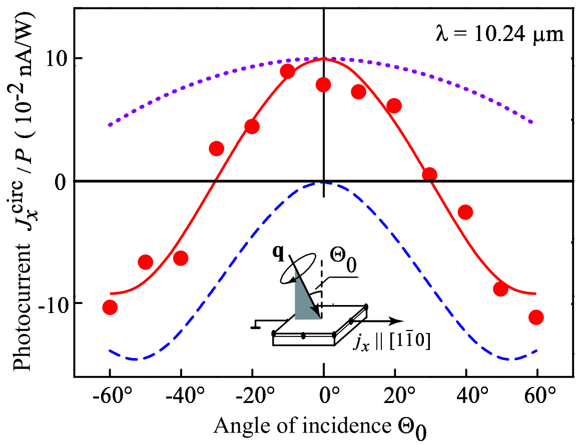

Fig. 1. Angular dependence of the helicity-dependent photocurrent. Curves are fit to experimental data (dots) and represent, correspondingly, the CPGE contribution (doted curve), the contribution of the circular photon drag effect (dashed curve), and the sum of both terms (solid curve). The inset shows the experimental geometry.

in unbiased structures via the voltage drop across a 50 Ω load resistor.

In this work we examine helicity dependent photocurrents, $J_x^{\rm circ}$, i.e. currents which reverse their sign upon switching the radiation helicity. In order to extract such a current contribution from the measured total current we determined the response to σ_+ and σ_- radiation and evaluated the data after

$$J_x^{\rm circ} = [J_x(\sigma_+) - J_x(\sigma_-)]/2 \,. \qquad (1)$$

The right-handed (σ_+) and left-handed (σ_-) circularly polarized radiation is achieved by means of a Fresnel rhomb in the infrared and λ-quarter quartz plates in the THz range.

III. Results and Discussion

Irradiating the samples at normal incidence, we have detected a photocurrent that is proportional to the radiation helicity $P_{\rm circ}$. This helicity dependent current has been observed with the contact pairs aligned along $x \parallel [1\bar{1}0]$ only. All these features hold for the infrared as well as THz wavelengths applied and are in agreement with the phenomenological theory of the circular photogalvanic effect [1]. In fact, asymmetric (110)-oriented heterostructures used in our experiments belong to media of the C_s point-group symmetry, which allows the CPGE at normal incidence. Sensitive to the light helicity intersubband optical transitions are possible in this geometry due to admixture of the valence-band states to the electron wave functions [6], [7].

However, at oblique incidence of the radiation we have observed a qualitatively different behaviour for photocurrents excited by the THz and infrared light. In the whole THz range, where the photocurrent is caused by the Drude absorption, we found that the circular photocurrent decreases monotonously with the magnitude of the incidence angle $|\Theta_0|$, being in accordance with the theory of the CPGE [1]. Surprisingly, for excitation with the infrared radiation, which causes intersubband transitions, a qualitative discrepancy to this dependence is observed. In contrast to the sign conserving behaviour, the signal changes its sign twice at $\Theta_0 = \pm 30°$ (see Fig. 1).

This angle inversion of the direction of helicity dependent current cannot be explained in the framework of the conventional theory of photogalvanic effects, which ignores the linear momentum transfer from photons to free carriers. To solve the problem we have developed the phenomenological theory of the circular photon drag effect, which takes into account transfer of both linear and angular momenta of photons to free carriers [8]. The circular photon drag effect gives an additional contribution to the helicity dependent photocurrent. This contribution vanishes at normal incidence of the light and increases with $|\Theta_0|$. The interplay between the CPGE and the circular photon drag effect may result in the observed twofold sign inversion of the total current by the variation of Θ_0 from $-\pi/2$ to $\pi/2$ if the circular photon drag and the CPGE photocurrents are oppositely directed. The fit of the calculated angle dependencies of the CPGE (doted curve) and the circular photon drag current (dashed curve) to the experimental data is shown in Fig. 1. It is seen that the sum of the CPGE and the circular photon drag currents (solid curve) describes the experimental data quite well.

Besides, we have developed the microscopic theory of the circular photon drag effect for the direct intersubband optical transitions in QW structures. The theory is based on optical spin orientation sensitive to the photon wave vector and subsequent asymmetric spin relaxation.

ACKNOWLEDGMENT

This work was supported by the Deutsche Forschungsgemeinschaft through SFB 689 and GRK638, the RFBR, the Russian Ministry of Education and Science, and by the Russian Science Support Foundation.

REFERENCES

[1] S.D. Ganichev and W. Prettl, Intense Terahertz Excitation of Semiconductors. Oxford Univ. Press, Oxford, 2006.
[2] E.L. Ivchenko and G.E. Pikus, in Semiconductor Physics, Ed. by V.M. Tuchkevich and V.Ya. Frenkel. Consultants Bureau, NY, 1986.
[3] V.I. Belinicher, Sov. Phys. Solid State **23**, 2012 (1981).
[4] S. Luryi, Phys. Rev. Lett. **58**, 2263 (1987).
[5] A.D. Wieck, H. Sigg, and K. Ploog, Phys. Rev. Lett. **64**, 463 (1990).
[6] R.J. Warburton, C. Gauer, A. Wixforth, et al., Phys. Rev. B **53**, 7903 (1996).
[7] E.L. Ivchenko and S.A. Tarasenko, JETP **99**, 379 (2004).
[8] V.A. Shalygin, H. Diehl, Ch. Hoffmann, et al., JETP Lett. **84**, 570 (2006).