

Magnetic field induced circular photogalvanic effect in InAs quantum wells

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We report on the first observation of a magnetic field induced circular photogalvanic effect (CPGE) in quantum wells (QWs). The experiments were carried out on (001)-MBE-grown n -InAs/AlGaSb QW structures with a 15 nm single InAs channel at 4.2 K. For optical excitation we used the $\lambda = 148 \mu\text{m}$ of a high power far-infrared pulsed NH_3 laser optically pumped by a TEA- CO_2 . The peak power of a single laser pulse was about 40 kW. The helicity P_{circ} of the incident light varied from -1 (left handed circular, σ_-) to +1 (right handed circular, σ_+) according to $P_{\text{circ}} = \sin 2\varphi$ where φ is the angle between the initial polarization plane and the optical axis of the $\lambda/4$ plate.

In the absence of a magnetic field, $\mathbf{B} = 0$, the irradiation of these semiconductor structures by far-infrared laser radiation results in a photocurrent, $\mathbf{j} \propto P_{\text{circ}}$, which reverses its sign by switching the helicity of radiation from left handed to right handed [1]. Due to the point-group symmetry C_{2v} of the studied QWs, the photogalvanic current at $\mathbf{B} = 0$ is only observed under oblique incidence. Here we demonstrate that the application of an external magnetic field, \mathbf{B} , in the interface plane induces a helicity-dependent current even at normal incidence. The current is proportional to B (up to 5 T) and inverts its direction with the reversal of the magnetic field. For the sake of brevity we refer to the effect under consideration as to the magneto-CPGE. For bulk materials this effect was theoretically treated in [2, 3] and observed in p -GaAs [4].

Phenomenologically, the magneto-CPGE is described by a third-rank tensor as

$$j_\alpha = \mu_{\alpha\beta\gamma} B_\beta i (\mathbf{E} \times \mathbf{E}^*)_y = \mu_{\alpha\beta\gamma} E^2 B_\beta \hat{e}_\gamma P_{\text{circ}}, \quad (1)$$

where \mathbf{E} is the amplitude of the electric field of the radiation, $E = |\mathbf{E}|$, and \hat{e} is a unit vector pointing in the direction radiation propagation.

In bulk crystals of the class T_d , the tensor $\mu_{\alpha\beta\gamma}$ has only one independent component $\mu \equiv \mu_{xyz}$, $\mu_{\alpha\beta\gamma} = \mu$ if $\alpha \neq \beta \neq \gamma$ and $\mu_{\alpha\beta\gamma} = 0$ otherwise. Hereafter we use the coordinate systems $x \parallel [100]$, $y \parallel [010]$, $z \parallel [001]$ and $x' \parallel [1\bar{1}0]$, $y' \parallel [110]$, $z \parallel [001]$. In a (001)-grown zinc-blende-lattice QW with non-equivalent normal and inverted interfaces, the point-group symmetry is reduced to C_{2v} . Under normal incidence of the light and for the magnetic field lying in the interface plane, the magneto-CPGE is described by two independent constants and, in the coordinate system (x', y', z) , can be presented as

$$\begin{aligned} \delta j_{x'} &= (\mu' + \mu) E^2 B_{x'} \hat{e}_z P_{\text{circ}}, \\ \delta j_{y'} &= (\mu' - \mu) E^2 B_{y'} \hat{e}_z P_{\text{circ}}. \end{aligned} \quad (2)$$

The photocurrent induced in the same geometry, $\hat{e} \parallel z$, $\mathbf{B} \perp z$, in a bulk T_d -symmetry crystal or in a D_{2d} -symmetry QW with symmetrical interfaces is described by Eqs. (2)

assuming $\mu \neq 0$, $\mu' = 0$. In this case the directions of the vectors \mathbf{j} and \mathbf{B} are interconnected by the mirror reflection in the plane (110) if $\mu > 0$ or the plane (1 $\bar{1}$ 0) if $\mu < 0$. In particular, \mathbf{j} and \mathbf{B} are parallel (or antiparallel) when the magnetic field is applied along x' or y' and perpendicular when $\mathbf{B} \parallel x$ or $\mathbf{B} \parallel y$.

Another limiting case $\mu = 0$, $\mu' \neq 0$ is allowed not only by the C_{2v} symmetry but also by the polar uniaxial symmetry $C_{\infty v}$. The latter corresponds to the symmetry of a QW structure which is grown as if from isotropic compositional materials and has non-equivalent left- and right-hand-side interfaces. Note that if $\mu = 0$ then Eqs. (2) can be rewritten in the following two-dimensional vector form

$$\mathbf{j} = \mu' E^2 \mathbf{B} \hat{e}_z P_{\text{circ}}, \quad (3)$$

i.e. the vectors \mathbf{j} and \mathbf{B} are parallel irrespective to the in-plane orientation of \mathbf{B} .

The present experimental results are well described by Eq. (3) indicating that the symmetry of the investigated QW is $C_{\infty v}$. This is supported by the investigation of the circular photocurrent in the same structure under oblique incidence at $\mathbf{B} = 0$ for different geometries.

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References

- [1] S. D. Ganichev, E. L. Ivchenko, S. N. Danilov, J. Eroms, W. Wegscheider, D. Weiss and W. Prettl, submitted to PRL.
- [2] E. L. Ivchenko and G. E. Pikus, *Problems in Modern Physics*, Nauka, Leningrad, 1980, p. 275.
- [3] E. L. Ivchenko, Yu. B. Lyanda-Geller and G. E. Pikus, *Sov. Phys. Solid State* **30**, 575 (1988).
- [4] A. V. Andrianov and I. D. Yaroshetskii, *Pis'ma Zh. Eksp. Teor. Fiz.* **40**, 131 (1984).

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