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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 $\lambda = 148$ μm 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 $P_{\mathrm{circ}} = \sin 2\varphi$ were 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 semicontuctor structures by far-infrared laser radiation results in a photocurrent, $\mathbf{j} \propto P_{\mathrm{circ}}$, 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

$$j_\alpha = \mu_{\alpha\beta\gamma} B_\beta i \left(\mathbf{E} \times \mathbf{E}^*\right)_\gamma = \mu_{\alpha\beta\gamma} E^2 B_\beta \hat{e}_\gamma P_{\mathrm{circ}}, \qquad (1)$$

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

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

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

The photocurrent induced in the same geometry, $\hat{\mathbf{e}} \parallel z$, $\mathbf{B} \perp z$, 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 **j** and **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, **j** and **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

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

i.e. the vectors **j** and **B** are parallel irrespective to the in-plane orientation of **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 investigaton of the circular photocurrent in the same structure under oblique incidence at $\mathbf{B} = 0$ for different geometries.

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