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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 $\lambda = 148 \mu$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 $P_{\text{circ}}$ of the incident light varied from -1 (left handed circular, $\sigma^-$) to +1 (right handed circular, $\sigma^+$) according to $P_{\text{circ}} = \sin 2\varphi$ were $\varphi$ is the angle between the initial polarization plane and the optical axis of the $\lambda/4$ plate.

In the absence of a magnetic field, $B = 0$, the irradiation of these semiconductor structures by far-infrared laser radiation results in a photocurrent, $j \propto P_{\text{circ}}$, 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 $B = 0$ is only observed under oblique incidence. Here we demonstrate that the application of an external magnetic field, $B$, 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

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

(1)

where $E$ is the amplitude of the electric field of the radiation, $E = |E|$, 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 $\mu = \mu_{xyz}$, $\mu_{\alpha\beta\gamma} = \mu$ 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 $x'$ $\parallel$ [110], $y'$ $\parallel$ [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

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

(2)

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

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

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**