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2009 J. Phys.: Condens. Matter 21 375802

(http://iopscience.iop.org/0953-8984/21/37/375802)

J. Phys.: Condens. Matter **21** (2009) 375802 (4pp) doi:10.1088/0953-8984/21/37/375802

# Anomalous-circular photogalvanic effect in a GaAs/AlGaAs two-dimensional electron gas

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Received 13 April 2009, in final form 24 July 2009
Published 21 August 2009
Online at stacks.iop.org/JPhysCM/21/375802

**Abstract**
We have studied the circular photogalvanic effect (CPGE) in a GaAs/AlGaAs two-dimensional electron gas excited by near infrared light at room temperature. The anomalous CPGE observed under normal incidence indicates a swirling current which is realized by a radial spin current via the reciprocal spin-Hall effect. The anomalous CPGE exhibits a cubic cosine dependence on the incidence angle, which is discussed in line with the above interpretation.

(Some figures in this article are in colour only in the electronic version)

Spin related properties in semiconductors have attracted considerable interest for the promising applications in spintronic devices and quantum computation [1–4]. Many researchers' attention is focused on the manipulation of spin generation, transport, and detection, which are based on the spin–orbit interaction (SOI) in nonmagnetic semiconductor materials [5–7]. Recently, optical spin polarization has been achieved by interband and intersubband optical absorption of circularly polarized excitation with photo-induced carriers in gyrotropic semiconductor structures [8–10]. This is the so-called circular photogalvanic effect (CPGE): the optical excitation with circularly polarized light induces a spin polarized charge current whose direction and magnitude depend on the degree of circular polarization. As has been pointed out, the CPGE is induced by optical spin orientation of carriers in material with band splitting in $k$ space owing to an additional $k$ linear SOI term in the Hamiltonian [11]. The SOI Hamiltonian with inversion asymmetry in the gyrotropic class has the form $H_{so} = \alpha_{so}(\boldsymbol{\sigma} \times \boldsymbol{k}) \cdot \boldsymbol{z}$ [12], where $\boldsymbol{\sigma}$ is the vector of Pauli matrices, $\boldsymbol{k}$ is the in-plane wavevector, and $\boldsymbol{z}$ is the unit vector along the growth direction, and $\alpha_{so}$ is the spin–orbital coupling parameter related to structure inversion asymmetry (SIA) and bulk inversion asymmetry (BIA). Up to now, another novel phenomenon based on SOI is the well-known spin-Hall effect (SHE), where a charge current can be converted into a transverse pure spin current [13–15]. Vice versa, the SOI also converts a spin current into a transverse charge current, which is called the reciprocal spin-Hall effect (RSHE) [16–18]. Different from the CPGE, the SHE and RSHE are not limited in gyrotropic systems. Lately, He *et al* reported an anomalous CPGE phenomenon in AlGaN/GaN heterostructures related with the RSHE under normal incidence of circularly polarized radiation [19], while in the normal CPGE the charge current is zero and can be only detected under oblique incidence. The anomalous CPGE suggests a method to investigate the RSHE and spin current on a macroscopic scale at room temperature.

In this paper, the normal CPGE under oblique incidence has been observed in GaAs/AlGaAs 2DEG for near infrared excitation by circularly polarized irradiation with wavelength 1060 nm, which indicates a sizeable spin–orbit interaction in the system. Moreover, by moving the spot location on the sample under normal incidence, the anomalous CPGE has been studied at room temperature, which suggests the existence of a swirling charge current round the light spot. The swirling charge current can be considered as a transformation of photon angular momentum into electron's orbital motion via the RSHE which converts a radial spin current into a swirling charge current. The dependence of the anomalous CPGE on the incidence angle has also been discussed.

The experiment is carried out on a 2DEG sample of modulation doped (001) GaAs/AlGaAs with an electron density of $5.2 \times 10^{11}$ cm$^{-3}$ and Hall mobility of 6.2 ×

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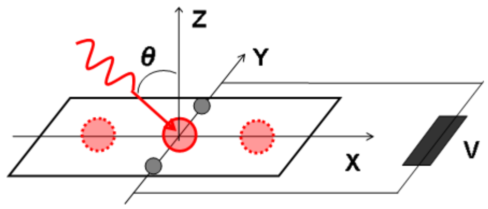


**Figure 1.** Schematic diagram of the experiment geometry. Large circles along the $X$ direction denote the light spots, small circles along the $Y$ direction denotes the pair of ohmic electrodes.

$10^3$ cm$^2$ V$^{-1}$ s$^{-1}$ at room temperature. The sample is cleaved along [110] and $[1\bar{1}0]$ (denoted as the $X$ and $Y$ directions, respectively) into a rectangle of 5 mm × 10 mm with a pair of ohmic contacts with a distance of 3 mm along the $Y$ direction, as shown in figure 1. The ohmic electrodes are made by indium deposition and annealed at 400 °C in nitrogen atmosphere. We use a diode pumped solid state laser as the radiation source with about 500 mW radiation power at a wavelength of 1060 nm. The photon energy is about 1.1 eV, so it excites electrons in 2DEG from the ground conduction band of the quantum well to higher states. The oblique incidence plane of light is perpendicular to the $Y$ direction and the radius of the light spot is about 1 mm. A polarizer and a quarter-wave plate are used to change the light helicity $P_c = \sin 2\varphi$ from left-handed ($\sigma^-$, $P_c = -1$) to right-handed ($\sigma^+$, $P_c = +1$) continuously, where $\varphi$ is angle between the initial polarization direction and the optical axis of the quarter-wave plate. Then the photogalvanic current can be measured via the voltage drop across a load resistance with a chopper and a lock-in amplifier.

Figure 2(a) shows the photogalvanic current as a function of phase angle $\varphi$ when the light spot is located at the centre of the sample along the $X$ direction with the incidence angle of $\theta = 45°$. The same as the results observed in other structures, the photogalvanic current consists of two components with different periodicities, which can be well fitted by the following equation:

$$j_y = j_{\rm C} \sin 2\varphi + j_{\rm L} \sin 2\varphi \cos 2\varphi + j_0, \qquad (1)$$

where $j_{\rm C}$ and $j_{\rm L}$ are the amplitudes of current induced by the normal CPGE and LPGE (linear photogalvanic effect) with periodicities of 180° and 90° respectively, and $j_0$ is the background current, probably caused by the photovoltaic effect or the Dember effect [11]. The amplitude of the CPGE induced current is as large as 32.4 nA with the radiation power about 330 mW, while the LPGE induced current is only negligible, 2.5 nA. The CPGE term is induced by unbalanced occupation in momentum space of carriers excited by circularly polarized light as a result of SOI induced $k$-linear band splitting and optical selection rules. The spin-independent LPGE term can be attributed to the asymmetric scattering of free carriers in noncentrosymmetrical media, and we will not discuss that in detail here. According to the previous report [11], the CPGE induced current $j_\lambda$ can be described by the phenomenological expression:

$$j_\lambda = \gamma_{\lambda\mu} e_\mu t_{\rm s} t_{\rm p} P_c I, \qquad (2)$$

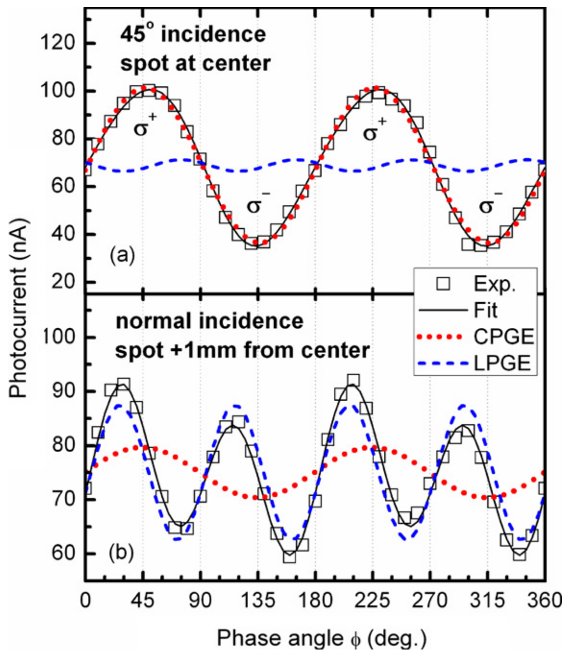


**Figure 2.** Photogalvanic current (open squares) as a function of phase angle $\varphi$ (a) for 45° incidence with the light spot located at central position of $X$ direction; (b) for normal incidence with the light spot located at the right side and 1 mm away from the central position of the $X$ direction. The solid lines are fitted by equation (1), which can be separated into the CPGE (red dotted curve) and the LPGE (blue dashed curve) components.

where $\gamma_{\lambda\mu}$ is the second-rank pseudo-tensor directly related to SOI parameter, $\boldsymbol{e}$ the unit vector in the direction of light propagation, $P_c = \sin 2\varphi$ the light helicity, $t_{\rm s}$ and $t_{\rm p}$ the transmission coefficients after Fresnel's formula for s and p polarization, and $I$ the light intensity. The CPGE current is in direct proportion to the projection of the light propagating in the $X$ direction (i.e. $j_y = \gamma_{yx} t_{\rm s} t_{\rm p} P_c I \sin\theta$ with the geometry of this sample), and thus can be only detected under oblique incidence. For simplicity, here we will name it the normal CPGE.

However, a sizeable current induced by circularly polarized light is also observed under normal incidence with the light spot deviating from the central position of the $X$ direction, which disobeys equation (2) mentioned above. Figure 2(b) illustrates the photogalvanic current as a function of phase angle $\varphi$ for normal incidence with the light spot located at right side 1 mm away from the central position of the $X$ direction. The photocurrent can also be well fitted by equation (1) and consists of CPGE and LPGE components. The amplitudes of the current induced by the CPGE and the LPGE are respectively 4.7 nA and 12.5 nA, and we call them the anomalous CPGE and LPGE, respectively. Apart from the LPGE, we further investigate the dependence of the anomalous CPGE current on spot location by moving the light spot along the $X$ direction. The results in figure 3 shows that the anomalous CPGE current is zero at the centre, then increases and reaches its maximum as the spot locates ±1 mm away from the centre, and finally decreases when the spot is far from the centre. Moreover, the current reverses its sign but with

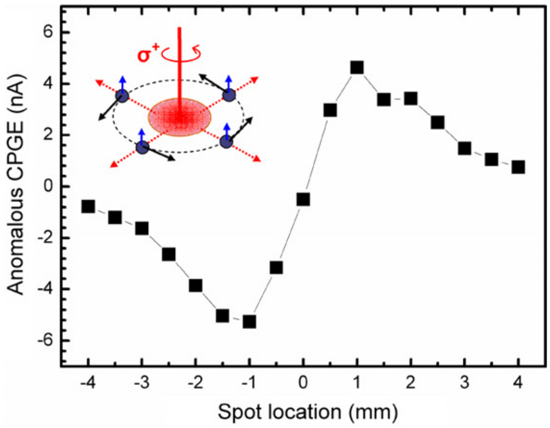


**Figure 3.** The anomalous CPGE current measured under normal incidence as a function of the light spot location along the $X$ direction. The inset sketches the origin of the anomalous CPGE photocurrent: spin polarized charge current swirling around the spot for $\sigma^+$ polarized radiation through the RSHE. The (red dotted) long radial arrows denote the spin current, the (blue solid) short upward arrows denote the direction of spin polarization, and the (black solid) arrows along the tangent direction denote the transverse charge current.

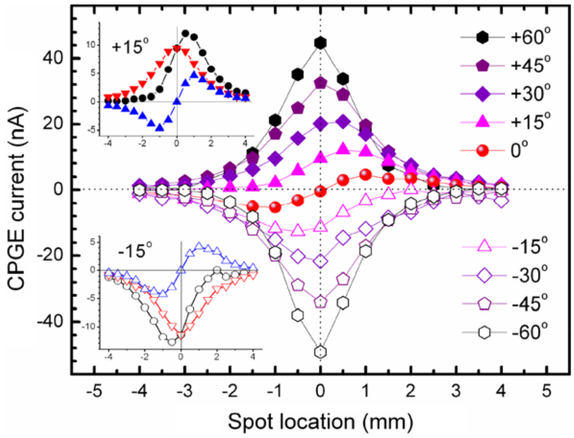


**Figure 4.** Total CPGE photocurrent as a function of the light spot location along the $X$ direction under different incidence angles from $-60°$ to $+60°$. The insets show that the total CPGE current (circles) under $\pm15°$ incidence is the superposition of two components: a symmetric normal CPGE (down triangle) and an antisymmetric anomalous CPGE (up triangle).

an equal value when the spot location moves from the right side to the left side, thus exhibiting antisymmetry about the centre in the $X$ direction. This result indicates that there must be a charge current swirling round the light spot rather than a directed current, as is shown in the inset of figure 3. When the electrode pair locates at the right or left side of the light spot, i.e., spot moving from the left to right side, the electrodes collect a current with an equal value but an opposite sign.

The swirling charge current can be considered as a transformation of photon angular momentum into the electron's orbital motion. It is realized by a radial pure spin current via spin–charge current coupling, known as the reciprocal spin-Hall effect (RSHE). Referring to the theoretical prediction [20], the absorption of circularly polarized light in semiconductor quantum wells induces a radial pure spin current (PSC) with the spin polarization in the $Z$ direction due to the conservation of angular momentum. The intensity distribution of the light spot causes a spatially inhomogeneous distribution of the $Z$-polarized spin density, whose gradient leads to a radially diffused PSC. Hence the radial PSC with a $Z$ component polarization $J_r^z$ is proportional to the degree of circular polarization as well as to the gradient of the $Z$-polarized spin density. According to the RSHE, the PSC flowing in a nonmagnet will receive a spin transverse force and thus generate a transverse charge current perpendicular to both the direction of the PSC and the spin polarization: $j \propto \bar{J}_r^z \times \bar{\sigma}_z$ [21]. Therefore, the radial PSC with $Z$-polarization generates a charge current in the tangent direction, i.e., a charge current swirling round the light spot. The swirling current around the light spot leads to the observed anomalous CPGE current shown in figure 3, which reaches its maximum of about $\pm5$ nA when the spot is located $\pm1$ mm away from the centre.

Under oblique incidence, besides the anomalous CPGE, we also obtain the band splitting related normal CPGE, which increases with the incidence angle according to $\sin\theta$ [11]. Figure 4 shows the dependence of the total CPGE current on spot locations from $-4$ to $+4$ mm along the $X$ direction under different incidence angles. Clearly, under a large incidence angle of $\pm60°$, the CPGE signal is dominated by the normal CPGE, i.e., the CPGE current gets its maximum at the centre and symmetrically decays when the spot moves away from the centre. Generally, the total CPGE current $j_t(x,\theta)$ under oblique incidence consists of a normal CPGE current $j_n$ which is an even function of spot location $x$ given by $j_n(x,\theta) = \frac{1}{2}[j_t(x,\theta) + j_t(-x,\theta)]$, and anomalous CPGE $j_a$, which is an odd function of $x$ given by $j_a(x,\theta) = \frac{1}{2}[j_t(x,\theta) - j_t(-x,\theta)]$. The insets in figure 4 show that the total CPGE (circles) under $\pm15°$ incidence is the superposition of such two components: a symmetric normal CPGE (down triangle) and an antisymmetric anomalous CPGE (up triangle). This superposition leads to an asymmetric spatial distribution of the total CPGE current when the incidence angle is not too large.

The normal and anomalous CPGE current are decomposed from the total CPEG, and figure 5 shows the maximum value of two components as a function of incidence angle. Clearly, the normal CPGE is proportional to $\sin\theta$ as is expected. For a comparison, the anomalous CPGE can be well fitted by $\cos^3\theta$. The angle dependence of the anomalous CPGE can be easily understood as follows. The radial PSC with $Z$ component polarization is proportional to gradient of the photo-excited carrier density $\nabla_r N(r)$ as well as the projection of the light intensity in the $Z$ direction. Under oblique incidence, the projection of the light intensity in the $Z$ direction contributes one $\cos\theta$, $N(r)$ contributes one $\cos\theta$, and $\nabla_r$ contributes one $\cos\theta$. As a result, a factor of $\cos^3\theta$ appears for the anomalous CPGE under oblique incidence.

In summary, the CPGE has been investigated in a GaAs/AlGaAs 2DEG sample excited by circularly polarized radiation with a wavelength 1060 nm with different incidence angles. Under normal incidence, the anomalous CPGE is observed with a light spot deviated away from the centre,

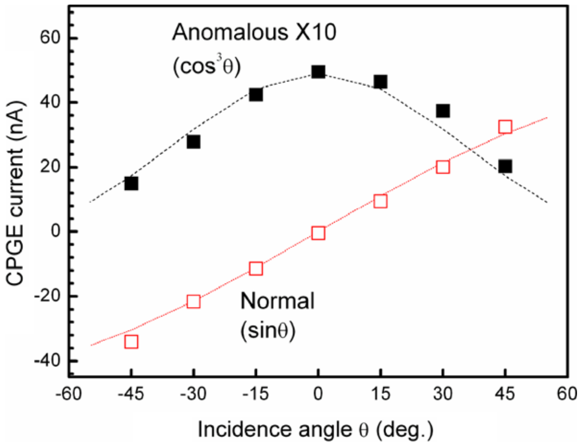


**Figure 5.** Peak current along the $X$ direction of the normal CPGE (open squares) and anomalous CPGE (solid squares) as a function of incidence angle $\theta$. Dotted and dashed lines indicate the sine and cubic cosine curves respectively.

and it suggests a swirling current which can be considered as a transformation of photon angular momentum into the electron's orbital motion. This swirling charge current is motivated through the RSHE by a light-injected radial spin current. The anomalous CPGE exhibits a cubic cosine dependence on the incidence angle. The experiment suggests a feasible way to study the RSHE and spin current on a macroscopic scale at room temperature.

## Acknowledgments

The authors thank Dr Y C Su and J H Yao for the growth of the sample. The work was supported by the National Natural Science Foundation of China (Nos 60625402 and 10804105) and the 973 programme (2006CB604908, 2006CB921607).

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