Anomalous Photogalvanic Effect of Circularly Polarized Light Incident on the Two-Dimensional Electron Gas in $Al_xGa_{1-x}N/GaN$ Heterostructures at Room Temperature

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Under normal incidence of circularly polarized light at room temperature, a charge current with swirly distribution has been observed in the two-dimensional electron gas in $Al_{0.25}Ga_{0.75}N/GaN$ heterostructures. We believe that this anomalous charge current is produced by a radial spin current via the reciprocal spin Hall effect. It suggests a new way to research the reciprocal spin Hall effect and spin current on the macroscopic scale and at room temperature.

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Spintronics is one of the most active fields of modern condensed matter physics in view of its possible application in information technology as well as many essential questions on the physics of electron spin [1]. In this field, the generation, the manipulation, and the detection of spin currents in semiconductors or metals are the major issues. All these issues relate closely to the novel phenomenon that a charge current can be converted into a spin current and *vice versa*, known as the spin Hall effect (SHE) and reciprocal spin Hall effect (RSHE) [2–4]. Experimentally, the SHE has been researched extensively [5,6], but RSHE has only been observed in bulk GaAs [7,8] and in Pt wire [9].

Both SHE and RSHE are based on the spin-orbit coupling, which means that the electron spin precession and orbit motion are mutually dependent, due to the relativistic effect. In semiconductors, the k-linear spin splitting of energy band (Rashba effect) plays the role of coupling the electron wave vectors with the spins [10]. As the key to developing intrinsic spin Hall effect [11], Rashba spin splitting can be observed experimentally using the circular photogalvanic effect (CPGE) [12]. According to CPGE, the inclined incidence of circularly polarized light excites the asymmetric distribution of carriers in K space, and forms an electric current whose direction and magnitude depends on the polarization degree of the light [13]. This effect has been applied widely to measuring the Rashba spin splitting in semiconductors [14–16]. The CPGE usually focuses on the spin splitting itself, but in this Letter we report on an anomalous CPGE related with RSHE which will extend the research possibilities of CPGE experiment.

The experimental setup is sketched in the inset of Fig. 1. A diode pumped solid state laser with 500 ± 10 mW radiation power and a wavelength of 1060 nm provides the radiation source. A quarter-wavelength plate is used to shift the polarization degree of the incident light; the CPGE current which is measured by a lock-in amplifier can be expressed as: $j_c = j_0 \sin 2\varphi$, where j_0 is the amplitude of current, and φ the angle between the polarization directions of incident light and the optical axis of the quarter-wave [13]. The samples were prepared by means of metal organic chemical vapor deposition. First, the 20-nm-thick GaN buffer layer was grown on c-plane sapphire substrate at 530 °C. Then, the GaN epilayer with a thickness of 2 μm was grown at 1050 °C. At last, the 20-nm-thick $Al_{0.25}Ga_{0.75}N$ barrier was grown on the GaN layer at 1090 °C. The typical value of the 2DEG mobility and the sheet concentration in the samples are 1530 $cm^2 V^{-1} s^{-1}$ and 1.15×10^{13} cm^{-2}, respectively. These samples were cut into narrow strips along the GaN [10-10] direction with a width of 4 mm and a length of

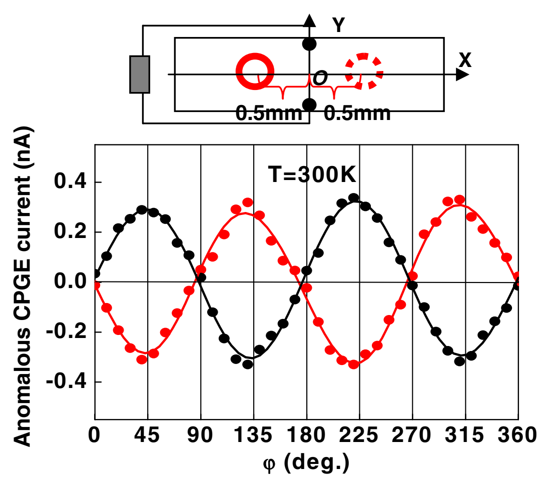

FIG. 1 (color online). The anomalous CPGE current as a function of the phase angle φ for normal incidence. The light (dark) dots show the measured current when the light spot is located at left (right) side of the central line X with 0.5 mm apart from the origin o. The inset shows the geometry of the experiment, in which light circles denote the light spot, and dark dots denote two electrodes.

25 mm, respectively. The geometry has been shown in the inset of Fig. 1, where two ohmic electrodes with a distance 2 mm were made along Y direction by evaporating Ti/Al/Ni/Au metal multilayer structure, and the incident light spot with a Gauss profile and with a diameter of 1.1 mm was located at the central line X between two electrodes. As the $Al_xGa_{1-x}N/GaN$ heterostructures, the photon energy about 1.1 eV is smaller than the band gap of GaN with 3.4 eV, so the absorption basically takes place in the 2DEG plane which will excite electrons from the first sub-band of the triangular quantum well (QW) to the higher states [15]. Because of the Rashba spin splitting of the sub-band in the triangular QW, a directed CPGE current can be observed under inclined incidence which has been reported [15,16]. In this Letter, we mainly focus on the anomalous CPGE discovered under normal incidence.

Theoretically, for the 2DEG in $Al_xGa_{1-x}N/GaN$ heterostructures with symmetry of point group C_{3v}, the CPGE current can be expressed as $J_y = \gamma_{yx} i(E_y \times E_z{}^*)_x$, where j is the photocurrent density, γ_{yx} a second-rank pseudotensor, E the complex amplitude of the electric filed of the polarized light, and x, y are two orthogonal directions in the plane of the 2DEG. Therefore, under normal incidence, the current should be zero due to the disappearance of the z component of the electric field [13]. However, in the experiment a nonzero periodic current has been measured under normal incidence. Figure 1 shows the measured current when the light spot was fixed at the left and right side of electrodes. This current corresponds to the typical characteristics of CPGE that can be described by formula $j_c = j_0 \sin 2\varphi$, so we name it anomalous CPGE current. We also investigated its dependence on spot location by moving the spot along the central line X. For a directed CPGE current along electrodes, it should be the biggest at the center and symmetrically decays at two sides of the electrodes by moving the light spot. But the experimental result shown by the lower dotted curve in Fig. 2 demonstrates that the current is zero at the center and increases remarkably when the spot deviates from the center. Furthermore, the current reverses the sign from the left to right side, just like a sine curve. It suggests that there is not a directed current, but a current swirling over the center of the light spot.

The dependence of the swirly current on the polarization degree of the light indicates the anomalous CPGE should be related with the spin orientation of photo-excited carriers. In the experiment, the intensity of the light spot has a Gauss profile; under normal incidence an inhomogeneous spin density will be excited on the 2DEG plane shown in Fig. 3(a). Its gradient generates a diffused spin polarization current (SPC): $q_r^z = -D\nabla_r N_z$, where D is the electron diffusion coefficient, N_z the vector of spin density along the z direction, and r the radial direction on the x-y plane [7,17]. The SPC has a radial distribution and is proportional to both the polarization degree of the light and the Z component of the light intensity [17]. Therefore, it can be further expressed as $q_\rho^z = -N_0 D \nabla G(r) \sin 2\varphi \cos\theta$, where θ is the incident angle, N_0 the average electron spin density with circular polarization ($\varphi = 45°, 135°$) and normal incidence ($\theta = 0$), $G(r)$ the spatial Gauss distribution of the light intensity. Reviewing the general theory of spin-charge current coupling [18], all possible charge currents related with a spin density N_z can be expressed as $j/e = \gamma\mu E \times N_z + \gamma D \nabla \times N_z$, where e is the absolute value of electron charge, γ a dimensionless coupling constant proportional to the spin-orbit interaction, μ and E the electron mobility and external electrical field, respectively. The first

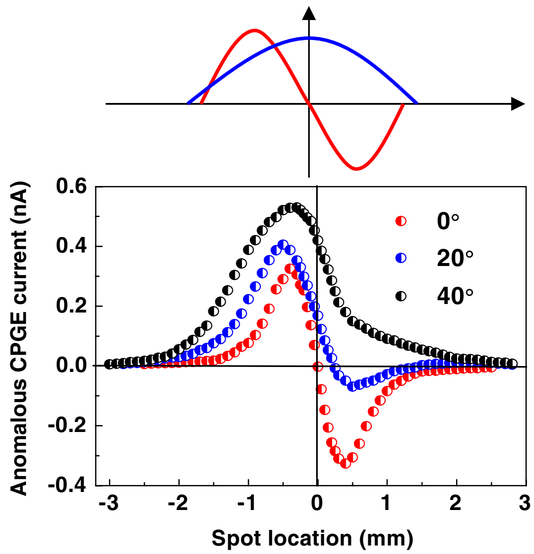

FIG. 2 (color online). The CPGE and anomalous CPGE current as a function of the light spot location. The data were obtained when the light spot moves along the central line X, in which 0° shows normal incidence. The inset sketches the superposition of CPGE with a similar Gauss function profile and the anomalous CPGE with a similar sine function profile.

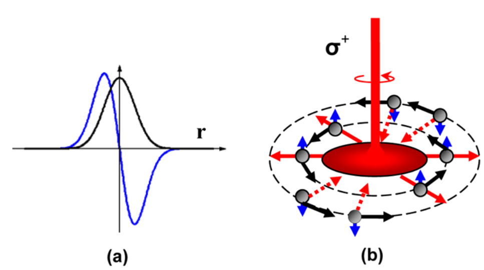

FIG. 3 (color online). (a) The spatial distribution of the inhomogeneous spin polarization density (dark curve) and its gradient (light curve). (b) Illustration of spin polarization electrons' movement under normal incidence with σ^+ polarized light. The real (dashed) long arrows denote the flowing of electrons and the light short arrows show the spin direction. Dark short arrows denote the spin transverse force acting on electrons.

term describes a charge current generated by anomalous Hall effect, where the N_z plays the role of the magnetic field. The second term describes a SPC generates a charge current perpendicular to both N_z and its gradient which is referred to RSHE [18]. The absence of an external electrical field in the experiment excludes the anomalous Hall effect, thus the only reason for the swirly current probably is RSHE. If so, the swirly current should decrease with the increase of the incident angle θ due to the decrease of the N_z. The measurements under different incident angles proved this inference. For simplicity, Fig. 2 only shows three sets of measured data in which the different dots denote the current as a function of the spot position under $\theta = 0°$, $20°$, $40°$. The result is a superposition of two current components with different spatial distribution which is sketched in the inset of Fig. 2. The current with symmetric distribution similar to a Gauss curve shows the directed CPGE current along electrodes, and the current with sine function profile shows the swirly anomalous CPGE current. According to Fig. 2, the increase of the incident angle θ strengthens the directed current but lowers the swirly current which indicates that the swirly current is just resulted from the radial SPC.

According to the foregoing analysis, the transverse charge current generated by SPC can be expressed as $j/e = -N_0 \gamma v_y^z \times \hat{z}$, where $v_y^z = D\nabla_y G(r)$ is the effective velocity of electrons along the y direction with spin z polarization and $\hat{z}$ is the unit vector perpendicular to the plane. In this process, spin polarization electrons generate transverse displacements which can be described by a spin transverse force. It is defined as $f_x(r) = \frac{m^* \gamma}{\tau_s} v_y^z \times \hat{z}$, where m^* and τ_s are the effective mass and spin relaxation time of electrons. The direction of $f(r)$ acting on the spin polarization electrons is perpendicular to both electrons' initial velocity and spin, so it makes electrons obtain a transverse velocity $v_x = f_x \tau_s / m^*$ in the relaxation time approximation. Therefore, if electrons with spin z polarization flowing with radial distribution are subjected to a spin transverse force, it will generate a transverse current swirling over the spot center shown in Fig. 3(b). Here we can find the direction of the charge current [dashed loop shown in Fig. 3(b)] is consistent with the rotational direction of the electrical field component of the light. In fact, it implies the conversion of the angular momentum of the system. It is known that directed CPGE current is a transfer of the photon angular momentum into the linear momentum of the free charge carriers which means a coupling of axial and polar vectors, and this coupling is only allowed by gyrotropic media [13]. Similarly, the swirly anomalous CPGE current can be considered as the transfer of the photon angular momentum into the angular momentum of electron's orbit motion along the center of the light spot which necessarily requires the uniformity of the direction of the swirly current and the electrical field component of the light. This transfer means a coupling of two axial vectors and should not be only limited to the gyrotropic systems.

Similar to the SHE, RSHE has the extrinsic and intrinsic mechanisms. The former originates from spin-dependent impurity scattering and the latter is based on the spin band splitting. Their difference can be demonstrated theoretically by the expression of the spin-orbit interaction constant γ [18]. For the 2DEG in the QW with inversion asymmetry, an intrinsic mechanism can contribute to RSHE because of Rashba spin splitting [19]. For QW with point group of C_{3v}, the spin transverse force based on intrinsic mechanism is theoretically given by $\langle f \rangle_x = \frac{4m^{*2}(\alpha^2+\beta^2)}{\hbar^2}(j_s^z \times z)$, where $\hbar$ is the plank constant, $j_y^z = \frac{\hbar}{4} \times \langle \{ v_y^z, \sigma_z \} \rangle$ the spin current, and α, β the Rashba and Dresselhaus spin splitting constant of the energy band [19]. In this case, the γ is expressed as $\gamma = \frac{m^* \tau_p}{\hbar}(\alpha^2 + \beta^2)$. On the other hand, as the extrinsic RSHE, γ depends on scattering amplitudes from impurities; a general form can be found in Ref. [2]. Since the 2DEG in the triangular QW of $Al_xGa_{1-x}N/GaN$ heterostructures have the sizeable Rashba effect [14], the extrinsic and intrinsic mechanisms probably coexist. It is hard for the experiment itself to distinguish the extrinsic and intrinsic origin of the RSHE, but an estimation of the spin transverse force and the Hall voltage induced by light spot is given based on the experimental results. Because the radius of light spot with about 1 mm is much bigger than the spin diffusion length L, the contribution of the SPC outside the light spot is neglected. For the 2DEG in the QW which can be considered as an ideal two-dimensional conductor, a circular electromotive force (EMF) within the area of the spot is offered by the irradiation, where the spin transverse force plays the role of nonelectrostatic force. The distribution of spin transverse force is expressed as $f(r) = -f_0 \frac{r}{\sigma^2} \exp(-\frac{r^2}{2\sigma^2})$, where σ is the distribution variance related with the full-width at half maximum (FWHM) of the light spot. And then the induced EMF is expressed as $\varepsilon(R) = \frac{2\pi}{q} \int_0^R f(r) r dr$, where q is the unit charge. The generation of the swirly current is described by a vortex electric field $E(R)$ which is determined through $\oint \vec{E}(R) \cdot d\vec{l} = \varepsilon(R)$, where R is the radius of the integral loop. The voltage between two points on the two-dimensional conductor is given by $V_{ab} = \int_a^b E \cdot dl$. Furthermore, we can get $\nabla \times E(R) = -\frac{f_0}{q} \cdot \frac{r}{\sigma^2} \times \exp(-\frac{r^2}{2\sigma^2})$, which indicates that the spin transverse force is the origin of the vortex electrical field. Neglecting the effect of the boundary of the sample, the current between two electrodes can be expressed by $I_{ab} = \frac{V_{ab}}{R_{ab}} = \frac{1}{R_{ab}} \times \iint_D \nabla \times E(r) ds$, where I_{ab}, R_{ab}, V_{ab} are the current, resistance, and voltage between two electrodes, respectively. D denotes the triangular area among the spot center and two electrodes. The sketch has been shown in the inset of Fig. 4. In addition, considering the saturation of the light absorption, in the saturated area, the gradient $\nabla_r N_z = 0$

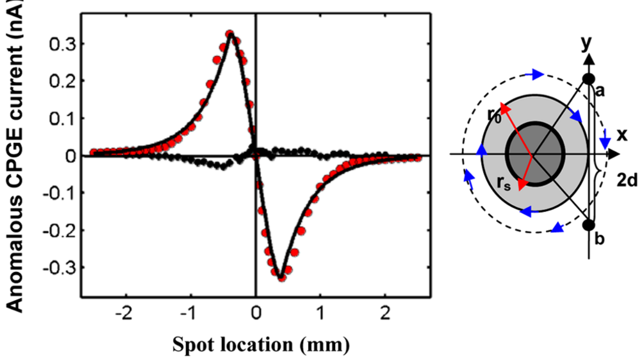

FIG. 4 (color online). The fitting (dark curve) of the experimental data (light dots). The dark dots are the experimental data obtained when the spot focused with a diameter of about 0.1 mm. The inset is the geometry of the light spot and two electrodes in which r_o is the radius of the light spot, r_s the radius of saturated absorption, dark spots denote electrodes, and short arrows indicate the direction of the vortex electrical field.

and then the spin current is zero. So the fan-shaped area within the saturated radius r_s will be deducted from the integral area D. Figure 4 gives the final fitting for the experimental data. Adopting $R_{ab} \approx 600\ \Omega$, $\sigma \approx 0.18$ mm, $d \approx 1$ mm, $r_s \approx 0.38$ mm, which are measured experimentally, the fitting yields $f_0/q \approx 1.5 \times 10^{-3}$ N/C. The spin transverse force acting on a single electron with spin z polarization due to RSHE is estimated to be 2.4×10^{-19} N through the expression $F = \frac{f_0}{q} e$. We define the circular Hall voltage generated by RSHE as $V_{\rm hall} = \varepsilon(r)0$, where $r_0 \approx 0.55$ mm is the radius of the light spot. Adopting $f_0/q \approx 1.5 \times 10^{-3}$ N/C, the Hall voltage $V_{\rm hall} = \frac{2\pi f_0}{q} \int_0^{r_0} \frac{r^2}{\sigma^2} \exp(-\frac{r^2}{2\sigma^2}) dr$ is estimated to be about 2.4 μV. The Hall voltage is sensitive to the size of the light spot since it is dependent on the SPC distributed in the area of the light spot. The dark dots in Fig. 4 represent the experimental results when the light spot is focused with the diameter of about 0.1 mm. We found that the anomalous CPGE current almost disappears due to the considerable decrease of the light spot's size.

In summary, under normal incidence of circularly polarized light at room temperature, a charge current with swirly distribution has been observed in the 2DEG in $Al_{0.25}Ga_{0.75}N/GaN$ heterostructures. This swirling, named anomalous CPGE current, can be considered as the transfer of photon angular momentum into the rotational motion of electrons which means the coupling of two axial vectors. Independent of the gyrotropic symmetry of a system, this coupling is realized through the RSHE which converts a radial spin current into a swirly charge current via a spin transverse force. Considering the 2DEG as an ideal two-dimensional conductor, we calculated the spin transverse force acting on a single electron and the Hall voltage for a light spot with given size. We believe that the anomalous CPGE is a universal phenomenon for the transport of electrons in various semiconductors and suggests an experimental way to study the RSHE and the spin current on the macroscopic scale and at room temperature.

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