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Spin transport study in a Rashba spin-orbit coupling system

SUBJECT AREAS:

SPINTRONICS

TWO-DIMENSIONAL MATERIALS

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One of the most important topics in spintronics is spin transport. In this work, spin transport properties of two-dimensional electron gas in $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructure were studied by helicity-dependent photocurrent measurements at room temperature. Spin-related photocurrent was detected under normal incidence of a circularly polarized laser with a Gaussian distribution. On one hand, spin polarized electrons excited by the laser generate a diffusive spin polarization current, which leads to a vortex charge current as a result of anomalous circular photogalvanic effect. On the other hand, photo-induced spin polarized electrons driven by a longitudinal electric field give rise to a transverse current via anomalous Hall Effect. Both of these effects originated from the Rashba spin-orbit coupling. By analyzing spin-related photocurrent varied with laser position, the contributions of the two effects were differentiated and the ratio of the spin diffusion coefficient to photo-induced anomalous spin Hall mobility $D_s/\mu_s = 0.08 \text{ V}$ was extracted at room temperature.

Spintronics keeps attracting physicists in view of its possible applications in information technology as well as revealing essential questions on the physics of spin^{1–4}. Spin-orbit coupling (SOC), being the heart of many spin-based devices, also gives rise to a series of interesting phenomena such as that a charge current can generate a spin current, known as the spin Hall effect (SHE)^{5,6}, and that a spin current can also generate a charge current. Depending on the specific mechanism, the latter can be subdivided into the anomalous circular photogalvanic effect (ACPGE)⁷ and anomalous Hall Effect (AHE)^{8–12}. One of the fundamental issues to realize spin device application is spin transport and its manipulation, including spin diffusion and drift in semiconductors or metals. The drift-diffusion model is a simple model for spin transport description, which remains a mainstream model in spintronic device simulation¹³. In this model, spin is similar to charge; the up-spin and down-spin carriers are assumed to be analogous to electrons and holes; and $D_s/\mu_s = kT/q$, the general Einstein relation still applies to spin transport in a two dimensional non-degenerate electron gas controlled by SOC. However, the result of $D_s/\mu_s = kT/q$ given in Eqs. 18–22 of Ref. 13 is only an approximation, as the authors neglected terms quadratic in the spin velocity operator which mixes polarized and non-polarized components of the current. As the authors stated, these corrections should be considered in the model, accounting for non-conservation of the spin current density in systems of a spin orbit interaction. In addition, this result also lacks experimental evidence. In this work, we propose a simple experimental setup to determine the ratio of the spin diffusion coefficient to photo-induced anomalous Hall mobility, D_s/μ_s , in $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure at room temperature, where the Rashba SOC is very strong¹⁴. The classic ratio D/μ for degenerate electron transport is then calculated by the Einstein relationship for comparison.

Results

Detection of photo-induced anomalous Hall effect (PIAHE)^{9–12}. Figure 1a shows a schematic illustration of the sample used in this study. When a circularly polarized light irradiates vertically on the sample, electrons will be spin polarized, inducing a spin imbalance. The flow of the spin polarized electrons driven by the longitudinal electric field leads to a transverse PIAHE current, as shown in Figure 2a. The amount of the spin polarized electrons is assumed to be proportional to the helicity of the incident light, $P_{\text{circ}} = \sin 2\varphi$ where φ is the rotation angle between the polarization direction of the incident light and optical axis of the quarter wave plate. Thus the PIAHE current can be expressed as: $j/e = \gamma\mu_s EN_s \sin 2\varphi$, where e is the electron charge, γ is the spin-orbit coupling coefficient, μ_s is the spin mobility, E is the external electric field, and N_z is the spin polarization density perpendicular to the sample plane when samples are irradiated by a circularly polarized light, respectively.

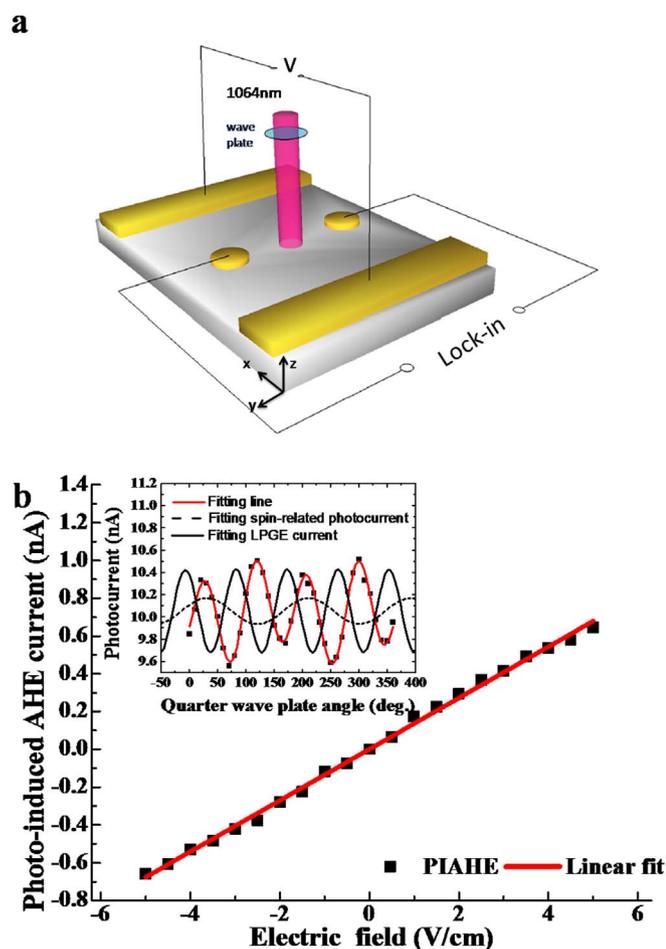


Figure 1 | Experimental set-up. (a) A schematic illustration of the geometry of the experiment. Two circle electrodes and two stripe electrodes are attached to the sample by evaporating the Ti/Al/Ni/Au metal multilayer structure. A laser with wavelength of 1064 nm vertically irradiates on the sample. (b) PIAHE current as a function of the longitudinal electric field in an $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure with the light irradiated vertically at the center of the two circle electrodes. The red solid line is a linear fit. Inset is the spin-related photocurrent measured as a function of the quarter wave plate angle when $E = -1 \text{ V/cm}$. The red solid line is the fitting line. The black dashed line is the extracted PIAHE current as a function of the quarter wave plate angle, which is sensitive to the circularly polarized light and achieves maximum when $\varphi = \pm 45^\circ$. The black line is the extracted LPGE current as a function of quarter wave plate angle, which is sensitive to the linearly polarized light and achieves maximum magnitude when $\varphi = \pm 90^\circ$.

The inset of Figure 1b shows the detected photo-galvanic current as a function of φ . The PIAHE current is extracted from the amplitude of $\sin 2\varphi$. Figure 1b shows the PIAHE current as a function of the longitudinal electric field when the laser spot is located at the center of the two circle electrodes, which is linearly well fitted. A non-zero spin-related photocurrent was measured when a longitudinal electric field was applied, which should result from the PIAHE. The photo-induced anomalous Hall conductance of the 2DEG in the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure can then be obtained from the linear fit line and the value is $1.4 \times 10^{-10} \Omega^{-1}$, about the same order of magnitude as the result in Ref. 12.

Spin-related photocurrent varied with laser position. When the incident light has a distribution of a Gaussian profile, it can be shown by solving a Boltzmann equation that the PIAHE current

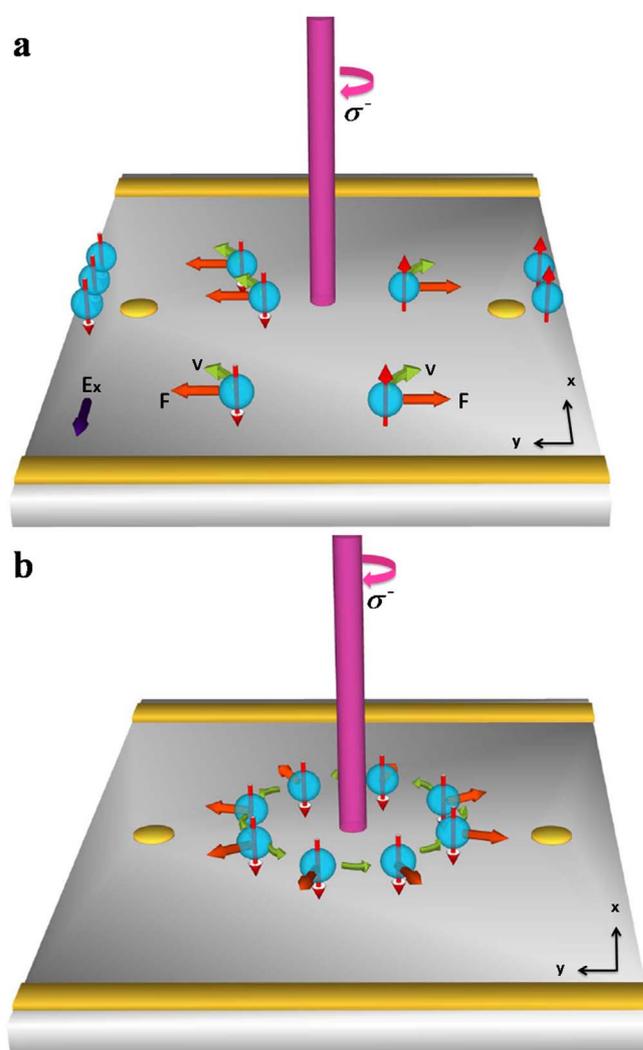


Figure 2 | Schematic mechanism. (a) A schematic diagram of the PIAHE. A left circularly polarized light vertically irradiates on the samples, exciting spin polarized electrons. The drift of spin polarized electrons driven by the longitudinal electric field leads to a transverse PIAHE current. (b) A schematic diagrams of the ACPGE. A left circularly polarized light with a Gaussian distribution in space leads to a similar spin polarization distribution. Spin diffusion occurs and electron spin density gradient generates a diffused SPC in the sample plane (denoted by orange arrows). This radial SPC then induces a vortex current j via the mechanism of ACPGE (denoted by green arrows).

should also have asymmetric Gaussian-like distribution as a function of the laser spot position along axis X.

A circularly polarized light with a Gaussian distribution arouses an inhomogeneous spin polarization. Spin diffusion occurs when there is a spin density gradient. The electron spin density gradient generates a diffused spin polarization current (SPC) in the sample plane, which is proportional to the gradient of spin polarization density and the helicity of the incident light¹⁵. This radial SPC then induces a transverse current j via the mechanism of the ACPGE, which can be expressed phenomenologically as: $j/e = \gamma D_s \nabla_x N_s \sin 2\varphi$ ^{16,17}, where γ is again the spin-orbit coupling coefficient, D_s is the spin diffusion coefficient and N_s is the spin polarization density perpendicular to the sample plane when the sample is irradiated by a circularly polarized light, respectively. A schematic diagram of the ACPGE current is pictured in Figure 2b. The vortex spin-related photocurrent collected from the two circle electrodes as a function of the laser spot position along axis X is thus an anti-symmetric curve.



According to the foregoing analysis, when an electric field is applied, a circularly polarized light with a Gaussian distribution will induce both an ACPGE and PIAHE current in the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructure. Under normal incidence, the total photocurrent can be described by the following formula:

$$J_{\text{total}} = (J_{\text{ACPGE}} + J_{\text{PIAHE}}) \sin 2\varphi + J_{\text{L0}} \sin 2\varphi \cos 2\varphi + J_0 \quad (1)$$

where J_{ACPGE} is the ACPGE current, J_{PIAHE} is the PIAHE current, J_{L0} is the amplitude of the linear photo-galvanic effect (LPGE) current which results from asymmetric scattering of electrons, and J_0 describes the background photocurrent originating from the Demer effect and/or other photovoltaic effects^{18,19}. It is noteworthy that both ACPGE current and PIAHE current are spin-related photocurrent which is proportional to the helicity of the incident light $P_{\text{circ}} = \sin 2\varphi$, but the latter only appears with external electric field applied, as shown in Figures 3a and 3b. There is no spin-related photocurrent detected when the electric field is zero when the light spot is located at the center between the two circle electrodes, indicating neither a PIAHE current nor an ACPGE current was detected.

Thus we can differentiate the two effects. In other words, when the light spot is located at the center between the two circle electrodes, the electric field induced spin-related current would be purely from PIAHE.

Figures 3a and 3b show the spin-related photocurrent as a function of the laser position with various electric fields. When $E = 0 \text{ V/cm}$, the spin-related photocurrent exhibits an anti-symmetric distribution. Naturally, this current arises solely from the ACPGE current. The total spin-related photocurrent as a function of the laser position was modulated when $E = -1 \text{ V/cm}$ and $E = 1 \text{ V/cm}$ as shown in Figure 3a and Figure 3b, respectively. The PIAHE current was also extracted by subtracting the ACPGE current from the total spin-related photocurrent. The extracted two curves in Figures 3a and 3b both exhibit a symmetric Gaussian-like distribution, confirming the current to be a PIAHE current. In addition, their directions are opposite, being consistent with the mechanism of PIAHE. When the external electric field reverses its direction, the spin-polarized electrons flow in an opposite direction and are consequently deflected to an opposite direction as well, thus leading to the reverse of the

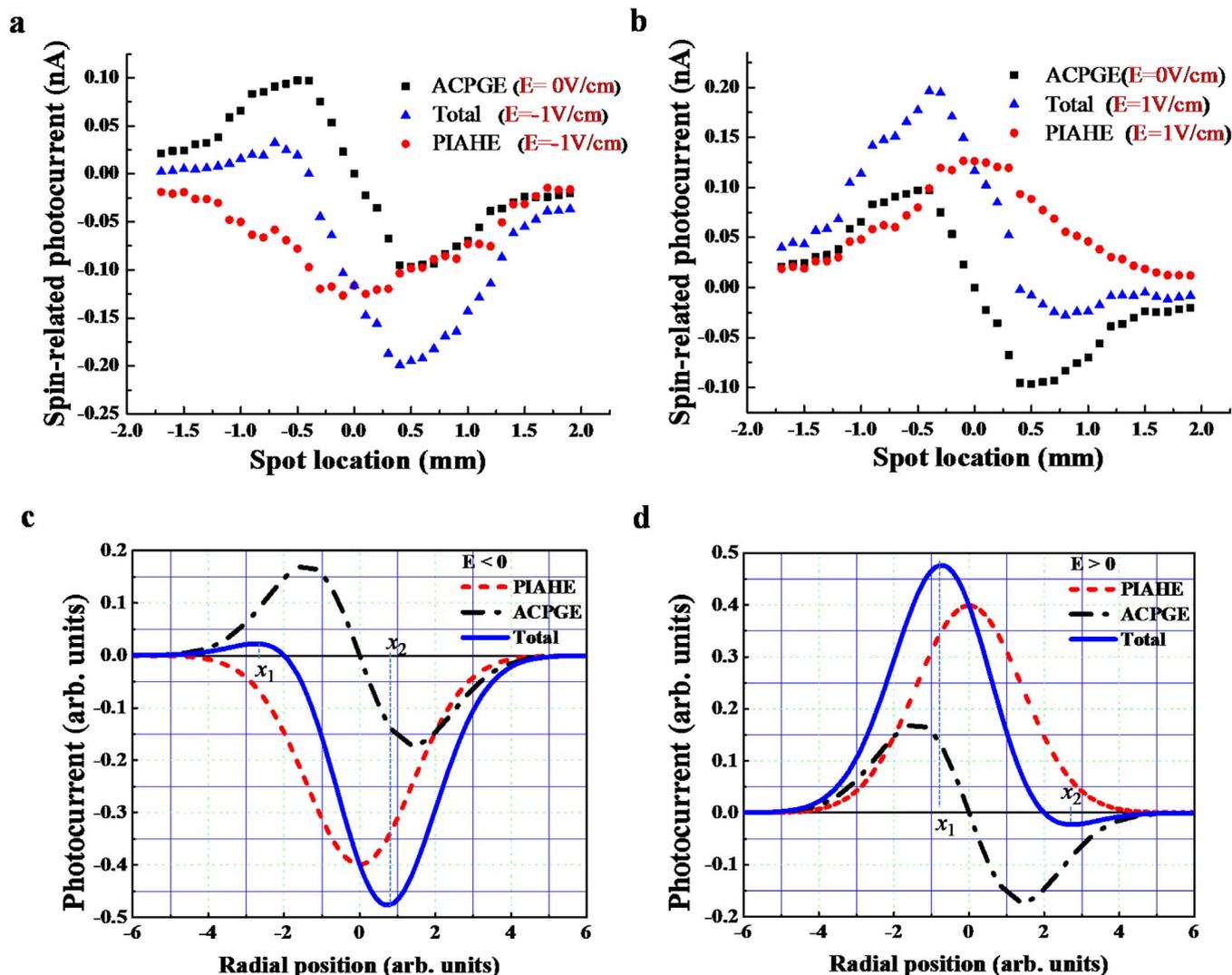


Figure 3 | Spin related photocurrent varied with laser position. (a) Spin-related photocurrent as a function of the light spot position along the X-axis of an $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure for $E = 0 \text{ V/cm}$ and $E = -1 \text{ V/cm}$, respectively. (b) Spin-related photocurrent as a function of the light spot position along X-axis of an $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure for $E = 0 \text{ V/cm}$ and $E = 1 \text{ V/cm}$, respectively. PIAHE current as a function of the laser spot position when $E = 1 \text{ V/cm}$ and $E = -1 \text{ V/cm}$ are also shown in (a) and (b) respectively. The Gaussian distribution confirms the PIAHE current. (c) Superposition of ACPGE and PIAHE current as a function of laser spot position when $E < 0 \text{ V/cm}$. (d) Superposition of ACPGE and PIAHE current as a function of laser spot position when $E > 0 \text{ V/cm}$.



PIAHE current. Hence, the sign reverse of the PIAHE current and their symmetric Gaussian distribution are both strong evidence of the proposed superposition mechanism.

Discussion

According to Dyakonov¹⁶, the transport phenomenon related to the coupling of spin current and charge current can be expressed phenomenologically by the following equations:

$$\vec{q}^0 = -\mu n \vec{E} - D \nabla n, \quad (2)$$

$$q_{ij}^0 = \mu E_i P_j - D \frac{\partial P_j}{\partial x_i}, \quad (3)$$

where \vec{q}^0 is the electron flow density, q_{ij}^0 is the spin polarization current density, μ and D are the usual electron mobility and diffusion coefficient, \vec{P} is the vector of spin polarization density, and \vec{E} is the electric field. When the spin-orbit interaction couples the two currents, explicit phenomenological expressions for the two currents can then be expressed as^{13,16}:

$$\vec{J}/e = \mu n \vec{E} + D \nabla n + \beta \vec{E} \wedge \vec{P} + \delta \text{curl} \vec{P}, \quad (4)$$

where $\beta = \gamma \mu$, $\delta = \gamma D$, γ is a coefficient representing the spin-orbit coupling strength. The parameters μ and D in the expression of β and δ are not the usual electron mobility and diffusion coefficient, so they are specified for spin in this letter and renamed as spin mobility μ_s and spin diffusion coefficient D_s , respectively. It is worth noting that as spin is non-conservative, its transport behavior could be quite different from that of the conservative electron particles.

Quantitatively, the ACPGE current and PIAHE current in this study can be expressed as $J_{ACPGE}/e = \gamma D_s \nabla N_z$ and $J_{PIAHE}/e = \gamma \mu_s E N_z$, respectively⁴. Using $N_z = \frac{c}{\sigma} e^{-x^2/\sigma^2}$, where c , x and σ are respectively an arbitrary constant, the spot coordinate along the X-axis and the standard deviation of the Gaussian distribution. The total spin-related photocurrent along the X-axis can then be expressed as:

$$J/e = J_{ACPGE} + J_{PIAHE} = \gamma \frac{c}{\sigma} e^{-x^2/\sigma^2} \left(-D_s \frac{2x}{\sigma^2} \mu_s E \right), \quad (5)$$

which turns out to always have two extreme values at corresponding values of x , as shown in Figure 3c and Figure 3d. The spot positions where the extreme values appear satisfy the following conditions:

$$2D_s x^2 - \sigma^2 E \mu_s x - D_s \sigma^2 = 0. \quad (6)$$

Hence, the two positions, x_1 and x_2 , where the spin-related photocurrent reaches its extrema, satisfy:

$$x_1 + x_2 = \frac{\sigma^2 \mu_s E}{2D_s}, \quad (7)$$

$$x_1 \cdot x_2 = -\frac{\sigma^2}{2}. \quad (8)$$

Therefore, by measuring the photocurrent as a function of the light spot position along the bisector of the two electrodes, the ratio of the photo-induced anomalous Hall mobility to spin diffusion coefficient, D_s/μ_s , can be derived by using the formula:

$$D_s/\mu_s = -E \frac{x_1 \cdot x_2}{x_1 + x_2}, \quad (9)$$

which can be determined by x_1 , x_2 and E .

It should be emphasized that Eq. (9) applies to spin polarization densities with any Gaussian distribution, regardless of its standard

deviation and amplitude. In Eq. (9), the ratio of the photo-induced anomalous Hall mobility to spin diffusion coefficient, D_s/μ_s depends only on the electric field and the two positions where the total spin-related photocurrent reaches its extrema. As shown in Figure 3a, when $E = 1 \text{ V/cm}$, x_1 and x_2 can be determined to be 0.8 mm and 0.4 mm, respectively. Adopting them into Eq. (9), one can obtain the value of $D_s/\mu_s = 0.08 \text{ V}$. Not surprisingly, Figure 3b gives the same result that further confirms the proposed mechanism.

According to the Einstein relationship for electron transport, the value of $D_s/\mu_s = kT/q$ is estimated to be about 0.026 V at room temperature, which is much smaller than the value of $D_s/\mu_s = 0.08 \text{ V} (\approx 3.08 \text{ kT/q})$ we obtained in this work. There are two reasons for the apparent difference. Firstly, the Einstein relationship above is valid for a non-degenerate case, where the Boltzmann distribution is valid. For a degenerate case, however, the distribution function f can be written in the form

$$f = \frac{1}{\exp\left(\frac{E-E_f}{kT}\right) + 1} = \frac{1}{\exp(\zeta - \eta) + 1}, \quad (10)$$

where $\zeta = (E - E_c)/kT$ and $\eta = (E_f - E_c)/kT$. The Einstein relationship for a degenerate 2D system is then

$$\frac{eD}{\mu} = -\frac{n}{\int_0^\infty N(E) \frac{\partial f}{\partial E} dE} = -\frac{n}{N_s \int_0^\infty \frac{\partial f}{\partial \zeta} d\zeta} = \frac{n}{N_s f(0)}, \quad (11)$$

where $N(E)$ is the density of state per unit area per unit energy in a 2D system²⁰. In an $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructure, $N_s = m/\pi\hbar^2 = 9.96 \times 10^{10}/\text{cm}^2 \text{meV}$. The sheet concentration of the two-dimensional electron gas $n = 1.15 \times 10^{13} \text{ cm}^{-2}$ corresponds to $E_f - E_c = 65 \text{ meV}$ i.e. $\eta = 2.5$ at room temperature. Substituting the above values into Eq. (11), we get $D/\mu = 0.12 \text{ V} = 4.8 \text{ kT/q}$ close to our experimental result. Secondly, we would like to clarify that D_s/μ_s for spin transport is not necessarily the same as D/μ for electron transport. The essential difference is that electrons are conservative, while spin is not, whereas the Einstein relationship is derived based on the conservation law of electrons. That might be an additional reason for the difference between our experimental result and the calculated result using the Einstein relationship.

In conclusion, the superposition of spin drift and spin diffusion is revealed and the corresponding ratio between the spin mobility and diffusion coefficient is determined to be 0.08 V in an $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure at room temperature. The difference between this value and that for electron transport which follows the Einstein relationship is discussed by electron degeneracy in our two dimensional system, and the non-conservative property of spin. It is also worth noting that the PIAHE measurement used in this study is conducted under ambient conditions with a simple setup and operation, and it applies in other spin related materials.

Methods

Sample preparation. The sample used in this study is $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ heterostructure which was prepared by means of metal organic chemical vapor deposition (MOCVD). A GaN epi-layer with a thickness of 2 μm was grown at 1050°C after a 20- nm -thick GaN buffer layer was grown on a c -plane sapphire substrate at 530°C. It was followed by a 20- nm -thick $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ barrier layer grown on the GaN epi-layer at 1090°C. The typical mobility and sheet concentration of the two-dimensional electron gas formed in the interface between GaN and $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ were 1170 cm^2/Vs and $1.15 \times 10^{13} \text{ cm}^{-2}$, respectively. Samples were cut into narrow strips along the GaN [10 $\bar{1}$ 0] direction with a width of 5 mm and a length of 15 mm, respectively. Two 0.4 mm diameter circle electrodes with a distance of 3 mm apart along the Y direction were made to collect photocurrent, and two stripe electrodes (0.4 \times 4 mm^2) with a distance of 8 mm in between were fabricated to apply electric field by evaporating a Ti/Al/Ni/Au metal multilayer structure, as shown in Figure 1a.

Measurement. A diode-pumped solid state laser with power of $500 \pm 10 \text{ mW}$ and wavelength of 1064 nm served as the radiation source. A rotatable quarter-wavelength plate was employed to modulate the helicity of the incident light. The helicity of the incident light P_{circ} equals $\sin 2\phi$, where the phase angle ϕ is the angle between the polarization direction of the incident light and the optical axis of the



quarter-wave plate. After passing through a chopper, a Gaussian profile light beam with a diameter of about 2.4 mm was irradiated vertically on the sample. Electrons in the triangular quantum well at the AlGa_N/Ga_N hetero-interface were excited to high energy states by the laser beam. The longitudinal electric field was applied by the two strip electrodes, and the current signal was collected by a lock-in amplifier after being pre-amplified.

- Žutić, I., Fabian, J. & Das Sarma, S. *Rev. Mod. Phys.* **76**, 323–410 (American Physical Society, 2004).
- Wu, M., Jiang, J. & Weng, M. Spin dynamics in semiconductors. *Phys. Rep.* **493**, 61–236 (2010).
- Dyakonov, M. I. & Khaetskii, A. V. Spin Hall Effect *Spin physics in semiconductors* Dyakonov, M. I. (Ed.) Vol. 157, 211–115 (Springer, Verlag Berlin Heidelberg 2008).
- Awschalom, D. D. & Flatté, M. E. Challenges for semiconductor spintronics. *Nat. Phys.* **3**, 153–159 (2007).
- Hirsch, J. Spin hall effect. *Phys. Rev. Lett.* **83**, 1834–1837 (1999).
- Stern, N. *et al.* Current-induced polarization and the spin Hall effect at room temperature. *Phys. Rev. Lett.* **97**, 126603 (2006).
- Hankiewicz, E. M. *et al.* Charge Hall effect driven by spin-dependent chemical potential gradients and Onsager relations in mesoscopic systems. *Phys. Rev. B* **72**, 155305 (2005).
- Nagaosa, N., Sinova, J., Onoda, S., MacDonald, A. & Ong, N. Anomalous hall effect. *Rev. Mod. Phys.* **82**, 1539 (2010).
- Miah, M. I. Observation of the anomalous Hall effect in GaAs. *J. Phys. D: Appl. Phys.* **40**, 1659 (2007).
- Yu, J. L. *et al.* Intrinsic photoinduced anomalous Hall effect in insulating GaAs/AlGaAs quantum wells at room temperature. *Appl. Phys. Lett.* **102**, 202408 (2013).
- Yu, J. L. *et al.* Observation of the photoinduced anomalous Hall effect spectra in insulating InGaAs/AlGaAs quantum wells at room temperature. *Appl. Phys. Lett.* **100**, 142109 (2012).
- Yin, C. M. *et al.* Observation of the photoinduced anomalous Hall effect in GaN-based heterostructures. *Appl. Phys. Lett.* **98**, 122104 (2011).
- Saikin, S. A drift-diffusion model for spin-polarized transport in a two-dimensional non-degenerate electron gas controlled by spin-orbit interaction. *J. Phys.: Condens. Matter* **16**, 5071 (2004).
- Yin, C. *et al.* Rashba and Dresselhaus spin-orbit coupling in GaN-based heterostructures probed by the circular photogalvanic effect under uniaxial strain. *Appl. Phys. Lett.* **97**, 181904 (2010).
- Zhou, B. & Shen, S.-Q. Deduction of pure spin current from the linear and circular spin photogalvanic effect in semiconductor quantum wells. *Phys. Rev. B* **75**, 045339 (2007).
- Dyakonov, M. I. Magnetoresistance due to Edge Spin Accumulation. *Phys. Rev. Lett.* **99**, 126601 (2007).
- He, X. *et al.* 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. *Phys. Rev. Lett.* **101**, 147402 (2008).
- Ivchenko, E. L. & Pikus, G. E. *Nonlinear Optics Superlattices and other heterostructures: symmetry and optical phenomena*. Vol. 110, 322–338 (Springer Verlag, 1997).
- Ganichev, S. D. & Prettl, W. Spin photocurrents in quantum wells. *J. Phys.: Condens. Matter* **15**, R935–R983 (2003).
- Smith, R. A. Diffusive of electrons and positive holes: Einstein's relationship *Semiconductors*. Vol. 173, 172–175 (Cambridge University Press Cambridge, 1978).

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Author contributions

F.M. and S.Z. contributed equally to this work. F.M., S.Z. and N.T. designed the experiment. F.M. and S.Z. collected the data, performed analysis of the data. F.X. provided the sample. N.T., W.G. and B.S. supervised the study. F.M., S.Z., N.T. and W.G. wrote the manuscript. F.M., S.Z., N.T., J.D. and Y.C. contributed to the analysis for the results. All the authors discussed the results and commented on the manuscript.

Additional information

Competing financial interests: The authors declare no competing financial interests.

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