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Electron density dependence of the spin Hall effect in GaAs probed by scanning Kerr rotation microscopy

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We studied electron density ($n$) dependence of the extrinsic spin Hall effect in $n$-doped GaAs with $n$ ranging from $1.8 \times 10^{16}$ to $3.3 \times 10^{17}$ cm$^{-3}$. By scanning Kerr microscopy measurements, we observed spin accumulation near the channel edges in all the samples due to the extrinsic spin Hall effect. The spin Hall conductivity $\sigma_{SH}$ is obtained for each sample by comparing the Kerr rotation induced by optically injected spins. $\sigma_{SH}$ is found to increase with $n$, and it is shown that a theoretical model reported earlier agrees well with the experimental $n$ dependence of $\sigma_{SH}$.

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Observations of the spin Hall effect (SHE) (Refs. 1 and 2) and the current-induced spin polarization3–5 in semiconductors have been reported in the route of exploring a possibility for electrical generation and manipulation of spin currents. In particular, SHE has attracted much attention since pure spin current can be generated in nonmagnetic material without using ferromagnetic material or applying an external magnetic field. In the SHE, an electrical current induces transverse pure spin current in nonmagnetic material resulting in spin accumulation at sample boundaries without charge accumulation. Similar to the anomalous Hall effect, spin-orbit interaction is the origin of the SHE, which can be classified into the “extrinsic” SHE,6,7 which is induced by impurity scattering, and the “intrinsic” SHE,8,9 which results from the band-structure Berry phase acquired by the moving charge. Kato et al.10 first reported experimental observation of local spin accumulation at the sample edges in $n$-GaAs and $n$-InGaAs.11 Subsequently, Wunderlich et al.12 showed circularly polarized light emission in a $pn$-junction-based structure due to spin-polarized holes at the edges of the structure. The former has been explained in terms of the extrinsic SHE because the spin Hall conductivity $\sigma_{SH}$ is small and independent of crystal orientation, while the latter has been attributed to the intrinsic SHE.

The extrinsic SHE in doped semiconductors has been further studied in quantum well structures,10 different materials,11 and specific sample geometry to elucidate the nature of the SHE.12,13 Moreover, time-resolved dynamics of spin accumulation induced by SHE has been demonstrated.14 Theoretical studies have also been put forward to explain the origin of the SHE (Refs. 15 and 16) revealing how the extrinsic SHE should depend on the basic semiconductor parameters such as the doping density. In this work, we investigate the electron density ($n$) dependence of SHE in $n$-doped GaAs. We determine $\sigma_{SH}$ as a function of $n$ ranging from $1.8 \times 10^{16}$ to $3.3 \times 10^{17}$ cm$^{-3}$ by comparing the local spin accumulation induced by SHE with the optically injected spins in $n$-GaAs. The results are compared with a theory put forward earlier.

In this study, five samples (labeled by A–E) with different doping concentrations on undoped (100) GaAs substrate grown by molecular beam epitaxy are used. They consist of a 2-μm-thick Si-doped GaAs grown on a 400 nm Al$_{0.3}$Ga$_{0.7}$As barrier and an undoped GaAs buffer layer. All samples have a 250-μm-long and 60-μm-wide Hall-bar structure with alloyed Ohmic contacts of Au/Ni/AuGe/Ni. The conductivity $\sigma$ and the electron density $n$ (cm$^{-3}$) are obtained by the Hall measurement done at 30 K with applying an electric field $E$ of 5 mV/μm. Taking into account the surface depletion, $\sigma$, $n$, and the effective thickness $d_{eff}$ of $n$-GaAs are calculated. The electron $g$ factor $g$ and spin relaxation time $\tau_{SP}$ longer than the pulse interval (samples A–C) is determined by using a resonant spin amplification technique. These data are summarized in Table I.

In order to probe the local spin polarizations induced by the SHE and by the optical spin injection, we implemented a spatially resolved scanning Kerr microscopy (SKM) system as shown in Fig. 1. As a source of the probe light, we employed a mode-locked Ti:sapphire laser, which generates 3 ps (the linewidth is less than 1 meV) pulse trains at 76 MHz repetition rate. The probe light intensity is 110 μW, and the photon energy is fixed at 1.503 eV, which is lower than the band gap of $n$-GaAs, in order to avoid optical excitation of excess electron-hole pairs in the sample. The Hall-bar sample is placed in a He-flow cryostat with an optical window and kept at 30 K. In SKM measurements, we take the origin of the coordinate at the center of the Hall bar, and the

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma$ (Ω$^{-1}$ m$^{-1}$)</th>
<th>$n$ (cm$^{-3}$)</th>
<th>$d_{eff}$ (μm)</th>
<th>$g$</th>
<th>$\tau_{SP}$ (ns)</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3200</td>
<td>$1.8 \times 10^{16}$</td>
<td>1.76</td>
<td>0.438</td>
<td>38.2</td>
<td>0.30</td>
</tr>
<tr>
<td>B</td>
<td>3500</td>
<td>$2.9 \times 10^{16}$</td>
<td>1.81</td>
<td>0.423</td>
<td>22.4</td>
<td>0.31</td>
</tr>
<tr>
<td>C</td>
<td>4400</td>
<td>$5.1 \times 10^{16}$</td>
<td>1.86</td>
<td>0.407</td>
<td>12.6</td>
<td>0.30</td>
</tr>
<tr>
<td>D</td>
<td>9400</td>
<td>$1.4 \times 10^{17}$</td>
<td>1.91</td>
<td>0.356</td>
<td>2.53</td>
<td>0.31</td>
</tr>
<tr>
<td>E</td>
<td>16000</td>
<td>$3.3 \times 10^{17}$</td>
<td>1.94</td>
<td>0.284</td>
<td>1.06</td>
<td>0.34</td>
</tr>
</tbody>
</table>

TABLE I. Physical properties of samples A–E studied in this work.
x and y axes are taken to be across and along the Hall-bar channel, respectively. An external magnetic field $B_{\text{ext}}$ is applied in the $x$ direction. The path of the probe light, whose intensity is modulated by acousto-optical modulator at $f_p = 50.6$ kHz, is bent 90° by a prism mirror placed in the cryostat to detect the out-of-plane ($z$) component of spins in the sample by measuring the Kerr rotation angle. The spot size on the sample was $\omega_0 \sim 1.25$ µm, where $\omega_0$ is Gaussian beam radius. An SKM image is taken by moving the cryostat integrated on a piezo nanoscanning stage. In SHE measurements, an ac electric field $E$ is applied along the $y$ direction at the frequency of 1 kHz. The Kerr rotation angle of the probe beam induced by the SHE, labeled by $\theta^{\text{SH}}_K$, is then measured by using a balanced photoreceiver and a lock-in amplifier at 1 kHz. For the measurements of optically injected spins, we use a cw Ti:sapphire laser as a pump light amplifier at 1 kHz. For the measurements of electronic modes, we use an ac electric field $E$ of $3.3 \times 10^{17}$ cm$^{-3}$ at $B = 5$ mV/µm. Open symbols are experimental data and (red) lines are fitting results. Constant offsets have been subtracted. (c)–(e) Dependence of $\tau^{\text{SH}}_s$, $L^{\text{SH}}_s$, and $|\theta^{\text{SH}}_K(\pm L_{\text{eff}}/2)|$ for all the samples as a function of $E = 5$–20 mV/µm.

First we examine the $n$ dependence of the SHE. Spatial profiles of the Kerr rotation $\theta^{\text{SH}}_K(x)$ across the channel measured at $y=0$ and $E = 5$ mV/µm are shown by open symbols in Fig. 2(a). In all the samples, peak structures near the channel edges are clearly shown. Figure 2(b) shows the Hanle curves by open symbols as a function of $B_{\text{ext}}$, which were measured at the peak position of $\theta^{\text{SH}}_K(x)$. These features are consistent with the results reported in Ref. 1. Based on the drift-diffusion model, the $z$ component of the spin density per unit volume, $S^{\text{SH}}_z(x)$, is given by $(E \sigma^{\text{SH}}_s L^{\text{SH}}_s / 2 L_{\text{eff}}^2) \sinh(x / L^{\text{SH}}_s) / \cosh(L_{\text{eff}} / 2 L^{\text{SH}}_s)$, where $L^{\text{SH}}_s$ is the spin diffusion length and $\tau^{\text{SH}}_s$ is the spin relaxation time under the application of $E$. $L_{\text{eff}}$ is the distance between the peaks of $\theta^{\text{SH}}_K(x)$ on both edges. In our SKM system, the probe beam profile has a symmetric Gaussian shape and is expressed as $\exp[-2(x^2 + y^2)/\omega^2_0]$. Assuming that $\theta^{\text{SH}}_K(x)$ is proportional to total amount of $z$ component of the spins with a constant $C^{\text{SH}}_0$, then

$$\theta^{\text{SH}}_K(x) = d_{\text{eff}} C^{\text{SH}}_0 \int_0^\infty \exp[-2(x^2 + y^2)/\omega^2_0] \sinh(x / L^{\text{SH}}_s) / \cosh(L_{\text{eff}} / 2 L^{\text{SH}}_s) dX = (d_{\text{eff}} C^{\text{SH}}_0 E \sigma^{\text{SH}}_s L^{\text{SH}}_s \tau^{\text{SH}}_s / L_{\text{eff}}^2) \sqrt{2 \pi} \omega_0 C^{\text{SH}}_0 / 2$$

where $C^{\text{SH}}_0(x) = \int_0^x \exp(-2x'^2 / \omega^2_0) \sinh(x / L^{\text{SH}}_s) / \cosh(L_{\text{eff}} / 2 L^{\text{SH}}_s) dX$. The experimental data shown in Fig. 2(a) can be fitted well by Eq. (1) as indicated by a (red) line, from which $L^{\text{SH}}_s$ and the peak values of $\theta^{\text{SH}}_K(x)$ at $x = \pm L_{\text{eff}}/2$ are obtained. In Fig. 2(b), the Hanle curve obtained at the boundary for each sample is fitted by a Lorentz function $\theta^{\text{SH}}_K(\pm L_{\text{eff}}/2) / (1 + (\mu_B B_{\text{ext}} \tau^{\text{SH}}_s / \hbar)^2)$, as shown by a (red) line. Here, $\mu_B$ is the Bohr magneton and $\hbar$ is the reduced Planck constant. From the fitting, $\tau^{\text{SH}}_s$ is obtained. For all the samples with different $n$'s, $E$ dependence (5–20 mV/µm) of $\tau^{\text{SH}}_s$, $L^{\text{SH}}_s$, and $|\theta^{\text{SH}}_K(\pm L_{\text{eff}}/2)|$ are shown in Figs. 2(c)–2(e) as a function of $n$. The decrease in $\tau^{\text{SH}}_s$ and $L^{\text{SH}}_s$ with increasing $n$ reflects the enhanced spin relaxation due to the D’yakonov-Perel’ mechanism. When $E$ is increased, $\tau^{\text{SH}}_s$ and $L^{\text{SH}}_s$ decrease again by the D’yakonov-Perel’ mechanism as a result of the increase in the electron temperature. As shown in Fig. 2(e), $|\theta^{\text{SH}}_K(\pm L_{\text{eff}}/2)|$ increases with $E$ and tends to saturate, as observed in Ref. 1. It should be noted in Fig. 2(e) that $|\theta^{\text{SH}}_K(\pm L_{\text{eff}}/2)|$ does not change with $n$ monotonically. This reflects the fact that $C^{\text{SH}}_0$ is sample dependent, and...
the distance from the center of the pump light spots, \( \theta_{K}^{\text{OP}} \) is the electron density dependence of the spin Hall angle, \( n \) is the amount of the absorbed light intensity in zero-order modified Bessel function of the second kind. \n
Thus, the calibration between the Kerr rotation angle and \( S_z \) is necessary.

In order to establish the relation between the Kerr rotation angle and \( S_z \) for each sample, we optically inject spins and measure the Kerr rotation by using the SKM system at the origin of the samples. In Fig. 3(a), experimental results of \( \theta_{K}^{\text{OP}}(B_{\text{ext}}) \) are shown as a function \( B_{\text{ext}} \). To derive the relation between \( \theta_{K}^{\text{OP}}(B_{\text{ext}}) \) and the spatial distribution of the \( z \) component of optically injected spin per unit area, \( S_z^{\text{OP}}(r) \), we employed a model described in Ref. 21. Taking into account that the spin polarization of optically injected electrons is 50% due to the optical selection rule,

\[
S_z^{\text{OP}}(r) = \frac{r \text{exp}(\alpha r) P}{2 \pi (L_s^{\text{OP}})^2 2E_{\text{pump}}} \text{Re} \left[ K_0 \left( \frac{r}{L_s^{\text{OP}}} \sqrt{1 + i\Omega r_z^{\text{OP}}} \right) \right],
\]

where \( \Omega = g \mu_B B_{\text{ext}}/h \) is the Larmor precession frequency, \( r \) is the distance from the center of the pump light spots, \( L_s^{\text{OP}} \) is the spin diffusion length of optically injected spins (at \( E = 0 \)), \( E_{\text{pump}} \) is the photon energy of the pump light, and \( K_0 \) is the zero-order modified Bessel function of the second kind. \( P \) is the amount of the absorbed light intensity in \( n \)-GaAs: in this work, we use \( P = I_{\text{pump}}(1-R)(1-\text{exp}(-d\alpha)) \), where \( d \) is the thickness of \( n \)-GaAs (2 \( \mu \)m) and \( \alpha \) is taken to be \( 10^4 \text{ cm}^{-1} \) for all the samples.\n
Then, \( \theta_{K}^{\text{OP}}(B_{\text{ext}}) \) induced by \( S_z^{\text{OP}}(r) \) is given by

\[
\theta_{K}^{\text{OP}}(B_{\text{ext}}) = C_{0}^{\text{OP}} \int_0^\infty \text{exp}(\alpha r^2) S_z^{\text{OP}}(r) dr,
\]

where

\[
C_{0}^{\text{OP}} = \frac{P}{(L_s^{\text{OP}})^2 2E_{\text{pump}}} \text{Re} \left[ K_0 \left( \frac{r}{L_s^{\text{OP}}} \sqrt{1 + i\Omega r_z^{\text{OP}}} \right) \right].
\]

Using Eq. (3), we fit the data shown in Fig. 3(a) with \( C_{0}^{\text{OP}} \) and \( L_s^{\text{OP}} \) as fitting parameters. As indicated by (red) lines, the fit reproduces the data well, from which \( L_s^{\text{OP}} \) is obtained. In Fig. 3(b) and 3(c), \( n \) dependence of \( L_s^{\text{OP}} \) and \( \theta_{K}^{\text{OP}}(0)/P \) are shown. \( L_s^{\text{OP}} \) decreases with increasing \( n \), similarly to the result of \( L_s^{\text{SH}} \) under applied electric fields. In Fig. 3(c), \( \theta_{K}^{\text{OP}}(0)/P \) shows nonmonotonic \( n \) dependence, like in the case of \( |b_{k}^{\text{SH}}(L_{\text{eff}})/2| \) [see Fig. 2(e)], reflecting the sample dependence of \( C_{0}^{\text{OP}} \).

Since the photon energy of the probe light is the same for both SHE and optical spin injection experiments, it is reasonable to take \( C_{0}^{\text{SH}} \approx C_{0}^{\text{OP}} \) for each sample. Based on this, we calculate \( \sigma^{\text{SH}} \) from Eqs. (1) and (3) using the experimentally obtained values \( |b_{k}^{\text{SH}}(L_{\text{eff}})/2| \) and \( \theta_{K}^{\text{OP}}(0) \). In Figs. 4(a)–4(c), \( \sigma^{\text{SH}} \), \( |s_{k}^{\text{SH}}(L_{\text{eff}})/2| \), and \( \sigma^{\text{SH}}/\sigma_z \) are indicated by solid symbols as functions of \( n \). It is shown in Fig. 4(a) that \( \sigma^{\text{SH}} \) increases with \( n \) and is almost independent of \( E \).

Finally, we refer to the theoretical expression of \( \sigma^{\text{SH}} \) which is given by

\[
\sigma^{\text{SH}} = \frac{m \lambda_e \alpha e_F \sigma^2}{3\hbar^2} + e^2 \lambda_e^2 \hbar n,
\]

where \( m \) is the effective mass of electron, \( e \) is the elementary charge, and \( e_F \) is the Fermi energy referred to as...
that the order of the spin Hall angle $\alpha^{\text{SH}}$ induced by SHE is enhanced by increasing the spin accumulation is reduced by enhanced spin relaxation corresponding spin polarization of around 1%. This indicates that $n_{\text{eff}}$ tends to increase with temperature. The calculated $|\Delta^{\text{SH}}(\pm L_{\text{eff}}/2)|$ tends to saturate up to the corresponding spin polarization of around 1%. This indicates that the spin accumulation is enhanced by reduced spin relaxation due to the D’yakonov-Perel’ mechanism, while the spin current induced by SHE is enhanced by increasing $n$. It is found that the order of the spin Hall angle $\alpha^{\text{SH}}/\alpha^{\text{SH}}$ passes through $10^{-2}$ and tends to increase with $n$ but saturates when $n$ is increased to $10^{17}$ cm$^{-3}$.

In conclusion, we have studied electron density dependence of the extrinsic SHE and spin Hall conductivity in $n$-doped GaAs by scanning Kerr microscopy. We have observed the Kerr rotation signal due to the spin accumulation near the channel edges in $n$-GaAs with $n$ ranging from $1.8 \times 10^{16}$ to $3.3 \times 10^{17}$ cm$^{-3}$. Based on a quantitative analysis of optical spin injection and SKM detection, we show that $\alpha^{\text{SH}}$ is enhanced by increasing $n$, and $\alpha^{\text{SH}}/\alpha^{\text{SH}}$ saturates at $10^{-2}$. We have also shown that the theoretical model proposed in Ref. 16 well explains our experimental data.

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