Magnetoelectric Photocurrent Generated by Direct Interband Transitions in InGaAs/InAlAs Two-Dimensional Electron Gas

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We report the observation of magnetoelectric photocurrent generated via direct interband transitions in an InGaAs/InAlAs two-dimensional electron gas by a linearly polarized incident light. The electric current is proportional to the in-plane magnetic field, which unbalances the velocities of the photoexcited carriers with opposite spins and consequently generates the electric current from a hidden spin photocurrent. The spin photocurrent can be evaluated from the measured electric current, and the conversion coefficient of spin photocurrent to electric current is self-consistently estimated to be $10^{-3} - 10^{-2}$ per Tesla. The observed light-polarization dependence of the electric current is well explained by a theoretical model which reveals the wave vector angle dependence of the photoexcited carrier density.

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Stimulated by the concept of nonmagnetic semiconductor spintronics devices [1], spin injection and detection by optical means have attracted much attention [2–17]. One way to generate spin current is to use linearly polarized optical excitations in bulk III–V semiconductors and quantum wells (QW) with asymmetric band structures induced by the strong spin-orbit coupling (SOC) [11–17]. The left and right circular components of the linearly polarized light generate the same amount of carriers with opposite spins and velocities, leading to a spin photocurrent accompanied by no electric current [18]. Because spin current carries neither net charge nor magnetization, it is necessary to convert the spin current to either electric current or magnetization for measurement [6–9,12,13,19–21]. An in-plane magnetic field may induce an imbalance of photoexcited carriers with opposite spins in the spin-split bands, resulting in an electric photocurrent. This field-induced conversion was systematically studied by intraband transitions involving abundant spin-dependent excitation and relaxation processes [16,17], and offered collateral evidence for pure spin currents. Since the induced charge current in the intraband transition is related to the scattering of carriers by phonon, impurity, or defect, it is difficult to use the method to estimate the field-induced conversion.

In this Letter we report a measurement of magnetoelectric photocurrent generated via direct interband transitions in an InGaAs/InAlAs two-dimensional electron gas by a linearly polarized light. The observed photocurrent and hence the hidden pure spin current, are several orders of magnitude larger than those via the intraband transition. The spin current generated thus appears promising as a step towards practical application. The simple picture of the direct interband transition enables us to have a reliable estimate of the pure spin current from the electric current, with the conversion rate found to be $10^{-3} - 10^{-2}$ per Tesla. The estimated spin current is further confirmed by an anisotropic photocurrent induced Hall effect when the light sheds on the edge of the sample in the presence of a perpendicular magnetic field.

We start with discussions of our experimental setup, sample parameters, and the optical process. The experiment is carried out on the modulation doped In$_x$Ga$_{1-x}$As/InAlAs QW grown along [001] direction, as shown in Fig. 1(a). The 40 nm InGaAs QW consists of graded indium composition from $x = 0.53$ to 0.59. The mobility and carrier (electron) density were measured as $\mu_m = 12000$ cm$^2$ V$^{-1}$ s$^{-1}$ and $n_e = 2.2 \times 10^{12}$ cm$^{-2}$ at room temperatures by Hall measurements. The experiment setup is shown in Fig. 1(b). A 1050 $\mu$m long ($L$) and 50 $\mu$m wide strip of 2DEG channel along [110] and [110] directions was fabricated by standard photolithography and wet etching. The linearly polarized light at 1 mW normally sheds on the channel through a $10\times$ objective lens. The electric photocurrent $J_x$ passing through two terminals is monitored via the voltage drop $V_x$ on a load resistor $R_{load} = 3.9$ k$\Omega$ with a lock-in amplifier.

The band gap of 0.764 eV is extracted from the photo-modulated differential reflectivity spectrum [22] as shown in Fig. 1(a). The pump source is a DFB packed laser diode at 1550 nm (0.80 eV), which excites the interband transition in the InGaAs channel. Since the photon energy is well above the band gap and the two lowest interband transition energies [marked by vertical dashed lines in Fig. 1(c)], the dominant optical absorption mechanism here is the direct interband transition, in which an electron in the valence band with the wave vector $k$ absorbs a photon of energy $\hbar \omega$ and transits to the conduction band with the same wave vector.

In the analysis below we assume linear Rashba type spin-orbit coupling only, which leads to the two spin-split...
netoelectric effect, which are about 1 order in magnitude smaller than the first term, and are consistent with the $C_{2v}$ crystal symmetry of the zinc blende QW grown along [001] direction [17,26].

Below we shall first present a simple picture to qualitatively explain the magnetic-field-induced conversion from the pure spin current to the electric photocurrent. The picture [Figs. 3(a) and 3(b)] can be illustrated by a valence band $|v,k\rangle$ and two spin-split conduction subbands $|c = \pm, k\rangle$ with the band dispersions

$$E_{\pm}(k) = \frac{\hbar^2}{2m^*} k^2 \pm \sqrt{(ak_x + h_i)^2 + (ak_y - h_j)^2},$$

(2)

where $k_{x,y}$ are the in-plane wave vectors, $k^2 = k_x^2 + k_y^2$, $\sigma_{xy}$ are the Pauli matrices, and $h_{i,j}$ denote the Zeeman energies of the in-plane magnetic fields. In $k$ space, the states involved in the interband transition form the constant energy contours which, in the absence of magnetic fields, are perfect concentric circles split by the SOC [Fig. 3(a)]. Because of the time-reversal symmetry, for each state on a constant energy contour, there always exists another state with opposite velocity and spin; therefore they cancel one another to give no electric photocurrent, but a nonzero spin photocurrent [11,14,15,18]. According to the above $E_{\pm}(k)$, applying in-plane fields will lead to the Zeeman shifts of the bands and distort the constant energy contours to Fig. 3(b). This shift then breaks the balance of both velocities and photoexcited carrier density on the constant energy contours and leads to a finite electric photocurrent. Besides the Zeeman effect, a shift can also be induced by the diamagnetic mechanism [27,28], but the consequence should be qualitatively similar.

Now we use a theoretical model to further explain the experimental observation in Eq. (1). The electric photo-
current density $j_x$ can be calculated by summing the velocities of the photoexcited carriers

$$j_x = -e \sum_{c,v} \int_0^{\pi/2} d\varphi \int_0^\infty kd\delta(k - k_{cv}) \rho_{cv,k} v'_{cv,k},$$

where $-e$ is the electron charge, $\rho_{cv,k}$ is the carrier density, and $v'_{cv,k}$ denotes the $x$-axis velocity of $|c,k\rangle$. For convenience, the summation over $k$ can be rewritten into an integral in polar coordinates

$$j_x = \frac{-e}{(2\pi)^2} \sum_{c,v} \int_0^{\pi/2} d\varphi \int_0^\infty kd\delta(k - k_{cv}) \rho_{cv,k} v'_{cv,k}, \quad (3)$$

where the wave vector angle $\varphi$ is defined as $\tan^2 \varphi = k_y/k_x$, $k_{cv}$ are the magnitudes of wave vectors on a constant energy contour. For small magnetic fields, we can expand the velocity $v'_{cv,k} \approx (1/\hbar) \delta E_x(k)/\delta k_x$ up to the linear order of the Zeeman energy $h_{x,y}$ along $x(y)$ axis as

$$v'_{\pm k} \approx \left(\frac{\hbar}{2m} k \pm \alpha \right) \cos^2 \varphi + \frac{\sin^2 \varphi}{2\hbar} h_x + \sin^2 \varphi h_y. \quad (4)$$

Similar to the second-order nonlinear optical susceptibility, $\rho_{cv,k}$ in Eq. (3) can be evaluated by the density matrix formalism [11]. Simply speaking, as a second-order optical quantity, $\rho_{cv,k}$ should be proportional to $|\mathbf{E} \cdot \mathbf{r}_{cv}|^2$ where $\mathbf{E} = E_0(\cos \theta, \sin \theta)$ is the polarization electric field vector and $\mathbf{r}_{cv} = (x_{cv}, y_{cv})$ is the expectation value of position operator between conduction and valence bands. Then $\rho_{cv,k}$ turns out to be well described by the form

$$\rho_{cv,k} = \rho_{cv}^0 + \rho_{cos}^0 \cos 2\varphi \cos^2 \theta + \rho_{cos}^{m} \sin 2\varphi \sin 2\theta. \quad (5)$$

As shown in Figs. 3(c)–3(e), $\rho_{cv,k}$ has an anisotropic $\varphi$ dependence. Putting the above $\rho_{cv,k}$ and $v'_{\pm k}$ into Eq. (3) immediately yields a current density in the same form as Eq. (1) [29]. For example, one can check that the first term of $\rho_{cv,k}$ and the last term of $v'_{cv,k}$ gives the $c_0 B_y$ term of Eq. (1). Above we neglect the hole contribution from the valence bands, as the lifetime and spin relaxation time of holes in the $n$-type well are much shorter than those of electrons.

The theoretical model allows us to estimate the magnitude of the zero-field pure spin photocurrent from the measured field-induced electric photocurrent. The zero-field spin velocities are defined as (flowing along $x$, polarized along $x$ and $y$ axes) $(s^{x/\gamma}_{l/k})_{\pm k} \equiv \langle \pm, \mathbf{1}_k | \hat{\sigma}_x, \hat{\sigma}_y \rangle |\pm, \mathbf{k}\rangle$, specifically, $(s^x_{l/k})_{\pm k} = \pm \frac{\hbar}{2m} k \sin 2\varphi$ and $(s^y_{l/k})_{\pm k} = (\frac{\hbar}{mc} k \cos^2 \varphi - \frac{\alpha}{\hbar})$. The spin currents can be evaluated by replacing $v'_{cv,k}$ in Eq. (3) with $(s^{x/\gamma}_{l/k})_{\pm k}$. Note that the zero-field spin velocity $\propto \hbar k/m^2$ and the magnetic-field-induced electron velocity variation $\propto h_y/\hbar$, their ratio $\hbar^2 k^2/m^2/\hbar h_y$ can be employed to approximate the ratio of the zero-field pure spin current over the field-induced electric current in strength. This ratio could be further interpreted as “kinetic energy over Zeeman energy.” The kinetic energy can be estimated to be about $10^{-2}$–$10^{-4}$ eV from the carrier density $n_e = 0.93 \times 10^{12}$ cm$^{-2}$, and the Zeeman energy $h_y$ is about $1.2 \times 10^{-4}$ eV/Tesla (Landé $g$ factor $=-4$ [23,30]). The field-induced electric photocurrent density of about $10^{-5}$ A/m can be found from the measured $J_x$ in Fig. 2. Summarizing above gives the spin photocurrent density about $10^{-3}$–$10^{-2}$ A/m for a 1 mW incident light, and a conversion coefficient from spin photocurrent to field-induced electric photocurrent about $10^{-3}$–$10^{-2}$ per Tesla. In the above analysis, we replace the unit $\hbar/2$ of the spin current with $-e$ for direct comparison with the electric current.

In what follows, we shall describe a second method to estimate the spin photocurrent by employing a photoexcited Hall measurement, in which the optical pumping acts like a current source in the usual Hall measurement. Our finding is consistent with and further supports the estimation of the spin current from the magnetoelectric photocurrent. We apply an out-of-plane magnetic field $B_z$, and scan the light spot across the channel along $y$ axis (Fig. 4). The light spot may generate photocurrents diffusing out of the spot edge in all directions with the identical charge current density $j_0$ (note that $j_0$ is completely different from the field-induced electric photocurrent in Fig. 2). When the spot is right focused on one edge of the sample, the anisotropic diffusion leads to a net current $Dj_0$ ($D = 10 \mu$m denotes the spot diameter) normal to the edge and consequently produces a Hall voltage along $x$ direction under the magnetic field $B_z$. Figure 4 shows $V_x$ as a function of the spot position $y_{spot}$ (the scanning path is marked by the dotted line). The positive and negative peaks
correspond to where the light spot is located at the left and right edges of the channel, respectively. If the spot is away from the edges, the diffusion of the photocurrent is isotropic and consequently the Hall voltage vanishes. The plateau in Fig. 4 is attributed to the in-plane magnetic field as those in Fig. 2. At the edges, $Dj_0$ is related to $V_x$ by a transverse Hall resistivity $\rho_{xy} = 2B_z/\pi\epsilon_n$, then $j_0 = \pi\epsilon_nV_x/2DB_z = 2.4 \times 10^{-2}$ A/m at the peaks ($|V_x| = 6.5 \mu$V) in Fig. 4. Roughly speaking, $j_0$ can be viewed as $j_1 + j_1$ while the spin current as $j_1 - j_1$, and $(j_1 - j_1)/(j_1 + j_1) = \Delta n/n$. With $\Delta n/n = 0.027$ [Fig. 1(d)], the spin photocurrent is estimated about $0.7 \times 10^{-3}$ A/m, and agrees with the low bound by the magnetoelectric effect. Furthermore, $j_0$ can also be evaluated from the conversion of the light power into the photocurrent. If the sample reflectance of 0.3, photon-carrier yield of 30%, and the absorption coefficient of $9 \times 10^3$ cm$^{-1}$ are assumed, the spin current density is found to be around $10^{-2}$ A/m, consistent with the high bound obtained by the magnetoelectric effect. Comparing the above spin current density range ($0.7 \times 10^{-3} - 10^{-2}$ A/m) with the electric photocurrent signal owing to $B_z$ (the plateau in Fig. 4, note when $\theta = 0$, $B_z$, and $B_y$ induced currents just add up to one another), one could estimate the conversion coefficient of spin photocurrent to field-induced electric photocurrent at $10^{-3} - 10^{-2}$ per Tesla, in good agreement with those by the magnetoelectric effect.

In summary, we have observed magnetic-field-induced electric photocurrent via the direct interband optical absorption. We have estimated the conversion coefficient of spin photocurrent to field-induced electric photocurrent to be $10^{-3} - 10^{-2}$ per Tesla. Our experiment demonstrates that optical injection via the direct interband transition is a promising means to generate and detect spin photocurrent, as well as a reference for future evaluation of pure spin currents. This should stimulate further experiments to study nonmagnetic spintronics towards its practical applications.

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[25] In the estimation [24], $\alpha = \frac{\Delta n}{m} \sqrt{\frac{\pi}{e^{2} \Delta n}}$, where $\Delta n = 0.93 \times 10^{13}$/cm$^{2}$ and $\Delta n = 0.025 \times 10^{13}$/cm$^{2}$ are the average value and the difference of the two carrier concentrations extracted in the inset of Fig. 1(d), and the effective mass $m^{*} = 0.04m_{0}$ is assumed.
[26] Our theoretical model assumes $C_{nv}$ symmetry, which can be generalized to $C_{2v}$ by considering anisotropic Rashba coefficients along $x$ and $y$ axes. For $C_{nv}$, $|c_{x}| = |c_{y}|$ in Eq. (1), which does not hold for $C_{2v}$.
[29] Under the same principle of the $\varphi$ dependence, the variation of $\rho_{cv,k}$ upon applying $B$ field also leads to a contribution to $J_{z}$ of the same order as those from $v_{k}$.