All-electrical spin-to-charge conversion in a mesoscopic GaAs hole system

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(Dated: July 3, 2019)

The ability to convert spin accumulation to charge currents is essential for applications in spintronics. In semiconductors, spin-to-charge conversion is typically achieved using the inverse spin Hall effect or using a large magnetic field. Using a ballistic, mesoscopic gallium arsenide hole system, here we demonstrate an all-electrical method of spin-to-charge conversion by exploiting non-linear interactions between spin and charge currents. Our work opens up new possibilities for all-electrical and fast detection of spin accumulation without the need for a long spin diffusion length or a magnetic field.

Introduction. Spintronics is a technology that uses the spin degree of freedom to manipulate information. All-electrical rapid spin control may be possible in systems with strong spin-orbit interactions. A key challenge in spintronics is the generation and detection of spin accumulation. In semiconductors, spin accumulation is typically generated by optical excitations or the intrinsic spin Hall effect, whilst spin-to-charge conversion (i.e. spin accumulation translating into a charge current or voltage) is achieved through the inverse spin Hall effect. Recently, holes have attracted great interest in semiconductor spintronics due to their exceptionally strong spin-orbit interaction. However, for holes the spin relaxation time is short (< 100 fs) and the spin-diffusion length is much shorter than the typical device dimensions (∼ 100 – 1000 nm). Traditional methods of generating spin accumulation via optical excitations or detecting spin accumulation via the inverse spin Hall effect are therefore challenging for holes.

In strongly spin-orbit coupled ballistic mesoscopic systems, charge currents are generally accompanied by spin currents, and a non-equilibrium spin accumulation can develop depending on the sample geometry as well as the strength and form of the spin-orbit interaction. One such configuration was suggested in Ref. [22], eliminating the need for long spin diffusion length or spin relaxation time. A non-equilibrium spin accumulation is then detected as a voltage signal, which contains contributions linear and non-linear in spin accumulation, via an energy-selective barrier. The linear spin-to-charge conversion was recently reported in a multiterminal mesoscopic cavity in GaAs holes. However, linear spin-to-charge conversion requires a large range of magnetic field, which is impractical and can suppress the desired spin accumulation. By contrast, non-linear spin-to-charge conversion does not require a magnetic field. Therefore, non-linear spin-to-charge conversion is all-electrical and fast, which could be useful for spin-based transistors.

Using ballistic, mesoscopic GaAs holes, we demonstrate in this work all-electrical generation and detection of spin accumulation, without the need for long spin diffusion length or a magnetic field. We first demonstrate spin-to-charge conversion in the linear regime using an in-plane magnetic field. We then show spin-to-charge conversion in the non-linear regime and confirm that it works even at zero magnetic field.

Experimental concept. We use a three-terminal geometry with a quantum point contact (QPC) as an energy-selective barrier. Passing a current $I_{sd}$ in the drive channel between terminals 1 and 2 results in a voltage difference $V_{sd}$ and a net non-equilibrium spin accumulation $\delta \mu_s$. Spins with orientation $\sigma_+$ have a higher chemical potential ($\delta \mu_+ \gt \delta \mu_-$) through the QPC. The kink in the drive channel helps direct the spin accumulation towards the QPC. Spin-to-charge conversion occurs if one spin species has a higher transmission probability $T(E)$ through the QPC than the other. In the linear regime, the difference in the transmission probability originates from the difference in the hole’s kinetic energy, which arises from, a Zeeman interaction due to an in-plane magnetic field $B$. However, in the non-linear regime, the energy dependence of the transmission probability $T(E)$ through the barrier causes the $\sigma_+$ spins to have a higher transmission probability through the QPC ($\delta \mu_+$) than $\sigma_-$ even at zero field. In both the linear and non-linear regimes, the charge current that flows across the QPC ($V_s$ and $g$) causes a restoring voltage $V_d$ to maintain zero net charge current through

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FIG. 1. (a) A schematic of the experimental setup. A current $I_{sd}$ flows between terminals 1 and 2, resulting in a voltage difference $V_{sd}$ across the drive channel. (b), (c) Near the quantum point contact (QPC), opposite spin orientations $\sigma_+$ and $\sigma_-$ accumulate on opposite sides of the drive channel. The QPC acts as an energy filter: Spin-to-charge conversion occurs due to the difference in the transmission probability through the QPC between each spin species. In the linear regime (d), this difference arises from a different kinetic energy caused by, for instance, a Zeeman interaction. (e) In the non-linear regime, the different local chemical potentials for $\sigma_+$ and $\sigma_-$ give rise to different transmission probabilities. In both (f) linear and (g) non-linear cases, spin-polarized holes accumulate after they pass through the QPC, resulting in a voltage $V_3$ between terminals 2 and 3. See text for more explanation.

The QPC with terminal 3 set as a floating probe. While the drive current $I_{sd}$ oscillates at a frequency $\omega$, the linear and non-linear signals oscillate at the first and second harmonics of $V_3$, i.e. $V_3(\omega)$ and $V_3(2\omega)$ respectively.

Theoretical analysis. Throughout this work, we keep the driving current $I_{sd}$ low such that the spin accumulation $\delta \mu_s$ is proportional to $I_{sd}$. We model the QPC with an energy-dependent transmission probability $T(E) \equiv T(E, B)$ \cite{26,27}. The transmission probability is most energy-dependent when the QPC is half-open. Since the spin-to-charge conversion depends on the QPC energy sensitivity, we expect that, to the lowest order, the spin signal is proportional to the QPC transconductance $\partial G_{qpc}/\partial V_{qpc}$, where $G_{qpc}$ and $V_{qpc}$ are the QPC conductance and the QPC gate voltage, respectively.

In the linear regime, the spin signal is proportional to the Zeeman splitting of the one-dimensional subbands, and is antisymmetric in the in-plane magnetic field $B$ \cite{27}. This gives rise to a three-terminal voltage $V_3(\omega) \equiv V_3(\omega, B)$ asymmetric in $B$. The asymmetry $\partial_B V_3(\omega)|_{B=0}$ is \cite{22}:

$$\partial_B V_3(\omega)|_{B=0} = -\frac{\sigma g \mu_B}{2} \left[ \frac{2e}{\hbar} \int dE (-\partial_E f(E)) \partial_E T(E) \right] \delta \mu_s,$$

(1)

where $\sigma$ is the sign of the spin accumulation, $g$ is the in-plane $g$-factor, $\mu_B$ is the Bohr magneton, and $f(E)$ is the Fermi-Dirac distribution. Eq. (1) allows one to quantify the spin accumulation from the voltage asymmetry. Similarly, one can evaluate the spin current flowing through the QPC using \cite{21,23,25}:

$$I_{spin} \simeq \frac{2h \Omega_{qpc} e^2}{\pi \mu_B} \partial_B V_3(\omega)|_{B=0},$$

(2)

where $h \Omega_{qpc}$ is the QPC saddle potential curvature \cite{20}.

In the non-linear regime, the difference in the transmission probability across the QPC is proportional to $\delta \mu_s$. Thus, the non-linear component of the spin signal $V_3$ is quadratic in $\delta \mu_s$:

$$V_3(2\omega) = \frac{1}{2} \left[ \frac{e}{\hbar} \int dE (-\partial_E f(E)) \partial_E T(E) \right] (\delta \mu_s)^2.$$  

(3)

Since the non-linear signal is independent of the sign of $\delta \mu_s$, the second harmonic of the three-terminal voltage $V_3(2\omega)$ is symmetric in $B$.

Besides quantifying the spin current and accumulation, Eqs. (1)-(3) allow us to verify the spin origin of the linear and non-linear signals via their dependence on the QPC gate voltage $V_{qpc}$, in-plane magnetic field $B$, and the excitation current $I_{sd}$. Furthermore, since $\partial E T(E)$ correlates (Eqs. (1) and (3)) with the transconductance $\partial G_{qpc}/\partial V_{qpc}$, we expect that the linear and non-linear signals are maximal when $\partial G_{qpc}/\partial V_{qpc}$ is maximal (i.e. when the QPC is set between two plateaus) and disappear at a QPC plateau.

Methods. An image of the device is shown in Fig. 2a. The device is made from an AlGaAs/GaAs heterostructure grown on a (100) GaAs substrate. For the measurements presented here, the two-dimensional hole density is $p = 2 \times 10^{11} \text{cm}^{-2}$, corresponding to a Fermi wavelength $\lambda_F = 56 \text{nm}$, a spin-orbit length $l_{SO} = 35 \text{nm}$, and a mobility $\mu = 550,000 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ (see Section S2 of the Supplementary Material \cite{28}). Surface gates define a conducting region in the shape of a ‘K’, with length 4 $\mu$m and width 1 $\mu$m, whilst the QPC is 370 nm.
FIG. 2. Device image and linear spin-to-charge conversion. (a) A scanning electron microscope image of the device. Light gray regions denote the surface gates, dark gray regions represent the AlGaAs/GaAs heterostructure, while light blue squares depict terminals 1-3. (b) QPC conductance versus QPC gate voltage. The dashed lines denote the second and third conductance risers as well as the second conductance plateau. (c) Color map of the two-terminal resistance \( V_{sd}/I_{sd} \) across the channel as a function of the QPC voltage \( V_{qpc} \) and \( B \), showing a symmetric dependence on \( B \). (d) Line cuts of \( V_{sd}/I_{sd} \) from (c) along the second and third QPC conductance risers, as well as along the middle of the second conductance plateau. (e) Color map of the three-terminal resistance \( V_{3}/I_{sd} \) as a function of \( V_{qpc} \) and \( B \). Its asymmetry in \( B \) indicates the presence of spin accumulation. (f) Line cuts of \( V_{3}/I_{sd} \) from (e) along the second and third QPC conductance risers, as well as along the middle of the second conductance plateau. The asymmetry in \( V_{3} \) in \( B \) is present at a QPC conductance riser but absent at a plateau. (g) The asymmetry \( \Delta(\omega) \equiv (\partial V_{3}/\partial B)/I_{sd} \) of the \( V_{3} \) as a function of \( V_{qpc} \) around the second riser, taken at different \( I_{sd} \). The asymmetry of the \( V_{3} \) persists up to \( I_{sd} = 10 \) nA, but becomes hard to correlate to the transconductance at 32 nA. The \( \Delta(\omega) \) traces are offset by 25 \( \Omega/T \) for clarity. The quantity \( \Delta(\omega) \) measures the amplitude of the asymmetry \( \Delta(\omega) \) relative to the background.

We send a current \( I_{sd} \) through the drive channel, and measure the resulting two-terminal \( V_{sd} \equiv V_{1} - V_{2} \) and three-terminal voltages \( V_{3} \) between terminals 2 and 3 (see also Fig. 1). Unless otherwise stated, \( I_{sd} \) is kept at 5 nA. Throughout this work, we concentrate our analysis on the second subband. While the first subband is affected by the “0.7 feature” [29-33], the spin signal is small for higher subbands \( N_{qpc} > 3 \): The conductance quantization is progressively worse for these subbands, diminishing the spin-to-charge conversion efficiency. Fig. 2d shows how the QPC conductance is tuned by the QPC gate voltage. The two outer dashed lines mark the second and third conductance risers, where the spin-to-charge conversion should be most pronounced. The middle dashed line locates the second QPC plateau, where the spin-to-charge conversion should be suppressed. Fig. 2f shows the two-terminal resistance \( V_{sd}/I_{sd} \) across the drive channel as a function of the QPC voltage \( V_{qpc} \) and \( B \). As expected from the Onsager reciprocity relation for electrical current in two-terminal systems, \( V_{sd}/I_{sd} \) is approximately symmetric in \( B \) (the QPC is a small perturbation to the drive channel, see Fig. S4 of the Supplementary Material [27]). Fig. 2f shows line cuts of Fig. 2e at the second and third QPC conductance risers and at the second QPC conductance plateau, confirming that \( V_{sd} \) is approximately symmetric in \( B \) regardless of \( V_{qpc} \).

Linear spin-to-charge conversion. We now examine the first harmonic of the three-terminal voltage \( V_{3} \). Fig. 2g shows \( V_{3}/I_{sd} \) as a function of \( V_{qpc} \) and \( B \), demonstrating that \( V_{3} \) is generally asymmetric in \( B \). The line cuts of Fig. 2g shown in Fig. 2h reveal that \( V_{3} \) is asymmetric in \( B \) on the second and third QPC conductance risers, but almost symmetric on the middle of the second conductance plateau. This is a crucial observation for the linear spin-to-charge conversion: The asymmetry of \( V_{3} \) with \( B \) is expected only if the spin accumulation is present and the QPC transmission is spin-(Zeeman energy) sensitive. At the QPC conductance plateau, even though the spin current is still flowing through the QPC, it is not converted to a charge voltage. The asymmetry in \( V_{3} \) as a function of \( B \) cannot be due to a Hall voltage as the sample was oriented to within \( \pm0.01^\circ \) with respect to the magnetic field [34], so that the out-of-plane magnetic field component is always below 0.5 mT.

We next quantify the spin current and estimate the spin-to-charge conversion efficiency. Fig. 2k shows the asymmetry \( \Delta(\omega) \equiv (\partial V_{3}/\partial B)/I_{sd} \) at 0 nA \( \propto I_{spin,linear} \) of the three-terminal resistance at \( I_{sd} = 2, 5, 10, 32 \) nA as
a function of the QPC gate voltage. The asymmetry $\Delta(\omega)$ is obtained by performing a linear fit of $V_3(\omega)$ against $B$ between $-1 \text{T} \leq B \leq 1 \text{T}$ in Fig. 3 [27]. There is a clear correlation between $\Delta(\omega)$ and $\partial I_{\text{sd}}/I_{\text{sd}}$, which also serves as evidence for linear spin-to-charge conversion (Eq. 1), for currents up to $I_{\text{sd}} = 10 \text{nA}$, which weakens at $I_{\text{sd}} = 32 \text{nA}$. The spin signal is thus suppressed for a large $I_{\text{sd}}$, which could occur due to averaging out of spin accumulations at different energies [23].

Using the results in Fig. 3, the spin Hall angle $\Theta$ can be extracted. We first calculate the spin current $I_{\text{spin}}$ using Eq. 2. Using $I_{\text{sd}} = 5 \text{nA}$, $g = 0.38 \pm 0.01$, $h\Omega_{\text{qpc}} = (0.17 \pm 0.01) \text{meV}$ (see Sec. S3 of the Supplementary Material), $\Delta(\omega) = 40 \Omega/\text{T}$, $N_{\text{drive}} = 14$ (see Sec. S4 of the Supplementary Material [27]) and $N_{\text{qpc}} = 1.5$, the spin current is $I_{\text{spin,linear}} = 37 \text{pA}$. The spin Hall angle is found to be $\Theta = (I_{\text{spin,linear}}/N_{\text{qpc}})/(I_{\text{sd}}/N_{\text{drive}}) = 6.8\%$, comparable to previous reports [13, 23, 37, 39].

Non-linear spin-to-charge conversion. Now that we have established evidence for spin-to-charge conversion in the linear regime, we show that it also occurs in the non-linear regime. As before, we evaluate the dependence of the non-linear signal on $B$, $V_{\text{qpc}}$, and $I_{\text{sd}}$. Fig. 3 shows a color map of the non-linear resistance $V_3(2\omega)/I_{\text{sd}}^2$ as a function of $B$ and $V_{\text{qpc}}$. The non-linear signal $V_3(2\omega)$ is symmetric in $B$, contrasting with the linear signal $V_3(\omega)$ (see Fig. 2), and in line with Eq. 3. Next, we examine the dependence of the non-linear signal $V_3(2\omega)$ on $V_{\text{qpc}}$ at various excitation currents $0 \leq I_{\text{sd}} \leq 44.1 \text{nA}$ at $B = 0 \text{T}$ (Fig. 3). The peak in the non-linear signal coincides with the QPC transconductance since $\partial G_{\text{qpc}}/\partial B(E)$ is maximal at $T(E) = 1/2$ when $B = 0 \text{T}$, consistent with Eq. 3.

We next compare the non-linear signals with the linear ones. Fig. 4a shows the amplitude $\Delta'(\omega)$ of the linear signal relative to the background, i.e. the value of $\Delta(\omega)$ at the second subband subtracted by the lowest minimum (see Fig. 2a), against $I_{\text{sd}}$. The spin current is linear in $I_{\text{sd}}$ (and hence $\partial I_{\text{sd}}/\partial I_{\text{sd}}$) at low excitation currents ($I_{\text{sd}} \leq 5 \text{nA}$, see Fig. 4b). For comparison, Fig. 4b shows how $V_3(2\omega)$ varies with $I_{\text{sd}}$. We find that the non-linear voltage is proportional to $I_{\text{sd}}^2$ for $I_{\text{sd}} \lesssim 7 \text{nA}$. While there is a possibility that Joule heating, which causes thermopower [10, 31], could contribute to the second-harmonic response, the fact that both the linear and non-linear signals saturate at similar $I_{\text{sd}}$ suggests that they are of a spin origin.

To further verify the spin origin of the linear and non-linear signals, we consider the effect of an in-plane magnetic field on the signals at low ($I_{\text{sd}} = 5 \text{nA}$) and high ($I_{\text{sd}} = 32 \text{nA}$) excitation currents. At low $I_{\text{sd}}$ (Figs. 4a and b), both the linear (Fig. 4a), see also Sec. S5 of the Supplemental Material [27] and non-linear signals (Fig. 4b) are suppressed at $B \gtrsim 1.4 \text{T}$, suggesting that a strong magnetic field suppresses the spin accumulation. In contrast, for high $I_{\text{sd}}$, where the spin-to-charge conversion is inefficient [22], both the linear and non-linear signals are almost unaffected by the in-plane magnetic field (see also Sec. S6 of the Supplemental Material [27]).

Conclusion. Using a ballistic mesoscopic GaAs hole system, we demonstrate spin-to-charge conversion by exploiting the energy-selective transmission of a QPC. In the linear regime, we identify the spin signal via its dependence on the applied in-plane magnetic field. We
present a new all-electrical non-linear technique for spin-to-charge conversion that does not require a magnetic field. We confirm the spin origin of the non-linear signals with multiple checks and by comparing the linear signals at |B| > 0 with the non-linear signals at B = 0. Performing spin-to-charge conversion in the non-linear regime is much faster and less invasive than in the linear regime [42], since the latter needs both positive and negative fields to be applied. The methods for detecting spin accumulation shown in this work are very general, and should be applicable for systems even when the spin-diffusion length is short.

Acknowledgments. The authors would like to thank Heiner Linke and I-Ju Chen for many enlightening discussions. This work was supported by the Australian Research Council under the Discovery Projects scheme and was performed in part using facilities of the New South Wales Node of the Australian National Fabrication Facility.

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