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### 14. ABSTRACT
A ferromagnet/semiconductor based electrically controlled spin-current amplifier using a dual-drain non-local lateral spin valve was demonstrated. The spin polarization injected by the source into the channel was amplified at the second drain contact. An amplified current spin polarization of 100% was measured. The device provided controlled spin-current gain, which was varied in the entire range from -1 to +1. The controlled variation of amplifier gain with bias was also demonstrated. The maximum operating temperature of the device was as high as 150 K. A pure spin-current generation with zero charge current was also demonstrated using this device. This was the first experimental demonstration of a spin-current amplifier. The observations were explained in the framework of the spin drift-diffusion model. The principle of operation of the device was very generic and could be adapted to any ferromagnet/semiconductor heterostructure system.

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Comprehensive Summary of the Significant Work Accomplished

Electrical injection, control, and detection of large spin polarization in semiconductors are indispensable for the realization of useful spintronic devices. Electrical spin injection and detection have been demonstrated in all-metal devices\(^1\) and ferromagnet/semiconductor based spin valves\(^2\) having distinct coercivity difference between ferromagnetic spin injectors and detectors. Despite these advances, achievement of current spin polarizations of 100\%, and effective electrical control of such polarizations have remained elusive. An electrically controlled spin-current amplifier is a desirable solution to this problem. Theoretical proposals for such devices have been made\(^3\), but experimental demonstration is lacking. Here we demonstrate an electrically controlled three terminal spin-current amplifier using a dual-drain non-local lateral spin-valve configuration, which can provide large polarization for both majority and minority spins, independent of the injected (source) polarization. The gain of the amplifier is varied electrically in the entire range from +1 to -1. A three terminal geometry is used for the device. The amplified output is extracted from the central terminal. The amplifier gain is precisely controlled through the input bias current and output extraction voltage. This device can be used to make spin-based memory and logic elements.

The principle of operation is based on spin injection and detection in semiconductors. When a current flows in a ferromagnet/semiconductor/ferromagnet lateral spin-valve, the electrochemical potentials of spin-up and spin-down electrons split in the semiconductor channel. The splitting depends on the relative directions of magnetization of the two ferromagnetic contacts. It is large when the two contacts (we call them source and drain\(_1\)) are magnetized in opposite directions, and small (with a crossover in the center) when the contacts are magnetized in the same direction. A contact (drain\(_2\)) is then placed at the center of the semiconductor channel of the spin-valve with anti-parallel magnetization of source and drain\(_1\) contacts, its potential is varied between spin-up and spin-down electrochemical potentials, enabling a controlled collection of spin-up and spin-down electrons. It is important to note that the two spin-currents flow in opposite directions and the current polarization is controlled by varying the current and drain\(_2\) bias. It is ensured that the drain\(_2\) contact acts as a high-impedance probe, so as to minimize any perturbation of the channel potentials.

Most Significant Advancements and Conclusions (include equations & figures as appropriate)

The schematic of a typical device is shown in Fig. 1a. The ferromagnetic source contact (S) injects a spin-polarized current into the non-magnetic GaAs channel through a Schottky tunnel barrier, which is collected at one of two ferromagnetic drain contacts (D\(_1\) and D\(_2\)). The contact D\(_2\) is exactly centered within the effective channel between S and D\(_1\). Figure 1b schematically shows the relative orientation of magnetization in S, D\(_1\) and D\(_2\) as magnetic field B is swept. When B is large and negative, S, D\(_1\) and D\(_2\) are all aligned in the same direction as B (state M\(_1\)). The contacts D\(_2\) (state M\(_2\)), D\(_1\) (state M\(_3\)) and S (state M\(_4\)) then flip, in that sequence, as B sweeps through zero in the positive direction because of the relative magnitude of the coercivities. If a bias current (I\(_{bias}\)) is applied between S and D\(_1\) having parallel magnetizations, the electrochemical potentials for spin-up (\(\mu_+\)) and spin-down (\(\mu_-\)) electrons in the channel are split. In our devices, higher doping in the channel and lower bias operation lead to negligible drift, which causes the splitting to be anti-symmetric with respect to the center, \(x = L_{chan}/2\).
Fig. 1 (a) Schematic diagram of a spin-current modulator (not to scale). All three contacts S, D1 and D2 have magnetic easy axes along the y direction (GaAs [110] direction). (b) The magnetization directions of the three ferromagnetic contact pads S, D1 and D2 as the magnetic field B is swept in both directions.

Hence, a bias voltage equal to the cross-over potential for spin-up and spin-down electrons in the channel can be applied at D2 ($V_{D2} = V_{null}$) to make current $I_{D2} = 0$ for states M1, M2 and M4 in Fig. 1b. However, $I_{D2}$ will be non-zero under the same bias condition for state M3 where S and D1 are anti-parallel, for which $\mu_1$ and $\mu_2$ are split at $x = 0$. Under this condition the spin-up ($I_{D2+}$) and spin-down ($I_{D2-}$) components of current flow in opposite directions in D2. The spin-current modulation index (which can also be termed as normalized gain) and the current spin-polarization gain are defined as, $\Pi_{D2} = (|I_{D2+}| - |I_{D2-}|) / (|I_{D2+}| + |I_{D2-}|)$ and $\alpha_{D2}/\alpha_f = (I_{D2+} - I_{D2-}) / (I_{D2+} + I_{D2-})$, respectively, where $\alpha_f$ is the spin polarization of the ferromagnet. For a fixed $I_{bias}$ in state M3, $V_{D2}$ can be varied to control $\Pi_{D2}$. The modulation index can also be controlled with variable $I_{bias}$ and $V_{D2} = V_{null}$.

Figures 2a and 2b show current $I_{D2}$ measured as a function of in-plane magnetic field B (directed along the y axis) for different temperatures T ($I_{bias} = 100 \mu A$) and $I_{bias}$ ($T = 10 K$), respectively. The voltage $V_{D2}$ is set to the corresponding null voltages ($V_{null}$).

A typical value for $V_{null}$ at 10 K and $I_{bias} = 100 \mu A$ is $-21 mV$. The peak of $I_{D2}$ coincides with the peak anti-parallel alignment between S and D1 at $B = 1.5 kOe$, which corresponds to state M3 in Fig. 1b. The sign of current $I_{D2}$ changes when the roles of S and D1 are reversed for the same value of B. The current decreases with increasing T and decreasing $I_{bias}$. The maximum temperature of operation is found to be 150 K for these devices. An increase in $I_{bias}$ increases the operating temperature. Magnetoresistance measurements with conventional and non-local spin valves show a peak at the same value of B (not shown), which also confirms that $I_{D2}$ is sensitive to the spin degree of freedom only. The symmetry of $I_{D2}$ for large positive and negative values for B validates our assumption that the drift is negligible in our devices. No response is observed for the control devices, with a nonmagnetic D2 contact pad.
The experimental observations are explained by invoking the spin-diffusion (drift is negligible) model\(^4\). The spin-selective tunnel barriers are considered as spin-dependent resistances at low temperature and the spin-up and spin-down electrochemical potentials in the ferromagnetic metal MnAs are assumed to be the same. The solution of the coupled spin-diffusion equation for the spin-up and spin-down electrons in S and D1 lateral MnAs/GaAs/MnAs spin valves yields the electrochemical potentials in the channel as:

\[
\mu_i(x) = \frac{j e}{\sigma} + \left( - \frac{2 A}{\sigma} \right) \left[ e^{-x/\lambda_s} + e^{x/\lambda_s} \right]^{-1}
\]

where \(j\) is the current density in the channel, \(e\) is the electron charge, \(\lambda_s\) is the spin-diffusion length in the channel, and \(\gamma\) is +1 (-1) when magnetizations of S and D1 are anti-parallel (parallel). It may be noted that the up- and down-stream diffusion lengths are equal as drift is neglected. The constant \(A\) is determined from the boundary conditions as:

\[
A = \frac{j e \sigma_x}{8} \left[ \frac{x}{\lambda_s} \right] \left[ \gamma + e^{x-\lambda_s} \right]^{-1}
\]

The current \(I_{D2}\) is then obtained as:

\[
\frac{I_{D2}}{W_{D2}} = \int_{L1}^{L2} \left[ G_1 (V_{D2} - \mu_i / e) + G_2 (V_{D2} - \mu_i / e) \right] dx
\]

where \(L1\) and \(L2\) are the bounding \(x\) coordinates of contact pad D2. Figure 3a shows the measured peak \(I_{D2}\) as a function of \(I_{bias}\) in state M3 of the device. Theoretically calculated values of peak \(I_{D2}\), using Eq. 3 and a value of \(\lambda_s = 7 \, \mu m\), are also shown alongside the measured data. The electrochemical potential difference between spin-up and spin-down electrons is plotted as a function of position along the channel in Fig. 3b. \(\mu_1\) and \(\mu_i\) remain anti-symmetric in the channel, making \(I_{D2}\) zero for all \(T\) and \(I_{bias}\) with \(V_{D2} = V_{null}\), when magnetizations of S and D1 are parallel. On the other hand, when the magnetizations of S and D1 are anti-parallel, the difference \(\Delta \mu\) decreases with decreasing \(I_{bias}\) and increasing \(T\), which results in reduced \(I_{D2}\) in spite of increased tunnel conductance at higher \(T\).

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**Fig. 3** (a) (upper panel) Peak drain current \(I_{D2}\) as a function of \(I_{bias}\) in state M3. The solid circles represent measured data at 10 K and the solid line represents the theoretically calculated values based on Eq. (3). The spin-diffusion length \(\lambda_s\) is found to be 7 \(\mu m\) at 10 K (lower panel). (b) The anti-symmetric (symmetric) electrochemical potential difference between spin-up and spin-down electrons in the channel when S and D1 contact magnetizations are parallel (anti-parallel) for two different temperatures \(T\) and \(I_{bias}\).

We next calculate \(\alpha_{D2}\) and \(\Pi_{D2}\) as a function of \(I_{bias}\) and \(V_{D2}\) from measured values of \(I_{D2}\). Figure 4a shows the current spin polarization gain \(\alpha_{D2}/\alpha\) and \(\Pi_{D2}\) as a function of \(V_{D2}\) for different \(I_{bias}\). The curves shift along the \(V_{D2}\) axis with increasing \(I_{bias}\) due to the increasing value of \(V_{null}\). Figure 4b shows the gain curves and \(\Pi_{D2}\) as a function \(I_{bias}\) for different values of \(V_{D2}\). The plots show
that the magnitude and sign of both the gain and $\Pi_{D2}$ can be varied by changing the value of $I_{bias}$ and $V_{D2}$. The gain curves exhibit several singularities along the $V_{D2}$ and $I_{bias}$ axes. These occur when the charge current at D2, $I_{D2} = 0$ ($I_{D2T} = -I_{D21}$), and a pure spin current, $I_{spin} (=I_{D21} - I_{D21})$, flows through this contact. The peak gain that can be measured is limited by the smallest possible increment of $V_{D2}$ and $I_{bias}$ around these singularities.

A ferromagnet/semiconductor based electrically controlled spin-current amplifier using a dual-drain non-local lateral spin valve is demonstrated. The spin polarization injected by the source into the channel is amplified at the second drain contact. An amplified current spin polarization of 100% is measured. The device provides controlled spin-current gain, which is varied in the entire range from -1 to +1. The controlled variation of amplifier gain with bias is also demonstrated. The maximum operating temperature of the device is as high as 150 K. A pure spin-current generation with zero charge current is also demonstrated using this device. This is the first experimental demonstration of a spin-current amplifier. The observations are explained in the framework of the spin drift-diffusion model.

This device is used to realize a spin-based memory device. A schematic of the device and memory characteristics are shown in Fig. 5a and 5b, respectively.

The memory is read-out by measuring the current through central drain-contacts (memory bits) as shown in Fig. 4b.
References


