Efficient gate control of spin-valve signals and Hanle signals in GaAs channel with p-i-n junction-type back-gate structure

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Abstract

Efficient gate control of spin-valve signals and Hanle signals was achieved in a GaAs channel with a p-i-n back-gate structure. Experiments showed that the amplitude of the spin-valve signal ($\Delta V_{NL}$) under constant injection current conditions increased for a cross nonlocal geometry when the channel was depleted by the gate voltage ($V_G$). In contrast, the $V_G$ dependence of $\Delta V_{NL}$ for a nonlocal geometry was complicated. The gate modulation efficiency of spin signals was approximately 48 times that with a graphene or Si channel.
Electrical injection of spin-polarized electrons from a ferromagnet into a semiconductor channel and their control using a gate voltage ($V_G$) are major prerequisites for creating viable semiconductor devices, such as spin transistors, which feature nonvolatility, reconfigurable logic functions, and ultralow power consumption.\textsuperscript{1,2} There have been many reports on electrical spin injection into various semiconductor channels, including GaAs,\textsuperscript{3-11} Si,\textsuperscript{12,13} and Ge.\textsuperscript{14} Both spin-valve measurements and Hanle-type spin precession measurements using nonlocal (NL) four-terminal devices have been conducted. Highly efficient spin injection and detection using a (Ga,Mn)As magnetic semiconductor or a Co-based Heusler alloy (Co$_2$FeSi) as a spin source have been demonstrated.\textsuperscript{4,9} We demonstrated the applicability of Co-based Heusler alloys to spin injection\textsuperscript{8,10,11} as well as magnetic tunnel junctions,\textsuperscript{15-18} and achieved an efficient spin injection from Mn-rich Co$_2$MnSi into a GaAs channel via an ultrathin CoFe insertion layer, resulting in electron spin polarization of up to 52\% at a ferromagnet/GaAs interface at 4.2 K.\textsuperscript{10} This value is more than one order of magnitude higher than those obtained for an Fe electrode and a CoFe electrode.

Compared to the spin injection experiments, only a handful of experiments on the gate control of spin signals have been reported. Moreover, the channel materials were limited to graphene\textsuperscript{19} or Si,\textsuperscript{20,21} and the $V_G$ needed to modulate the spin signals was relatively high (~50 V). To fully understand how spin signals are modulated by $V_G$, the range of channel materials and device geometries that can be used should be broadened. In addition, gate controllability should be greatly improved from the device application point of view.

The purpose of the study reported here was to achieve efficient gate control of spin signals. For this we fabricated a lateral spin transport device consisting of an Fe spin source and n-GaAs channel with a p-i-n junction-type back-gate structure and systematically investigated the dependence of both spin-valve signals and Hanle signals by using a four-terminal cross nonlocal (CNL) geometry and a conventional NL geometry.

Layer structures consisting of (from the substrate side) a p-GaAs (250 nm and Be =
5.0×10^{18} \text{cm}^{-3}) buffer layer, an i-Al_{0.3}Ga_{0.7}As (50 nm) gate-insulating layer, an n^-GaAs (700 nm and Si = 3.0×10^{16} \text{cm}^{-3}) channel layer, and an n^+GaAs (30 nm and Si = 5.0×10^{18} \text{cm}^{-3}) highly doped layer were grown by molecular beam epitaxy at 590°C on a p-GaAs (Zn = 5.0×10^{18} \text{cm}^{-3}) (001) substrate. An Fe(10 nm)/Al(10 nm) layer was then grown at room temperature. For gate operation, a p-i-n junction-type back-gate structure was fabricated (Fig. 1). The application of a negative (positive) gate voltage to the p-GaAs with respect to the Fe electrodes induced depletion (enhancement) of the channel. To increase the gate controllability, we reduced the thickness of the n^-GaAs channel from the 2.5 μm used previous\textsuperscript{6,8,10} to 700 nm, resulting in a channel with a sheet doping concentration of 2.0×10^{12} \text{cm}^{-2}. Although this value is still higher than that of a conventional field-effect transistor, we expect an improved gate modulation.

Using electron beam lithography and Ar ion milling, we fabricated the four-terminal lateral spin-transport devices shown in Fig. 1. The sizes of the injector contact (contact-3) and the detector contact (contact-2) were 0.5 × 10 μm and 1.0 × 10 μm, respectively, and the spacings between them were 0.7, 1.0, and 2.0 μm. The spin-valve signal and Hanle signal were measured for the CNL geometry, in which the nonlocal voltage (V_{NL}) between contact-2 and contact-4 was measured as a function of both the in-plane and out-of-plane magnetic fields under a constant bias current (I_{bias}) supplied between contact-1 and contact-3 (see Fig. 1(a)). Since the injector contact-3 was grounded, the Fe/n-GaAs Schottky junction under the injector contact-3 was reverse-biased in the case for positive I_{bias}, and spin polarized electrons were injected at contact-3 from an Fe electrode into the n^-GaAs channel (spin injection). The electron then drifted toward contact-1. For comparison, spin-valve signals and Hanle signals for the conventional NL geometry were also measured. The V_{NL} between contact-1 and contact-2 was measured while I_{bias} was supplied between contact-3 and contact-4 (Fig. 1(b)). All measurements were conducted at 77 K.

Figure 2 shows the V_G dependence of the channel resistivity (ρ) for V_G from +1.4 to −2.4 V.
The $\rho$ was estimated from the $I$-$V$ characteristics, in which the voltage between contact-2 and contact-3 was measured while $I$ was supplied between contact-3’ and contact-4 (see the inset of Fig. 2). The spacing between contact-3’ and contact-2 is 0.7 $\mu$m. The $\rho$ increased by approximately 8 times when $V_G$ was changed from +1.4 to –2.4 V, indicating a proper gate operation. The right vertical axis of Fig. 2 indicates the drift velocity ($v$), whose value was calculated from the relation of $v = \rho \mu J$, where $\mu$ is the mobility and $J$ is the current density.

We estimated $\mu = 1.3 \times 10^4$ cm$^2$/V·s at 77 K from the Hall-effect measurement, and assume that it is constant against a change of $V_G$.

Figures 3(a) and 3(b) show plots of spin-valve signals and Hanle signals along with fitting curves for the CNL geometry, and Figures 3(c) and 3(d) show ones for the NL geometry. The $I_{bias}$ was set to 20 $\mu$A, and $V_G$ was varied from +1.4 to –2.4 V. The plots show clear spin-valve signals and Hanle signals for all the $V_G$ for both geometries. These results indicate injection, transport, and detection of spin-polarized electrons in an Fe/n′-GaAs/Fe lateral junction. The amplitudes of the signals were modulated by $V_G$, especially for the CNL geometry. The fitting results for the Hanle curves will be discussed later.

Figure 4 shows the $V_G$ dependence of the amplitude of the spin-valve signals, $\Delta V_{NL}$, at $I_{bias}$ ranging from 5 to 30 $\mu$A for the CNL and NL geometries. Experiments showed that $\Delta V_{NL}$ increased as $|V_G|$ increased for all $I_{bias}$ values for the CNL geometry while the $V_G$ dependence of $\Delta V_{NL}$ for the NL geometry was complicated. One possible reason for this is that the channel potential under the detector contact is well fixed in the CNL geometry while it may be unstable in the NL geometry, because the channel between contact-1 and contact-2 is electrically floating in the NL geometry. Thus, we will hereafter focus on the CNL geometry.

Figure 5 plots the channel length ($d$) dependence of $\Delta V_{NL}/I_{bias}$ for the CNL geometry for $V_G$ from +1.4 to –2.4 V with $I_{bias}$ set to 20 $\mu$A. The value of $\Delta V_{NL}/I_{bias}$ decreased as $d$ increased because $\Delta V_{NL}/I_{bias}$ is proportional to exp($-\alpha d$), where $\alpha$ is a constant that relates to the spin diffusion length ($\lambda_N$), spin lifetime ($\tau$), and $v$. The curves for $\Delta V_{NL}/I_{bias}$ vs. $d$, however, are
slightly deviated from \( \exp(-\alpha d) \), suggesting that some parameters, such as \( v \), depend on \( d \).

We introduce \( \Delta R_s/(C_G \Delta V_G) \) as a measure of the gate modulation efficiency of spin signals, where \( \Delta R_s = [\Delta V_{NL}(V_{G1}) - \Delta V_{NL}(V_{G2})]I_{bias} \), \( C_G = \varepsilon \tau \) is the gate capacitance per unit area, \( \varepsilon \) and \( \tau \) are the permittivity and thickness of the gate insulator, \( \Delta V_G = V_{G1} - V_{G2} \), and \( V_{G1} \) and \( V_{G2} \) are the maximum and minimum values of \( V_G \). The value of \( \Delta R_s/(C_G \Delta V_G) \) increased as \( d \) increased. Table I compares the gate modulation efficiency achieved with that achieved in previous work. Although the experimental conditions were not identical, we achieved an efficiency more than 48 times those in previous work.\(^{19,20}\)

Now we will discuss the origin of the gate modulation. According to spin drift-diffusion theory,\(^{12,22-24}\) the \( \Delta V_{NL}/I_{bias} \) is given by

\[
R_s = \frac{\Delta V_{NL}}{I_{bias}} = P^2 \left( \rho \frac{\sqrt{D \bar{T}}}{A} \right) \exp \left[ -\frac{d}{\lambda_N} + \frac{d \nu \tau}{2 \lambda_N^2} \right] \left( 1 + \omega^2 \bar{T}^2 \right)^{-\frac{1}{4}} \times \exp \left[ -\frac{d}{\lambda_N} \left( \sqrt{\frac{1 + \omega^2 \bar{T}^2}{2}} + 1 \right) \right] \times \cos \left[ \frac{\arctan(\omega T)}{2} + \frac{d}{\lambda_N} \sqrt{\frac{1 + \omega^2 \bar{T}^2}{2} - 1} \right]
\]

where \( P \) is the spin polarization, \( A \) is the channel cross-sectional area, \( D = \lambda_N^2/\tau \) is the diffusion constant, \( \bar{T} = \nu^2/4D + 1/\tau \), \( \omega \) is the Larmor frequency, \( g \) is an electron g-factor (we assumed \( g \)-values of \( -0.44 \) for GaAs), \( \mu_B \) is the Bohr magneton, and \( h \) is the reduced Planck’s constant. Since \( \Delta V_{NL} \) is proportional to \( \rho \) from eq. (1), one possible origin for the increase in \( \Delta V_{NL} \) with \( |V_G| \) is the increase in \( \rho \) with \( |V_G| \). However, we found that the \( \Delta V_{NL} \) increased by approximately two times while \( \rho \) increased by approximately 8 times when \( V_G \) was changed from 1.4 to 2.4 V. This indicates that the change in \( \Delta V_{NL} \) with \( V_G \) cannot be simply explained by the change in \( \rho \). Other factors, such as a change in \( P, \tau, \lambda_N \), and/or \( \nu \) with \( V_G \), must also play a role. To check this we fitted the Hanle curves with eq. (1). We assumed \( \nu = 1080, 1740 \)
and 8810 m/s at $V_G = +1.4$, 0 and $-2.4$ V, respectively, whose values were estimated from Fig. 2. The observed Hanle curves can be fitted well with eq. (1) for all the $V_G$, as shown in Fig. 3(b). Table 2 summarizes the fitting parameters of $P$, $\tau$ and $\lambda_N$ for each $V_G$. The $\tau$ and $\lambda_N$ increased as $V_G$ decreased, and a similar tendency was reported in Si.\textsuperscript{20} On the other hand, the $P$ decreased from 19% at $V_G = +1.4$ V to 6.5% at $V_G = -2.4$ V. The origin of such a large change in $P$ with $V_G$, however, is not clear at present. There have been several experimental\textsuperscript{3,5} and theoretical\textsuperscript{25-27} investigations into whether the magnitude and sign of the spin polarization for a Fe/GaAs heterojunction are affected by the voltage across the injector contact ($V_{\text{inj}}$). To check this effect we investigated the $V_G$ dependence of $V_{\text{inj}}$ at $I_{\text{bias}} = 20 \mu$A, and found that the maximum amount of change in $V_{\text{inj}}$ was approximately 20 mV when $V_G$ was changed from +1.4 to $-2.4$ V. In this case the amount of change in $P$, which was estimated from $V_{\text{inj}}$ dependence of $\Delta V_{\text{NL}}$ (not shown), is only 1.6%, negligibly small. Thus, the large change in $P$ with $V_G$ in Table II cannot be explained by the change in $V_{\text{inj}}$, and further investigations are necessary to clarify its origin.

In summary, we systematically investigated the gate control of spin-valve signals and Hanle signals in a GaAs channel by using four-terminal CNL and NL geometries with a p-i-n back-gate structure. We experimentally found that the CNL geometry is more advantageous than the NL one for gate modulation and demonstrated efficient gate modulation efficiency approximately 48 times higher than with previous channels. These findings will help in developing basic technologies for implementing spin transistors.

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Reference list


Figure captions

Fig. 1. Schematic device structures and circuit configurations for (a) cross nonlocal (CNL) geometry and (b) conventional nonlocal (NL) geometry.

Fig. 2. $V_G$ dependence of channel resistivity and drift velocity. Inset shows a circuit configuration for the resistivity measurement.

Fig. 3. (a) Plots of spin-valve signals and (b) Hanle signals along with fitting curves (solid lines) in CNL geometry. (c) Plots of spin-valve signals and (d) Hanle signals in NL geometry for $V_G$ ranging from $+1.4$ to $-2.4$ V with $I_{\text{bias}}$ of 20 μA.

Fig. 4. Comparison of $V_G$ dependence of $\Delta V_{\text{NL}}$ at $I_{\text{bias}}$ ranging from 5 to 30 μA between (a) CNL and (b) NL geometries.

Fig. 5. Channel length ($d$) dependence of $\Delta V_{\text{NL}}/I_{\text{bias}}$ in CNL geometry for $V_G$ ranging from $+1.4$ to $-2.4$ V.
Table

Table I. Comparison of gate modulation efficiency.

<table>
<thead>
<tr>
<th>Terminal geometry</th>
<th>Measured temperature (K)</th>
<th>Gate capacitance $C_G$ (Fm$^{-2}$)</th>
<th>Operation voltage $\Delta V_G$ (V)</th>
<th>Gate modulation efficiency $\Delta R_S/(C_G \Delta V_G)$ (Ωm$^2$F$^{-1}$V$^{-1}$)</th>
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<tr>
<td>Graphene$^{19}$</td>
<td>4.2</td>
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<td>This work</td>
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<td>1312</td>
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Table 2. Estimated values of spin polarization, spin lifetime and spin diffusion length as a function of the gate voltage

<table>
<thead>
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<th>$V_G$ (V)</th>
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<th>0</th>
<th>1.4</th>
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<tr>
<td>Spin polarization (%)</td>
<td>6.5</td>
<td>16.2</td>
<td>19.0</td>
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<td>Spin lifetime (ns)</td>
<td>4.6</td>
<td>2.6</td>
<td>1.1</td>
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<tr>
<td>Spin diffusion length (μm)</td>
<td>9.8</td>
<td>2.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Figures

Cross nonlocal (CNL) geometry

(a) [Diagram showing current flow and voltage relationships.

Nonlocal (NL) geometry

(b) [Diagram showing current flow and voltage relationships.

Fig. 1.

Fig. 2.

[^1]: Channel resistivity (m) 77 K

Drift velocity (m/s)

-2 -1 0 10

200
400
600
800
1000
1200
0
2000
4000
6000
8000
10000

[^1]: 77 K

[^2]: Channel resistivity (Q/µm)

[^3]: Drift velocity (m/s)

[^4]: V_G (V)
Fig. 3.
Fig. 4.

Fig. 5.