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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 (ΔV_{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 ΔV_{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.^{1,2)} There have been many reports on electrical spin injection into various semiconductor channels, including GaAs,³⁻¹¹⁾ Si,^{12,13)} and Ge.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 (Co₂FeSi) as a spin source have been demonstrated.^{4,9)} We demonstrated the applicability of Co-based Heusler alloys to spin injection^{8,10,11)} as well as magnetic tunnel junctions,¹⁵⁻¹⁸⁾ and achieved an efficient spin injection from Mn-rich Co₂MnSi 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.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 graphene¹⁹⁾ or Si,^{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 $B_e =$

$5.0 \times 10^{18} \text{ cm}^{-3}$) buffer layer, an $\text{i-Al}_{0.3}\text{Ga}_{0.7}\text{As}$ (50 nm) gate-insulating layer, an n^- -GaAs (700 nm and $\text{Si} = 3.0 \times 10^{16} \text{ cm}^{-3}$) channel layer, and an n^+ -GaAs (30 nm and $\text{Si} = 5.0 \times 10^{18} \text{ cm}^{-3}$) highly doped layer were grown by molecular beam epitaxy at 590°C on a p-GaAs ($\text{Zn} = 5.0 \times 10^{18} \text{ cm}^{-3}$) (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^{6,8,10)} to 700 nm, resulting in a channel with a sheet doping concentration of $2.0 \times 10^{12} \text{ cm}^{-2}$. 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 $0.5 \times 10 \mu\text{m}$ and $1.0 \times 10 \mu\text{m}$, 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 ρ 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 μm . The ρ 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 μ is the mobility and J is the current density. We estimated $\mu = 1.3 \times 10^4 \text{ cm}^2/\text{V}\cdot\text{s}$ 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 μA , 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, ΔV_{NL} , at I_{bias} ranging from 5 to 30 μA for the CNL and NL geometries. Experiments showed that ΔV_{NL} increased as $|V_G|$ increased for all I_{bias} values for the CNL geometry while the V_G dependence of ΔV_{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 $\Delta V_{\text{NL}}/I_{\text{bias}}$ for the CNL geometry for V_G from +1.4 to -2.4 V with I_{bias} set to 20 μA . The value of $\Delta V_{\text{NL}}/I_{\text{bias}}$ decreased as d increased because $\Delta V_{\text{NL}}/I_{\text{bias}}$ is proportional to $\exp(-\alpha d)$, where α is a constant that relates to the spin diffusion length (λ_N), spin lifetime (τ), and v . The curves for $\Delta V_{\text{NL}}/I_{\text{bias}}$ vs. d , however, are

slightly deviated from $\exp(-\alpha d)$, suggesting that some parameters, such as ν , 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 $\Delta R_S = [\Delta V_{NL}(V_{G1}) - \Delta V_{NL}(V_{G2})]/I_{bias}$, $C_G = \epsilon/t$ is the gate capacitance per unit area, ϵ and t 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

$$\begin{aligned}
 R_S = \frac{\Delta V_{NL}}{I_{bias}} = & P^2 \left(\rho \frac{\sqrt{DT}}{A} \right) \exp \left[-\frac{d}{\lambda_N} + \frac{d\nu\tau}{2\lambda_N^2} \right] (1 + \omega^2 T^2)^{-\frac{1}{4}} \\
 & \times \exp \left[-\frac{d}{\lambda_N} \left(\sqrt{\frac{\sqrt{1 + \omega^2 T^2} + 1}{2}} - 1 \right) \right] \\
 & \times \cos \left[\frac{\arctan(\omega T)}{2} + \frac{d}{\lambda_N} \sqrt{\frac{\sqrt{1 + \omega^2 T^2} - 1}{2}} \right] \quad (1) \\
 \omega = & \frac{g\mu_B B_z}{\hbar}
 \end{aligned}$$

where P is the spin polarization, A is the channel cross-sectional area, $D = \lambda_N^2/\tau$ is the diffusion constant, $T^{-1} = \nu^2/4D + 1/\tau$, ω is the Larmor frequency, g is an electron g -factor (we assumed g -values of -0.44 for GaAs), μ_B is the Bohr magneton, and $\hbar$ is the reduced Planck's constant. Since ΔV_{NL} is proportional to ρ from eq. (1), one possible origin for the increase in ΔV_{NL} with $|V_G|$ is the increase in ρ with $|V_G|$. However, we found that the ΔV_{NL} increased by approximately two times while ρ increased by approximately 8 times when V_G was changed from 1.4 to -2.4 V. This indicates that the change in ΔV_{NL} with V_G cannot be simply explained by the change in ρ . Other factors, such as a change in P , τ , λ_N , and/or ν 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 , τ and λ_N for each V_G . The τ and λ_N increased as V_G decreased, and a similar tendency was reported in Si.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^{3,5)} and theoretical²⁵⁻²⁷⁾ 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_{inj}). To check this effect we investigated the V_G dependence of V_{inj} at $I_{bias} = 20$ μ A, and found that the maximum amount of change in V_{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_{inj} dependence of ΔV_{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_{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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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_{bias} of 20 μA .

Fig. 4. Comparison of V_G dependence of ΔV_{NL} at I_{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.

	Terminal geometry	Measured temperature (K)	Gate capacitance C_G (Fm ⁻²)	Operation voltage ΔV_G (V)	Gate modulation efficiency $\Delta R_S/(C_G \Delta V_G)$ ($\Omega\text{m}^2\text{F}^{-1}\text{V}^{-1}$)
Graphene ¹⁹⁾	NL-4T	4.2	1.12e-4	50.0	26.7
Si ²⁰⁾	L-3T	300	1.68e-4	50.0	1.2
This work	CNL-4T	77	4.60e-4	3.8	1312

Table 2. Estimated values of spin polarization, spin lifetime and spin diffusion length as a function of the gate voltage

V_G (V)	-2.4	0	1.4
Spin polarization (%)	6.5	16.2	19.0
Spin lifetime (ns)	4.6	2.6	1.1
Spin diffusion length (μm)	9.8	2.3	2.3

Figures

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.