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Fabrication of a spin injection device having a top-gate structure

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Abstract

A lateral spin injection device having a top-gate structure was fabricated. A clear spin injection from an Fe electrode into an n^{-}-In$_{0.04}$Ga$_{0.96}$As channel was demonstrated through the observation of spin-valve signals in a cross nonlocal geometry. Furthermore, a gate control of spin-valve signals was achieved. Experiments showed that the amplitude of the spin-valve signal under constant injection current conditions decreased when the channel was depleted by the gate voltage. These results indicate that the developed top-gate structure paves the way to implementing spin transistors.

1. Introduction

Electrical injection of spin-polarized electrons into a semiconductor channel and their control by a gate voltage are major prerequisites for creating viable semiconductor spintronic devices such as spin transistors, which feature nonvolatility, reconfigurable logic functions, and ultralow power consumption [1,2]. While there have been many reports on spin injection into GaAs, Si, or Ge, only a handful of experiments on the gate control of spin signals have been reported [3-5]. Moreover, the gate operation was done only in back-gate structure. However, the back-gate structure suffers from a low operation speed and a large power consumption due to a large parasitic capacitance. Thus, a top-gate structure is indispensable for practical applications. In this study we fabricated a spin injection device having a top-gate structure, and demonstrated a gate control of spin-valve signals in InGaAs channel.

2. Experimental Method

A layer structure consisting of (from the substrate side) a 250-nm-thick undoped GaAs buffer layer, a 700-nm-thick n^{-}-In$_{0.04}$Ga$_{0.96}$As channel layer, a 15-nm-thick n^{-}-In$_{0.04}$Ga$_{0.96}$As → n^{+}-GaAs transition layer, and a 15-nm-thick n^{+}-GaAs layer was grown by molecular beam epitaxy (MBE) on semi-insulating GaAs(001) substrates. The doping concentration of the n^{-}-In$_{0.04}$Ga$_{0.96}$As channel layer was 3×10^{16} cm^{-3} and that of the n^{+}-GaAs layer was 5×10^{18} cm^{-3} to form a narrow Schottky barrier. Samples were transferred to the second MBE chamber without exposure to air and a 10-nm-thick Fe spin source layer and a 10-nm-thick Al cap layer were then grown at room temperature.

The sample was then processed into a lateral spin transport device by using electron beam lithography and Ar ion milling techniques. The size of the injector contact and detector contact were 0.5 × 10 μm and 1.0 × 10 μm, respectively, and the spacing between them was 6.0 μm. The top-gate electrode of Al was deposited on the n^{-}-In$_{0.04}$Ga$_{0.96}$As channel between the injector and detector contact (Fig. 1). The size of the top-gate electrode was 2.0 × 10 μm. Spin-dependent transport properties for lateral spin transport devices were evaluated in a four-terminal cross–nonlocal geometry where the nonlocal voltage (V_{NL}) between contacts 3 and 1 was measured under a constant current (I_{bias}) supplied between contacts 2 and 4 at 4.2 K (Fig. 1). The negative V_G was applied to the top-gate with respect to terminal 2, which was grounded.

3. Results and Discussion

Figure 2 shows *I*–*V* characteristics for (a) a Fe/n^{+}-GaAs Schottky tunnel junction (injector/detector contact) and (b) an Al/n^{-}-In$_{0.04}$Ga$_{0.96}$As Schottky junction (gate/channel contact) at 4.2 K. The *I*–*V* curves for a Fe/n^{+}-GaAs junction

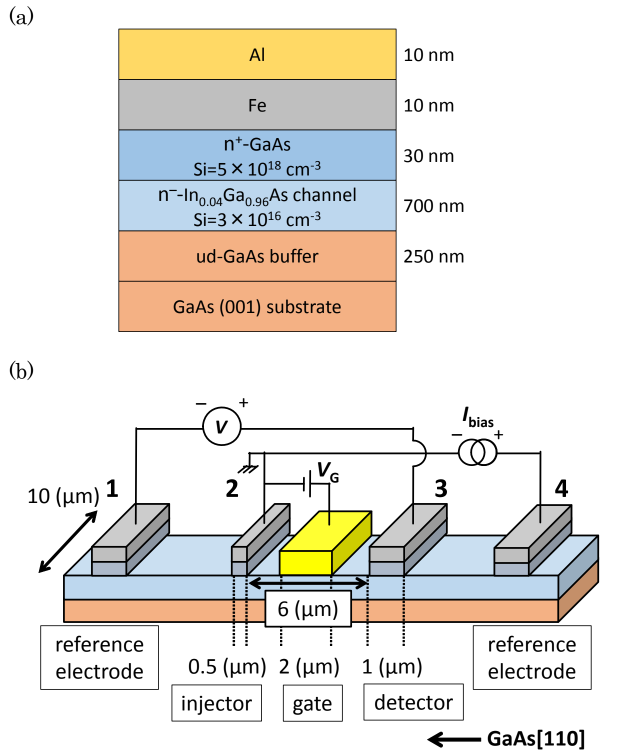

Fig. 1. (a) Layer structure and (b) a lateral spin injection device with a top-gate structure and circuit configuration.

exhibit nonlinear characteristics and are almost symmetric against the bias polarity, indicating that the tunneling conduction is dominant. The typical values of the resistance-area products ($R{\cdot}A$) was 130 k$\Omega\mu m^2$, where R is the resistance which was evaluated from the slope of the I–V curve at V = 0 V, and A is the junction area. The $R{\cdot}A$ value was close to our previous results [6]. The I–V curve for an Al/n$^-$-In$_{0.04}$Ga$_{0.96}$As junction, on the other hand, exhibits a clear rectifying nature, indicating that the Schottky barrier was formed at Al/n$^-$-In$_{0.04}$Ga$_{0.96}$As interface.

Figure 3 shows the V_G dependence of the channel resistivity (ρ) for V_G from 0 to −1.4 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-1 and contact-4. The ρ increased by approximately 1.5 times when V_G was changed from 0 to –1.4 V, indicating a proper gate operation.

Figure 4 shows spin-valve signals at 4.2 K for a cross-nonlocal geometry at V_G = 0, –1.0 and –1.4 V. The injection current was set to 40 μA. We observed clear spin-valve signals for all V_G, indicating the injection of spin-polarized electrons into an n$^-$-In$_{0.04}$Ga$_{0.96}$As channel. The amplitudes of the spin-valve signals decreased as $|V_G|$ increased. This contrasted with our previous results, in which the amplitudes of the spin-valve signals increased as $|V_G|$ increased [5]. Although the origin of this discrepancy was not fully understood at present, this is the first demonstration of the gate control of spin signals through a top-gate structure.

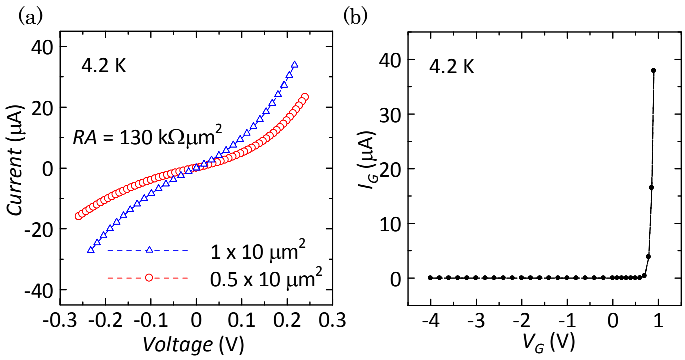

Fig. 2. I-V characteristics for (a) a Fe/n$^+$-GaAs Schottky tunnel junction (injector/detector contact) and (b) an Al/n$^-$-In$_{0.04}$Ga$_{0.96}$As Schottky junction.

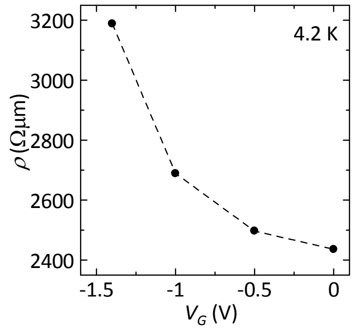

Fig. 3. V_G dependence of the channel resistivity (ρ).

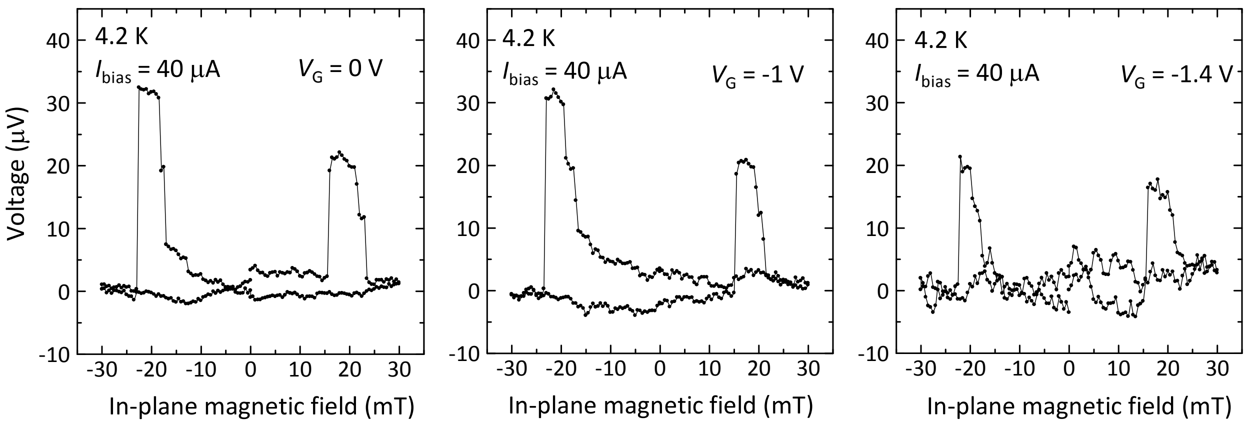

Fig. 4. Spin-valve signals at 4.2 K for a cross nonlocal geometry at V_G = 0, −1.0 and −1.4 V.

Acknowledgments

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