Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp985-986

PS-12-09

Spin-Dependent Transport of Ferromagnetic-Semiconductor GaMnAs-Based Lateral Spin-Valve Devices

H. Asahara[1], T. Kanaki[1], S. Ohya[1, 2, 3], and M. Tanaka[1, 2]

[1] Department of Electrical Engineering and Information Systems, The University of Tokyo
[2] Center for Spintronics Research Network, The University of Tokyo
[3] Institute of Engineering Innovation, Graduate School of Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone : +81-3-5841-6729 E-mail : asahara@cryst.t.u-tokyo.ac.jp

We investigate the spin-dependent transport properties of ferromagnetic-semiconductor GaMnAs-based lateral spin-valve devices with/without a gate electrode. Our devices are composed of a Hall-bar structure of a GaMnAs layer, and the drain and source electrodes are separated by a narrow trench, which is made by milling the GaMnAs layer. The characteristic of the drain current I_D – drain voltage V_{DS} shows nonlinear behavior, which suggests that a thin depleted GaMnAs layer still remains between the source and drain and has a role of a tunnel barrier. Large magnetoresistance (MR) ratios up to 10% are obtained. The magnetic-field-direction dependence of the MR curve is different from that of anisotropic magnetoresistance of GaMnAs, which confirms that the MR signal originates from the spin-valve effect. Furthermore, we successfully modulate I_D by the gate electric field in a different GaMnAs lateral spin-valve device.

1. Introduction

Spin metal-oxide-semiconductor field-effect-transistors (spin MOSFETs), whose source and drain are composed of ferromagnetic materials, are promising candidates for post-scaling era [1]. In the previous studies of spin MOSFETs, however, the magnetoresistance (MR) ratios reported so far were less than 1% [2, 3]. To improve the MR ratio for practical applications, it is necessary to use ferromagnets that are compatible with semiconductors for the suppression of spin scattering at the interfaces. The ferromagnetic semiconductor GaMnAs is one of the ideal model materials; we can obtain an atomically abrupt interface between GaMnAs and GaAs. In fact, we have recently obtained a large MR ratio up to 60% in a GaMnAs-based *vertical* spin MOSFET [4]. However, the modulation ratio of I_D was only 0.5%. In this study, to obtain both large MR and large I_D modulation by gate voltages, we have fabricated GaMnAs-based *lateral* spin-valve devices with/without a gate electrode and investigated their spin-dependent transport properties.

2. Experiments

The sample is composed of $Ga_{0.94}Mn_{0.06}As$ (25 nm) / GaAs (100 nm) grown on a semi-insulating GaAs (001) substrate by low-temperature molecular beam epitaxy. After the growth, Hall-bars, whose size is 50 μm (width) × 200 μm (length), were formed by standard photolithography and wet etching. Then, a narrow trench, whose nominal width *d* is 200 nm, was formed across the Hall-bar by using electron beam lithography and Ar ion milling to separate the source and drain electrodes [Fig. 1(a)]. The depth of the trench was about 20 nm.

As shown in Fig. 2, nonlinear drain current I_D – drain voltage V_{DS} characteristic was obtained at 3.5 K, which suggests that a thin depleted GaMnAs layer still remains between the source and drain and has a role of a tunnel barrier [Fig. 1(b)]. Figure 3 shows the MR curves obtained with various in-plane magnetic-field directions at V_{DS} = 100 mV and at 3.5 K. Here, the MR ratio is defined as $[R(H) – R(H = 0)] / R(H = 0) \times 100$ (%), where R and H correspond to the tunnel resistance and magnetic field applied along the in-plane channel direction. Large MR ratios up to 10% were obtained. The MR ratio of the device remained positive for all in-plane magnetic-field directions, which confirms that this signal does not

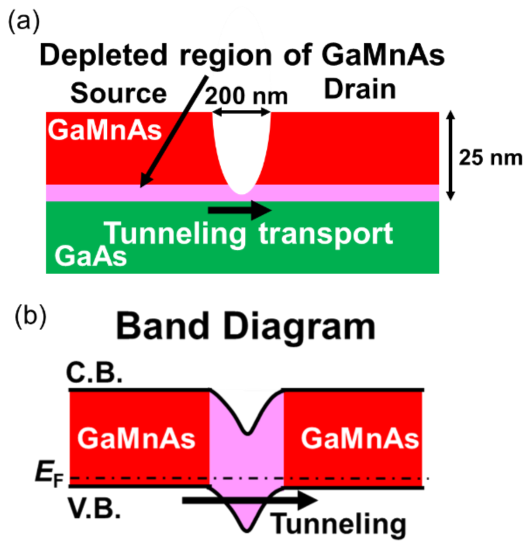

Fig. 1 (a) Schematic cross-sectional structure of the GaMnAs-based lateral spin-valve device investigated in this study, which is composed of $Ga_{0.94}Mn_{0.06}As$ (25 nm) / GaAs (100 nm) grown on a semi-insulating GaAs (001) substrate. (b) Expected band diagram of the GaMnAs-based lateral spin-valve device along the source-channel-drain direction.

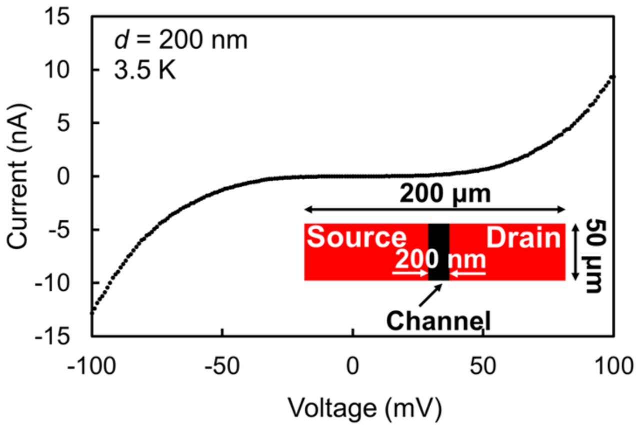

Fig. 2 Drain current (I_D) as a function of the drain-source voltage (V_{DS}) of the GaMnAs-based spin-valve device at 3.5 K.

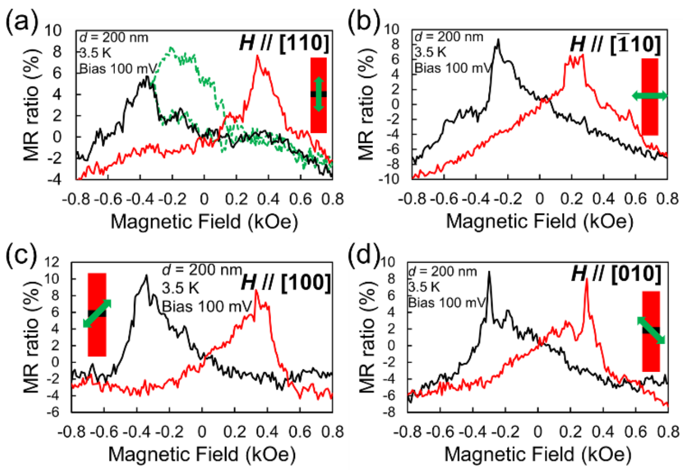

Fig. 3 MR ratio as a function of the in-plane magnetic field applied along the [110] (a), [$\bar{1}$10] (b), [100] (c), and [010] (d) axes at 3.5 K with V_{DS} = 100 mV. The black and red plots correspond to a major loop and the green plots to a minor loop. The green arrows show the magnetic field sweep direction of the major and minor loops. The MR ratio amounted to about 10%.

originate from anisotropic magnetoresistance (AMR) but from the spin-valve effect. Furthermore, we have fabricated a lateral spin MOSFET structure with d = 100 nm as shown in Fig. 4 (a) and successfully modulated I_D by applying the gate voltage V_{GS} [Figs. 4(b)-(d)]. We have successfully achieved a large gate modulation ratio [= (I_D (V_{GS} = -3 V) - I_D (V_{GS} = 3 V)) / I_D (V_{GS} = 3 V) ×100 (%)] about 10% at V_{DS} = 350 mV.

3. Summary

We have fabricated GaMnAs-based lateral spin-valve devices with/without a gate electrode and investigated their spin-dependent transport properties. We obtained large MR ratios up to ~10%. The magnetic field direction dependence of the MR curve is different from that of AMR, which confirms that our signal originates from the spin-valve effect. Furthermore, we fabricated GaMnAs-based lateral spin MOSFET structures, which are suitable for efficient gate electric-field modulation, and successfully achieved the gate modulation ratio of I_D of ~10%.

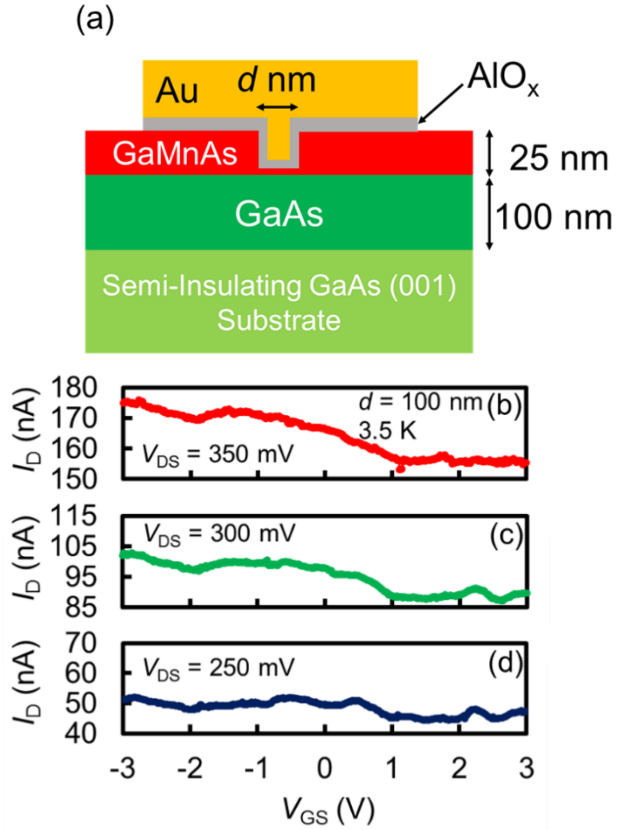

Fig. 4 (a) Schematic sample structure of the GaMnAs-based lateral spin MOSFET device with a gate electrode. (b), (c), (d) V_{GS} dependence of I_D with the drain voltage V_{DS} of 350 mV (b), 300 mV (c), and 250 mV (d) at 3.5 K when d is 100 nm.

Acknowledgements

This work was partly supported by Grants-in-Aid for Scientific Research including Specially Promoted Research, Project for Developing Innovation Systems of MEXT, and Spintronics Research Network of Japan (Spin-RNJ).

References

[1] S. Sugahara and M. Tanaka, Appl. Phys. Lett. **84**, 2307 (2004).

[2] R. Nakane, T. Harada, K. Sugiura, and M. Tanaka, Jpn. J. Appl. Phys. **49**, 113001 (2010).

[3] T. Tahara *et al.*, Appl. Phys. Express **8**, 113004 (2015).

[4] T. Kanaki, H. Asahara, S. Ohya, and M. Tanaka, Appl. Phys. Lett. **107**, 242401 (2015).