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Large magnetoresistance and spin-dependent output voltage in a lateral MnGa/GaAs/MnGa spin-valve device

Koki Chonan[1], Nguyen Huynh Duy Khang[1], Masaaki Tanaka[2,3] and Pham Nam Hai[1,3]

[1] Department of Electrical and Electronic Engineering, Tokyo Institute of Technology
2-12-1 Ookayama, Meguro, Tokyo 152-0033, Japan
Phone: +81-3-5734-3258 E-mail: chonan.k.aa@m.titech.ac.jp
[2] Department of Electrical Engineering and Information Systems, The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[3] Center for Spintronics Research Network, Graduate School of Engineering, The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Abstract

We investigated the spin-dependent transport properties of a lateral spin-valve device with MnGa electrodes and a 600 nm-long GaAs channel layer. Its current-voltage characteristics show nonlinear characteristics below 50 K, indicating tunnel transport at low temperatures. Large magnetoresistance (MR) ratio up to 12% and spin-dependent output voltage of 33 mV are obtained at 4 K. These values are much larger than those reported for lateral spin-valve devices. The bias voltage dependence and the magnetic field direction dependence of MR indicate that observed MR signal originates from the spin-valve effect.

1. Introduction

The spin MOSFET, whose source and drain are made of ferromagnetic materials, is a promising device for the post-scaling era [1]. In a spin MOSFET, the drain current depends not only on the gate voltage but also on the relative magnetization configuration of the source and drain. With this spin-dependent output characteristics, spin MOSFETs can be applied to non-volatile memory cells and reconfigurable logic circuits. To realize spin MOSFETs, highly efficient spin injection into semiconductors is needed. However, due to the conductivity mismatch between ferromagnetic electrodes and semiconductor channels, it is difficult to obtain high spin injection efficiency. In fact, only small magnetoresistance (MR) ratio (~ 1%) and spin-dependent output voltage below 1 mV have been reported in microscale devices [2][3].

To improve the MR ratio and the spin-dependent output voltage for practical applications, it is essential to choose suitable ferromagnets and semiconductors with small lattice mismatch for epitaxial growth. Perpendicularly magnetized MnGa alloys and GaAs are potential candidates for the drain/source electrodes and semiconductor channel material, respectively. Good homogeneity and abrupt interface of MnGa grown on GaAs were reported [4][5]. Moreover, MnGa alloys have large perpendicular magnetic anisotropy, which is necessary for thermal stability in nanoscale devices and are theoretically shown to have high spin polarization of 71% at the Fermi level [6]. MnGa alloys also have high Curie temperature. In this study, we prepared a lateral spin-valve device with MnGa electrodes and a 600 nm-long GaAs channel and investigated its spin-dependent transport properties. We obtained a large MR ratio up to 12% and a spin-dependent output voltage of 33 mV, which are much larger than those in lateral spin-valve devices reported so far.

2. Experiments and Results

The spin-valve device is composed of $Mn_{0.6}Ga_{0.4}$ (10 nm) / GaAs:Se (20 nm) with the electron density of $n \sim 1\times10^{17}$ cm^{-3}, grown by molecular beam epitaxy on a semi-insulating GaAs(001) substrate. A 600 nm-long GaAs channel was formed by using electron beam lithography and Ar ion milling to separate the source and drain MnGa electrodes, as schematically shown in Figure 1. In this structure, large MR can be expected by spin injection using tunneling transport through the MnGa/GaAs Schottky barrier.

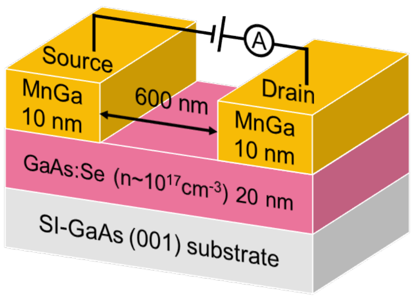

Fig. 1 Schematic structure of the lateral spin-valve device with MnGa electrodes and a 600 nm-long GaAs channel.

Figure 2(a) shows the drain-source voltage V_{DS} dependence of the drain current I_{DS} at various temperatures. I_{DS} showed nonlinear behavior up to 50 K and Ohmic behavior above 100 K. These results indicate that at low temperature, thermionic emission of electrons over the MnGa/GaAs Schottky barrier is suppressed and tunnel current through the Schottky barrier is dominant.

Figure 2(b) shows the MR characteristics obtained at 4 K with V_{DS} = 150 mV while applying a magnetic field along the (001) axis. In Figure 2(b), the red and blue curves correspond to major loops obtained by sweeping a magnetic field H from positive to negative and from negative to positive, respectively. Clear jumps of resistance were observed. Importantly, a large MR ratio of 12% was obtained, which is much larger than those reported for lateral spin-valve devices (~1 %). We further investigated the V_{DS} dependence and the magnetic field direction dependence of MR, and concluded that the observed MR signal does not originate from the anisotropic magnetoresistance (AMR) of the MnGa electrodes or the tunneling anisotropic magnetoresistance (TAMR) at the MnGa/GaAs Schottky barrier, but it is caused by the spin-valve effect.

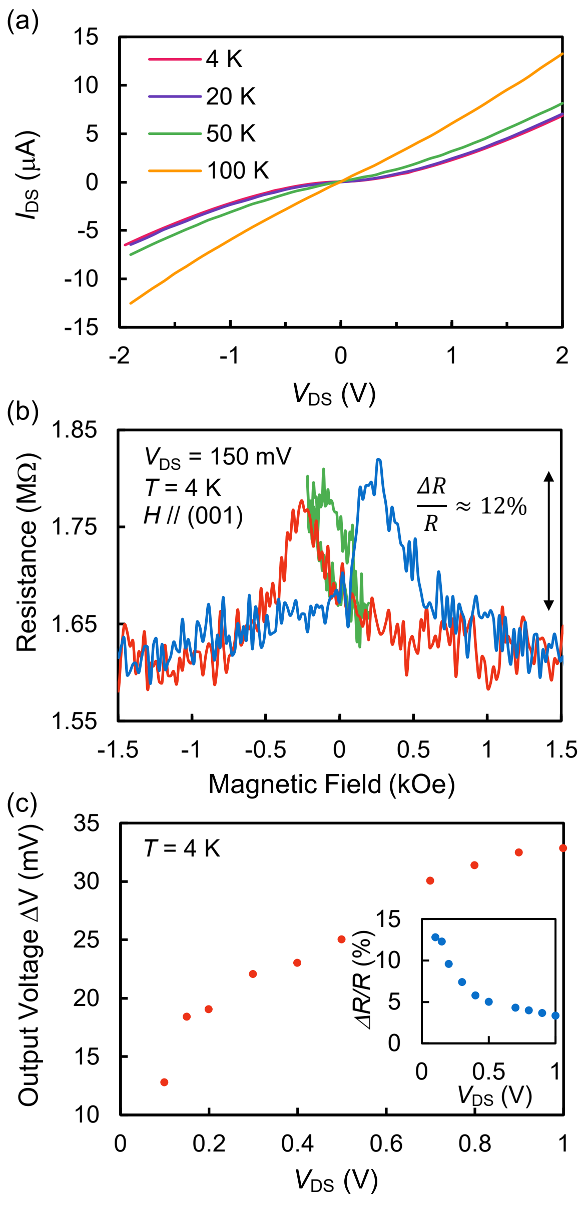

Fig. 2 (a) Drain current I_{DS} as a function of the drain-source voltage V_{DS} of the spin-valve device with MnGa electrodes at various temperatures (T = 4 - 100 K). (b) MR characteristics obtained at 4 K with V_{DS} = 150 mV while applying a magnetic field H along the [001] axis perpendicular to the film plane. The red and blue lines correspond to major loops obtained by sweeping H from 1.5 kOe to -1.5 kOe and from -1.5 kOe to 1.5 kOe, respectively. The green line is a minor loop. (c) V_{DS} dependence of the spin-dependent output voltage $\Delta V = (\Delta R/R)V_{DS}$ at 4 K. The inset shows the V_{DS} dependence of the MR ratio $\Delta R/R$ at 4 K.

Figure 2 (c) shows the V_{DS} dependence of the spin-dependent output voltage at 4 K. For practical applications, a spin-dependent output voltage ΔV of the order of 100 mV is required for correct read-out. In our device, ΔV = 33 mV at V_{DS} = 1 V was obtained. Although this value is still behind the target value of ~100 mV, it is the highest values reported so far in lateral spin-valve devices.

3. Conclusions

We prepared a lateral spin-valve device with MnGa electrodes and a 600 nm-long GaAs channel and investigated its spin-dependent transport properties. We obtained large MR ratio of 12% at V_{DS} = 100 mV and large spin-dependent output voltage of 33 mV at V_{DS} = 1 V, which are much larger than those in lateral spin-valve devices reported so far. The V_{DS} dependence and the magnetic field direction dependence of the MR indicate that observed MR signal originates from the spin-valve effect. Our results provide an important step toward realization of practical spin MOSFETs.

Acknowledgements

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