K-9-4

Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp1223-1224

Tunnel barrier thickness dependence of Hanle-type signals in CoFe/MgO/n-Si and CoFe/MgO/n-Ge junctions investigated through three-terminal configuration

Tetsuya Uemura[1], Gui-fang Li[1], Jun Fujisawa[1], Kenji Kondo[2], Ken-ichi Matsuda[1], and Masafumi Yamamoto[1]

[1] Graduate School of Information Science and Technology, Hokkaido University.
Kita-14, Nishi-9, Kita-ku, Sapporo 060-0814, Japan
Phone: +81-11-706-6440 E-mail: uemura@ist.hokudai.ac.jp
[2] Research Institute for Electronic Science, Hokkaido University.
Kita-20, Nishi-10, Kita-ku, Sapporo 001-0020, Japan

1. Introduction

Spintronics, where the spin states of carriers are utilized as an additional degree of freedom for information processing and storage, is a promising technology for highly advanced electronics in the future. The injection of spin polarized carriers from a ferromagnetic electrode inside semiconductors (spin injection) is the first step towards creating viable semiconductor spintronic devices. The Hanle effect measurement using three-terminal configuration has been widely used to evaluate the spin accumulation in a semiconductor beneath the ferromagnetic electrode, and clear Hanle-type signals have been observed in several semiconductor materials, such as GaAs [1], Si [2-5] and Ge [6-10]. In most cases, however, the magnitude of these Hanle-type signals was several orders of magnitude higher than those expected from theory [11]. Furthermore, we have shown that the three-terminal Hanle signals are proportional to the tunnel resistance in $Co_{50}Fe_{50}$(CoFe)/MgO/n-Si tunnel junctions [12], which suggests that the observed Hanle-type signals are not caused by the Hanle effect in the semiconductor.

The purpose of our present study is to further clarify the origin of the giant three-terminal Hanle signals. For that purpose we investigated the effect of semiconductor materials on the MgO thickness (t_{MgO}) dependence of the three-terminal Hanle-type signals, and found that the t_{MgO} dependence of the Hanle-type signals were insensitive to the choice of semiconductor materials. This finding supports the understanding that the giant Hanle-type signals observed using three-terminal geometry were caused not by spin accumulation in the semiconductor region but by modulation of the tunneling resistance with a magnetic field due to the spin precession in possible localized states formed in the tunnel junctions [13].

2. Experimental Method

We prepared two kinds of semiconductor substrates: a heavily-doped n-type (001) silicon-on-insulator (SOI) substrate (~1×10^{19} cm^{-3}) and a n-type (001) germanium (Ge) substrate. In order to form a heavily-doped n-type Ge channel, phosphorus ions were implanted with an input dosage of 1×10^{14} cm^{-2} (50 keV) into the lightly-doped n-type Ge substrates, and ion-implanted substrates were annealed at 550 °C for 5 min, resulting in a n-type channel (2.7×10^{18} cm^{-3}) with a channel thickness of ~100 nm at room temperature. The resistivity (ρ) of the channels for both n-Si and n-Ge is summarized in Table I. All layers in the layer structure consisting of Ru cap (5 nm)/CoFe (5 nm or 10 nm)/MgO barrier (1 nm to 3 nm) were successively deposited on both substrates in an ultrathin vacuum chamber through the combined use of magnetron sputtering for CoFe and electron beam evaporation for MgO with a wedge structure having a thickness ranging from 1 nm to 3 nm. Junctions with sizes ranging from 50×50 μm² to 250×250 μm² were fabricated. The magnetoresistance of each junction were measured at 293 K using three-terminal configuration (Fig. 1). The bias polarity was defined with respect to the semiconductor channel.

Table I. Resistivity (ρ), spin lifetime (τ_{sf}), and spin resistance ($\rho\lambda_{sf}$) of the channel, and spin-resistance area products ($\Delta R_S \cdot A$) observed in a CoFe/MgO/n-Si junction with t_{MgO} of 2.2 nm and a CoFe/MgO/n-Ge junction with t_{MgO} of 2.4 nm.

channel	ρ [Ω· μm]	τ_{sf} [psec]	$\rho\lambda_{sf}$ [Ω· μm²]	$\Delta R_S \cdot A$ [Ω· μm²]
n-Si	50	150	10	3.5×10^5
n-Ge	37	120	16	4.7×10^5

3. Results and Discussion

Figure 2(a) and 2(b) show the change in junction resistance for (a) a CoFe/MgO/n-Si tunnel junction with t_{MgO} of 2.2 nm and (b) a CoFe/MgO/n-Ge tunnel junction with t_{MgO} of 2.4 nm as functions of both the in-plane and out-of-plane magnetic field. The constant bias current (I_{bias}) of −20 μA for a CoFe/MgO/Si tunnel junction or −50 μA for a CoFe/MgO/Ge tunnel junction was supplied. Under this bias condition electrons tunnel from CoFe to the semiconductor channel (spin injection). The junction resistance decreases as the out-of-plane magnetic field increases (Hanle effect), while it increases as the in-plane magnetic field increases (inverted Hanle effect) in both samples. The observation of the inverted Hanle effect suggests the finite roughness of the CoFe/MgO interface [14]. Table I summarizes spin lifetime (τ_{sf}) and spin resistance ($\rho\lambda_{sf}$) of the channel, and observed spin-resistance area products ($\Delta R_S \cdot A$) in both samples, where ΔR_S is defined by the sum of the resistance change in the Hanle curve and the inverted Hanle curve, and A is a junction area. The τ_{sf} was estimated by fitting the Hanle curve by Lorentzian function, and the spin diffusion length (λ_{sf}) was estimated from τ_{sf} and the mobility. Based on the model of Fert and Jaffrès, $\Delta R_s \cdot A$ is given by [11]

$$\Delta R_s \cdot A = \gamma^2 \rho \lambda_{sf} \qquad (1)$$

in the case for $R \cdot A \gg \rho\lambda_{sf}$, which condition are satisfied in our devices, as shown below, where γ ($-1 \leq \gamma \leq 1$) is spin polarization of the spin-dependent tunnel resistance, R is an averaged tunnel resistance between majority and minority spins. If eq. (1) is applicable, $\Delta R_s \cdot A$ should not exceed $\rho\lambda_{sf}$. However, the observed $\Delta R_s \cdot A$ is more than four-orders of magnitude larger than the values of $\rho\lambda_{sf}$ in both samples. Such an enhancement of $\Delta R_s \cdot A$ has been observed in many literatures [1-10,14], and a sequential tunneling model was proposed to explain the enhancement effect [1].

Figure 3(a) and 3(b) show t_{MgO} dependence of $\Delta R_S \cdot A$ for (a) CoFe/MgO/Si tunnel junctions and (b) CoFe/MgO/Ge tunnel junctions. The values of $R \cdot A$ are also plotted for comparison. The $R \cdot A$ shows clear exponential dependence on t_{MgO} in both samples, indicating the MgO layer works as a tunneling barrier. If eq. 1 of the model of Fert and Jaffrès is applicable, $\Delta R_S \cdot A$ should be constant against $R \cdot A$. However, the $\Delta R_S \cdot A$ also exhibits exponential dependence on t_{MgO}, and $\Delta R_S \cdot A$ is proportional to $R \cdot A$ over a relatively wide range of from 3×10^6 to 5×10^8 $\Omega\cdot\mu m^2$ for CoFe/MgO/Si tunnel junctions and of from 1×10^8 to 3×10^9 $\Omega\cdot\mu m^2$ for CoFe/MgO/Ge tunnel junctions. This experimental finding that the magnitude of $\Delta R_S \cdot A$ depends on t_{MgO} cannot be explained by the sequential tunneling model. One possible origin for the giant t_{MgO}-dependent $\Delta R_S \cdot A$ is the modulation of tunnel resistance of a MgO barrier with a magnetic field due to the spin precession in possible localized states formed at CoFe/MgO interface [13]. As shown in Fig. 3, the t_{MgO} dependence of the Hanle-type signals is insensitive to the choice of semiconductor materials. This result also supports this model of tunneling resistance modulation.

4. Conclusions

We observed giant t_{MgO}-dependent Hanle-type signals in both CoFe/MgO/Si tunnel junctions and CoFe/MgO/Ge tunnel junctions in three-terminal configuration. The t_{MgO} dependence of the Hanle-type signals is insensitive to the choice of semiconductor materials. These results indicate that the signals originating from the modulation of tunneling resistance of a MgO barrier mask the true spin accumulation signal. Thus, the three-terminal measurement is not suitable to detect exactly spin accumulation in the semiconductor in the case that the tunnel resistance is much larger than the spin resistance of the channel, and the four-terminal non-local measurement is indispensable.

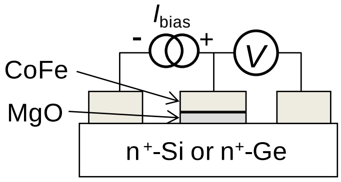

Fig. 1 Schematic diagram showing the device structure and the three-terminal measurement circuit.

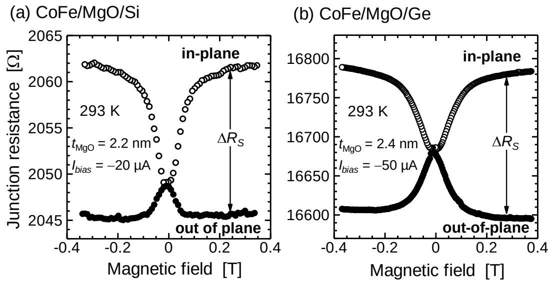

Fig. 2 Change in junction resistance for (a) a CoFe/MgO/n-Si tunnel junction with t_{MgO} of 2.2 nm and (b) a CoFe/MgO/n-Ge tunnel junction with t_{MgO} of 2.4 nm as functions of both the in-plane and out-of-plane magnetic field.

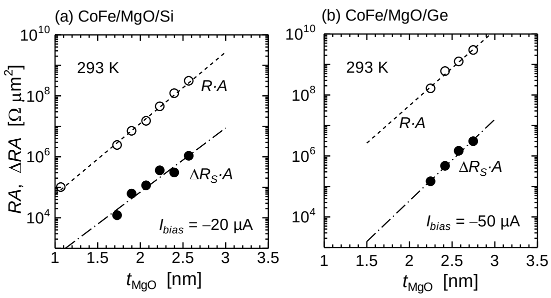

Fig. 3 t_{MgO} dependence of $R \cdot A$ and $\Delta R_S \cdot A$ for (a) CoFe/MgO/Si tunnel junctions and (b) CoFe/MgO/Ge tunnel junctions

References

[1] M. Tran, *et al.*, Phys. Rev. Lett. **102** (2009), 036601.

[2] S. P. Dash, *et al.*, Nature **462** (2009), 491.

[3] C.H. Li, *et al.*, Nature Commun. **2** (2011), 245, and http://arxiv.org/abs/1110.1620

[4] N. W. Gray and A. Tiwari, Appl. Phys. Lett. **98** (2011), 102112.

[5] K. Jeon, *et al.*, Appl. Phys. Lett. **98** (2011), 262102.

[6] H. Saito, *et al.*, Solid State Commun. **151** (2011), 1159.

[7] A. Jain, *et al.*, Appl. Phys. Lett. **99** (2011), 162102.

[8] K. Jeon, *et al.*, Appl. Phys. Lett. **99** (2011), 162106.

[9] A.T. Hanbicki, *et al.*, Solid State Commun. **152** (2012), 244.

[10] S. Iba, *et al.*, Appl. Phys. Expr. **5** (2012), 023003.

[11] A. Fert and H. Jaffrès, Phys. Rev. B **64** (2001), 184420.

[12] T. Uemura et al., Int'l Magnetics Conf.2012 (INTERMAG 2012), AD-06, Vancouver, Canada, May7-11, 2012.

[13] T. Uemura, et al., *submitted.*

[14] S. P. Dash, *et al.*, Phys. Rev. B **84** (2011), 054410.