N-7-4

Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1460-1461

Effect of MgO Barrier Insertion on Spin-dependent Transport Properties of CoFe/n-GaAs

Takafumi Akiho, Tetsuya Uemura, Masanobu Harada, Ken-ichi Matsuda, and Masafumi Yamamoto

Division of Electronics for Informatics, Hokkaido University
Kita 14, Nishi 9, Kita-ku, Sapporo,
Hokkaido, 060-0814, Japan
Phone: +81-11-706-6442 E-mail: akiho@nsed.ist.hokudai.ac.jp

1. Introduction

The injection of spin-polarized electrons from a ferromagnet (F) into a semiconductor (SC) is one of the most important challenges in spintronics. We recently observed a tunneling anisotropic magnetoresistance (TAMR) in $Co_{50}Fe_{50}$(CoFe)/n-GaAs [1] and Co_2MnSi/n-GaAs [2] Schottky tunnel junctions, and suggested that the TAMR resulted from the injection of spin-polarized electrons from a ferromagnet into GaAs. Moreover, we observed a non-local spin-valve effect and the Hanle effect in a CoFe/n-GaAs Schottky tunnel junction, those are the direct evidences for the spin injection [3]. Recently, the spin injection using a MgO tunnel barrier also has attracted much attention [4]. In this study, we investigated the effect of MgO tunnel barrier insertion on both the TAMR effect and the non-local spin-valve effect in CoFe/n-GaAs junctions.

2. Experimental Methods

Layer structures consisting of (from the substrate side) i-GaAs (250 nm thick), n^--GaAs (Si = 3×10^{16} cm^{-3}, 2500 nm), and n^+-GaAs (Si = 5×10^{18} cm^{-3}, 30 nm) were grown by molecular beam epitaxy at 600 °C on GaAs (001) substrates. The samples were then capped with an arsenic protective layer and transported to a magnetron sputtering chamber. After the arsenic cap was removed by heating the samples to 300–400 °C, a 0.8-nm-thick MgO layer was grown by electron-beam evaporation at 350 °C. Finally, a 5-nm-thick CoFe film was deposited by magnetron sputtering at room temperature (RT). Reflection high energy electron diffraction (RHEED) patterns observed *in situ* for each layer during preparation indicated that both MgO and CoFe layers grew epitaxially on GaAs. Samples without a MgO barrier were also fabricated identically. Using an electron-beam lithography and Ar ion milling techniques, four-terminal non-local devices shown in Fig. 1(b) were fabricated. The size of the injector contact (contact-2) and detector contact (contact-3) were 0.5 × 10 µm and 1.0 × 10 µm, respectively, and the spacing between them was 0.5 µm. The TAMR and non-local spin-valve characteristics were measured at 4.2 K using a three-terminal geometry [Fig. 1(a)] and a four-terminal geometry [Fig. 1 (b)], respectively. The bias voltage was defined with respect to the n-GaAs.

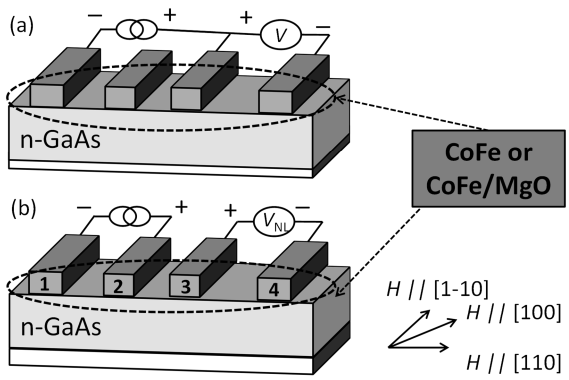

Fig 1; Circuit configurations of (a) a three-terminal geometry for measuring a TAMR effect, and (b) a four-terminal geometry for measuring a non-local spin-valve effect.

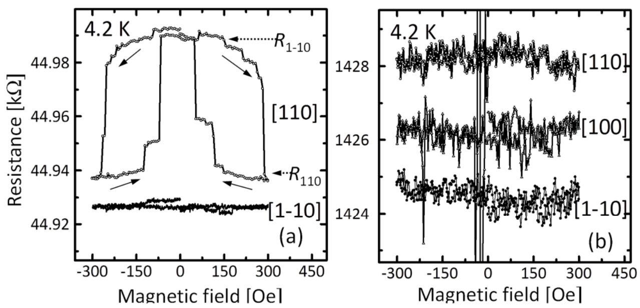

Fig 2; MR curves measured at 4.2 K for CoFe/MgO/n-GaAs single junctions with (a) no MgO layer and (b) t_{MgO} of 0.8 nm. An in-plane magnetic field was applied along (a) [110] and [1-10], (b) [110], [100], and [1-10], of GaAs, respectively. The MR curves are offset for clarity.

3. Results and Discussion

Figures 2(a) and (b) show magnetoresistance (MR) curves measured at 4.2 K for CoFe/MgO/n-GaAs single junctions with and without a MgO barrier. The bias voltage was –0.15 V, and the in-plane magnetic field (H) was applied along the [110] and [1-10] directions of GaAs for CoFe/n-GaAs [Fig. 2(a)], and along the [110], [100], and [1-10] directions for CoFe/MgO/n-GaAs [Fig. 2(b)]. The [110] direction of GaAs corresponds to the hard axis direction for the shape anisotropy of the junction. The curves shown in Figs. 2(a) and 2(b) are offset for clarity. The sample without a MgO barrier showed clear MR due to the TAMR effect when H was swept along the [110] direction.

This effect was explained by the modulation of the tunneling probability depending on the spin direction of the spin-polarized electrons due to the Rashba-type spin-orbit interaction (SOI) at the CoFe/n-GaAs heterointerface and the Dresselhaus-type SOI inside the GaAs Schottky tunnel barrier [5]. This TAMR effect produces the resistance difference between R_{110} and $R_{1\text{-}10}$, where R_{110} and $R_{1\text{-}10}$ stand for the tunnel resistances when the magnetization (M) of CoFe oriented along [110] and [1-10], respectively. On the other hand, no significant MR was observed when H was swept along the [1-10]. This is because there was no state for $M \parallel [110]$ when the magnetic field was swept along [1-10] direction.

In the case of CoFe/MgO/n-GaAs, no significant MR was observed for all three different directions ([110], [100], and [1-10]) of the magnetic field. This result indicates that the insertion of a MgO barrier between CoFe and GaAs suppressed the TAMR effect. Since both the Rashba-type and Dresselhaus-type SOIs are necessary to produce the TAMR, the suppression of the TAMR upon insertion of the MgO barrier suggests that electrons do not tunnel through the GaAs Schottky barrier, but tunnel only through the MgO barrier. The insertion of a MgO barrier probably decreased the density of metal-induced gap-states or defects formed at the CoFe/n-GaAs interface, thereby suppressing the Fermi-level pinning and lowering the Schottky barrier height [6].

Figure 3 plots non-local voltages (V_{NL}) measured at 4.2 K as a function of the magnetic field along the [1-10] direction in (a) a four-terminal device consisting of CoFe/n-GaAs Schottky tunnel junctions and (b) CoFe/MgO/n-GaAs tunnel junctions. The non-local voltage was measured between contact-3 and contact-4, while constant current (I) of –10 μA [Fig. 3(a)] or –1μA [Fig. 3(b)] was supplied between contact-1 and contact-2. Both samples showed clear spin-valvelike signal. As shown in Figs 2(a) and (b), no significant MR was observed for a CoFe/n-GaAs single junction or a CoFe/MgO/n-GaAs single junction when the magnetic field was swept along the [1-10] direction. Thus, observed non-local signal was due to the parallel (P)/anti-parallel (AP) switching in magnetization configuration between the injector contact and the detector contact.

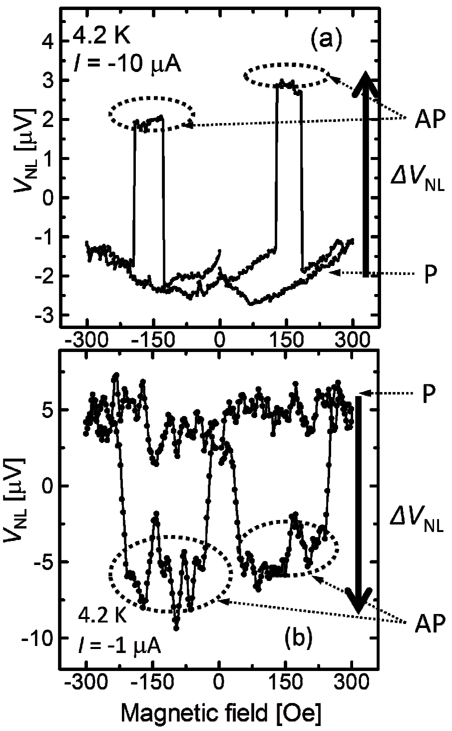

Fig 3; Plots of non-local voltage at 4.2 K as a function of in-plane magnetic field ($H \parallel$ [1-10]) (a) CoFe/n-GaAs Schottky tunnel junctions and (b) CoFe/MgO/n-GaAs tunnel junctions.

The non-local voltage change (ΔV_{NL}) was approximately 4 μV for CoFe/n-GaAs and –10 μV for CoFe/MgO/n-GaAs. Here, ΔV_{NL} was defined by $V_{NL}^{AP} - V_{NL}^{P}$, where V_{NL}^{AP} and V_{NL}^{P} are non-local voltages for AP and P configurations, respectively, between the injector contact-2 and detector contact-3. Interestingly, the magnitude of $\Delta V_{NL}/I$ of the CoFe/MgO/n-GaAs increased by 40 compared with that of the CoFe/n-GaAs. Since $\Delta V_{NL}/I$ is proportional to the product of P_{inj} and P_{det}, where P_{inj} and P_{det} are the spin polarizations at injector contact and detector contact, respectively [7], the increase in $\Delta V_{NL}/I$ upon MgO insertion suggests the enhancement of the effective spin polarization. One possible reason is a coherent tunneling in a MgO barrier. Moreover, the sign of $\Delta V_{NL}/I$ are opposite between CoFe/n-GaAs and CoFe/MgO/n-GaAs, indicating the sign change of the effective spin polarization.

4. Conclusion

We experimentally found that the TAMR effect was suppressed by inserting a MgO barrier between CoFe and n-GaAs, indicating the Fermi-level depinning and lowering of the Schottky barrier height of GaAs. We also found that the non-local spin-valve signal was enhanced and the sign was reversed by inserting a MgO barrier, suggesting that the effective spin polarization increased due to coherent tunneling in MgO.

Reference

[1] T. Uemura, Y. Imai, M. Harada, K.-i. Matsuda, and M. Yamamoto, Appl. Phys. Lett. **94**, (2009) 182502.

[2] T. Uemura, M. Harada, K.-i. Matsuda, and M. Yamamoto, Appl. Phys. Lett. **96**, (2010) 252106.

[3] T. Uemura, M. Harada, T. Akiho, K.-i. Matsuda, and M. Yamamoto, Technical Digests, Int'l Magnetics conf. Taipei, Taiwan, BP-08, April 25 – 29, (2011).

[4] T. Sasaki, T. Oikawa, T. Suzuki, M. Shiraishi, Y. Suzuki, and K. Noguchi, IEEE Trans. Magn. **46**, (2010) 1436.

[5] A. Matos-Abiague and J. Fabian, Phys. Rev. B **79**, (2009) 155303.

[6] T. Akiho, T. Uemura, M. Harada, K.-i. Matsuda. And M. Yamamoto, Appl. Phys. Lett. **98**, (2011) 232109.

[7] S. Takahashi and S. Maekawa, Phys. Rev. B **67,** (2003) 052409.