Enhanced spin accumulation obtained by inserting low-resistance MgO interface in metallic lateral spin valves

Y. Fukuma,[1,a)] L. Wang,[1,2] H. Idzuchi,[3] and Y. Otani[1,2,3]
[1]*Advanced Science Institute, RIKEN, 2-1 Hirosawa, Wako 351-0198, Japan*
[2]*Department of Material Physics and Chemistry, University of Science and Technology Beijing, Beijing 100083, People's Republic of China*
[3]*Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan*

(Received 26 April 2010; accepted 15 June 2010; published online 9 July 2010)

We have systematically investigated the interface contributions to the spin injection characteristics in permalloy/MgO/Ag lateral spin valves. The spin valve signal remarkably increases with MgO thickness and reaches a maximum when the interface resistance is about 100 fΩ m^2 for 1 nm thick MgO, which is two orders of magnitude lower than that of the typical tunnel junction. Our quantitative analysis based on the spin-dependent diffusion equation considering variable spin polarization in the MgO layer well describes the observed trend in the spin valve signals. © *2010 American Institute of Physics*. [doi:10.1063/1.3460909]

The injection, manipulation, and detection of spin currents are key ingredients in spintronics, which is an emergent field offering additional spin degrees of freedom in solid-state electronics.[1,2] The nonlocal spin injection in lateral spin valves has provided a wealth of scientific interest as an effective method to generate a pure spin current, i.e., a diffusive flow of spin angular momentum accompanied by no flow of charge which can induce a variety of spin dependent phenomena.[3–7] The pure spin current flows along the slope of the spin accumulation, which decays exponentially with a factor of $\exp(-x/\lambda_S)$ where x is the distance from the interface and λ_S is the spin-diffusion length. Subsequent spin relaxation takes place in an additional ferromagnet or nonmagnet with very small λ_S in the range 3–10 nm such as permalloy ($\mathrm{Py}:\mathrm{Ni}_{80}\mathrm{Fe}_{20}$) or platinum in Ohmic contact with the host nonmagnetic metal sustaining spin accumulation.[8] This is so called "spin absorption" behavior which can be used as an effective means to inject the pure spin current into ferromagnets or strong spin-orbit materials to study spin torque switching or spin Hall effects in lateral spin valve structures.[5–7,9–11] For such experiments, it is beneficial to develop more efficient way to generate large pure spin current as well as large spin accumulation.

Lateral spin valves can be classified into two kinds, i.e., one consists of Ohmic junctions and the other consists of tunnel junctions. Their characteristics depend only on whether the magnitude of the interface resistance between the ferromagnets and nonmagnets is smaller or larger than the spin resistance of the host nonmagnetic metal. In the case of the transparent Ohmic junction, the spin valve signal, i.e., the overall change ΔR_S in spin signal $\Delta V/I$ between the parallel and antiparallel ferromagnetic electrodes configuration, is in the order of 1 mΩ at room temperature due to the spin resistance mismatch and the spin absorption both at injector and detector junctions.[12–14] On the other hand, the tunnel junction realizes much larger value of ΔR_S since the above mentioned unfavorable effects are well suppressed.[15–18] However, the polarization, i.e., spin injection efficiency, is drastically decreased with increasing applied voltage.[16] It is important to enhance the applied current I as well as ΔR_S to realize larger spin accumulation in the lateral spin valves.

In the present work, we have studied systematically the influence of the MgO interface layer on the spin injection and the spin accumulation in Py/Ag/Py lateral spin valves. The value of ΔR_S is remarkably increased by inserting the interface resistance. The experimental results are well reproduced by the quantitative analysis based on the spin-dependent diffusion equation considering the MgO interface with variable spin polarization. We show here that the spin resistance mismatch problem can be solved by inserting the interface resistance, even two orders of magnitude smaller than the conventional tunnel resistance, and thus a large spin accumulation of ~ 10 μV is realized.

Lateral spin valves with clean ferromagnetic/nonmagnetic interfaces are prepared on a $\mathrm{Si}/\mathrm{SiO}_2$ substrate by means of shadow evaporation using a suspended resist mask, which is patterned using bilayer resists of 500 nm thick methyl-methacrylate and 50 nm thick polymethyl methacrylate by e-beam lithography. Ferromagnetic Py and nonmagnetic materials including Ag and MgO are e-beam deposited separately in the interconnected two different evaporation chambers with base pressures of 2×10^{-8} Torr and 4×10^{-10} Torr, respectively, to prevent magnetic impurities worsening the spin diffusion length of Ag. The injector and detector Py electrodes of 120 nm width are obliquely deposited at a tilting angle of 45° from substrate normal. Then a thin interface layer of MgO is deposited at the same tilting angle as the Py deposition. Finally a 170 nm wide Ag wire bridging the two Py electrodes is deposited normal to the substrate. The thickness of the Ag nanowire is 50 nm.

Figure 1 shows the MgO thickness t_{MgO} dependence of the interface resistance R_I for ferromagnetic/nonmagnetic junctions at room temperature. The measurements performed at low temperatures also show a similar trend. The value of R_I increases exponentially with t_{MgO} like a tunnel junction.[19,20] However, the R_I is much lower than that for the typical tunnel junction and the current-voltage characteristics of the Py/MgO/Ag junction exhibit linear variation. As shown in the inset of Fig. 2, the cross-sectional transmission electron micrograph (TEM) reveals that the interface layer

[a)]Electronic mail: yfukuma@riken.jp.

 © 2010 American Institute of Physics

Author complimentary copy. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp

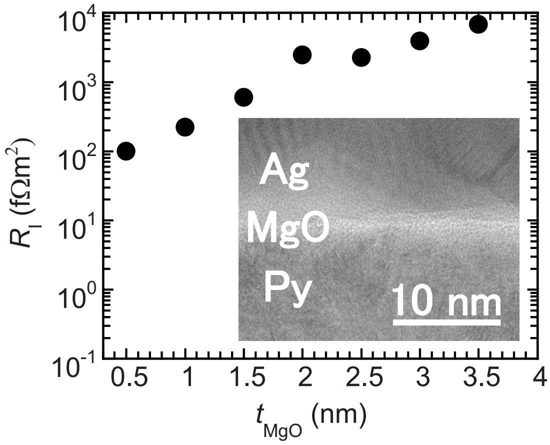

FIG. 1. MgO thickness dependence of interface resistance at room temperature. The inset shows the cross-sectional TEM image for the Py/MgO(0.5 nm)/Ag junction.

consists of homogeneous amorphous MgO with no pinholes. The small value of R_I for the MgO layer may be due to defects such as oxygen vacancies.[21]

Figure 2 shows typical spin valve behaviors in nonlocal geometries with the separation d between the injector and the detector of 300 nm measured at room temperature. The nonlocal spin valve (NLSV) measurements are carried out by conventional current-bias lock-in technique with a probe current $I=200$ μA. For Py/Ag transparent junction, the spin valve signal ΔR_S is 0.6 mΩ. The value of ΔR_S is remarkably increased by a factor of ~6 by inserting the interface MgO layer ($t_{MgO}=0.5$ nm). It should be noted that ΔR_S stays unchanged up to 1 mA, and that the observed spin valve behaviors ($\Delta R_{S\ NLSV}\sim 4$ mΩ for $t_{MgO}\sim 0.5$ nm) are reproducible for all the prepared devices in the present study.

The spin valve signals ΔR_S in the NLSV measurements are summarized together with the fitted curves for lateral spin valves with different t_{MgO} and d in Fig. 3. The ΔR_S versus R_I plot exhibits a gradual increase, a maximum at $R_I\sim 100$ fΩ m^2 for $t_{MgO}\sim 1$ nm, and a sharp drop with an increase in R_I. To better understand the behavior, the analytical expression for ΔR_S is deduced by solving the one-dimensional spin dependent diffusion equation with a spin dependent interface.[22]

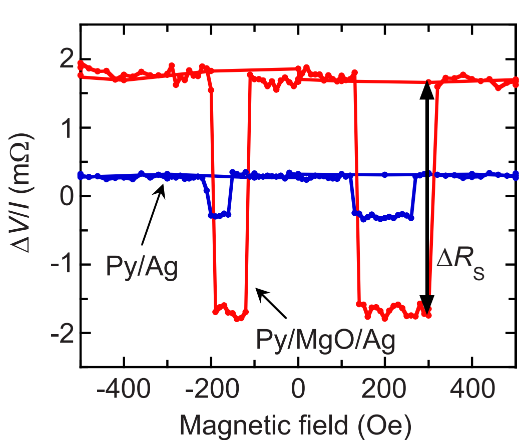

FIG. 2. (Color online) Field dependence of nonlocal spin signal for Py/Ag and Py/MgO(0.5 nm)/Ag junctions at room temperature.

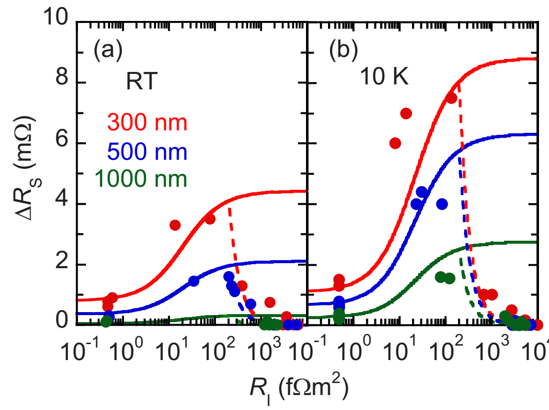

FIG. 3. (Color online) Interface resistance dependence of spin valve signal for NLSV measurement in the lateral spin valves with various separations between injector and detector (a) room temperature and (b) 10 K. The solid lines show fitting curves using Eq. (1). The broken lines show fitting curves using Eq. (1) with Eq. (2) taking into account variable spin polarization in the MgO layer.

$$\Delta R_S = 2R_{SN}\frac{\left(P_I\frac{R_{SI}}{R_{SN}}+P_F\frac{R_{SF}}{R_{SN}}\right)^2 e^{-d/\lambda_N}}{\left(1+2\frac{R_{SI}}{R_{SN}}+2\frac{R_{SF}}{R_{SN}}\right)^2-e^{-2d/\lambda_N}}, \qquad (1)$$

where P is the spin polarization and λ is the spin diffusion length. $R_{SN}=2\rho_N\lambda_N/t_N w_N$, $R_{SI}=2R_I/w_F w_N(1-P_I^2)$, and $R_{SF}=2\rho_F\lambda_F/w_F w_N(1-P_F^2)$ are the spin resistance where ρ the resistivity, t the thickness, and w the width. The subscripts I, N, and F in the above relations, respectively, represent the interface MgO, the nonmagnetic Ag, and the ferromagnetic Py layers. The fitting parameters of Eq. (1) to the experimental results are P_I, P_F, λ_F, and λ_N. First the value of P_F is determined from the results measured for the Py/Ag junctions with $R_I=0.5$ fΩ m^2. The value of R_I is below the resolution ability of 1 fΩ m^2 in our measurement system. We thus assume that R_I for the Py/Ag junction is comparable to the representative value of 0.5 fΩ m^2 reported for clean Co/Ag, Py/Cu, and Co/Cu junctions.[23]

As can be seen in Fig. 3, solid curves calculated using Eq. (1) with $P_F=0.25$, $P_I=0.11$, and $\lambda_F=5$ nm at the both temperatures and $\lambda_N=270$ nm and 550 nm at $T=$RT and 10 K, respectively, well reproduces the gradual increase in ΔR_S in the low R_I region. However, Eq. (1) cannot account for the sharp decrease in ΔR_S in the high R_I region. As mentioned earlier, the MgO layer is amorphous and an electrically leaky insulator. Therefore, the thick MgO layer may not work as a single spin-dependent interface but may decay the spin polarization in the high R_I region. To take into account this effect at the interface, we introduce the modified Valet–Fert two spin-channel resistor circuit comprised of spin-dependent interface resistance $R_{I1}(t)$ and spin-independent interface resistance $R_{I2}(t)$ as illustrated in Fig. 4.[24] For the thickness $t_{MgO}<1$ nm, the interface acts as a spin filter, i.e., spin-dependent interface resistance $R_{I1}(t)$ with the spin polarization P_{I1}. As the thickness t_{MgO} increases over 1 nm, the excess MgO layer becomes a spin-independent interface resistance $R_{I2}(t)$ connected in series with $R_{I1}(1\text{ nm})=223$ fΩ m^2. The thickness dependence of interface resistance is determined by the experimental data in Fig. 1. The spin polarization at this interface is thus given by

Author complimentary copy. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp

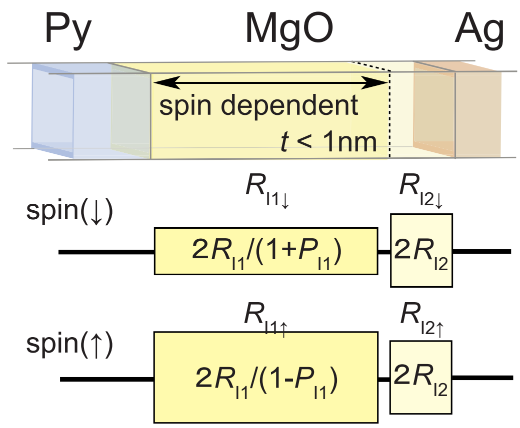

FIG. 4. (Color online) Simplified resistor model for MgO layer with spin-dependent interface $R_{I1}(t)$ and spin-independent interface $R_{I2}(t)$.

$$P_I = \frac{R_{I\uparrow} - R_{I\downarrow}}{R_{I\uparrow} + R_{I\downarrow}} = \frac{P_{I1} R_{I1}(t)}{R_{I1}(t) + (1 - P_{I1}^2) R_{I2}(t)}. \quad (2)$$

Here $R_{I1}(t)=0.5+223t_{\mathrm{MgO}}$ and $R_{I2}(t)=0$ for $t_{\mathrm{MgO}}<1$ nm, and $R_{I1}(t)=223$ and $R_{I2}(t)=55e^{1.4t_{\mathrm{MgO}}}-223$ for $t_{\mathrm{MgO}}>1$ nm, where the unit of the interface resistance and the thickness is fΩ m^2 and nm, respectively. The dashed curves in Fig. 3 are obtained by fitting the results to Eq. (1) combined with Eq. (2), and they well describe the trend of the spin signals with R_I. Note here that the value of $P_I=0.11$ obtained by the fitting is reasonable compared to the values reported for the tunnel junction in the lateral spin valves,[15–18] and that the value of ΔR_S reaches close to the maximum even at $R_I \sim 100$ fΩ m^2 for $t_{\mathrm{MgO}} \sim 1$ nm.

In summary, the results reveal that the value of $R_I \sim 100$ fΩ m^2, two orders of magnitude smaller than that of the tunnel junction, could effectively overcome the spin resistance mismatch between the ferromagnetic and nonmagnetic metals. Moreover, the low R_I junction can lead to increase in the spin accumulation voltage $\Delta V_S = \Delta R_S I$ since the maximum applied current can be increased. A large spin accumulation voltage $\Delta V \sim 10$ μV for $I \sim 1$ mA is obtained in the present lateral spin valves with the Py/MgO/Ag junctions.

We thank J. Hamrle for useful discussions. This work is partly supported by Grant-in-Aid for Scientific Research in Priority Area "Creation and control of spin current" (Grant No. 19048013) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

[1]S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnár, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science **294**, 1488 (2001).
[2]I. Žutić, J. Fabian, and S. D. Sarma, Rev. Mod. Phys. **76**, 323 (2004).
[3]M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985).
[4]F. J. Jedema, A. T. Filip, and B. J. van Wees, Nature (London) **410**, 345 (2001); F. J. Jedema, H. B. Heersche, A. T. Filip, J. J. A. Baselmans, and B. J. van Wees, *ibid.* **416**, 713 (2002).
[5]S. O. Valenzuela and M. Tinkham, Nature (London) **442**, 176 (2006).
[6]T. Kimura, Y. Otani, T. Sato, S. Takahashi, and S. Maekawa, Phys. Rev. Lett. **98**, 156601 (2007).
[7]T. Seki, Y. Hasegawa, S. Mitani, S. Takahashi, H. Imamura, S. Maekawa, J. Nitta, and K. Takanashi, Nature Mater. **7**, 125 (2008).
[8]T. Kimura, J. Hamrle, and Y. Otani, Phys. Rev. B **72**, 014461 (2005).
[9]T. Kimura, Y. Otani, and J. Hamrle, Phys. Rev. Lett. **96**, 037201 (2006).
[10]T. Yang, T. Kimura, and Y. Otani, Nat. Phys. **4**, 851 (2008).
[11]J. Z. Sun, M. C. Gaidis, E. J. O'Sullivan, E. A. Joseph, G. Hu, D. W. Abraham, J. J. Npwak, P. L. Trouiloud, Y. Lu, S. L. Brown, D. C. Worledge, and W. J. Gallagher, Appl. Phys. Lett. **95**, 083506 (2009).
[12]Y. Ji, A. Hoffmann, J. S. Jiang, and S. D. Bader, Appl. Phys. Lett. **85**, 6218 (2004).
[13]Y. Ji, A. Hoffmann, J. E. Pearson, and S. D. Bader, Appl. Phys. Lett. **88**, 052509 (2006).
[14]T. Kimura, T. Sato, and Y. Otani, Phys. Rev. Lett. **100**, 066602 (2008).
[15]S. Garzon, I. Žutić, and R. A. Webb, Phys. Rev. Lett. **94**, 176601 (2005).
[16]S. O. Valenzuela, D. J. Monsma, C. M. Marcus, V. Narayanamurti, and M. Tinkham, Phys. Rev. Lett. **94**, 196601 (2005).
[17]A. Vogel, J. Wulfhorst, and G. Meier, Appl. Phys. Lett. **94**, 122510 (2009).
[18]X. J. Wang, H. Zou, L. E. Ocola, and Y. Ji, Appl. Phys. Lett. **95**, 022519 (2009).
[19]S. S. P. Parkin, C. Kaiser, A. Panchula, P. M. Rice, B. Hughes, M. Samant, and S.-H. Yang, Nature Mater. **3**, 862 (2004).
[20]S. Yuasa, T. Nagahama, A. Fukushima, Y. Suzuki, and K. Ando, Nature Mater. **3**, 868 (2004).
[21]W. Wulfhekel, M. Klaua, D. Ullmann, F. Zavaliche, J. Kirschner, R. Urban, T. Monchesky, and B. Heinrich, Appl. Phys. Lett. **78**, 509 (2001).
[22]S. Takahashi and S. Maekawa, Phys. Rev. B **67**, 052409 (2003).
[23]J. Bass and W. P. Pratt, Jr., J. Magn. Magn. Mater. **200**, 274 (1999).
[24]T. Valet and A. Fert, Phys. Rev. B **48**, 7099 (1993).

Author complimentary copy. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp