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Thermal stability of the spin injection in Co/Ag/Co lateral spin valves*

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Spin injection, spin diffusion, and spin detection are investigated in Co/Ag/Co lateral spin valves at room temperature. Clear spin accumulation signals are detected by the non-local measurement. By fitting the results to the one-dimensional diffusion equation, $\sim 8.6\%$ spin polarization of the Co/Ag interface and ~ 180 nm spin diffusion length in Ag are obtained. Thermal treatment results show that the spin accumulation signal drastically decreases after 100 °C annealing, and disappears under 200 °C annealing. Our results demonstrate that, compared to the spin diffusion length, the decrease and the disappearance of the spin accumulation signal are mainly dominated by the variation of the interfacial spin polarization of the Co/Ag interface.

Keywords: spin injection, spin diffusion length, Co/Ag contact, lateral spin valve

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1. Introduction

Spintronics, aiming at manipulating not only the electron charge but also the electron spin to carry information, has gained a lot of attention in recent years.[1,2] Spin current generation is the key to unraveling the spin dependent transport phenomena. So far, several methods have been proposed to generate pure spin currents, such as spin pumping,[3] spin hall effect,[4] and spin injection.[5] Electrical spin injection is one of the most effective ways to generate spin current.[6] The basic concept is that the materials in the ferromagnetic state have a substantial degree of equilibrium carrier spin polarization. When a charge current flows across the interface between a ferromagnetic material and a nonmagnetic material, spin polarized carriers in the ferromagnetic material would give rise to the net current of magnetization and lead to a non-equilibrium magnetization in the nonmagnetic material. The length of the non-equilibrium magnetization in the nonmagnetic material is described by the spin diffusion length, and its magnitude could be detected by another ferromagnetic material.[1] The pioneering experimental demonstration on spin injection and detection was carried out by Mark Johnson and Silsbee[7] in 1985 using a lateral spin valve structure and non-local measurement technique. They used permalloy as the injection source and injected a spin current into a bulk aluminum. The non-equilibrium magnetization in the bulk aluminum was detected by using another thin film of permalloy at low temperature. After a quiet period of nearly two decades, and benefitting from the micro-nano fabrication technology, Jedema[5] successfully performed the spin injection and detection in metal at room temperature. This stimulated the researchers' interest on spin injection in lateral spin valves.[8–10] So far, spin polarized current has been injected into various kinds of materials, such as copper,[11] silver,[12–14] gold,[15,16] magnesium,[17] and two dimensional materials.[18–20] It is found that the magnitude of the spin accumulation signal is quite small when the ferromagnetic material is directly attached to the non-ferromagnetic materials. The low value is mainly due to the resistance mismatch problem and the spin absorption.[21] The small spin accumulation signal could be enhanced by introducing a tunnel junction which could provide a high interfacial spin polarization to the interface between the ferromagnetic materials and the non-magnetic materials,[22] but the high interface resistance of the tunnel junction limits the total current flow into the nonmagnetic material. Fukuma[23] further reported that by performing a thermal treatment, a low interface resistance could be achieved to overcome the resistance mismatch problem and improve the spin accumulation in the tunnel junction. So far, few works have been reported on the effect of the thermal treatment on the lateral spin valves with transparent contacts. In this paper, we investigate the electrical spin injection into Ag from Co through a transparent interface at room temperature with and without thermal treatment. The lateral spin valves with cobalt (Co) and silver (Ag) are selected to investigate the thermal effect because of the following reasons. First,

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Ag usually gives a higher spin accumulation signal in lateral spin valves than other metals, such as Cu, Mg, or Au. Second, Co has high bulk spin polarization. Third, both materials can be fabricated by a physical vapor deposition system, which would provide a high quality interface.

2. Experimental method

The Co(30 nm)/Ag(50 nm)/Co(30 nm) lateral spin valves were fabricated on Si/SiO_2 substrate by the shadow evaporation technique. Electron beam lithography (EBL) was used to transfer the shadow mask to the top of the bi-layer resister consisting of the polymethyl methacrylate (PMMA, 300 nm) and the methyl methacrylate (MMA, 700 nm). As shown in Fig. 1(a), due to the different sensitivities of PMMA and MMA, a suspended shadow mask was obtained after the development process. The Co layer and the Ag layer were deposited by a commercial electron beam evaporation system (DE400). The deposition process is illustrated in Fig. 1(b). 30 nm thick Co and 50 nm thick Ag were deposited at angles of 45° and 0° from the substrate normal, respectively. Both layers were deposited sequentially in one run without breaking the high vacuum (10^{-7} Torr) to ensure a clean interface and guarantee the consistent quality of samples fabricated at different patches. Non-local measurement was performed to measure the spin accumulation in Ag at room temperature. The thermal treatment was carried out in a rapid thermal process oven under a nitrogen atmosphere.

3. Results and discussion

Figure 1(c) shows a scanning electron microscope (SEM) image of a Co/Ag/Co lateral spin valve fabricated by the shadow evaporation technique. The electrodes marked by the red dash line are the 30 nm thick Co strips in different sizes to acquire two different coercivities. The spin accumulation in the Ag wire is measured by the non-local measurement. During the measurement, an ac current of 1 mA in amplitude and 77 Hz in frequency is injected from Co1 into the Ag wire. The voltage between Co2 and the right side of the Ag wire is measured by using an SR830 lock-in amplifier.

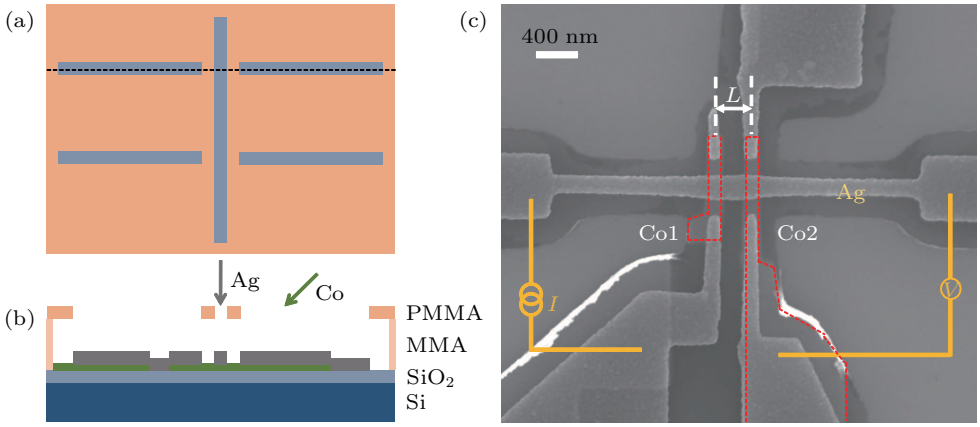


Fig. 1. (color online) (a) Top view of the shadow mask consisting of 300-nm-PMMA and 700-nm-MMA. (b) Side view of the shadow mask along the dash line in (a). (c) SEM image of a Co/Ag/Co lateral spin valve. The center to center distance (L) between the injector (Co1) and the detector (Co2) is 400 nm.

Figure 2(a) shows the magnetic field dependence of the measured nonlocal spin accumulation for the device shown in Fig. 1(c) at room temperature. During the measurement, an external in-plane magnetic field is applied to configure the direction of the magnetizations of the injector and detector. The red solid line in Fig. 2(a) corresponds to the sweeping of the external magnetic field from −800 Oe to 800 Oe. The magnetizations of Co1 and Co2 are parallel for $H < 200$ Oe and $H > 440$ Oe, and the measured voltage V is normalized by the injection current I, and gives as $R_s = V/I$ in the units of resistance. At this time, the measured resistance is ~ 10.60 mΩ. When the external magnetic field ranges 200 Oe $< H <$ 440 Oe, the magnetizations of Co1 and Co2 are anti-parallel, the measured resistance is ~ 10.48 mΩ. The spin accumulation signal ($\Delta R_s = \Delta V/I$) is defined as the difference between the high and low resistances. The reversal loop of the applied magnetic field from 800 Oe to −800 Oe has similar behavior, as marked by the black solid line in Fig. 2(a). The measured spin accumulation signal (ΔR_s) for the lateral spin valves with 400 nm center to center distance is 0.12 mΩ.

To gain further insight into the spin injection from Co and spin accumulation in the Ag wire via the transparent contact, lateral spin valves with different center to center distances between the injector and detector are fabricated. The nonlocal measurement is performed on each device to obtain their spin accumulation signals. Figure 3 shows the measured spin accumulation signal for each device as-deposited (black rectangle ▲) with different distance. The spin accumulation signal

decreases exponentially with the increasing distance. The analytical expression of the spin accumulation signal (ΔR_s) versus the distance (L) is deduced by solving the one-dimensional diffusion equation[8]

$$\Delta R_s = \frac{4P^2}{(1-P^2)^2} R_N \left(\frac{R_i}{R_N}\right)^2 \frac{e^{-L/\lambda_N}}{1-e^{-2L/\lambda_N}} \quad (1)$$

where R_i is the Co/Ag interface resistance; $R_N = \rho_N \lambda_N / w_N d_N$ is the spin resistance of the Ag wire; $R_F = \rho_F \lambda_F / w_N w_F$ is the spin resistance of the Co wire; λ_N and λ_F are the spin diffusion lengths of Ag and Co, respectively; ρ_N and ρ_F are the resistivities of Ag and Co, respectively; w_N and w_F are the widths of the Ag wire and Co wire, respectively; d_N is the thickness of Ag; P is the spin polarization of the Co/Ag interface; and L is the center to center distance between the two Co wires. The interface resistances (R_i) of several samples are measured and the averaged value for our device is $\sim 0.2\ \Omega$. The measured resistivities of Co and Ag in our devices are $\sim 300\ \Omega$·nm and $\sim 55\ \Omega$·nm, respectively. The widths of Co and Ag are ~ 150 nm and ~ 200 nm, respectively. By fitting the experimental data to Eq. (1), the spin diffusion length of Ag as deposited is ~ 180 nm and the interfacial spin polarization of Co/Ag is $\sim 8.6\%$ at room temperature. Besides the quality of Ag,[8] the shorter spin diffusion length of our samples should be mainly attributed to the spin flip at the top and side surface of the Ag wire.[24,25]

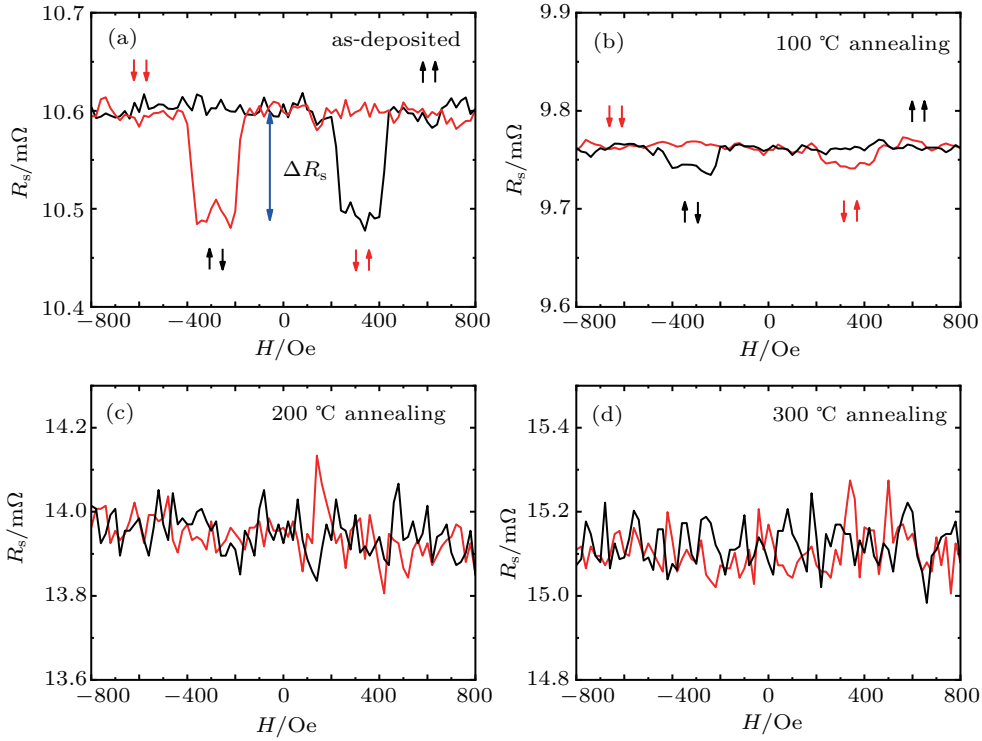


Fig. 2. (color online) The dependence of spin accumulation on the magnetic field for the (a) as-deposited, (b) 100 °C annealed, (c) 200 °C annealed, and (d) 300 °C annealed devices.

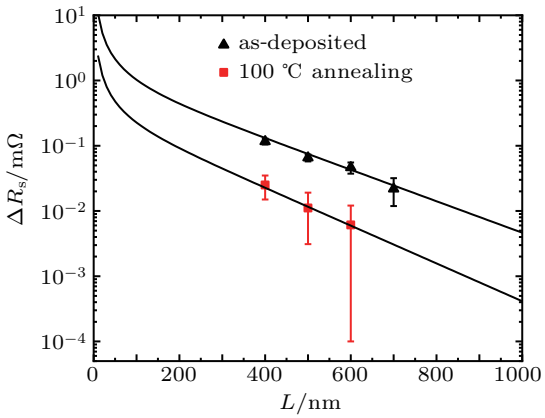


Fig. 3. (color online) The dependence of the spin accumulation signal on the center to center distance L. The black solid lines are fitting curves.

To investigate the thermal stability of lateral spin valves with transparent contacts, the devices are annealed in a rapid thermal process oven under nitrogen atmosphere at 100 °C for 30 min. Non-local measurement is performed on each device. Figure 2(b) shows the field dependence of the nonlocal spin accumulation signal after 100 °C annealing for the same device with 400 nm center to center distance. The spin accumulation signal drops from 0.12 mΩ to 0.025 mΩ. The spin accumulation signals of the devices with various center to center distances are plotted in Fig. 3 with red square (■). All the spin accumulation signals of the devices after 100 °C annealing are smaller than those of the as-deposited counterparts. The same process is performed to deduce the interfacial spin polarization and the spin diffusion length. By fitting the experimental data to Eq. (1), we find that after 100 °C annealing treatment, the spin polarization drastically drops from 8.6% to 3.4% and

the spin diffusion length slightly decreases from ∼ 180 nm to ∼ 150 nm. Thus the decrease of the spin accumulation signal should be due to the lower interfacial spin polarization as well as the shorter spin diffusion length.

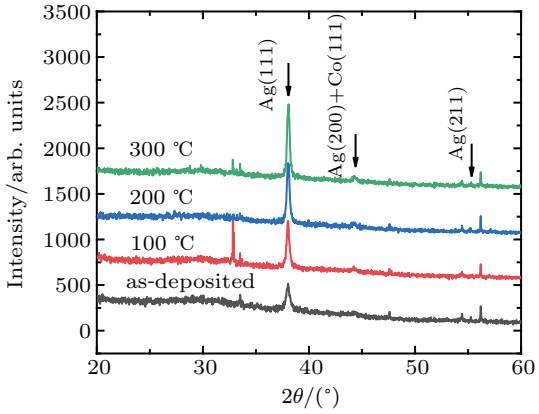


Fig. 4. (color online) XRD patterns for as-deposited, 100 °C annealed, 200 °C annealed, and 300 °C annealed Co/Ag films.

Further annealing up to 200 °C and 300 °C is carried out on the lateral spin valves. As shown in Figs. 2(c) and 2(d), the non-local measurement results show no spin accumulation signal and an intact device structure. Other samples with longer distances also give zero spin accumulation signals after 200 °C and 300 °C annealing. To clarify the changes of the spin accumulation signal after the thermal treatment, the microstructure of the samples before and after thermal treatment is studied by using x-ray diffraction (XRD). Figure 4 gives the XRD patterns of the as-deposited and thermal annealed Co/Ag films. For the Ag layer, all the samples before and after the thermal treatment show a (111) preferential orientation. For the Co layer, as the Co(111) reflection coincides with the Ag(200) reflection, the Co(111) reflection cannot be distinguished. It should be noted that there are no other reflections corresponding to Co. Thus we assume that the effect of the thermal treatment on the Co layer could be omitted. Unlike the Co layer, the intensity of Ag(111) increases with the annealing temperature increasing, indicating that the grain size of Ag becomes larger as the annealing temperature increases. In our experiment, the spin accumulation signal decreases after 100 °C annealing and vanishes after 200 °C and 300 °C annealing. It is hard to connect the drop and vanish of the spin accumulation signal with the change of the Ag grain size.

There are two main factors dominating the spin accumulation: the spin diffusion length and the interfacial spin polarization. To clarify the disappearance of the spin accumulation signal, lateral spin valves with Co/MgO/Ag junctions are fabricated and annealed at 300 °C for 30 min. As shown in Fig. 5, clear spin accumulation signal ∼ 1.8 mΩ is observed in this sample. Even after 400 °C annealing, the spin accumulation signal could be clearly observed in lateral spin valves with Co/MgO/Ag junctions.[26] As the interface is the only difference between these two lateral spin valves, the disappearance of the spin accumulation signal of the Co/Ag contact after high temperature annealing should be attributed to the zero interfacial spin polarization. One possible reason for the zero interfacial spin polarization may be the interdiffusion at the Co/Ag interface. Our results show that the interfacial spin polarization plays a dominant role in the spin accumulation.

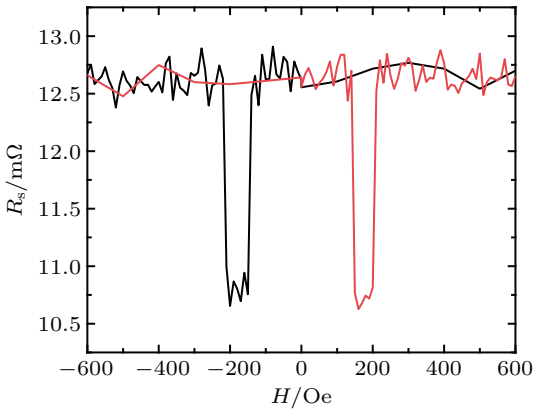


Fig. 5. (color online) The dependence of spin accumulation on the magnetic field for the lateral spin valve with Co/MgO/Ag junctions, the distance L between the injector and the detector is 400 nm.

4. Conclusion

We have successfully injected spin polarized current into the Ag wire from the Co electrode and detected the spin accumulation signal at room temperature in the lateral spin valves by the non-local measurement. By fitting the experimental results to a one-dimensional diffusion equation, ∼ 180 nm spin diffusion length of 50 nm Ag and ∼ 8.6% interfacial spin polarization of Co/Ag were deduced for the as-deposited devices. Thermal treatment (100 °C annealing) results show that the spin polarization drastically drops (3.4%) and the spin diffusion length slightly decreases (∼ 150 nm). Therefore, the spin accumulation signal significantly decreases after the thermal treatment. Our results demonstrate that, compared to the spin diffusion length, the decrease of the spin accumulation signal is mainly caused by the decrease of the interfacial spin polarization of the Co/Ag interface.

References

[1] Zutic I, Fabian J and Das Sarma S 2004 *Rev. Mod. Phys.* **76** 323
[2] Wolf S A, Awschalom D D, Buhrman R A, Daughton J M, von Moln A R S, Roukes M L, Chtchelkanova A Y and Treger D M 2001 *Science* **294** 1488
[3] Tserkovnyak Y, Brataas A and Bauer G E W 2002 *Phys. Rev. Lett.* **88** 117601
[4] Dyakonov M I and Perel V I 1971 *Phys. Lett. A* **35** 459
[5] Jedema F J, Filip A T and van Wees B J 2001 *Nature* **410** 345
[6] Fert A and Valet T 1993 *Phys. Rev. B* **48** 7099
[7] Silsbee R H and Johnson M 1985 *Phys. Rev. Lett.* **55** 1790
[8] Maekawa S and Takahashi S 2003 *Phys. Rev. B* **67** 52409
[9] Rashba E I 2000 *Phys. Rev. B* **62** R16267

[10] Zhao H L and Hershfield S 1997 *Phys. Rev. B* **56** 3296
[11] Murphy B A, Vick A J, Samiepour M and Hirohata A 2016 *Sci. Rep.* **6** 37398
[12] Kimura T and Otani Y 2007 *Phys. Rev. Lett.* **99** 196604
[13] Johnson M and Godfrey R 2006 *Phys. Rev. Lett.* **96** 136601
[14] Mihajlović G, Schreiber D K, Liu Y, Pearson J E, Bader S D, Petford-Long A K and Hoffmann A 2010 *Appl. Phys. Lett.* **97** 112502
[15] Ku J, Chang J, Han S, Ha J and Eom J 2006 *J. Appl. Phys.* **99** 08H705
[16] Ku J, Chang J, Kim H and Eom J 2006 *Appl. Phys. Lett.* **88** 172510
[17] Idzuchi H, Fukuma Y, Le Wang and Otani Y 2010 *Appl. Phys. Express* **3** 63002
[18] Liang S, Yang H, Renucci P, Tao B, Laczkowski P, Mc-Murtry S, Wang G, Marie X, George J, Petit-Watelot S, Djeffal A, Mangin S, Jaffrès H and Lu Y 2017 *Nat. Commun.* **8** 14947
[19] Dankert A and Dash S P 2017 *Nat. Commun.* **8** 16093
[20] Popinciuc M, Józsa C, Zomer P J, Tombros N, Veligura A, Jonkman H T and van Wees B J 2009 *Phys. Rev. B* **80** 214427
[21] Kimura T, Hamrle J and Otani Y 2005 *Phys. Rev. B* **72** 14461
[22] Valenzuela S O and Tinkham M 2006 *Nature* **442** 176
[23] Fukuma Y, Wang L, Idzuchi H, Takahashi S, Maekawa S and Otani Y 2011 *Nat. Mater.* **10** 527
[24] Erekhinsky M, Sharoni A, Casanova F and Schuller I K 2010 *Appl. Phys. Lett.* **96** 22513
[25] Idzuchi H, Fukuma Y, Wang L and Otani Y 2012 *Appl. Phys. Lett.* **101** 22415
[26] Zhao B, Zhang Z, Chen X, Zhang X, Pan J, Ma J, Li J, Wang Z, Wang L, Xu X and Jiang Y 2017 *J. Magn. Magn. Mater.* **432** 291