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Aging effect of spin accumulation in non-local spin valves

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ABSTRACT

A temporal evolution of spin accumulation of Co/MgO/Ag spin valves have been studied by using the nonlocal spin detection technique over almost a 3-month period in the ambient environment after the fabrication of the devices. Three different stages of the spin accumulation are first observed due to aging effect. The aging effect comes from two contributions–the gradual oxidation of the Ag/MgO and MgO/Co interfaces at the junctions' areas which arises from the annealing process and the oxidation of the side surfaces of the Ag channels. The theories of S. Takahashi and A. Fert are introduced to evaluate the different evolution stages of spin accumulation.

1. Introduction

Spintronics [1,2], which aims at manipulating not only the charge but also the spin of electrons, is a hot topic in condensed matter physics. With a great progress in the past decades, a new generation of spintronics devices could be achieved with pure spin current, which is an essential revolution in a promising spin-only circuit integrating logics and memories. The new devices based on spin current have been proved to have low power consumption and high speed to process information [3].

Non-local spin injection is one of the most effective methods to generate pure spin currents [4]. When the spin-polarized current is injected from a ferromagnet (FM) into a nonmagnet (NM), spins are accumulated in the vicinity of the FM/NM interface. The accumulated spins diffuse into the NM, decoupling a pure spin current from an electrical current. The non-local spin injection was first demonstrated by Johnson and Silsbee [4] in 1985. Then the experiment was revisited and improved by Jedema et al. [5,25] in 2001. It has motivated intensive experimental [6–10] and theoretical [11,12] research efforts in the optimization and enhancement for non-local lateral spin-valves (LSVs) related spintronics applications [23,9,24]. Up to now, however few people pay attention to the temporal evolution of the performance of spintronics devices during their whole lifetime. Monsma et al. [13] studied the spin-polarization evolving over time in ferromagnetic tunnel junctions at 0.25 K. Wang et al. [14] have studied the nonlocal spin signal, spin polarization and spin diffusion length as functions of time. However, the lifetime was limited because of the damage of the samples during measurement. Therefore, it is important to study how the device performance evolves during the lifetime. In this paper, by studying non-local LSVs with a stacking structure of Co/MgO/Ag, we try to figure out the mechanism behind the aging effect and propose some advice to raise the service efficiency of future spintronics devices.

2. Experiments

The Co (30 nm)/MgO (2.5 nm)/Ag (50 nm) four-terminal devices were prepared on Si/SiO_2 substrates by a shadow evaporation method, which makes it possible to deposit all the materials without breaking vacuum. The one step fabrication ensures perfectly clean interfaces between different materials [15]. Since the magnetic impurities attached to the side walls of non-magnetic channel will induce spin-flip scattering of conduction electrons and consequently reduce the spin diffusion length [14], we deposited Co first at an angle of 45° and then Ag at 90° to avoid Co impurities on the Ag side walls. All the materials were deposited at about 10^{-6} Pa. After the lift off process, the devices were annealed at 400 °C for 40 min in vacuum better than 5×10^{-5} Pa. All the samples were kept in vacuum after each measurement to maintain a long lifetime. Fig. 1(a) is the scanning electron microscopy image of a fabricated device. The bright parts are Ag (50 nm), covered by MgO (5 nm) as the protection layer. The dark parts are Co

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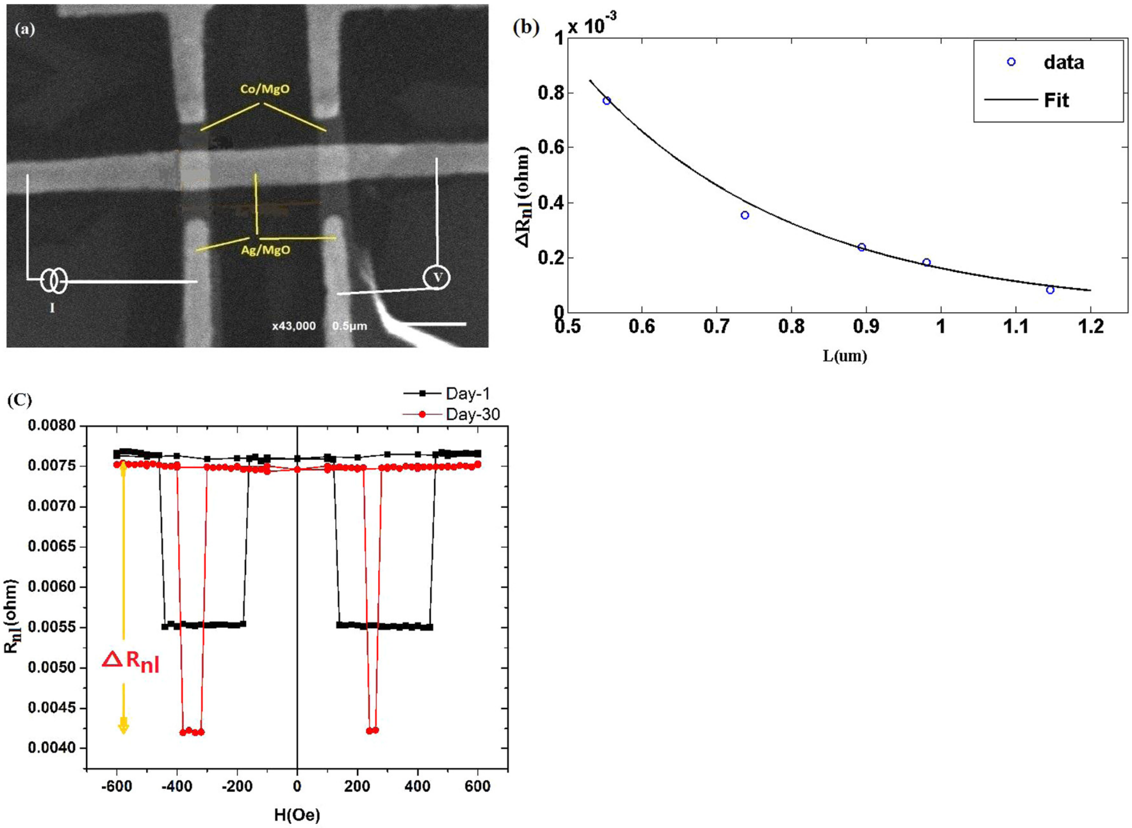

Fig. 1. (a) SEM of a four-terminal device. (b) Non-local spin signals ΔR_{nl} as a function of L. Solid line is the fitting curve by Eq. (1). (c) Nonlocal spin signals ΔR_{nl} of Sample 2 measured at different time.

(30 nm), covered by MgO (2.5 nm) as the tunneling barrier. The electrical measurements were performed with standard nonlocal techniques [4,5,16] in the ambient environment simulating the practical applications. A dc testing current was set in the range of 100 μA to 1 mA by using Keithley 2400, while the voltage signal was tested by Keithley 2182.

3. Results and discussion

As shown in Fig. 1(a), non-local spin injection measurements were performed on the LSVs to evaluate the spin diffusion lengths in the Ag channels. The spin signal is defined as $\Delta R_{\mathrm{nl}} = R_{\mathrm{P}} - R_{\mathrm{AP}}$ and $R_{(\mathrm{A})\mathrm{P}} = V_{(\mathrm{A})\mathrm{P}}/I$, where $V_{(\mathrm{A})\mathrm{P}}$ is the voltage measured for (anti)parallel magnetic electrodes under external magnetic field [16]. Fig. 1(b) shows the nonlocal spin signals ΔR_{nl} as a function of the distance L between the two Co electrodes. These results were measured as soon as the fabrication was finished. We estimated the spin diffusion length λ by the equation [12,17]

$$\Delta R_{\mathrm{nl}} = \pm \frac{4\mathrm{P}^2 R_{\mathrm{sq}}\lambda}{\mathrm{W}} \frac{(\mathrm{R}/\lambda)^2 \exp(-L/\lambda)}{(1+2\mathrm{R}/\lambda)^2 - \exp(-2L/\lambda)}, \tag{1}$$

where $R = \frac{R_c}{R_{\mathrm{sq}}} W$ represents the spin relaxation due to the finite contact resistances R_c in the junctions of both the injector and detector. R/λ represents the ratio between the contact resistance and Ag channel resistance over one spin-relaxation length. R_{sq} is the square resistance of the Ag channel, while W is the width and L the separation between the two Co electrodes. P is the effective polarization of the injector (detector). Eq. (1) is in agreement with the theory of S. Takahashi and S. Maekawa under our assumptions of negligible ferromagnet spin resistances with respect to the contact and Ag channel resistance and small polarizations of the injector and detector electrodes [12,17]. From the fit in Fig. 1(b), we have extracted $P = 0.22$, $\lambda = 285$ nm, which is comparable to the reference [18]. Fig. 1(c) shows the nonlocal signals of the sample with $L = 838$ nm measured at different time. The black curve (square) denoted as “day-1” was measured as soon as the fabrication was finished, while the red one (circle) denoted as “day-30” was obtained 30 days after the fabrication. When the magnetizations of the two electrodes are parallel, the base resistances are almost the same while the values of R_{nl} under the anti-parallel state are quite different over time. Additionally, there is a significant difference between the coercivity of the same device measured at day-1 and day-30. In our study, we attribute the difference of coercivity to the evolution of domain wall structures. It is the same device measured all through its life with the same bias current. Thus the shape and current could not cause the difference of coercivity. The role of domain walls is complicated in determining the device coercivity. The defects, such as grain boundaries and impurities, act as nucleation sites for reversed-magnetization domains. They may diffuse while the bias current was loaded.

Two samples were chosen to study the aging effect on their properties, one with $L = 640$ nm (Sample 1) and the other one with $L = 838$ nm (Sample 2). Fig. 2(a) gives the time dependence of the interface resistances (R_cA), nonlocal resistances (ΔR_{nl}) and resistivity (ρ) of the Ag channels, respectively. For both samples, the interface resistances increase to their saturation values and then decreases over time. Sample 1 cannot last long enough to go through a full cycle of its life due to the damage during the measurement. Other samples with the same structure showing similar trends or having been damaged during measurements are not displayed here. Fig. 2(b) presents the nonlocal spin-valve signals ΔR_{nl} as the function of the interface resistances R_cA for the two samples. Sample 2 shows a typical three-stage curve. Many literatures have