Spin Diffusion Characteristics in Magnesium Nanowires

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The spin diffusion characteristics of magnesium have been investigated by using lateral spin-valve structures consisting of permalloy spin injector and detector electrodes bridged by a magnesium-nanowire. Large spin valve signals of 3.6 and 1.1 mΩ were observed at 10 K and room temperature (RT). From the spin injector–detector distance dependence, the spin diffusion length in magnesium was determined to be 720 nm at 10 K and 230 nm at RT, indicating magnesium matches common materials such as Al, Cu, and Ag in terms of the spin diffusion length.

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Spintronics has drawn great attention in recent years because of novel functionalities derived from both the electronic charge and spin. The spin injection has thus been a key technique in the nanoscale spintronic device consisting of ferromagnetic and non-magnetic materials.[1,2] Injecting the spin-polarized electrons from ferromagnetic into nonmagnetic metals causes a split in the electro-chemical-potential near the interface.[3,4] This so-called spin accumulation decays exponentially over the spin diffusion length of the order of a few hundred nanometers.[5–7] For the device application, a long spin diffusion length is strongly desired. The origin of the spin relaxation in a metal is known mainly due to the Elliott and Yafet mechanism, where admixture of the opposite spin states due to spin–orbit interaction causes spin-flips via phonon and impurity scatterings.[8,9] Therefore, light metals such as Al and Mg could be suitable as a host nonmagnetic metal sustaining spin accumulation. To our knowledge, there is no report on the spin injection into Mg from the ferromagnetic metal whereas the spin diffusion length of Al is reported in the order of micrometer at low temperatures.[7] Here, we report the spin injection and accumulation characteristics in Mg nanowires.

Lateral spin-valve devices are fabricated by means of shadow evaporation using a suspended resist mask. The resist mask consisting of a bilayer resist 500-nm-thick methyl methacrylate and 50-nm-thick poly(methyl methacrylate) are prepared on Si/SiO_2 substrates by e-beam lithography. First, permalloy (Py) layer is e-beam deposited at an angle of 45° from substrate normal. After the deposition of Py, the substrate is transferred to the separate deposition chamber for Mg with a base pressure 5×10^{-10} Torr to prevent magnetic impurities worsening the spin diffusion length of Mg. Mg layer is e-beam deposited normal to the cooled Si/SiO_2 substrate by liquid nitrogen. Finally, 5-nm-thick MgO capping layer is deposited to avoid oxidation of the device surface. After the lift-off process, the device structure is checked by means of the scanning electron microscopy (SEM), as shown in Fig. 1. The 130-nm-wide spin injector and detector Py wires are bridged by a 170-nm-wide Mg wire. The thickness of Py and Mg is 20 and 100 nm, respectively. The center to center separation d between the injector and the detector is 400 nm in this device. In the present study, the separation d is varied from 300 to 1000 nm to determine the spin diffusion length λ_{Mg} of Mg. After the SEM observation, 10-nm-thick SiO_2 capping layer is also sputter deposited to prevent oxidation of side edges of the Mg nanowire.

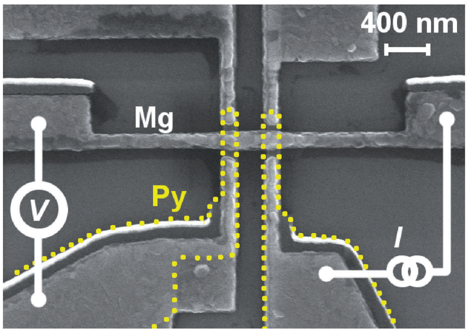

Fig. 1. SEM image of a fabricated lateral spin valve device. The region of Py electrode is marked by the dotted line.

The spin injection from Py into Mg is carried out by the non-local spin valve (NLSV) technique, as shown in Fig. 1. The NLSV measurements are performed by using conventional current-bias lock-in technique with amplitude of 0.20 mA with a frequency of 79 Hz. The magnetic field is applied parallel to the Py wires. The field dependence of the NLSV signal for the lateral spin valve with $d = 300$ nm is shown in Fig. 2, representing a clear spin valve behavior. The switching field of each Py wire is controlled by the domain-wall nucleation, i.e., the injector has a large domain wall reservoir at the edge, producing lower switching field than the detector. The spin valve signal ΔR_S is 1.1 and 3.6 mΩ at room temperature (RT) and 10 K, respectively. The interface resistance of the Py/Mg junction is below the resolution ability of 1 fΩ m^2 in our measurement system, and thus we assume that the Py/Mg junctions are transparent, i.e., zero interface resistance. The amplitude of ΔR_S is relatively high in the metallic lateral spin valves with the transparent ohmic contact such as Py/Cu, Co/Cu, and Co/Al junctions,[1,10–12] implying the high spin injection efficiency of the Py/Mg junction.

Figure 3 shows NLSV signal at 10 K for the Py/Mg devices with a variable separation $d = 400$, 600, and 800 nm. The spin valve signal ΔR_S decreases with increasing d due to a spin flip scattering in the Mg nanowire. A clear ΔR_S of 1.2 mΩ is observed for the device even with the long

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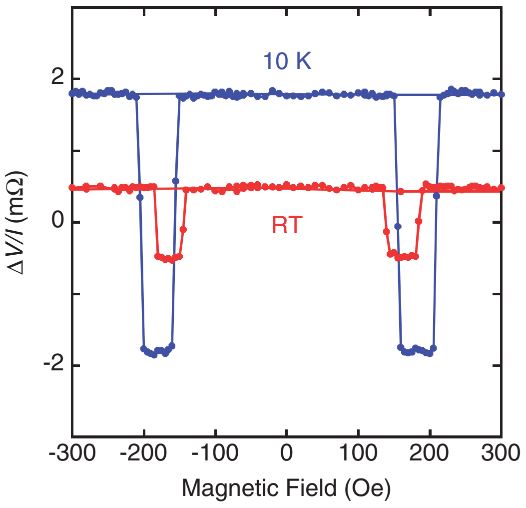

Fig. 2. Field dependence of nonlocal spin valve signal at 10 K and at RT for a device with the injector–detector separation of 300 nm.

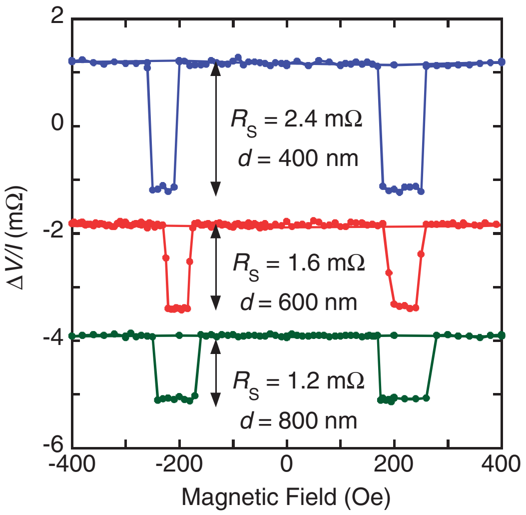

Fig. 3. Field dependence of nonlocal spin valve signal at 10 K for devices with the injector–detector separation of 400, 600, and 800 nm.

separation $d = 800$ nm. For the lateral spin valves with ohmic junctions, ΔR_S can be given as a solution of one-dimensional spin dependent diffusion equation considering additional spin relaxation in the Py detector whose spin resistance is much lower than that of nonmagnetic Mg.[13)]

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

where P_F is the spin polarization for Py. $R_{SN} = 2\rho_N\lambda_N/t_N w_N$ and $R_{SF} = 2\rho_F\lambda_F/w_F w_N/(1-P_F^2)$ are respectively the spin resistances for Mg and Py with resistivity ρ, spin diffusion length λ, thickness t, and width w. The subscripts F and N represent Py and Mg, respectively.

Figure 4 shows ΔR_S as a function of d at RT and 10 K. The experimental results are fitted to eq. (1) by adjusting

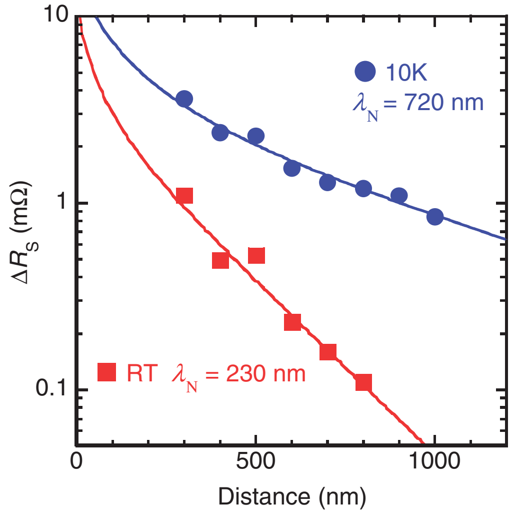

Fig. 4. Spin valve signals in Py/Mg spin valves as a function of the injector–detector separation. The lines are fitting curves to the data set using eq. (1).

parameters P_F and λ_N. For the Py/Mg devices in the present study, the resistivities of Py and Mg are 4.7×10^{-7} and 1.0×10^{-7} Ω cm at RT, and 3.5×10^{-7} and 4.0×10^{-8} Ω cm at 10 K, respectively. The spin diffusion length λ_F of Py is fixed to the value of 5 nm from the literature.[14)] From the fitting, the values of λ_N and P_F are respectively found to be 720 nm and 0.43 at 10 K, and 230 nm and 0.33 at RT. The value of P_F is relatively high in the lateral spin valve, indicating a good quality of the Py/Mg interface. The spin diffusion length of Mg shows a similar value reported for Ag, Cu, and Al.[7)] Among these nonmagnetic materials so far used in the lateral spin valves, Mg is a lightest element, implying a smallest spin–orbit interaction. However, the obtained spin diffusion length of Mg is below micron. This may be due to the existence of spin-hot-spots pointed out by Fabian and Sarma.[15)] Polyvalent metals such as Al and Mg have Fermi surfaces which cross Brillouin zone boundaries. This causes accidental degeneracy points between majority and minority spin bands and thus enhances the spin relaxation in the light metals. We stress here that this unexpected short spin diffusion length for the light element Mg is not attributed to the quality of Mg nanowire because the residual resistivity ratio (RRR) of our Mg nanowire is 2.5, which is in the same order of magnitude reported for Cu and Al nanowires (RRR = 2.1–3.4).[1,5,11)]

In summary, we have examined the spin diffusion characteristics in lateral spin valves consisting of Permalloy spin injector and detector electrodes bridged by Mg nanowire. Clear spin signals are observed for all the devices in the present study. The amplitude of the spin signal is relatively large among lateral spin values with transparent ohmic junctions. The spin diffusion length of Mg is found to be 720 nm at $T = 10$ K and 230 nm at RT from the measurement of the spin valve signal as a function of the separation between injector and detector. The obtained spin diffusion length for Mg is not much longer than that for Al, Cu, and Ag possibly because of existing spin–hot-spots in the vicinity of Brillouin zone boundaries.

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