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Spin relaxation mechanism in epitaxial Pt nanowires studied by spin absorption method

Department of Advanced Materials Science, 47-206036, Yasuyuki Hirai
Supervisor: Professor Yoshichika Otani

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1. Introduction, Motivation

Spintronics, a new field in electronics, utilizes electronic charge and spin degrees of freedom. Spin current, the flow of angular momentum, is a core concept in spintronics because pure spin currents flow with no charge current and therefore have no joule heating. That is beneficial to low power consumption electronic devices such as magnetic memories spin logic devices [1]. Thus, the efficient generation, detection, and long-distance propagation of the spin current are essential for developing spintronics. The spin-orbit interaction induces the interconversion between charge and spin currents, called direct and inverse spin Hall effects (SHEs). These effects have been utilized to generate and detect the spin current. Heavy elements such as Ta, Pt, and Bi exhibit large spin Hall angles (the conversion efficiency) due to the considerable spin-orbit interaction. In return, the spin currents decay in short distance (~10 nm), i.e., short spin diffusion length, in the heavy elements. The materials with both large spin Hall angles and long spin diffusion lengths would be beneficial in spintronic devices because they would work as an efficient generator and detector for spin currents at once. Moreover, the high order SHE can be expected in that material, in which SHE and inverse SHE occur consecutively [2].

Platinum (Pt) is a representative spin Hall material [3,4] that exhibits various spintronic phenomena, including the spin Seebeck effect, the spin-orbit torque magnetization switching, and the spin Hall magnetoresistance. We fabricated epitaxial Pt thin films with a conductivity one order of magnitude higher than that of polycrystalline Pt [2]. We have succeeded in observing high order SHE in this Pt thin film, and it is necessary to have a long spin diffusion length for it to occur. According to the Elliott-Yafet (EY) spin relaxation mechanism, the spin diffusion length λ is proportional to the electrical conductivity [5]. Also, the EY mechanism is used to explain the spin relaxation of metals, but the Dyakonov-Perel (DP) mechanism [6] may also make a significant contribution to the Pt thin film. Thus, we can expect large λ in this Pt. This study investigates the spin diffusion length and the spin Hall angle of the epitaxial Pt by spin absorption method in nonlocal spin valve (NLSV) structures. [7].

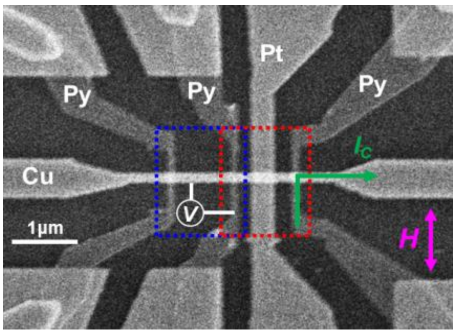

Figure 1. The scanning electron microscopy image of the NLSVs with and without Pt wire marked by blue and red squares, respectively.

2. Experimental

Figure 1 shows the scanning electron microscopy image of the NLSVs. A 61 nm-thick epitaxial Pt (111) thin film was grown on Al_2O_3 (111) substrate by sputtering and annealing process [2]. We fabricated the Pt film into a 200 nm wide- wire using electron beam lithography (EBL) and Ar ion milling. Two $Fe_{19}Ni_{81}$ (Py) wires were then deposited parallel to the Pt wire with a distance of 1 μm by EBL and e-beam deposition. The width and thickness of the Py wire (ω_{Py}, t_{Py}) are 100 nm and 30 nm, respectively. We finally deposited a Cu bridge wire perpendicular to Py and Pt wires. The width and thickness of the Cu wire (ω_{Cu} and t_{Cu}) are 100 nm. Each NLSV device contains two Py/Cu junctions, but one on the right-hand side has a Pt wire between the Py electrodes, as shown in the red dashed square in Fig. 1. When a spin-polarized current is injected from one Py electrode to the right of Cu wire, spins accumulate at the Py/Cu interface. The accumulated spins diffuse along the Cu wire, generating pure spin currents detected as a voltage by the other Py electrode. This structure prevents magnetoresistance from adding in principle since no charge currents in the detection electrodes. We defined the nonlocal resistance R_{NL} by dividing the measured voltage V_{NL} by the applied current I_C. The R_{NL} changes its sign when the relative orientation of the two Py magnetization of electrodes switches from parallel to antiparallel by sweeping magnetic field H. we define the spin valve signal as an overall change ΔR_{NL} from positive to negative. We measured the reference value $\Delta R_{NL}^{w/o}$ without the Pt wire (marked by the blue square in Fig. 1). In the device with the Pt wire (marked by the red square in Fig. 1), a part of the spin current diffusing along the Cu wire will be absorbed into the Pt wire and a spin valve signal ΔR_{NL}^{w} would be smaller than that without Pt wire. We estimate the spin diffusion length of Pt λ_{Pt} from the ratio of both spin valve signals. By repeating the measurement at different temperatures, we obtained the longitudinal conductivity σ_{Pt} dependence of λ_{Pt}.

3. Results and Discussion

Figure 2(a) shows the nonlocal spin valve signals ΔR_{NL}^{w} ($\Delta R_{NL}^{w/o}$) with (without) the Pt wire. The reduction of ΔR_{NL}^{w} is the evidence of that the spin current is absorbed into the Pt wire. The λ_{Pt} at 3.3 K is estimated to be 166±18 nm, which is ten times larger than that of polycrystalline Pt [5]. We plot the λ_{Pt} as a function of σ_{Pt} in Fig. 2(b). The λ_{Pt} increases with increasing σ_{Pt}, which is consistent with the EY relaxation mechanism as mentioned above. We also observed an σ_{Pt} independent component as a manifestation of the offset in the linear fitting result produced by the DP spin relaxation [6], where spins dephase between scattering events. According to the DP mechanism, λ_{Pt} is constant regardless of the σ_{Pt}. However, the slope of the plots is larger than that of the previous study [5], implying that the spin-orbit interaction in the epitaxial Pt is smaller than that of polycrystalline Pt. We did not detect any SHE and inverse SHE signal of the Pt in the same device. From the detection limit (~ 10 μΩ), we estimated the spin Hall angle to be lower than 0.04.

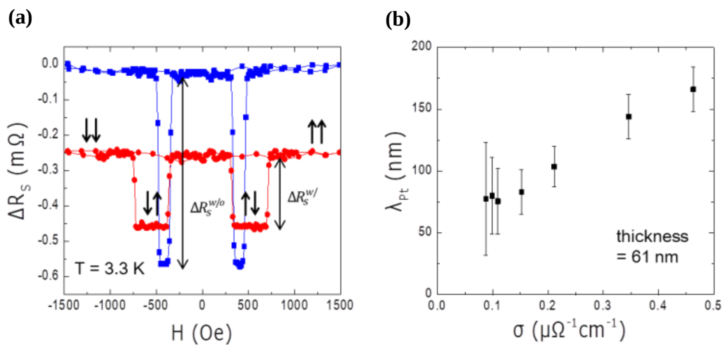

Figure 2. (a) NLSV signals as function of the magnetic field along Py wires. Red (blue) curve is measured in the devices with (without) the Pt wire, respectively. Black arrows show the magnetization directions of Py electrodes. (b) σ_{Pt} dependence of λ_{Pt}.

In addition, we confirmed the nonlocal spin valve signals using LSV structures with Pt bridge wire, in which two Py wires are bridged at a distance of 200 nm by an epitaxial Pt wire [8]. We detected the nonlocal spin valve signals. Since λ_{Pt} must be as long as several tens of nm or more to obtain this signal, this result implies λ_{Pt} is sufficiently large.

4. Summary

We investigated the spin diffusion length, and spin Hall angle of the Pt wire fabricated from the epitaxial thin films with high conductivity ~ $0.4\times10^6\ \Omega^{-1}\mathrm{cm}^{-1}$ by using the spin absorption method with NLSV structures. The spin diffusion length is ten times larger than that of polycrystalline Pt. The EY and DP mechanisms explain the linear variation and long λ_{sd} in our epitaxial Pt. We could not detect SHE and inverse SHE signals in the spin absorption method. This is because the signal magnitude is expected to be lower than the detection limit. We plan to measure the inverse SHE of the epitaxial Pt by the local spin injection with a ferromagnetic wire on the T-shaped Pt wire, where the spin-polarized currents are injected directly to the Pt from the adjacent ferromagnet.

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Presentation

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