Spin Hall effect in Molybdenum wires

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The spin Hall effect in molybdenum wires has been experimentally investigated by means of spin absorption method using lateral spin valve structure. The spin Hall conductivity of Mo wire is negative and decreases with increasing the resistivity. These tendencies are surprisingly consistent with the recent theoretical calculation based on the intrinsic spin Hall effect. © 2009 American Institute of Physics [DOI: 10.1063/1.3076145]

Spin-orbit interaction influences the transport properties of conduction electrons and induces the nontrivial physical properties. Anisotropic magnetoresistance effect1 and anomalous Hall effect (AHE) (Ref. 2) in ferromagnets are well known phenomena originated from spin-orbit interaction. Similar transport phenomena are also induced in nonmagnets. One of the phenomena is a spin Hall (SH) effect (SHE) (Ref. 3) caused by the same mechanism of the AHE.4 In the presence of the spin-orbit interaction, the charge current in the nonmagnet produces the transverse spin currents. Although the SHE was theoretically expected long time ago,3 there has been no experimental demonstration. However, progress in spin injection and detection techniques enable us to study the SHEs in nonmagnetic materials.5–9 Especially, recent experiments revealed large SH conductivities in metallic systems.9,10 For example, SH conductivity for Pt is 2.4×10^4 S/m at room temperature, which is about 10^4 times larger than that reported in n-type semiconductors.9 Since SHE can be used for generating the spin current without ferromagnets, exploring the material with large SHE is a challenging issue from the technological view point.

SHE is theoretically discussed in terms of two completely distinct physical mechanisms. One is intrinsic and the other one is extrinsic. Two different mechanisms, skew scattering11 and side jump,12 are known as extrinsic origins for SHE. These mechanisms were intensively studied a few decades ago as AHEs of the ferromagnets. On the other hand the intrinsic SHE is a band-structure effect and is independent of impurity scattering.13 Interestingly, recent theoretical study shows that SHE observed in the Pt wire can be regarded as intrinsic SHE.14,15 However, the extrinsic SHE is also a possible origin for the observed SHE. Thus identifying the origin of the SHE is still a controversial issue. Very recently, theoretical calculations based on intrinsic SHEs showed that the magnitude and sign of SH conductivities for 4d and 5d transition metals change systematically with respect to the number of d electrons.16 Therefore, the experimental study of SHEs in various transition metals may help to distinguish the origin of the observed SHE. In this paper, we study the SHE in molybdenum, which is one of 4d transition metals.

We employed the spin absorption method using lateral spin valve structure to study SHE in Mo wire. In this method, the injected spin current into the Mo wire can be accurately estimated from the nonlocal spin valve signal.17,18 This enables us to evaluate quantitatively the SHE conductivity of the material with a large spin-orbit interaction. Figure 1 shows a scanning electron micrograph of the fabricated device for the present study. The device was fabricated through three lift-off processes. First, we fabricated a pair of Permalloy (Py) wires 30 nm in thickness and 100 nm in width by the electron-beam evaporation. Then, the middle Mo wire was inserted by rf magnetron sputtering. Here, we use two kinds of Mo wires (Mo1 and Mo2) fabricated by conventional lift-off processes with different resists ZEP520A (Nippon Zeon Corporation) and polymethymethacrylate (PMMA), respectively. The size of Mo1 is 30 nm in thickness and 200 nm in width, while that of Mo2 is 10 nm in thickness and 100 nm in width. As we reported in Ref. 19, the resistivity of the sputtered wire with PMMA resist mask is increased because of codeposition of PMMA. In the present case, the resistivities of Mo1 and Mo2 wires are 33 and 150 µΩ cm, respectively. Finally, a Cu strip is fabricated by a joule evaporator. Prior to the Cu evaporation, a careful Ar ion beam etching was carried out for cleaning the surface to obtain highly transparent ohmic contacts. The dimensions of the Cu wire are 150 nm in width and 100 nm in thickness. In all lateral spin valve devices, the...
center to center distance between the Py wires is fixed to 1 \( \mu \text{m} \). In inverse SHE measurements, the voltage induced along the Mo wire is measured by applying the charge current \( I_c \) from the Py wire to the Cu wire as shown in the inset of Fig. 3(a). In the direct SHE measurement, the voltage between the Cu and Py wires is measured by applying \( I_c \) along the Mo wire as shown in the insets of Fig. 3(b). The measurements were carried out by using ac lock-in technique with the charge current amplitude of 100 \( \mu \text{A} \) and the frequency of 173 Hz in a He flow cryostat.

First, we measured the nonlocal spin valve signal to evaluate the spin current injected into the Mo wires precisely. The spin signal is defined by the resistance change between parallel and antiparallel states and the resistance is defined by the nonlocal voltage divided by the injecting charge current. As we already reported, when an additional wire is inserted in the middle of the lateral spin valve, the spin signal decreases because of the spin absorption into the middle inserted wire. One-dimensional spin diffusion model with transparent interfaces yields the ratio of the spin signal with and without a Mo insertion, \( \Delta R_{\text{with}} \) and \( \Delta R_{\text{without}} \), as

\[
\frac{\Delta R_{\text{with}}}{\Delta R_{\text{without}}} = \frac{R_{\text{Mo}}}{R_{\text{Cu}}} \frac{\sinh \left( \frac{d}{\lambda_{\text{Cu}}} \right)}{\cosh \left( \frac{d}{\lambda_{\text{Cu}}} \right) - 1} + \frac{R_{\text{Mo}}}{R_{\text{Cu}}} \frac{\sinh \left( \frac{d}{\lambda_{\text{Cu}}} \right)}{\lambda_{\text{Cu}}},
\]

where \( R_{\text{Mo}} \) and \( R_{\text{Cu}} \) are the spin resistances for the Mo and Cu wires, respectively, and \( \lambda_{\text{Cu}} \) is the spin diffusion length for the Cu wire and \( d \) is the center-center distance between two Py wires (1 \( \mu \text{m} \) in the present study). Therefore, \( R_{\text{Mo}} \) can be estimated from the magnitude of the reduction in the spin signal.

Figures 2(a)–2(c) show the nonlocal spin valve signals for without Mo wire, with Mo1 and with Mo2, respectively. All devices exhibit clear spin signals and spin absorption effects for both Mo1 and Mo2 wires. These assure that the spin currents are really injected into the Mo wire via the Cu strips. The magnitude of the reduction in the spin signal of Mo1 is larger than that of Mo2, from which \( R_{\text{Mo1}} \) and \( R_{\text{Mo2}} \) are estimated as 0.25 and 0.65 \( \Omega \), respectively. This indicates that Mo2 has larger spin resistance than that of Mo1, reflecting the larger resistivity of Mo2 than that of Mo1.

Then, we began with the inverse SHE measurement for Mo1. The inverse SHE measurements were carried out by measuring the voltage along the Mo wire under the nonlocal spin injection as shown in Fig. 3(a). As described above, the injected spin current is preferably absorbed into the Mo wire. The spin current injected into the Mo wire attenuates over the spin diffusion length of the order of 10 nm, the flowing direction of which is thus almost perpendicular to the junction. When the magnetization of the Py injector corresponding to the quantized axis of the spin current is parallel to the Cu strip, the charge current is induced along the Mo wire in accordance with the relationship \( \mathbf{S} \times \mathbf{I}_\text{p} \) with the spin polarization vector \( \mathbf{S} \) and the spin current density \( \mathbf{I}_\text{p} \). Since the induced charge current is reversed by switching the magnetization, the inverse SH signal can be evaluated as the overall voltage change in the transverse magnetic field sweep. As in Fig. 3(a), the charge accumulation due to the inverse SHE is clearly seen as an overall resistance change of 80 \( \mu \Omega \).

The direct SHE was also measured by exchanging the voltage and current probes. In this configuration, the spin accumulation induced by SHE in the Mo wire is transmitted through the Cu strip to the Py voltage probe to be measured as nonlocal spin valve signal. Figure 3(b) shows the field dependence of the spin accumulation due to direct SHE of the Mo wire. We also see clear spin accumulation signal with overall resistance change of 80 \( \mu \Omega \). One should note that \( \Delta R_{\text{SH}} \) is the same as that of \( \Delta R_{\text{DSHE}} \), indicating the reciprocal relationship between the charge and spin currents.

The spin Hall conductivity of Mo can be calculated by the following equation:

\[
\sigma_{\text{SHE}} = \frac{w_{\text{Mo}} \sigma_{\text{Mo}}}{I_c/I_s} \Delta R_{\text{SHE}},
\]

where \( w_{\text{Mo}} \) and \( \sigma_{\text{Mo}} \) are the width of the Mo wire and the conductivity of the Mo wire. \( \sigma_{\text{Mo}}, \Delta R_{\text{SHE}} \) can be directly measured by the experiment. \( I_c/I_s \) is the ratio of the injected spin current \( I_s \) into Mo wire to the excitation charge current \( I_c \). This can be obtained from the results of nonlocal spin valve measurement. Here, we did not take into account small effect of Mo thickness dependence on the SH conductivity. The calculated SH conductivity is \( 7.0 \times 10^3 \) S/m at 10 K.
which is much smaller than that of Pt. The spin Hall angle is $2.0 \times 10^{-3}$.

Finally, we discuss the SHE observed in Mo wires. First, we examine the sign of the SH conductivity of the Mo wire. Figure 4(a) shows the inverse SHE in a Pt wire with the same probe configuration. The slope of the SHE is opposite to that in Fig. 3(a). This means that the sign of the SH conductivity of Mo wire is negative. This is consistent with the theoretical calculation based on the intrinsic SHE. We then measured the inverse SHE of Mo2. As seen in Fig. 4(b), $\Delta R_{\text{SHE}}$ in Mo2 was larger than that in Mo1 because of the large resistivity of Mo2. However, the calculated SH conductivity was $0.5 \times 10^3$ S/m about a factor of 3 smaller than that in Mo1. Surprisingly, this tendency is also seen in the theoretical calculation. Thus, the observed results infer the intrinsic origin of the SHE.

In conclusion, we have fabricated lateral spin valves with Mo insertions to study spin Hall effect in molybdenum. The spin Hall conductivity for Mo is found to have negative sign. This is consistent with the recent theoretical calculation based on the intrinsic spin Hall effect. The resistivity dependence of the spin Hall conductivity also agrees with the theoretical results.

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