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Detecting Spin Hall Signals of Permalloys and Heavy Metals through the Inverse Spin Hall Effect

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A sample with the spin Hall effect causes spin-orbit coupling to induce spin-polarized electrons that accumulate inverse signals on either side of the sample. In this study, a multiterminal device was fabricated using a tantalum Hall bar and a spin injector of the permalloy nanowire to detect inverse Hall effect signals. This device can read the different spin Hall signals emitted from the magnetic state of the permalloy wire. Our results reveal that the different magnetic states of the permalloy wire cause an asymmetric shift of the inverse spin Hall voltage and also display various signals at opposite directions of currents. As the input current increases, the voltage also exhibits nonlinear growth. This indicates that the inverse spin Hall signals are affected by the magnetic state of the permalloy wire and the input current direction. This also indicates that the inverse spin Hall signals from the multiterminal device can inspire the design of the sensor for detecting spin electrons and neuron-like magnetization states.

1. Introduction

Artificial intelligence, pattern recognition, and artificial neural computing pattern recognition have recently attracted considerably attraction. Some research groups proposed a concept of neuro-inspired computing that employed spintronics or domain wall-based devices. Therefore, the spin Hall effect (SHE) and its detection also attracted attention.(1,2) When a current flows through a conductor and a magnetic field is applied perpendicularly to the direction of the current, a force known as the Lorentz force affects electrons, causing them to shift perpendicularly to the direction of the current. Consequently, an electric potential difference is generated on both sides of the conductor. This phenomenon was discovered by Edwin Hall in 1879 and was therefore called the Hall effect. In the 1970s, Dyakonov and Perel(3) predicted the existence of the SHE. They discovered that, despite the absence of an external magnetic field perpendicular to the direction of the current, spin-up carriers shifted to one side and spin-down carriers shifted to the other side because of the spin-orbit coupling (SOC) effect. In addition, a spin polarization current was generated in the direction perpendicular to the flow

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of the charges. However, because the spin-up and spin-down carriers have the same concentration, the electric potential difference on both sides is zero. A new phenomenon called the inverse SHE (ISHE) has been observed in thin metallic films, highlighting the conversion of spin current into charge current.(4) After Albert Fert and Peter Grünberg discovered giant magnetoresistance materials,(5,6) many researchers started to focus on spin-related transport. Generally, various methods can be used to generate spin current.(7,8) For instance, SOC can be used to induce a spin current on the surface of a material.(9) When a material produces a temperature gradient, spin flow occurs, which is also known as the spin Seebeck effect.(8–10) Similarly, when microwaves pass through a ferromagnetic material under resonance, ferromagnetic resonance is produced, which in turn generates a spin current that is injected from the ferromagnetic material to a nonferromagnetic material. This phenomenon is called spin pumping.(11,12)

Shunting occurs when a current flows through the interface between two materials. This scenario is analogous to a parallel circuit in the which current flows to the material with higher conductivity. Consequently, the currents passing through the two materials are not identical. Therefore, to determine the ratio of shunting, both electrical conductivity and material thickness must be considered. In this study, we investigated the effect of shunting on spin Hall angle measurements. Because the spin diffusion length of copper is large, we use it as a channel for spin electron transport. Therefore, we fabricated a sub-micron wire with a copper thin film and then put the tantalum Hall bars to detect spin Hall signals. As mentioned, shunting occurs when a current flows through the interface of two different materials, and this effect partly originates from the differences in conductivity and SHE. This indicates that inverse spin Hall signals are affected by the magnetic state of the permalloy wire and the input current direction. Therefore, the design of the sensor can detect spin electrons and neuron-like magnetization states.

2. Materials and Methods

When a current passes through a tantalum layer, SOC occurs, and spin-up and spin-down electrons shift in opposite directions. Tantalum has two crystal phases, namely, an α-phase and a β-phase. Compared with the α-phase, the β-phase is associated with stronger SOC. Because each crystal phase is associated with unique resistivity, we used the resistivity to identify crystal phases. The α-phase is associated with the resistivity of 15–60 μΩ·cm and the β-phase is associated with the resistivity of 170–210 μΩ·cm.(13)

Many factors can affect the characteristics of the thin film in the sputtering process. In this study, we examined the relationship between thin-film thickness and resistivity. After testing, we established a background pressure of 2×10^{-7} mTorr, a gas flow rate of 20 sccm, a rotation speed of 20 rpm, and a working pressure of 3 mTorr as optimal sputtering parameters. These parameters enabled depositing a β-phase thin film. In addition, we selected such thin films with a thickness of 8 nm to obtain a current with 2D-like behavior during transmission.

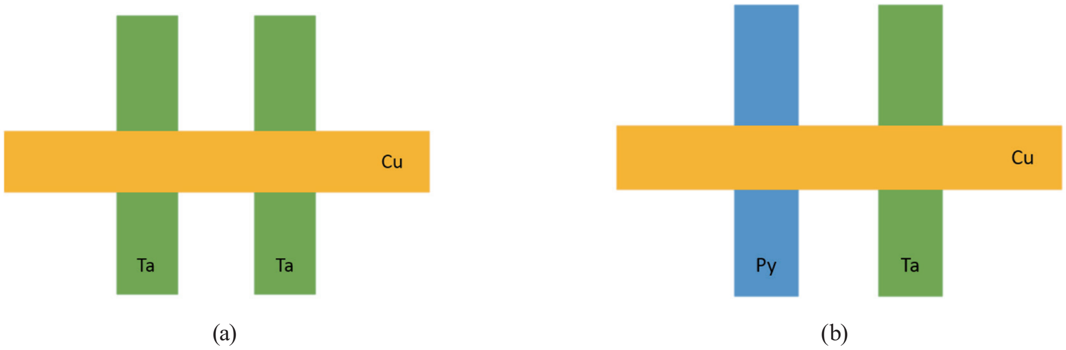
Nonlocal measurement is a common technique for measuring spin current. In nonlocal measurement, the applied current and the measured voltage are located on different lines.(14,15) This current induces SOC to generate a spin current. When this spin current diffuses into another wire, an ISHE occurs, and the spin current is converted into a charge current, which can be measured from the voltage of the wire.(16–20)

In this experiment, we used silicon dioxide as a substrate. Samples were cleaned using acetone and isopropanol, and an electrode pattern was established using photolithography. A thin-film electrode was then deposited through the thermal evaporation of chromium and gold. Chromium was used to stabilize gold on the substrate. Subsequently, electron-beam lithography was used to fabricate a Hall bar, and then magnetron sputtering was used to deposit permalloy, tantalum, and copper films. After liftoff, the sample was complete. As shown in Fig. 1, we fabricated Hall bars to examine the shunting effect and SHE. The thicknesses of the permalloy, tantalum, and copper bars were 20, 8, and 10–40 nm, respectively.

3. Results and Discussion

Four-point measurements were conducted to obtain the current–voltage (*I*–*V*) curves for the samples. Keithley 6221 was used to input a current and Keithley 2182A was used to measure the voltage. The input current started at 1 μA and was increased every 1 μA until it reached 50 μA. To confirm whether these *I*–*V* curves followed Ohm's law, linear regression was performed. First, we carried out an *I*–*V* measurement for a β Ta wire only. Then, we deposited the copper wire perpendicularly to the Ta wire, as shown in Fig. 1(a), and measured the *I*–*V* curve again. The data showed that both curves were consistent with Ohm's law and their shunt parameters were calculated.

According to our measurement results and the effects of the shunting parameters on material thickness, the shunting effects of copper with thicknesses of 10 and 20 nm were 0.58 and 0.44, respectively. When the current passed through copper with a thickness of 10 nm, 58% of the current flowed through the lower layer of tantalum, thus triggering a SHE in tantalum. By contrast, when current passed through copper with a thickness of 20 nm, only 44% of the current flowed through the lower layer of tantalum, also triggering a SHE in tantalum. Because the conductivity of tantalum is considerably lower than that of copper ($\sigma_{Ta}/\sigma_{Cu} = 0.005$), when the current flowed through the interface of the thicker copper sample, most of it flowed into the



(a) (b)

Fig. 1. (Color online) Experimental patterns used in this study: (a) shunt parameter and (b) nonlocal measurements.

copper, resulting in a small shunting parameter. These results indicated that no proportional increase occurred in the measured voltage when the current was increased. An analysis of negative voltage changes revealed that resistance varied logarithmically. In the double-layered structure at the intersection, measurements of the shunting effect revealed that changes in the magnitude of current did not affect the measurement results.

In the second part of the experiments, we conducted nonlocal spin valve measurements to detect anomalous Hall voltages and spin Hall signals. We changed the magnitude of the current to establish an *I*–*V* curve, and we observed the trends of resistance change. To evaluate the stability and accuracy of our measurement system, we conducted a relatively simple test, namely, a current transmission test. As shown in Fig. 2, we designed a six-cross structure for measurement and used tantalum and copper as materials for the vertical and horizontal lines, respectively. Using a four-point measurement technique, we applied a square wave current (defining downward as a positive current) to a single tantalum strip and measured the voltage of the neighboring tantalum strip. The current magnitude was set to 10 A. As expected, we detected a voltage signal similar to a square wave. As the distance between the tantalum strips increased, the measured voltages decreased. These results demonstrated that when the direction of the input current was changed, the transmitted electrons were shifted in different directions, resulting in both positive and negative voltages.

As shown in Fig. 1(b), we injected square waves into a double cross device and measured the voltage. Permalloys have a magnetic saturation of approximately 860 emu/cc. We applied external magnetic fields of +1000 and −1000 Oe along the long axis (easy axis of magnetization) to ensure a magnetic saturation state. By passing a current with a square wave through the Py ferromagnetic layer, we measured a square wave signal at the tantalum end. When a current passed through tantalum, a spin current was initially generated at both ends of the segment as a result of the SHE. However, as this current passed through the ferromagnetic layer first, the magnetization direction affected the types of spin electrons that could traverse. Consequently, the electrons reaching the measurement terminal were affected by the magnetization state of the ferromagnetic layer.

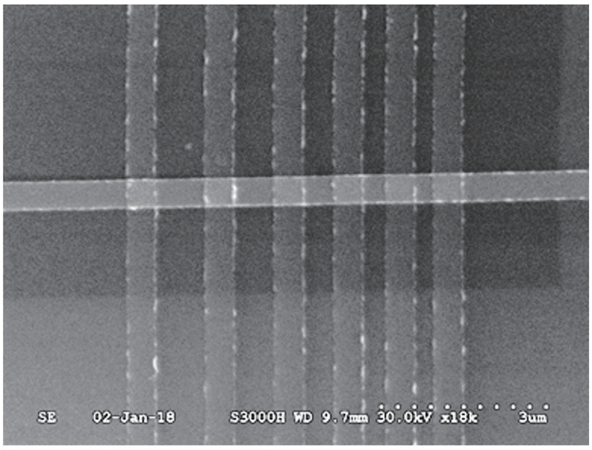


Fig. 2. SEM image of the six-cross Hall bar. Tantalum and copper were used as materials for the vertical and horizontal wires, respectively.

Ferromagnetic materials are characterized by anisotropic magnetoresistance (AMR). In this study, after applying an external field to the easy and hard axes of the ferromagnetic layer, we measured the voltage and obtained the AMR ratio. We then changed the materials of the six-cross structure to tantalum for the vertical lines and permalloys for the horizontal lines. In this structure, the magnetization state of the ferromagnetic layer affected the transmission of electrons between the two tantalum wires.

As mentioned, previous experiments have indicated that the ferromagnetic layer can control the transmission of spin electrons in the easy-axis magnetization direction. Therefore, in this study, we separately measured the magnetic fields applied along the hard and easy axes. Because the magnetic saturation field was greater along the hard axis than along the easy axis, we adjusted the magnetic field for measurement along the hard axis to ±2500 Oe. Finally, we determined the average of the easy and hard axes and calculated AMR as 4.90%.

Our measurement results revealed a slight discrepancy between the waveforms of the measured voltage and the input current. The voltage signal appeared to shift in a certain direction. Therefore, we conducted another measurement with the remaining input current as a square wave but varied the current magnitude. The results are presented in Fig. 3. With a magnetic field fixed at 2500 Oe, when the current was increased from 10 to 320 μA, the measured voltage also increased, and the asymmetry became more pronounced. To confirm this correlation, voltages with both positive and negative currents were extracted, and the relationship between voltage and current is plotted in Fig. 4. The results indicated that the voltage variations observed in the two directions did not follow a linear relationship. As the current increased, the voltages in the positive direction rapidly increased until they reached a constant value as shown in Fig. 4(a). In the negative direction, the voltages increased more gradually and did not plateau at a certain value before 320 μA. This phenomenon presumably occurred because of the differential proportion of spin channels formed within the magnetized ferromagnetic layer as the electrons polarized by the SHE. Only the electrons that passed through the ferromagnetic layer were measurable at the other end through the inverse SHE, resulting in asymmetry. Because the

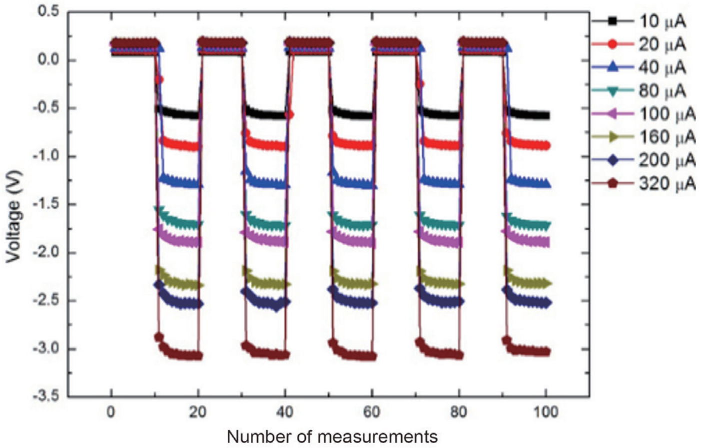
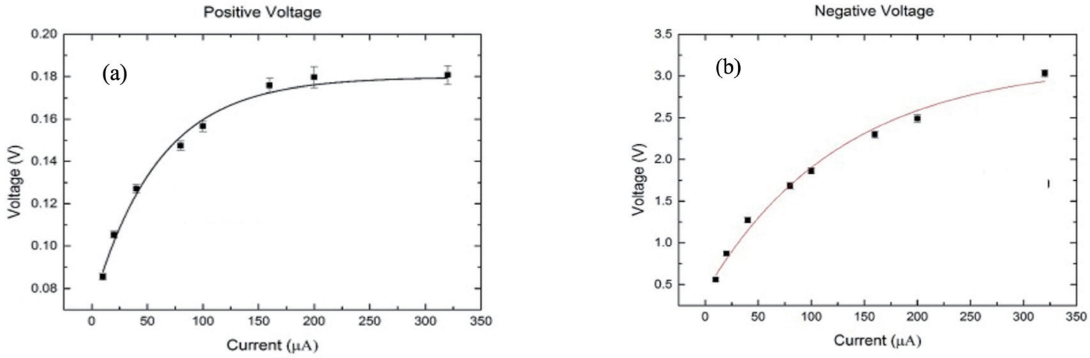


Fig. 3. (Color online) Voltages versus different input currents of a square wave within a positive magnetic field.



(a) (b)

Fig. 4. (Color online) I–V curves of the positive (a) and negative (b) voltages in Fig. 3.

resistance of the ferromagnetic layer was not identical for electrons with opposite spin directions, two distinct curves were observed in Figs. 4(a) and 4(b). In addition, the current passing through the tantalum layer changed the proportion of spin electrons. The effects occurred simultaneously with each other. Therefore, increasing the magnitude of the current merely increased the likelihood of electron diffusion to the other end, resulting in varying levels of voltage increase. Therefore, if these mechanisms are not considered, errors may arise in spin Hall angle measurements. In the future, we intend to measure the spin Hall resistances of different materials and estimate their spin Hall angles in order to design other spin devices.

4. Conclusions

In this study, multiple measurements were conducted to examine the shunting effect and SHE. The results indicated that the magnetization state of the ferromagnetic layer resulted in substantial variations in resistance for spin electrons. The anomalous magnetoresistance was also calculated. Overall, the final structure combined the anomalous Hall effect and SHE on electron spin, and the number of polarized electrons and channel size affected the behavior of electron diffusion. Therefore, the inverse spin Hall signals from this multiterminal device can inspire the design of the sensor for detecting spin electrons. These results open a way toward a spintronic application that detects neuron-like magnetization states.

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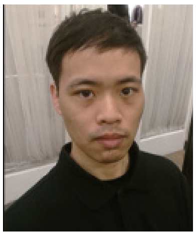

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