Applied Physics Express

LETTERS

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To cite this article: Taisei Ariki *et al* 2017 *Appl. Phys. Express* **10** 063004

Applied Physics Express **10**, 063004 (2017)
https://doi.org/10.7567/APEX.10.063004

Effective suppression of thermoelectric voltage in nonlocal spin-valve measurement

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Received April 13, 2017; accepted April 27, 2017; published online May 18, 2017

We demonstrate that the background signal in the nonlocal spin-valve measurement can be sufficiently suppressed by optimizing the electrode design of the lateral spin valve. A relatively long length scale of heat propagation produces spin-independent thermoelectric signals under the combination of the Peltier and Seebeck effects. These unfavorable signals can be reduced by mixing the Peltier effects in two transparent ferromagnetic/nonmagnetic junctions. Proper understanding of the contribution from the heat current in no spin-current area is a key for effective reduction of the spin-independent background signal.

Spintronics is a research field for understanding and utilizing quantum properties of electron spin, which is one of the exciting subjects in condensed matter physics.[1–5] Recent developments in nanofabrication techniques enable us to realize laterally configured ferromagnetic/nonmagnetic metal hybrid nanostructures. In such systems, various intriguing phenomena can be induced in association with spin-dependent transport. However, owing to a small magnitude of spin-related signal, it is very hard to evaluate spin transport precisely. The nonlocal spin-injection technique is a powerful mean for detecting small spin-related signals because current-induced spurious signals can be suppressed significantly.[6–10] However, even in the nonlocal configuration, the detecting voltage includes large spin-independent background signals, which are serious obstacles for the reliable operation of spin-based memory and logic circuits.

There are several models for explaining the origin of spin-independent background signal in the nonlocal configuration. One is the current-spreading effect in the vicinity of the injecting junction, as discussed by Johnson and Silsbee.[11] This effect becomes important when the linewidth of the metallic wire is larger than the interval and/or the film thickness. Spin-dependent scattering at the detecting junction has been considered as one of the possible reasons for the background voltage with the different mechanism.[12] However, this mechanism is difficult to explain the experimental results quantitatively and systematically. The most important contribution for the nonlocal background voltage is believed to be the interplay between the Peltier and Seebeck effects.[13] The spin injection across the ferromagnetic/nonmagnetic junction produces the Peltier heating/cooling effect, resulting in heat propagation through the nonmagnetic strip. This heat current produces the measurable electrical voltage because of the Seebeck effect in the detecting junction with a relatively large Seebeck coefficient for a ferromagnetic metal. Although this mechanism provides the quantitative explanation, nobody focuses on the suppression of the background voltage. In particular, in nanosized electronic devices, suppression and/or reduction of the background signals are important for the reliable operation of spin-based devices.[14] Here, we demonstrated that the background voltage can be minimized by preparing an additional injecting junction. In addition, we showed that the outside terminal of the lateral spin valve contributes to the nonlocal background signal significantly.

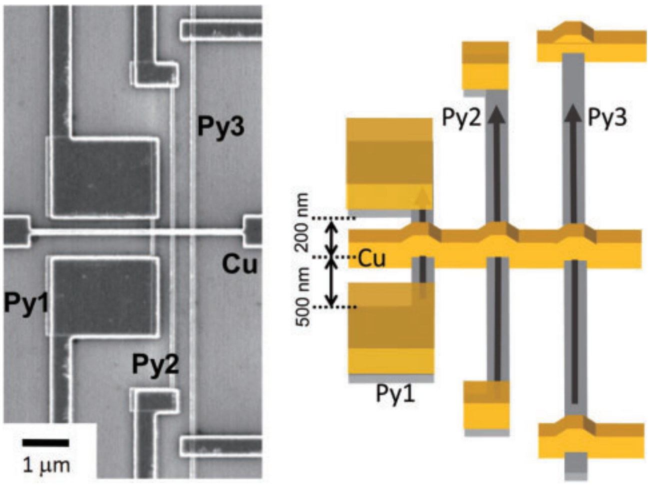

Fig. 1. SEM image for the fabricated lateral spin valve consisting of triple ferromagnetic Py wires, Py1, Py2, and Py3 with a nonmagnetic Cu strip together with a schematic illustration of the fabricated lateral spin valve. Here, the location of the Cu strip is shifted to the upper side from the center of the Py wires.

A lateral spin valve consisting of three ferromagnetic wires bridged by a Cu strip has been fabricated on a SiO_2/Si substrate by the two-step lift-off process. First, the ferromagnetic permalloy (Py) wires were fabricated by using electron-beam lithography and an electron-beam evaporator. The base pressure during Py evaporation was 10^{-8} Pa. The thickness of the Py film was 20 nm. Then, we deposited a 200-nm-thick Cu film by using a Joule evaporator in order to make a strip bridging the ferromagnetic Py wires. Here, the widths of the Py wires and the Cu strip are fixed to be 80 nm. The electrical resistivities of the Py and Cu wires are 35 and 2.8 μΩ cm at room temperature, respectively. The interfaces between Py and Cu were well cleaned by low-voltage ion milling, resulting in highly transparent interfaces. Figure 1 shows the schematic illustration of the fabricated lateral spin valve together with the scanning electron microscopy (SEM) image. Here, the three ferromagnetic wires have different end shapes, resulting in different coercive fields.[9] We emphasize that the Cu strip is slightly shifted to the upper side from the center of the Py wires. The spin and heat transports were evaluated by the standard current-bias lock-in detection technique with the first-harmonic voltage response under an excitation current of 100 μA. In this measurement, we can neglect the influence of the thermal spin injection because the

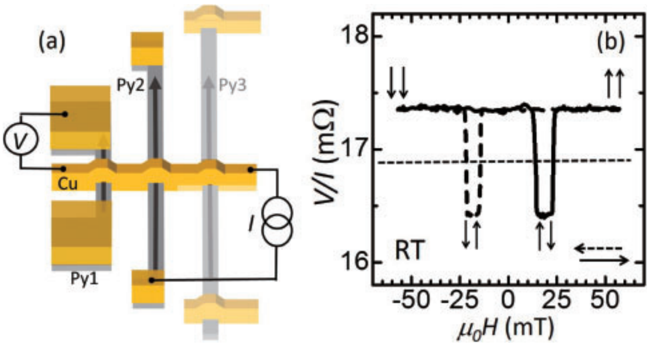

Fig. 2. (a) Schematic illustration of the probe configuration of the conventional nonlocal spin-valve measurement using Py2 injector and Py1 detector. (b) Field dependence of the nonlocal spin valve signal measured at room temperature.

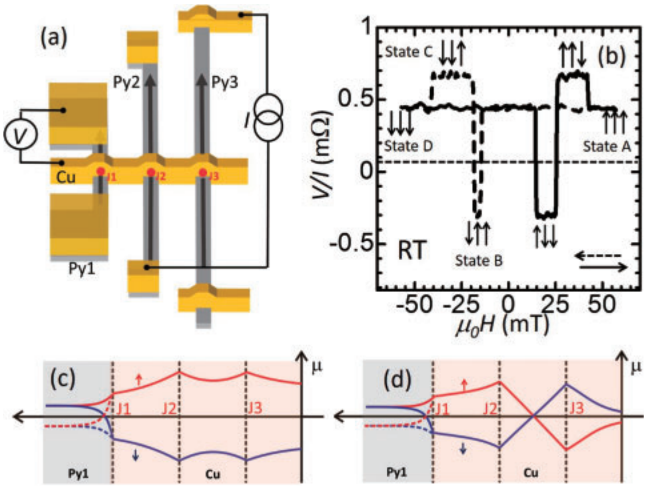

Fig. 3. (a) Schematic illustration of the probe configuration for the nonlocal spin-valve measurement under the spin injection with the two interfaces comprising of Py2/Cu and Cu/Py3. (b) Field dependence of the nonlocal signal measured at room temperature. (c) Schematic illustrations of the induced spin-dependent chemical potential when the magnetizations for Py2 and Py3 are aligned anti-parallel and (d) that for the parallel alignment. J_1, J_2, and J_3 represent the Py1/Cu, Py2/Cu, and Py3/Cu junctions, respectively.

thermal spin injection is mainly induced by the Joule heating effect, which shows the second-harmonic response. Moreover, we emphasize that the thermal spin injection efficiency under an excitation current of 100 μA should be very low because of a small spin-dependent coefficient of Py.[15)]

First, we performed a conventional nonlocal spin-valve measurement with the probe configuration shown in Fig. 2(a). We observed a clear spin-valve signal with a magnitude of 0.95 mΩ, as shown in Fig. 2(b). The obtained signal is slightly larger than typical values reported in Py/Cu lateral spin valves at room temperature.[7,9,10)] This is because the junction size of our Py/Cu is smaller than those in previous devices. We also see a large background signal with a magnitude of 16.1 mΩ. By using the Seebeck coefficients for Py, $S_{Py} = -20\,\mu V/K$, and Cu, $S_{Cu} = 1.6\,\mu V/K$, the background signal can be understood by a small temperature change of 70 mK due to the Peltier effect.[13,14)] Thus, a relatively large Seebeck coefficient for Py produces non-negligible nonlocal voltage, which is much larger than the nonlocal spin-valve signal at room temperature.

We then changed the current-probe configuration as shown in Fig. 3(a) and again measured the nonlocal spin-valve signal. The current flows across the two interfaces comprising the Py2/Cu (J_2) and Cu/Py3 (J_3) junctions. These two junctions produce the Peltier heating and cooling effects depending on the current direction. In this case, owing to a large heat conductivity for the Cu strip, the heat current generated from J_2 is mostly absorbed into J_3. Therefore, the heat current propagating to the voltage junction, Py1/Cu (J_1) junction, should decrease sufficiently, resulting in a significant reduction in the Seebeck voltage. As can be seen in Fig. 3(b), a small background signal occurs if the Peltier effects in the two junctions are canceled.

Here, we carefully consider the field dependence of the nonlocal spin-valve signal shown in Fig. 3(b). We observed three abrupt changes consisting of −0.75, +0.98, and −0.23 mΩ both in the forward and backward field sweeps of the nonlocal signal. These three sudden changes correspond to magnetization switching of the three ferromagnetic wires. From the shapes of the wire ends, we know that the first, second, and third sudden changes correspond to the switching of the spin voltage detector (Py1), middle spin injector (Py2), and right-hand-side spin injector (Py3), respectively. As shown in Fig. 3(c), when Py2 and Py3 are aligned anti-parallel to each other, spin-splitting of the chemical potential is relatively large because of the effective spin accumulation. On the other hand, as shown in Fig. 3(d), when Py2 and Py3 are aligned parallel to each other, spin-splitting of the chemical potential becomes small. The detected voltage is given by the voltage difference between the chemical potential for Py1 and that for Cu. Thus, the change of the spin-valve signal can be simply understood by spin splitting of the nonequilibrium chemical potential in the Cu strip based on the one-dimensional spin-diffusion model with a transparent interface.[9,16)]

From the above consideration, we understand that the background resistance is given by the mean value between the resistance at state B and that at state D. The estimated background resistance is 0.07 mΩ, which is much smaller than the spin-valve signal. Thus, two Peltier effects with different polarities significantly reduce the heat current propagating to the voltage terminals (J_1 junction). An observed small finite background voltage indicates that the heat current due to the Peltier effect generated in the J_3 junction partially diffuses into the substrate during the propagation in the Cu strip between Py2 and Py3.[17)]

Then, we measure the nonlocal spin-valve signal for the half configuration, where the current and voltage probes are located at the same side, as schematically shown in Fig. 4(a).[9)] Figure 4(b) shows the nonlocal spin signal for the half configuration. The obtained spin-valve signal is also 0.97 mΩ, the same as that in Fig. 2(b). Thus, we can confirm that the difference of the spin signal between the two configurations (the half and cross configurations) is negligibly small. This is because the difference in the effective distance between the two configurations is much smaller than the spin diffusion length for the Cu wire, which is 500 nm at room temperature.[18)] On the other hand, we obtain a small difference of the background signal between the two configurations. This difference can be explained by considering the asymmetric geometry of the lateral spin valve with respect to the Cu strip as follows. As shown in Fig. 1, the

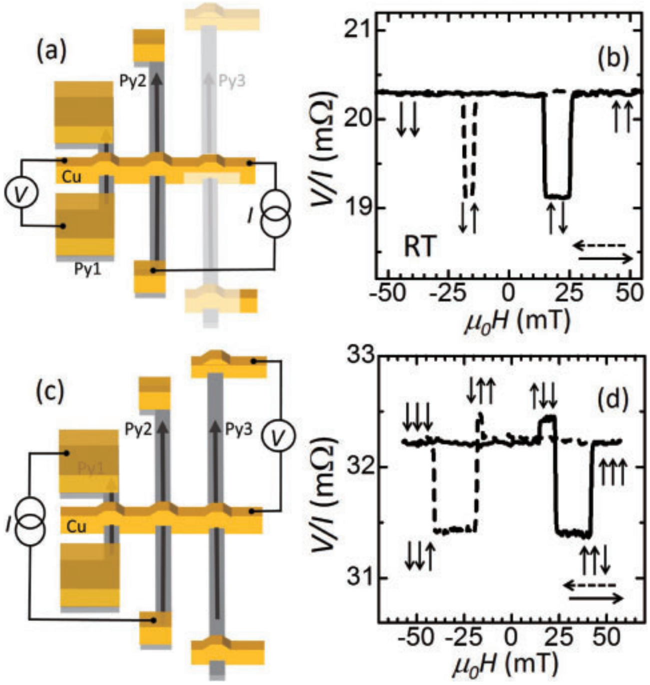

Fig. 4. (a) Schematic illustration of the probe configuration for the nonlocal spin-valve measurement with the half configuration, where the current and voltage probes are located at the same side and (b) the nonlocal spin-valve signal observed at room temperature. (c) Schematic illustration of the probe configuration for the Peltier canceling effect using the Py2/Cu and Cu/Py1 junctions and (d) the nonlocal spin-valve signal observed at room temperature.

length of the distance between the Cu strip and the Cu contact for the upper-side Py wire is 200 nm, which is shorter than that for the lower side (500 nm). Therefore, the temperature difference between the Cu strip and the Cu contact for the upper side is smaller than that for the lower side, resulting in a smaller Seebeck voltage. Thus, the geometry of the voltage terminal including the outside of the junction is also important for the quantitative understanding of the background signal.

Finally, we examine a similar Peltier canceling effect by interchanging the current and voltage probes. Figure 4(d) shows the nonlocal spin-valve signal with the probe configuration shown in Fig. 4(c). The aspect of the field dependence is different from that in Fig. 3(b). This is because the roles of Py1 and Py3 are different from those in Fig. 3. We emphasize that the observed three resistance changes consisting of 0.23, 0.75, and 0.98 mΩ are completely the same as those in Fig. 3(b). Therefore, each resistance change due to the switching of the Py wires can be understood by the similar one-dimensional spin diffusion model.[15]

According to a simple one-dimensional spin-heat diffusion model,[13,14,19] we should observe the same field dependence of the nonlocal voltage as that in Fig. 3(b) because each interface produces the reversible contribution both for the spin and heat currents. Indeed, the obtained spin signal is completely the same as that in Fig. 3(b), as we expected. However, the magnitude of the background signal is much larger than that in the previous configuration, indicating the nonreversible relationship.

To understand this discrepancy, we reconsider the whole device structure of the lateral spin valve including the outside of the spin-transport area. If we focus on the current path in this configuration, we find another Py/Cu interface on the large Py pad. This extra Py/Cu interface is located in the vicinity of the Py1/Cu injecting junction (J_1) and induces an additional Peltier effect.[13] Therefore, a similar Peltier canceling effect occurs via the Py wire. As a result, the main Peltier heat current generated in J_2 does not reduce considerably. It also should be noted that the background signal in this configuration is larger than that in Fig. 2(b) although the probe configuration in Fig. 2(a) does not include any negative Peltier effect. This can be explained by considering the temperature profile in the ferromagnetic voltage probe. As discussed above, the Seebeck voltage depends on the length of the ferromagnetic voltage probe because the heat current propagates over one micron even in the Cu and Py wires. This means that the background signal in the previous nonlocal spin-valve measurement with the probe configuration shown in Fig. 3(a) is reduced not only by canceling the Peltier effects, but also by the suppression of the Seebeck voltage. Thus, the present probe configuration induces the actual Seebeck voltage. These extra effects from the outside of the spin-transport area only affect the heat transport. The spin-current distribution is not modified by these outside structures because of its extremely short spin-diffusion length for a ferromagnetic metal.

In summary, we confirmed that the background signal in the nonlocal spin valve measurement was induced by the thermoelectric voltage under the combination between the Peltier and Seebeck effects. We found that the background signal was effectively suppressed by combining the Pelteir effects of two Py/Cu interfaces. The thermoelectric effect from the outside of the spin transport regime is found to produce a non-negligible effect in the nonlocal background signal.

Acknowledgment This work is partially supported by a Grant-in-Aid for Scientific Research on Innovative Areas, "Nano Spin Conversion Science" (26103002) and that for Scientific Research (S) (25220605).

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