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Large Spin Current Injection in Nano-Pillar-Based Lateral Spin Valve

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Abstract. We have investigated the influence of the injection of a large pure spin current on a magnetization process of a non-locally located ferromagnetic dot in nano-pillar-based lateral spin valves. Here, we prepared two kinds of the nano-pillar-type lateral spin valve based on Py nanodots and CoFeAl nanodots fabricated on a Cu film. In the Py/Cu lateral spin valve, although any significant change of the magnetization process of the Py nanodot has not been observed at room temperature. The magnetization reversal process is found to be modified by injecting a large pure spin current at 77 K. Switching the magnetization by the nonlocal spin injection has also been demonstrated at 77 K. In the CoFeAl/Cu lateral spin valve, a room temperature spin valve signal was strongly enhanced from the Py/Cu lateral spin valve because of the highly spin-polarized CoFeAl electrodes. The room temperature nonlocal switching has been demonstrated in the CoFeAl/Cu lateral spin valve.

INTRODUCTION

Spin current is a key quantity for the operation of the spintronic devices because it is the origins for the spin-dependent transport and the spin-transfer torque [1-3]. Since the spin-dependent transport and the spin transfer torque are able to manipulate the electric current and the magnetization, respectively [4-7], the efficient manipulation of the spin current is indispensable for the low-power operation of the spintronic devices. The spin current is in general, superimposed on the electric charge current, namely spin-polarized current. However, recent development of the nano-fabrication technology and the theoretical under-standing for the spin transports enable to create the spin current without accompanying the charge current [8, 9]. This is known as pure spin current [10-12]. Pure spin currents have several advantages over the conventional spin-polarized current because of the absence of the electric current. The suppression of the extra Joule heating increases the maximum injecting spin current. Moreover, the non-generation of the Oersted field simplifies the magnetization reversal process due to the spin transfer torque, resulting in the ideal situation for investigating the spin-transfer torque experimentally. Indeed, the magnetization switching due to the pure spin current injections has been demonstrated recently [13-15]. However, the experimental demonstrations were limited only at low temperature because of the low generation efficiency of the pure spin current. Therefore, establishing the efficient method for generating pure spin currents is an important milestone for developing the nano-spintronic devices based on the pure spin current.

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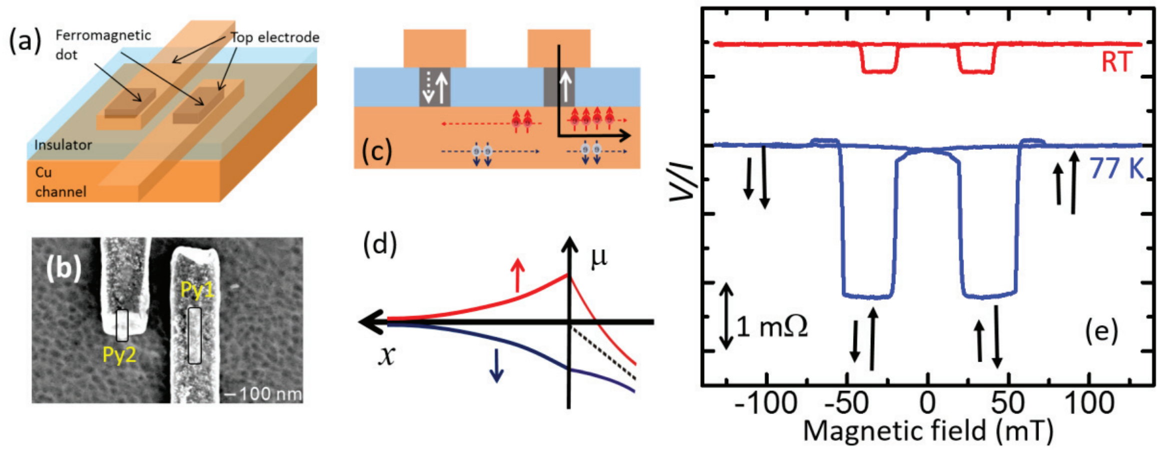

FIGURE 1. (a) Scanning electron microscope image of the fabricated nano-pillar-based lateral spin valve consisting of two Py nanodots and Cu electrodes. (b) Schematic illustration for the fabricated lateral spin valve. The top and bottom electrodes are electrically connected via the Py nanopillars and other regions are separated by a 100-nm-thick SiO_2 insulating layer. Schematic illustrations for (c) cross section of the fabricated lateral spin valve and (d) Spin dependent chemical potentials induced by the spin injection from Py2. (e) Field dependences of nonlocal spin valve signal measured at room temperature and 77 K.

To solve this issue, we have developed a different type lateral spin valve structure consisting of a pair of the closely located ferromagnetic nanopillars on a uniform nonmagnetic film [16]. Owing to the large nonmagnetic channel and small volume of the high resistive ferromagnetic injector, the Joule heating is efficiently suppressed, resulting in a large improvement of the maximum tolerance current. It also should be noted that the present structure is suitable for increasing the spin injection efficiency, because the increase of the effective cross section for the nonmagnetic layer reduces the spin resistance of the nonmagnet [17-19]. This enables to generate a large pure spin current and may lead to realize the magnetization switching in the nonlocal configuration. Here, we investigate the influence of the large pure spin current injection into on the magnetization of the nonlocally located ferromagnetic nanodot by using nano-pillar based lateral spin valves. To realize the magnetization switching at room temperature, we perform the material improvement.

EXPERIMENTAL

Py/Cu-Based Nanopillar Lateral Spin Valve

A nano-pillar-based lateral spin valve used for the present study has been fabricated as follows. First, 200-nm-thick Cu and 15-nm-thick Permalloy (Py) films were deposited by electron-beam evaporations on a thermally oxidized Si substrate at the base pressure of 4×10^{-9} Torr. Subsequently, an electron-beam lithography was performed to form the elliptical-shaped TGMR-resist masks. Then, Ar ion milling process has been performed to make the Py nano-pillar structures, followed by the SiO_2 sputtering. After making the contact holes in the SiO_2 insulating layer, the top Cu electrodes were formed by the conventional lift-off process. Here, the desired lateral dimensions for the Py1 and Py2 are approximately 80 nm × 250 nm and 80 nm × 150 nm, respectively. Figure 1(a) shows the schematic illustration of the fabrciated lateral spin valve together with the SEM image. Here, the distance between the dots is 400 nm. The resistivity for the Py is 30 μΩcm at RT and 24 μΩcm at 77 K and that for Cu is 2.4 μΩcm at RT and 1.6 μΩcm at 77 K. As shown in Fig. 1(b), when the spin-polarized current was injected from the Py1 to the right hand side of the Cu channel, the spin current without accompanying the charge current, namely pure spin current, is induced in the left hand side of the Cu channel because of the diffusion of the non-equilibrium spins.

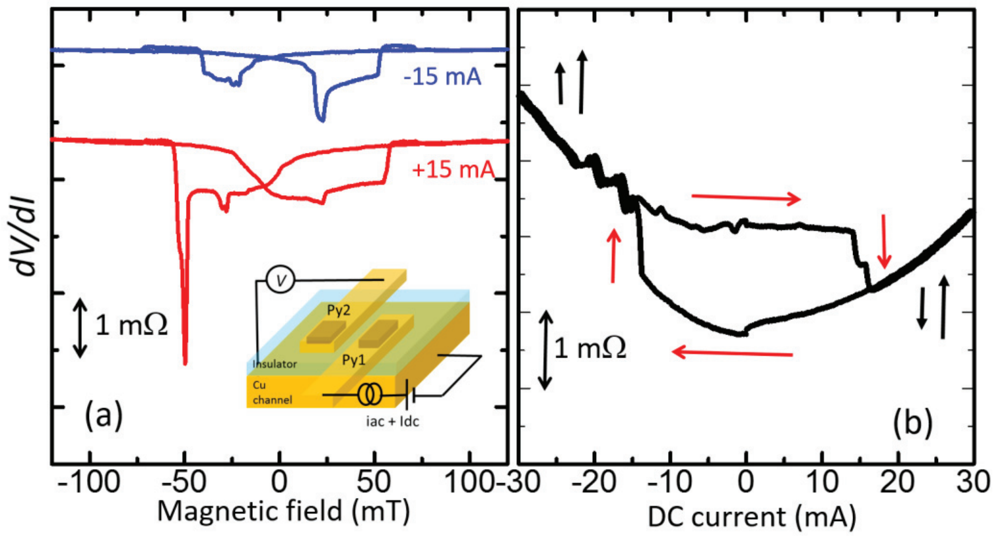

FIGURE 2. (a) Field dependences of the nonlocal spin valve signal under the dc bias currents of +15 mA and –15 mA together with the schematic illustration of the probe configuration for the nonlolcal spin injection. (b) Differential nonlocal spin signal as a function of the bias dc current measured at 77 K under the magnetic field of 4 mT.

First, we measured the conventional nonlocal spin valve signal with the probe configuration, where Py1 is the spin injector and Py2 is the spin detector. As shown in Fig. 1(c), the bipolar spin signals with the magnitude of 0.4 mΩ at RT and 2.2 mΩ at 77 K were clearly observed. Since the coercive force for the Py2 should be smaller than that for the Py1, the negative and positive resistance jumps are the magnetization reversals for Py2 and Py1, respectively.

To investigate the influence of the spin transfer torque on the magnetization of Py2, we have measured the nonlocal spin valve signal under high bias dc current. Here, as shown in the inset of Fig. 2(a), the positive current means the current flows from the Py1 to the Cu channel. As mentioned above, we can flow a large amount of the current in the nano-pillar structure because of its large heat sink of the Cu channel. Although the spin signal shows the gradual reduction at room temperature, we did not obtain any significant change in the shape of the nonlocal spin signal curve even under the high bias current of 20 mA. At room temperature measurements, we did not flow the current larger than 20 mA in order to prevent the damage of the sample. We then performed the similar measurements at 77 K. The shape of the nonlocal spin signal curve is found to change with changing the bias current. Figure 2(a) shows the representative curves for I = +15 mA and I = –15 mA, respectively. Here, in the positive bias current, the field range for the anti-parallel configuration seems to increase. On the other hand, the field range for the parallel configuration seems to decrease in the negative bias current. From the point of view of the spin transfer torque, since the negative (positive) current generates the spin current parallel (anti-) to the magnetization of the spin injector, the observed tendency can be understood by the spin transfer torque [5].

To elucidate the influence of the spin-transfer torque more clearly, we have performed the current-sweep measurement with fixing the magnetic field at 4 mT. Figure 2(b) shows the nonlocal spin signal as a function of the injecting current. We have clearly seen the switching of the magnetization configuration from parallel to anti-parallel and vice versa under the nonlocal spin injection, indicating that the magnetization of the Py dot is reversed by the spin current injection.

CoFeAl/Cu-Based Nanopillar Lateral Spin Valve

In the previous experiment, we showed that the magnetization of the Py dot can be reversed by the nonlocal spin injection. However, the demonstration was limited only at 77 K because the spin signal at room temperature is not sufficiently large to induce the effective spin transfer torque. This means that the injection efficiency for the spin current at room temperature should be improved for the room temperature demonstration. One of the way for improving the injection efficiency is to use the ferromagnetic metal with a highly spin polarized material. Recently, we have found that CoFeAl alloy has relative large spin polarization even though the CoFeAl was prepared by the

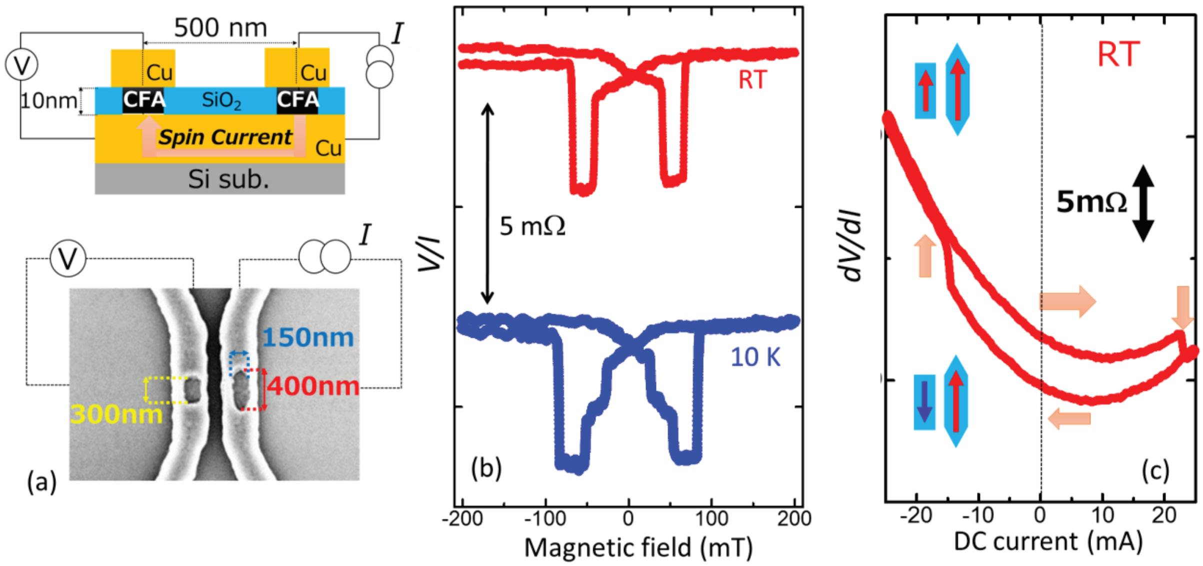

FIGURE 3. (a) Scanning electron microscope image of the fabricated nano-pillar-based lateral spin valve consisting of two Py nanodots and Cu electrodes together with the schematic illustration for the fabricated lateral spin valve. (b) Field dependences of nonlocal spin valve signal measured at room temperature and 10 K. (c) Differential nonlocal spin signal as a function of the bias dc current measured at room temperature in the absence of the magnetic field.

simply evaporated polycrystalline film [20, 21]. Here, we have fabricated CoFeAl/Cu-based nanopillar lateral spin valve.

The sample fabrication procedure was completely same as that for the Py/Cu-based nanopillar based lateral spin valve. Here, the thickness for the CoFeAl and that for the Cu are 10 nm and 200 nm, respectively. The electrical resistivity for the CoFeAl is 45 μΩcm at room temperature and 41 μΩ at 10K. Figure 3(a) shows the SEM image of the fabricated nanopillar lateral spin valve together with the schematic illustration. Here, the lateral dimension of the ferromagnetic dots are 140 nm × 300 nm and 140 nm × 400 nm.

Figure 3(b) shows the nonlocal spin valve signal measured at room temperature and 10 K. The room temperature spin signal is 3.4 μΩ, which was signifficantly improved from the Py/Cu lateral spin valve. However, the spin signal does not change with the temperature and is 3.5 mΩ also at 10K. In the conventional lateral spin valve based on the CoFeAl wires, the spin signal increases with decreasing the temperature, similarly to the Py/Cu lateral spin valve. However, in the nanopillar-based lateral spin valve, the temperature dependence is quite different from that for the Py/Cu one. Although the reproducibility of the non-sensitive temperature dependence was well confirmed experimentally, we do not understand the main reason for this at the moment.

We then performed the current sweep measurement of the nonlocal spin valve signal at room temperature in the absence of the magnetic field. Here, the current was injected from CoFeAl1 and the maximum magnitude of the current is 25 mA. As seen in Fig. 3(c), the clear resistance switching from the parallel to the anti-parallel state and that from the anti-parallel to the parallel state have been clearly observed at room temperature. The current for switching the magnetization was not so low in spite of the high spin polarization of the CoFeAl. The reason of this may be because the magnetization and the damping constant for the CoFeAl are larger than those for the Py. Interestingly, the switching current for the positive bias is much larger than that for the negative bias. This asymmetric property may be explained by considering the thermal spin injection. Since the CoFeAl has an extremely large thermal spin injection efficiency, we have to take into account the influence of the spin current induced by the thermal spin injection even in the nanopillar structure. From our previous experiment, the induced spin current due to the thermal spin injection is opposed to the magnetization direction, the thermally excited spin current align the magnetization with the anti-parallel configuration [20]. Therefore, the smaller switching current from the parallel to the anti-parallel state is consistent with the spin-transfer torque model.

CONCLUSION

We have evaluated the device performance for nanopillar-based lateral spin valves consisting of Py/Cu and CoFeAl/Cu bilayers by investigating the influence of the magnetization process under the high bias current injection. In the Py/Cu lateral spin valve, we confirmed that the magnetization of the ferromagnetic dot has been modulated and also been switched by the nonlolcally injected spin current at low temperature. However, at room temperature, the effect of the nonlocal spin injection seems to be very small. On the other hand, in the CoFeAl lateral spin valve, we confirmed that the magnetization can be reversed by the nonlocal spin injection even at room temperature. Although the driving current is still quite high over 10 mA, we believe that the material and structural developments significantly improve the device performance based on the pure spin currents.

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