March 2012

Generation of large accumulation and its application to superconductivity modulation

Department of Advanced Materials Science, 47-106045 Taro Wakamura

Advisor: Prof. YoshiChika Otani

Keywords: Spintronics, Spin Current, Superconductivity, Josephson Junction, Mesoscopic Physics

Introduction

In condensed matter physics, spintronics is becoming one of the essential research fields recently. In spintronics, a pure spin current is a key quantity and its generation, detection and manipulation is intensively investigated. The pure spin current is a flow of spins without any charge currents. Since the spin current is defined as a product of the conductivity and the gradient of the electro chemical potential (ECP), the pure spin current always accompanies the ECP difference between up-spin electron and down-spin electron. This ECP difference is called the spin accumulation and can be regarded as the Zeeman-splitting of conduction electrons in an external applied field. Therefore, inducing the spin accumulation is equivalent to apply a magnetic field locally to conduction electrons. The local application of an effective magnetic field by using the spin injection technique is theoretically predicted to be useful to control the energy state of the systems and to be able to induce some phase transitions [1]. The experimental realization of such theoretical predictions is one of the urgent tasks as a next stage for spintronics.

In our studies, we aimed to control the physical phenomena relevant to the superconductivity by using the spin injection technique. Especially, we focused on the ground state control of the Josephson junction. When a superconductor (S) is attached to a normal metal (N), Cooper pairs in S can penetrate into N within a finite length from the interface and a part of N becomes superconducting. This is called the superconducting proximity effect and the superconductivity in N is represented as an exponential decay of the order parameter. Especially if N is a ferromagnet (F), the order parameter not only decays, but also oscillates in F [2]. This oscillation derives from the spin-polarized state in F where conduction electrons have different momentum according to the direction of their spin due to spin subbands structure caused by an exchange field. Modulation of this exchange-splitting state induces some exotic phenomena such as a 0-π transition. In the 0-π transition, the phase difference between two superconductors at equilibrium changes from 0 to π. This phenomenon is significant for understanding the relation between Cooper pair and the magnetic field. In our system, this magnetic field is characterized by the energy splitting between the up-spin electron state and the down-spin electron state due to the spin accumulation. In order to see explicitly the effect of the spin injection on the Josephson junction, we first attempted to enhance the amount of the spin accumulation. After the demonstration of the enhancement of the spin accumulation we next tried to inject a pure spin current into the Josephson junction. In this abstract, we briefly show the results and the conclusions of the these experiments.

Spin accumulation enhancement

The amount of the spin accumulation in N depends on the difference of spin resistances between F and N, defined as a product of the spin diffusion length and the electrical resistivity. Larger mismatch generates smaller spin accumulation [3]. Therefore we insert the MgO layer between F and N in order to compensate the mismatch.

Our samples have the spin valve structure. A parallel pair of 100-nm-wide and 20-nm-thick Py wires are bridged by a 200-nm-wide and 100-nm-thick Cu wire. One of the two Py wires has a large square pad at its edge in order to induce the difference between the switching fields of the two Py wires. All samples shown here are fabricated *in situ* by a shadow evaporation technique. The devices are patterned using an electron beam lithography on a thermally oxidized silicon substrate covered with a polymethyl-methacrylate (PMMA)/methyl-methacrylate (MMA) bilayer resist. One should refer to [4] for the details of the sample fabrication. The measurements are performed using an ac lock-in amplifier and a He flow cryostat. For all measurements, the ac current is fixed to 90 μA and a magnetic field is applied along the easy axis of the Py wires.

The relation between the spin accumulation signal ΔR and the interface resistance R_{I} at 10 K is shown in Fig. 1(a). The value of the spin accumulation signal is defined as in Fig. 1(b). By optimally modulating the value of the interface resistance, the maximum value of ΔR reaches 10 mΩ, and the data are well reproduced by the theoretical equation based on Ref. [5].

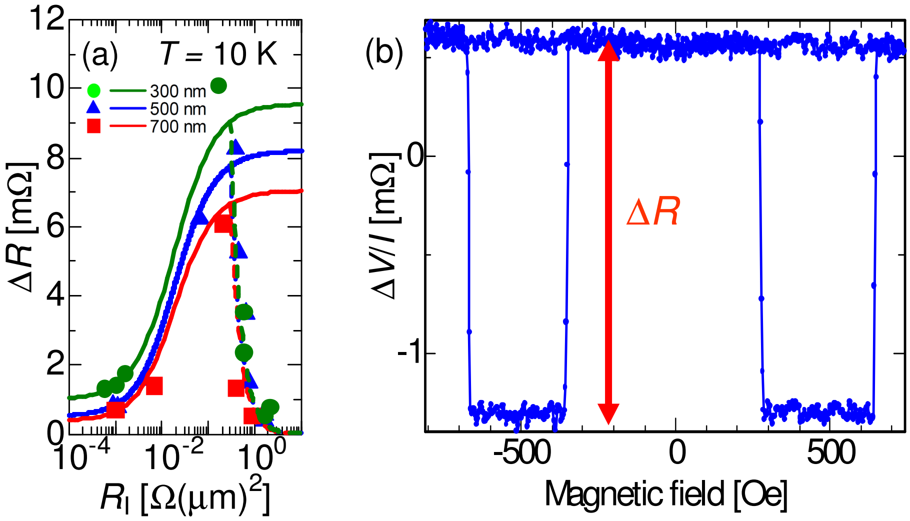

Figure 1: (a): Relation between the interface resistance R_{I} and the spin accumulation signal ΔR. (b): Definition of the spin accumulation signal ΔR.

Pure spin current injection into Josephson junctions

Next we discuss the spin injection into the Josephson junction. In order to apply the large spin accumulation generation technique mentioned above, we attempt to generate large spin accumulation in the N part of S/N/S Josephson junctions. In all samples, Nb is used as a superconductor because it has the highest critical temperature among pure metals. The N part is a Cu strip and is extended to attach to a Py wire for spin injection. All samples are fabricated *in situ* by using the shadow evaporation technique. The deposition conditions of Py and Cu are the same as the conditions for the spin valve structure fabrication, and Nb is deposited at an angle of 30° toward the vertical axis onto the substrate. The measurements are performed at 350 mK using a ^{3}He cryostat. We measure the critical currents of the Josephson junction by flowing both an ac bias current in the junction and a dc spin injection current through the Cu/Py interface. The critical current is defined as a minimum current which can flow the junction without generating any voltages between the two superconductors.

The relation between the critical current and the dc spin injection current obtained from a sample with the Ohmic Cu/Py contact is shown in Fig. 2(a). As the spin injection current increases, the critical current shows a decrease. This behavior is mainly due to the pair-breaking effect of the spin accumulation in the N part of the Josephson junction. Any sharp cusps typical for the 0-π transition [6] are not observed. One of the possible reasons is that the value of the spin-split is not enough to induce the transition.

We can consider two different pair-breaking effects in this system. One is the effect from the spin accumulation and another is the effect from the Joule heating. Since we flow a current through the Py wire for the spin injection, the Joule heating generated there can affect the condition of the junction. In order to investigate this effect, we replace the Py wire to a Pd wire. We chose the Pd wire because the resistivity of Pd is comparable to that of Py, and by modulating the thickness of the Pd wire appropriately, we can reproduce the resistance of the Py wire. By using the Pd wire, we can rule out the effect of the spin accumulation and investigate only the effect of the Joule heating.

We show the experimental results in Fig. 2(b). Although originally the scale of the critical current is different from that of the experiments with the Py spin injector, we can compare the two results after normalization. As you can see, there are few differences in the relation between the spin injection current and the critical current. This indicates that the decrease of the critical current observed in the Josephson junction with the Py spin injector is mainly due to the effect of Joule heating.

Conclusion and Perspective

Spin accumulation enhancement and its induction into the S/N/S Josephson junction were investigated. Insertion of the MgO layer between F and N modulated the spin accumulation signals. By optimally tuning the interface resistance we obtained the enhanced signals of the spin accumulation by more than ten times than those from the samples without the MgO interlayer at 10 K. Spin injection into the S/N/S Josephson junction was also demonstrated. The clear decrease of the critical

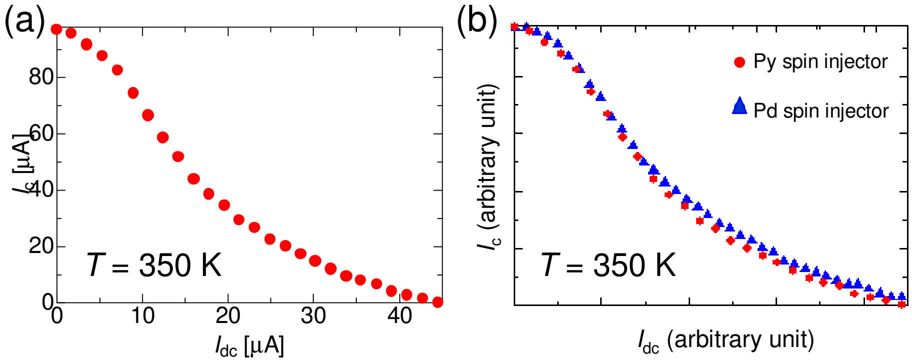

Figure 2: Relation between the spin injection current I_{dc} and the critical current I_{c} in the sample with Py spin injector (a) and its comparison with the relation in the sample with Pd spin injector (b).

current was observed as the spin injection current increased. However, the sharp cusp typical for the 0-π transition was not observed. In order to investigate the effect of the Joule heating from the Py wire on the Josephson junction, we replaced the Py spin injector into a Pd wire. These two wires are fabricated to have almost the same resistance. The critical current change under the increase of a current flow in the Pd wire was measured. The critical current decrease showed almost similar behavior to the former cases. Therefore we concluded that the decrease of the critical current derives from the effect of Joule heating.

In order to see explicitly the effect of the spin accumulation on Josephson junction, it is necessary to reduce the Joule heating effect. One of the resolutions is to pillow the layer of ferromagnet on a metallic layer with more heat capacity. This is what to try for the realization of the spin injection modulation of the physical phenomena in the low temperature physics.

References

[1] T. Yamashita, S. Takahashi and S. Maekawa, Phys. Rev. B **73**, 144517 (2006).

[2] A. I. Buzdin, Rev. Mod. Phys. **77**, 935 (2005).

[3] G. Schmidt *et al.*, Phys. Rev. B **62**, 4790 (R) (2000).

[4] T. Wakamura *et al.*, Appl. Phys. Exp. **4**, 063002 (2011).

[5] S. Takahashi and S. Maekawa, Phys. Rev. B **67**, 052409 (2003).

[6] V. V. Ryazanov *et al.*, Phys. Rev. Lett. **86**, 2427 (2001).

Presentation and Publication

Domestic conference

1. **T. Wakamura**, K. Ohnishi, Y. Niimi and Y. Otani, JPS 65th Autumn Meeting (Poster), Osaka, Japan (2010).
2. **T. Wakamura**, K. Ohnishi, Y. Niimi and Y. Otani, 4th Transfield Conference of Solid State Physics (Poster), Tokyo, Japan (2010).
3. **T. Wakamura**, K. Ohnishi, Y. Niimi and Y. Otani, JPS 66th March Meeting (Oral), Niigata, Japan (2011).
4. **T. Wakamura**, K. Ohnishi, Y. Niimi and Y. Otani, JPS 67th Autumn Meeting (Oral), Toyama, Japan (2011).
5. **T. Wakamura**, K. Ohnishi, Y. Niimi and Y. Otani, JPS 68th March Meeting (Poster), Kobe, Japan (2012).
6. K. Ohnishi, **T. Wakamura**, Y. Niimi and Y. Otani, JPS 68th Autumn Meeting (Oral), Kobe, Japan (2012).

International conference

1. **T. Wakamura**, K. Ohnishi, Y. Niimi and Y. Otani, The 6th International School and Conference on Spintronics and Quantum Information Technology (Poster), Matsue, Japan (2011).
2. **T. Wakamura**, K. Ohnishi, Y. Niimi and Y. Otani, The 26th International Conference on Low Temperature Physics (Poster), Beijing, China (2011).
3. **T. Wakamura**, K. Ohnishi, Y. Niimi and Y. Otani, 2nd ASRC International Workshop on Magnetic Materials and Nanostructures (Poster), Tokai, Japan (2012).

Publication

T. Wakamura, K. Ohnishi, Y. Niimi and Y. Otani, Appl. Phys. Exp. **4**, 063002 (2011).