Generation of Large Spin Accumulation in S/N/S Josephson Junctions

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Abstract.

We have studied the generation of spin accumulation much larger than the conventional value in lateral spin valves. The accumulation can be used as an alternative means to apply the exchange field in the Josephson junction to induce exotic superconductive phenomena such as 0-π transition. In Cu/MgO/permalloy (Py) lateral spin valve devices, the MgO interface layer enhances the spin accumulation at 10 K by a factor of ten. The spin diffusion length of 1.3 µm at 10 K for Cu assures homogeneous spin polarization in the region of interest. Thereby we intend to inject the spin current with the large spin accumulation into superconductor(S)/normal metal(N)/superconductor Josephson junctions. As a primary attempt, we fabricated in-situ samples for spin injection into Josephson junction with Ohmic contact between Cu and Py. The clear suppression of the critical current of the Josephson junction is observed as the spin injection current increases.

1. Introduction

Superconducting proximity effect is one of the fascinating phenomena in the low temperature physics. When a superconductor(S) is attached to a normal metal(N), Cooper pairs in the S can penetrate into the N within a finite length from the interface and the part of the N becomes superconducting. This is called the superconducting proximity effect and the superconductivity in the N is represented as an exponential decay of the order parameter. Especially if the N is a ferromagnet(F), the order parameter not only decays, but also oscillates in the F [1]. This oscillation derives from the spin-polarized state in the 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.

The 0-π transition is first induced in S/F/S multilayer structures by modulating the thickness of the F layer and sample temperatures [2, 3]. A cusp is observed as a function of the critical current of junctions and the F layer thickness or the sample temperature, which indicates the occurrence of the transition. However, since one sample can have only one magnetic property, at constant temperature it is impossible to induce the transition in the same sample. Furthermore, the F layers sometimes have multidomain structures due to its micro-scale sample size, and this makes interpretations of the obtained data complicated. It is still unclear how the junctions respond purely to the change of the exchange field.
In condensed matter physics, spintronics is becoming one of the crucial research fields nowadays. In spintronics, a pure spin current is a key quantity and its generation, detection and manipulation are intensively investigated. A pure spin current is a flow of spins without charge, and accompanies spin-split state around Fermi levels called a spin accumulation. This spin-split state corresponds to the Zeeman-splitting of conduction electrons, and therefore inducing the spin accumulation is equivalent to apply a magnetic field locally to conduction electrons. The spin injection technique is expected to be applied to some exotic physical phenomena related to magnetism or magnetic field.

In this work, we attempt to modulate the coupling of two superconductors by the exchange-splitting through the way of spin injection technique. The exchange-splitting corresponds to the spin accumulation brought by spin injection into the N region of S/N/S Josephson junctions. By using this technique, we can continuously modulate the exchange energy by the amount of the current for the spin injection and have a capability to induce 0-π transition at a constant temperature. Since larger spin accumulation is necessary for inducing the transition, we first show the way to enhance the spin accumulation then show preliminary results of a spin injection into the Josephson junctions.

2. Spin accumulation enhancement

In order to apply the spin accumulation to induce the 0-π transition, $E_{\text{ex}} \gg kT \sim 30 \, \mu\text{eV}$ [1] is needed since our samples are all measured at 350 mK. Here $E_{\text{ex}}$ represents the exchange energy. This value is much larger than $\sim 1 \, \mu\text{eV}$ which is conventionally obtained in previous studies. Thus it is necessary to enhance the spin accumulation in some ways for inducing the transition.

The amount of the spin accumulation in the 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. One of the ways to retrieve this mismatch is to insert an insulating layer such as MgO or Al$_2$O$_3$ between F and N. In our studies, we insert the MgO layer between Py and Cu. By optimizing the interface resistance of the MgO layer, we obtain more than ten times larger spin accumulation voltages ($\sim 10 \, \mu\text{V}$) compared with values obtained in devices without the MgO layer, i.e. the Ohmic junction at 10 K.

![Figure 1](image_url)

Figure 1. (a) A scanning electron microscope (SEM) image of the spin valve structure and the electronic probing configuration. (b) The interface resistance dependence of the spin accumulation signal of the samples with different distances between two Py wires (300 nm, 500 nm and 700 nm) at 10 K. (c) A typical NLSV signal and the definition of the spin accumulation signal $\Delta R$. 
Our samples have the spin valve structure as shown in Fig. 1(a). 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 (not shown in Fig. 1(a)) 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. Details of the sample fabrication are referred to [4]. The measurements are carried out using an ac lock-in amplifier and a He flow cryostat. For all the measurements, the ac current is fixed to 90 μA and magnetic fields are applied along the easy axis of the Py wires.

The relation between the spin accumulation signals ΔR and the interface resistance R1 at 10 K is shown in Fig. 1(b). Here ΔR is defined as in Fig. 1(c). The maximum value of ΔR reaches 10 mΩ, and the data are well reproduced by the following theoretical equation [5]

\[
\Delta R = 4R_{SN} \left( \frac{P_I R_{SI}}{R_{SN}} + \frac{P_F R_{SF}}{R_{SN}} \right)^2 e^{-d/\lambda_N} \tag{1}
\]

where \( R_{SN} = \rho_N \lambda_N / t_N \), \( R_{SF} = \rho_F \lambda_F / t_F \), \( R_{SI} = R_1 (1 - P_I^2) / P_I \).

However, when \( R_1 \) exceeds \( 3.0 \times 10^{-3} \) Ω(μm)², the experimental data start to deviate from the theoretical curve and cannot be analyzed by the eq. (1). In order to explain this behavior, we use a spin-dependent two-channel resistance circuit model. Details are to be referred to [4].

In order to estimate the spin diffusion length of Cu, we plot the nonlocal spin valve(NLSV) signals without the MgO layer as a function of the distance \( d \) between the two Py wires. By fitting the data with eq. (1), we obtain \( P_F = 0.26, \lambda_N = 1.3 \) μm, and \( \lambda_F = 5 \) nm at 10 K. The spin diffusion length of Cu reported here is about twice larger than that for Ag at 10 K. The longer spin diffusion length is preferable for inducing 0-π transition because it generates a homogeneous spin-polarized state in the N which can affect the supercurrent in Josephson junctions homogeneously.

3. Pure spin current injection into Josephson junctions

Next we discuss the spin injection into Josephson junction. Using 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. The Scanning Electron Microscope(SEM) image of a sample is shown in Fig. 2(a). In all samples, Nb is used as a superconductor owing to the highest critical temperature among pure metals. The N part is a Cu strip extended to attach to a Py wire for spin injection. All samples are in-situ fabricated using 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 with an angle of 60° onto the substrate. The measurements are performed at 350 mK using a 3He cryostat. We measure the critical current of the Josephson junctions 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 flows the junction with a finite value of the voltage 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 junction is shown in Fig. 2(b). As the spin injection current increases, the critical current shows a sinusoidal decrease. This behavior is partly due to the pair-breaking effect of the spin accumulation in the N part of the Josephson junction. The heating effect from the interface between Cu and Py is still an open question. On the other hand, a sharp cusp typical for the 0-π transition [2] is not observed. One of the possible reasons is that the value of the spin-split is not enough to induce the transition.
Figure 2. (a) Scanning electron microscope (SEM) image of the sample structure for the spin injection into the S/N/S Josephson junction. (b) The relation between the critical current and the dc spin injection current at 350 mK. Inset: the definition of the critical current in the figure of the relation between the bias current and the voltage through the junction.

4. Summary
Spin accumulation enhancement and its induction in the S/N/S Josephson junctions are investigated. Insertion of the MgO layer between a ferromagnet and a nonmagnet modulates the spin accumulation signals. Optimal tuning of the interface resistance leads to the enhancement of the spin accumulation signal more than ten times than that from the samples without the MgO interlayer at 10 K. Spin injection into the S/N/S Josephson junctions is also performed. The clear decrease of the critical current is observed as the spin injection current increases. However, the sharp cusp typical for the 0-π transition is not observed. Larger spin accumulation should be necessary for the transition.

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