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Transport properties of Nb/PdNi bilayers and Nb/PdNi/Nb Josephson junctions

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Abstract. The superconducting proximity effect was examined in both Nb/PdNi (SF) bilayer films and Nb/PdNi/Nb (SFS) Josephson junctions. In Nb/PdNi bilayer films, nonmonotonic behavior of T_c was observed as a function of PdNi thickness d_F. The effective exchange energy E_{ex} extracted from the data was about 13 meV. In Nb/PdNi/Nb (SFS) Josephson junctions, the existence of a crossover between the 0 state and the π state was confirmed in the PdNi thickness dependence of I_c. For the junction with d_F = 9 nm, such a crossover was observed in the temperature dependence of I_c. E_{ex} estimated from the junctions characteristics was about 19 meV. These behaviors can be interpreted from the view point of a damped oscillatory superconducting order parameter induced at the SF interface.

1. Introduction

In recent years, transport properties of superconductor (S) - ferromagnet (F) heterostructures have been attracted considerable attention in the field of quantum electronics[1]. SFS Josephson junctions (JJs)[2–4] and FSF spin valves[5] are examples of such SF heterostructure devices. In these SF heterostructures, the proximity effect at the SF interface has intensively been investigated since there seems to be an antagonism between the conventional superconducting state and the ferromagnetic ground state in spin ordering. Recent theoretical work [6] has predicted the existence of the oscillating superconducting order parameter in F layer.

In recent experimental studies, weak ferromagnetic alloys, whose E_{ex} can be controlled by changing the amount of magnetic element, are of great interest. $Cu_{1-x}Ni_x (x \sim 0.5)$ and $Pd_{1-x}Ni_x (0 < x < 0.3)$ are two cases where E_{ex} can be varied within the millielectron-volt range by changing the Ni concentration. There have been several reports on the proximity effect with such weak forromagnets and E_{ex} have also been estimated. Although those results can qualitatively be interpreted from the view point of damped oscillatory superconducting order parameter, the magnitude of E_{ex} obtained from the experiments seem to be inconsistent even if the same ferromagnetic materials have been utilized. Robinson et al. have pointed out the effect of the magnetic dead layer on the proximity effect in SFS Josephson junctions with strong ferromagnetic materials[7; 8]. However, it seems that there may be some other factors to be taken into account to interpret the experimental results on the superconducting proximity effect in SF heterostructures.

In this paper, we investigated transport properties in two different types of SF heterostructures: (i) Nb(35 nm)/$Pd_{0.85}Ni_{0.15}$(d_F nm) bilayers and (ii) Nb/$Pd_{0.85}Ni_{0.15}$(d_F nm)/Nb (SFS) Josephson junctions. In Nb/PdNi bilayer films, nonmonotonic behavior of T_c

was observed as a function of PdNi thickness d_F. The effective exchange energy E_{ex} extracted from the data was about 13 meV. In Nb/PdNi/Nb (SFS) Josephson junctions, the existence of a crossover between the 0 state and the π state was confirmed in the PdNi thickness dependence of I_c. For the junction with $d_F = 9$ nm, such a crossover was observed in the temperature dependence of I_c. E_{ex} estimated from the junction characteristics was about 19 meV. Although the magnitude of E_{ex} obtained from bilayer films was slightly smaller than that of junctions, these behaviors can be interpreted from the view point of a damped oscillatory superconducting order parameter induced at the SF interface.

2. Experimentals

In this study, we prepared two different samples: (i) Nb/$Pd_{0.85}Ni_{0.15}$ (SF) bilayers and (ii) Nb/PdNi/Nb (SFS) Josephson junctions(see fig.1). All SF layer structures were deposited on oxidized Si substrates using a multisource RF magnetron sputtering system at room temperature. Nb thin films were deposited using ultra-pure Ar gas at 2.5 mTorr from a solid target at a rate of 3.28 nm/min. After Nb deposition, $Pd_{0.85}Ni_{0.15}$ (hereafter PdNi) were successively deposited at 4.6 mTorr from an ingot target at a rate of 1.36 nm/min in the same vacuum run. The Curie temperature of the PdNi alloy used in this study was approximately 260 K. The lateral size of the bilayer samples was 5×5 mm^2. SFS Josephson junctions were fabricated by conventional photolithographic techniques. A typical junction area was 10×10 μm^2. From atomic force microscope measurement, we took the surface roughness for our films to be less than 0.25 nm in RMS.

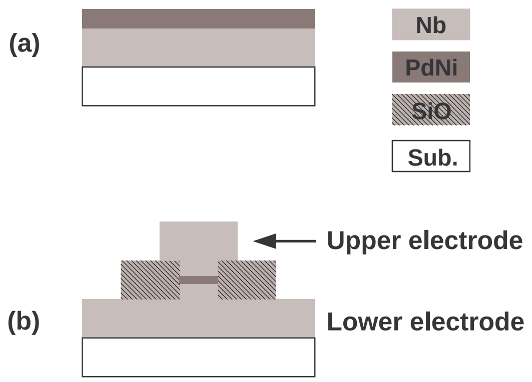

Figure 1. Schematic cross sectional view of (a) Nb(35 nm)/PdNi(d_F nm) bilayer film and (b) Nb/PdNi(d_F nm)/Nb Josephson junction. The size of the bilayer samples was 5×5 mm^2. Typical junction area was 10×10 μm^2.

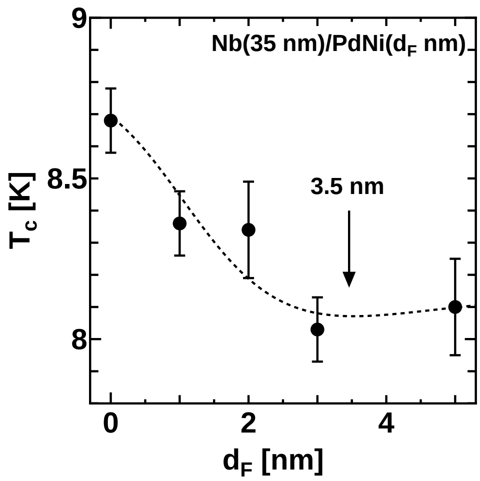

Figure 2. The PdNi thickness dependence of T_c for Nb(35 nm)/PdNi(d_F nm) bilayers. The dotted line is the guide for the eyes.

3. Results and discussion

Figure 2 shows the PdNi thickness dependence of the superconducting transition temperature for Nb(35 nm)/PdNi(d_F nm) bilayers. Data were extracted from the temperature dependence of the resistance measured using four-probe configuration. It is clearly shown that T_c rapidly decreases with increasing d_F until $d_F \sim 3$ nm and reached a minimum value at about $d_F = 3.5$ nm.

The basic physics behind this non-monotonic behavior of T_c can be interpreted within the framework of a damped oscillatory behavior of the superconducting order parameter induced in the F layer because of the proximity effect[6; 9]. Due to energy conservation, a Cooper pair entering a ferromagnet acquires a finite center-of-mass momentum, Δp, from the spin splitting of the up and down bands. In the dirty limit, Δp can be expressed as $\Delta p = 1/\xi_{\mathrm{F}} = \sqrt{E_{\mathrm{ex}}/(\hbar D_{\mathrm{F}})}$, where D_{F} is the diffusion coefficient in the F-layer[2]. This additional momentum modifies the phase of the pair wave function, $\theta = \Delta p \cdot x$, which increases with the distance x from the SF interface. Therefore, Cooper pairs that experience normal reflections at the vacuum interface of an F layer causes the interference, which can lead to oscillations of T_{c} as a function of d_{F}. According to the definition of Δp, the effective exchange energy E_{ex} can be estimated to be $E_{\mathrm{ex}} \sim 13$ meV[10–12]. This result is in good agreement with the result reported by C. Cirillo *et al.*[13].

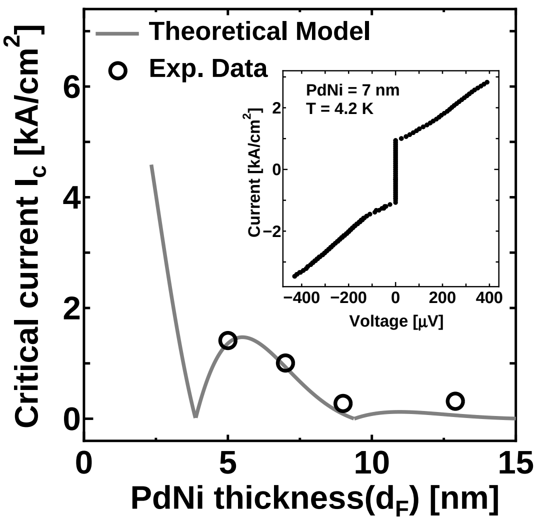

Figure 3. I_{c} as a function of PdNi thickness at 4.2K. Inset: I-V curve for $d_{\mathrm{F}} = 7$ nm at 4.2 K. The solid line is a theoretical model with $E_{\mathrm{ex}} = 19$ meV.

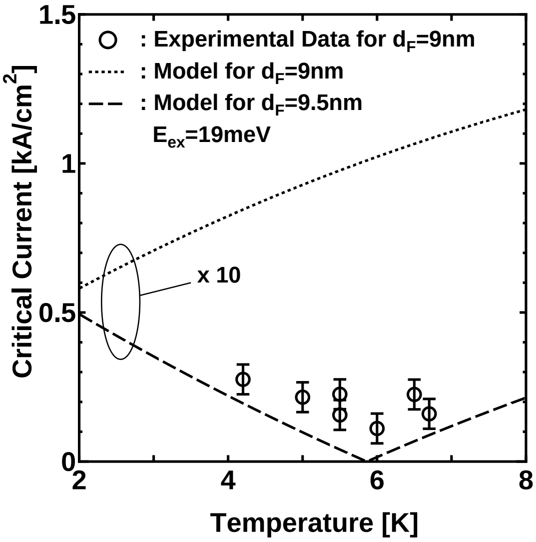

Figure 4. Temperature dependence of I_{c} for a junction with $d_{\mathrm{F}} = 9$ nm. A small dip at about $T = 6$ K corresponds to a crossover between 0 state and π state. The dotted line: theoretical model for $d_{\mathrm{F}} = 9$ nm. The dashed line: theoretical model for $d_{\mathrm{F}} = 9.5$ nm. $E_{\mathrm{ex}} = 19$ meV is assumed in both cases.

Josephson critical current I_{c} as a function of PdNi thickness at 4.2K is shown in Fig. 3. The inset shows a typical I-V curve for $d_{\mathrm{F}} = 7$ nm at 4.2 K. As can be seen, data are fitted by theoretical model with $E_{\mathrm{ex}} = 19$ meV. The magnitude of the effective exchange energy E_{ex} obtained from above data is slightly larger than that of Nb/PdNi bilayer films.

Figure 4 shows the temperature dependence of I_{c} for a junction with $d_{\mathrm{F}} = 9$ nm. A Clear reentrant behavior can be seen at about $T = 6$ K. This behavior corresponds to a crossover between 0 state and π state. The dotted line in the figure is a theoretical calculation for the junction with $d_{\mathrm{F}} = 9$ nm and $E_{\mathrm{ex}} = 19$ meV. The result of the calculation can not explain the experimental data. When the PdNi thickness is assumed to be $d_{\mathrm{F}} = 9.5$ nm the data can qualitatively be explained. However, the magnitude of I_{c} obtained in our experiments are 10 times larger than that of model calculations. A possible explanation of this difference is the coexistence of 0 and π coupling in the junction due to the SF interface fluctuations and/or to the inhomogeneities in the exchange energy[14]. If such non-uniformities exist in the junction, some fraction of the junction area makes a crossover from the 0 state to the π state as the temperature is lowered while the remaining part stays in the 0 state. Experimentally, the evidence of the existence of such non-uniformities should appear in the Fraunhofer patterns[15]. We, indeed, observed asymmetric magnetic field dependence of I_c in several junctions.

4. Summary

The superconducting proximity effect was examined in both Nb/PdNi (SF) bilayer films and Nb/PdNi/Nb (SFS) Josephson junctions. In Nb/PdNi bilayer films, nonmonotonic behavior of T_c was observed as a function of PdNi thickness d_F. The effective exchange energy E_{ex} extracted from the data was about 13 meV. In Nb/PdNi/Nb (SFS) Josephson junctions, the existence of a crossover between the 0 state and the π state was confirmed in the PdNi thickness dependence of I_c. For the junction with $d_F = 9$ nm, such a crossover was observed in the temperature dependence of I_c. E_{ex} estimated from the junction characteristics was about 19 meV. Although the magnitude of E_{ex} obtained from bilayer films was slightly smaller than that of junctions, these behaviors can be interpreted from the view point of a damped oscillatory superconducting order parameter induced at SF interface.

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