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Magnetic and Transport Properties of Nb/PdNi Bilayers
Ken-ichi Matsuda, Hirotaka Niwa, Yosuke Akimoto, Tetsuya Uemura, and Masafumi Yamamoto

Abstract—We investigated the superconducting proximity effect in both Nb(35 nm)/PdNi superconductor (S)-ferromagnet (F) bilayer and Nb–Nb(10 nm)/PdNi–Nb (S–SF–S) variable-thickness bridges (VTBs). In Nb(35 nm)/PdNi(d_F nm) SF bilayer, non-monotonic behavior of the superconducting transition temperature T_c was observed as a function of PdNi thickness, d_F. This non-monotonic behavior of T_c can be interpreted from the view point of damped oscillatory superconducting order parameter induced in F-layer, and the effective exchange energy E_{ex} extracted from the data was approximately 150 K. On the other hand, in VTBs, it was found that the superconducting critical current I_c was monotonically decreased with increasing d_F.

Index Terms—Proximity effect, superconducting films, superconductor-ferromagnet heterostructures.

I. INTRODUCTION

The interplay between ferromagnetism and superconductivity in thin film superconductor-ferromagnet (SF) heterostructures has attracted considerable interest in both theoretically and experimentally in the field of electronic devices [1], [2]. SFS Josephson junctions (JJs) [3]–[5] and FSF spin valves [6] are examples of such SF heterostructure devices.

Especially, SFS JJs have great advantages for manipulating a spin degree of freedom in Josephson-junction-based electronics, for example, JJ-based qubits [7]. In SFS JJs, π-Josephson junction (π-JJs) behaviors have been predicted due to exchange field-induced oscillations of the superconducting order parameter over the coherence length \( \xi_F \) in the ferromagnetic layer (see Fig. 1), i.e., the coupling of the magnetic field to the quasiparticle spins dominates over the orbital coupling, leading to pairing between exchange-split Fermi surface, and hence to oscillatory behavior of superconducting order parameter. This spatially non-uniform superconducting order parameter in F-layer is a sort of Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state [8], [9].

Experimentally, such oscillations of the order parameter have been observed in FSF trilayer systems involving Fe or Co ferromagnetic layer [10]. In these systems with such strong ferromagnets, however, exchange energies \( E_{ex} \) are typically of the order of 1 eV, and therefore, \( \xi_F \) may be 0.1 \( \sim \) 1 nm even at sufficiently low temperatures. In general, it is difficult to fabricate such a homogeneous thin film using conventional deposition techniques. This difficulty is one of the reason why experimental studies on the superconducting proximity effect in SF heterostructures are still in their infancy.

For this reason, 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 the cases, where \( E_{ex} \) can be varied in meV range by changing Ni concentration. In these systems, \( \xi_F \) may be of the order of 5 \( \sim \) 10 nm. Moreover, Nb/PdNi heterostructure has an advantage that the interdiffusion between the two layers will be limited by the difference of the crystal structures between BCC and FCC.
In this paper, we investigated magnetic and transport properties in two different types of SF bilayer: (i) Nb(35 nm)/Pd_{0.85}Ni_{0.15}(d_F nm) bilayer and (ii) Nb(100 nm)−Nb(10 nm)/Pd_{0.85}Ni_{0.15}(d_F nm)−Nb(100 nm) (S-SF-S) variable-thickness bridge (VTB). While the non-monotonic behavior of the superconducting critical temperature, $T_c$, was observed as a function of $d_F$ in Nb/Pd_{0.85}Ni_{0.15} bilayer, the critical current, $I_{c'}$, of VTB monotonically decreased with increasing $d_F$.

II. EXPERIMENTALS

In this study, we prepared two different samples: (i) Nb/Pd_{0.85}Ni_{0.15} (SF) bilayers and (ii) Nb−Nb/Pd_{0.85}Ni_{0.15}−Nb (S−SF−S) variable-thickness bridges (VTBs) (see Fig. 2). All samples were deposited on oxidized Si substrates using 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 a stoichiometric ingot target at a rate of 1.36 nm/min. The Curie temperature of the PdNi alloy used in this study was approximately 260 K. The lateral size of the bilayer samples is $5 \times 5$ mm$^2$.

VTB samples were fabricated by using conventional photolithographic technique. Schematic view of VTB structure and a SEM image of the bridge part are shown in Fig. 2. The VTB sample consists of 100 nm-thick Nb electrode and Nb(10 nm)/PdNi($d_F$ nm) bridge. The lateral size of the bridge is $5 \mu$m $\times$ $5 \mu$m.

III. RESULTS AND DISCUSSIONS

A. Nb(35 nm)/PdNi($d_F$ nm) Bilayer

Fig. 3 shows the PdNi thickness dependence of the superconducting transition temperature for Nb(35 nm)/PdNi($d_F$ nm) bilayer. Data were extracted from the temperature dependence of the magnetic susceptibility measured by SQUID magnetometer. It is clearly shown that $T_c$ rapidly decreases with increasing $d_F$ until $d_F$ $\sim$ 3 nm and has a minimum value at around $d_F$ = 3.5 nm. Physically, this non-monotonic behavior of $T_c$ can be interpreted in the framework of damped oscillatory behavior of superconducting order parameter induced in F layer by proximity effect [11], [12]. Due to energy conservation, a Cooper pair entering into ferromagnet acquires a finite center-of-mass momentum, $\Delta p$, from the spin splitting of the up and down bands. In the dirty limit, $\Delta p$ can be expressed as

$$\Delta p = \frac{1}{\xi_F} \sqrt{\frac{E_{ex}}{\hbar D_F}},$$

(1)

where $D_F$ is the diffusion coefficient in F-layer and $E_{ex}$ is an exchange energy [3]. This additional momentum modifies the phase of the pair wave function, $\theta = \Delta p \cdot x$, that increases with the distance, $x$, from the S/F interface. Therefore, Cooper pairs that experience normal reflections at the vacuum interface of F layer causes the interference, which can lead to oscillations of $T_c$ as a function of $d_F$. When $\theta = \pi$, the interference effect should be destructive, and therefore $T_c(d_F)$ takes minimum value. In our experimental data, $T_c(d_F)$ shows minimum at around $d_F$ = 3.5 nm.

According to (1), the effective exchange energy $E_{ex}$ can be estimated from $d_F$ at which $T_c(d_F)$ takes minimum value. The diffusion constant $D_F$ in F-layer is related to the residual resistivity, $\rho_F$, of PdNi through the electronic mean free path, $l_F$, by

$$D_F = \frac{v_F l_F}{3},$$

(2)

in which

$$l_F = \frac{1}{v_F \gamma_F \rho_F} \left( \frac{\pi k_B}{e} \right)^2,$$

(3)

where $\gamma_F$ is the electronic specific heat coefficient and $v_F$ is the Fermi velocity [13]. The residual resistivity of 100 nm-thick PdNi obtained from the preceding experiment was approximately 22 $\mu\Omega$ cm. If we adopt the values of $\gamma_F = 1.12$ mJ/K$^2$ cm$^3$ and $v_F = 2 \times 10^5$ cm/sec for pure Pd instead of PdNi, $l_F$ can be calculated as $l_F = 1.48$ nm, which results in $D_F = 9.9 \times 10^{-5}$ m$^2$/sec. Using these parameters, we can estimate the effective exchange energy to be $E_{ex} \sim 150$ K. This result is in good agreement with the result reported by C. Cirillo et al. [14].
In our results, any clear indicated a similar behavior. From the view of VTBs, F-layer thickness at 10 K. A clear transition between superconducting state for VTBs with various dependence of the superconducting critical cur-

ancy between the non-monotonic behavior of $I_c$ in Nb/PdNi bilayer and the monotonic behavior of $I_c$ in VTBs. These results imply that there is another effect behind the transport properties of VTBs that we do not take into account.

**IV. Conclusion**

The superconducting proximity effect was examined in both Nb(35 nm)/PdNi superconductor-ferromagnet (SF) bilayer and Nb–Nb(10 nm)/PdNi–Nb (S–SF–S) variable-thickness bridges (VTBs). In Nb(35 nm)/PdNi(d$_F$ nm) SF bilayer, non-monotonic behavior of the superconducting transition temperature $T_c$ was observed as a function of PdNi thickness, $d_F$. This non-monotonic behavior of $T_c$ can be interpreted from the view point of damped oscillatory superconducting order parameter induced in F-layer, and the effective exchange energy $E_{ex}$ extracted from the data was approximately 150 K. On the other hand, in VTBs, it was found that the superconducting critical current $I_c$ was monotonically decreased with increasing $d_F$.

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**References**


