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Perpendicular interface resistance in Co/Nb$_x$Ti$_{1-x}$ multilayers for normal and superconducting NbTi alloy with $x=0.4$, 0.6

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We report here the resistance of Co/Nb$_x$Ti$_{1-x}$ multilayers, for $x=0.4$ and 0.6, with current flowing perpendicular to the layer plane at 4.2 K. When NbTi films are sandwiched between Co, we found that there are critical thicknesses of 20 nm for $x=0.4$ and 27 nm for $x=0.6$, below which no superconducting transition could be found. Using a series resistor model, we extracted the unit area resistance of one pair of Co/NbTi interfaces and compared with the pure Nb case we have reported. The influence of mean free paths and superconducting coherence lengths is analyzed. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1850373]

The interplay between superconductor (S) and ferromagnetic (F) materials has been proven to be an excellent system for studying the proximity effect. One of the most interesting effects observed in F/S structures is the π junction effect. Wave functions on two sides of interlayer can have a phase shift of π, which induced a spontaneous current. One experimental evidence for a π junction on Nb/CuNi/Nb small structures with current perpendicular to the plan (CPP) showed that the critical current density was not a monotonic function of temperature for certain CuNi thickness.[1]

It is interesting to study the interface resistance at metallic interface between ferromagnetic, superconducting, and normal metal. Unfortunately, determining F/S interface resistance is not easy because the resistance is always zero in the S state when current is flowing in the layer plan (CIP). We report here the resistance of Co/Nb$_x$Ti$_{1-x}$ multilayers for $x=0.4$ and $x=0.6$, with CPP measurement at 4.2 K. Then, we compare our data with the pure Nb case we have presented and analyze the influence of mean free paths and superconducting coherence lengths on the interface resistance. CPP resistance measurement is a powerful tool to quantitatively analyze metallic multilayer thin films through separating the interface and bulk contributions.

CPP samples were made by dc magnetron sputtering onto Si (100) substrates at room temperature. Eight samples could be fabricated in the same run to minimize error in different preparation conditions. Superconducting strips (see Fig. 1) were used as current and potential contacts for four-point measurements. The CPP sample required three contact masks, which were changed *in situ* to assure clean interfaces. As previously reported,[2] each sample had circular electrodes to ensure uniform measuring current throughout the whole multilayer sample. However, using such contacts leads to a possible problem due to the proximity effect between superconductor and normal metals (N).[3] The Cooper pairs can penetrate from S into N. As a result, the thin N layer near the N/S interface becomes superconducting.[4] This problem can be eliminated by placing ferromagnetic metal like Co next to the S electrodes.

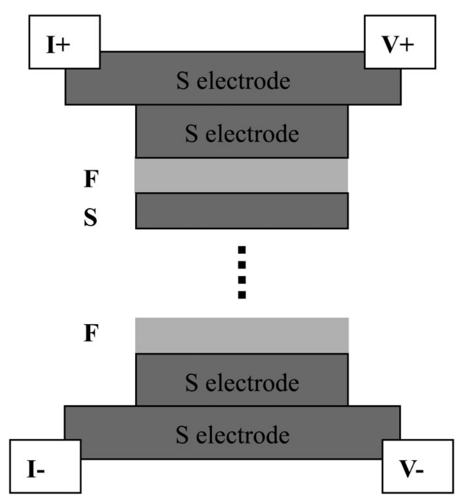

FIG. 1. Geometry of a current perpendicular to plane sample on a substrate. The middle part is the actual multilayer. The drawing is not to scale.

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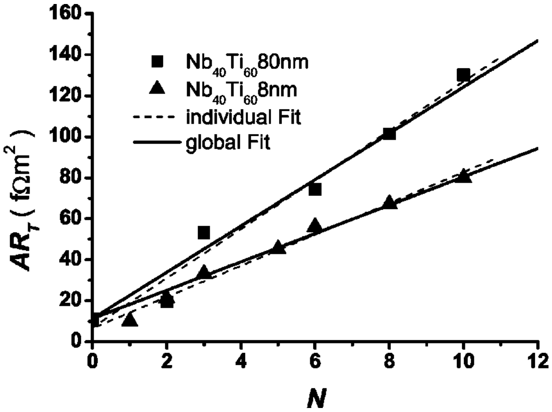

FIG. 2. Unit area resistance, AR_T vs bilayer number N of two sets of samples with $Nb_{40}Ti_{60}$ thicknesses fixed at 8 and 80 nm, respectively. The dashed lines are linear least-squares fits to individual sets. Solid lines are global fit to two sets of data simultaneously.

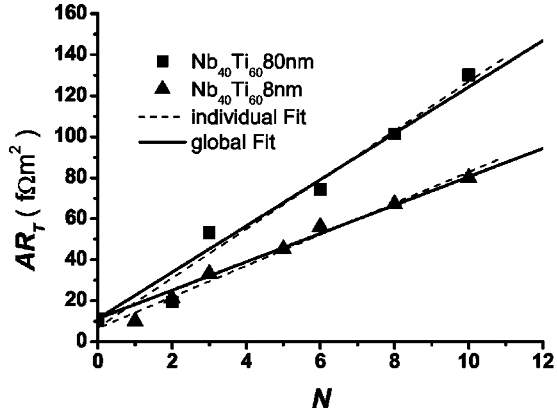

FIG. 3. Unit area resistance, AR_T vs bilayer number N of two sets of samples with $Nb_{60}Ti_{40}$ thicknesses fixed at 15 and 80 nm, respectively. The dashed lines are linear least-squares fits to individual sets. Solid lines are global fit to two sets of data simultaneously.

It was difficult to measure our CPP structure due to the 3.4 mm diameter of sample area, which results in a resistance less than 1 $\mu\Omega$. Ever since the development of the Josephson effect based detectors, even such a small resistance, could be measured by a superconducting quantum interference device based picovolt meter. One set of multilayer was composed of NbTi alloy which had an atomic percent ratio of 40 to 60, while the other set had 60:40 ratio. The CIP samples were also made for Tc and resistivity measurement.

The bulk resistivities at 10 K measured on sputtered single films of $Nb_{40}Ti_{60}$ and $Nb_{60}Ti_{40}$ were 40 $\mu\Omega$ cm and 80 $\mu\Omega$ cm, respectively, with errors of about 10%. The Tc was determined by electrical resistivity measurement. The bulk Nb_xTi_{1-x} had Tc=8.8 and 7.0 K for x=0.4 and 0.6, respectively. When Nb_xTi_{1-x} films were sandwiched between Co, it was clearly found that there were critical thicknesses of 20 nm for x=0.4 and 27 nm for x=0.6, below which no superconducting transition could be found. Since the Cooper pairs in S were subjected to pair breaking by the strong exchange field of Co at the S/F interfaces, with decreased S thickness, Tc showed a continuous reduction down to a critical thickness. Detailed analysis using Radovic's model[5,6] will be presented elsewhere. When S thickness was thinner than the critical values, we had N/F multilayers; when S was thicker, we had S/F multilayers. In the present experiment, we focused upon samples in which the thicknesses of NbTi, Co were fixed and the numbers of layers were varied. We could organize our CPP samples into four groups: (1) the $Nb_{40}Ti_{60}$ thicknesses were fixed at 8 nm for normal state; (2) the $Nb_{40}Ti_{60}$ thicknesses were fixed at 80 nm for superconducting state; (3) the $Nb_{60}Ti_{40}$ thicknesses were fixed at 15 nm for normal state; and (4) the $Nb_{60}Ti_{40}$ thicknesses were fixed at 80 nm for superconducting state. In all series of samples, the Co thicknesses were fixed at 20 nm and the numbers of bilayers were varied.

We found the CPP resistance was linearly proportional to the number of bilayers for all four sets of samples. Plots of the product of sample area A and total resistance R against bilayer number N are given in Fig. 2 for $Co/Nb_{40}Ti_{60}$ multilayers. The dash lines in Fig. 2 are least-squares fits to each set of data. Parkin reported antiferromagnetic coupling of Co through 0.9 nm of Nb, but no further coupling for large thickness.[7] Therefore, according to a one-band mode, the linear behavior of AR against N can be written as $AR_T = 2AR_{F/S(S)} + \rho_F t_F + N(\rho_F t_F + \rho_S t_S + 2AR_{F/S(N)})$ for normal NbTi and $AR_T = 2AR_{F/S(S)} + \rho_F t_F + N(\rho_F t_F + 2AR_{F/S(S)})$ for superconducting NbTi. Here R_T is the measured total resistance of multilayers, t is the thicknesses, ρ is the resistivities, and $R_{F/S(N),(S)}$ is the interface resistances between Co and Nb_xTi_{1-x} layers for normal and superconducting states, respectively. For an individual fit to the data set of $Nb_{40}Ti_{60}$ =80 nm, we can write $AR_T = C_1 + C_2 N$ with $C_1 = C_2 = 2AR_{Co/Nb_{40}Ti_{60}(S)} + \rho_{Co} t_{Co}$. In Table I, we see the value of C_1 and C_2 are within mutual uncertainties. Because of the two sets of data share the same parameter, we can perform a global fit to all data simultaneously. This gives $C_1 = C_2 = 11.3 \pm 1.3\ f\Omega\ m^2$ for $Nb_{40}Ti_{60}$=80 nm, $C_1 = 11.3 \pm 1.3\ f\Omega\ m^2$ and $C_2 = 6.9 \pm 0.6\ f\Omega\ m^2$ for $Nb_{40}Ti_{60}$=8 nm. Used the bulk resistivities at 10 K for Co and normal $Nb_{40}Ti_{60}$ layers, we extracted $2AR_{Co/Nb_{40}Ti_{60}(S)} = 9.9 \pm 1.3\ f\Omega\ m^2$ and $2AR_{Co/Nb_{40}Ti_{60}(N)} = 2.3 \pm 0.8\ f\Omega\ m^2$.

TABLE I. Linear least-square fits to the two sets of data in Figs. 2 and 3. The fits are independent of the model.

	Individual fit				Global fit			
	$Nb_{40}Ti_{60}$		$Nb_{60}Ti_{40}$		$Nb_{40}Ti_{60}$		$Nb_{60}Ti_{40}$	
	80 nm	8 nm	80 nm	15 nm	80 nm	8 nm	80 nm	15 nm
C_1	7.0±1.4	6.6±0.5	13.8±1.7	6.4±1.1	11.3±1.3		7.7±0.6	
C_2	12±1.0	7.6±0.4	22.9±1.4	19.6±0.6	11.3±1.3	6.9±0.6	24±1.7	19±0.9

TABLE II. The best derived values and parameters for the Co/Nb, $Co/Nb_{40}Ti_{60}$, and $Co/Nb_{60}Ti_{40}$ multilayers.

	$2AR_S$ $f\Omega m^2$	ρ_s $\mu\Omega$ cm	ξ nm	$\rho_s l_a$ $f\Omega m^2$	$2AR_N$ $f\Omega m^2$
Co/Nb	6.3 ± 0.9	~8	12	1.5	3.5 ± 0.7
$Co/Nb_{40}Ti_{60}$	9.9 ± 1.3	~40	4	2.5	2.3 ± 0.8
$Co/Nb_{60}Ti_{40}$	22.6 ± 1.7	~80	4.5	5.7	5.6 ± 1.5

Figure 3 shows a plot of AR_T versus N for $Nb_{60}Ti_{40}$. The linear behavior also permitted us to use the above equations. The S electrodes in these samples were pure Nb because it had higher Tc. The lines of individual fit intercept the ordinate axes at nonzero values, which represent the Co/Nb interface resistance plus $\rho_{Co}t_{Co}$. But in Table I, we see C_1 from $Nb_{60}Ti_{40}=15$ nm and from $Nb_{60}Ti_{40}=80$ nm individual fits are different. To get the quantitative analysis, we also performed a global fit to both sets of data simultaneously. When we put in the bulk resistivities at 10 K for normal $Nb_{60}Ti_{40}$ layers and the Co/Nb interface resistance we have presented,[2] the best value of $2AR_{Co/Nb_{60}Ti_{40}(S)}$ is 22.6 ± 1.7 $f\Omega$ m^2 and $2AR_{Co/Nb_{60}Ti_{40}(N)}$ is 5.6 ± 1.5 $f\Omega$ m^2 derived from the fit. When superconducting layer was composed of alternating 0.5 nm thick layers of Nb and Ti, $2AR_{Co/NbTi}=12.4\pm0.7$ $f\Omega$ m^2 was reported in the literature.[8] We have a smaller value in $Nb_{40}Ti_{60}$ and bigger a value in $Nb_{60}Ti_{40}$ when superconductor layer is NbTi alloy materials.

According to Pippard's model of partial quenching of Andreev reflection by impurities in the superconductor,[9,10] the residual (S/N) boundary resistance can be written as

$$2AR = 2\left(\frac{l_a}{2l_s}\right)_s (\rho_0 l_0)_N = \left(\frac{\rho_s l_a}{\rho_s l_s}\right)(\rho_0 l_0)_N, \quad (1)$$

where $l_a=(\pi/2)\xi$ is the extinction length in S of the electron evanescent wave from N, ξ is the intrinsic coherence length in S, $\rho_0 l_0$ is the product of bulk resistivity ρ_0 and the mean free path l_0, and $\rho_s l_s$ is the product of ρ_s and l_s, when S is in the normal state just above Tc. The second from Eq. (1) shows that AR should be proportional to $\rho_s l_a$. In a prior work,[9] the data were compatible with a linear dependence on the resistivity up to at least 20 $\mu\Omega$ cm. Therefore, we want to test the linear dependence of AR on $\rho_s l_a$ predicted by Eq. (1). Table II contains our values of $2AR$ for $Nb_{40}Ti_{60(S)(N)}$ and $Nb_{60}Ti_{40(S)(N)}$ together with reported values of Co/Nb by previous studies.[2]

From the Ginzburg–Landau (GL) theory, H_{c2} for layered F/S structures can be written as $H_{c2\|}=\phi_0/[2\pi\xi_\|(T)\xi_\perp(T)]$ *and* $H_{c2\perp}=\phi_0/[2\pi\xi_\|^2(T)]$, where $H_{c2\|}$ and $H_{c2\perp}$ are measured with field parallel and perpendicular to plans, respectively, ϕ_0 is the flux quantum, and ξ are GL coherence lengths. The GL coherence length at zero temperature can be written as $\xi_{GL}(0)=\sqrt{\phi_0/2\pi ST_c}$, where $S=-dH_{c2}/dT$ close to Tc. In Table II, we also list the coherence lengths derived from the temperature-dependent upper-critical field measurements of $H_{c2\perp}$ (T). The value of $(2AR)_S$ for Co/Nb is only about ~64% as large as that for $Co/Nb_{40}Ti_{60}$ with similar ratio for $(\rho_s l_a)_{Nb}/(\rho_s l_a)_{Nb_{40}Ti_{60}}$. Similarly, the ratio for $(2AR)_S$ for Co/Nb is ~28% for $Co/Nb_{60}Ti_{40}$, also close to $(\rho_s l_a)_{Nb}/(\rho_s l_a)_{Nb_{60}Ti_{40}}$. Thus, Eq. (1) held for ρ_s as large as 80 $\mu\Omega$ cm in our S samples. But the experimental values of AR in the linear regime were smaller than predicted by the Eq. (1). Pippard proposed the effect of Fermi surface mismatching between the S and N metals of the sandwich as a partial explanation for the discrepancy.[10] The values of interface resistance when superconductor is in normal state did not change systematically with $\rho_s l_a$. We will discuss this else where.[11]

In summary, we have presented the linear increase of the CPP resistance with the number of bilayers in both normal and superconducting states for $Co/Nb_{40}Ti_{60}$ and $Co/Nb_{60}Ti_{40}$ multilayers. Global fit by one band model derived the best value of interface resistance. The AR between S and F was proportional to $\rho_s l_a$ which conform to the Pippard's model.

[1] V. V. Ryazanov, V. A. Oboznov, A. Yu. Rusanov, A. V. Veretennikov, A. A. Golubov, and J. Aarts, Phys. Rev. Lett. **86**, 2427 (2001).
[2] S. F. Lee, S. Y. Huang, J. H. Kuo, Y. A. Lin, and Y. D. Yao, J. Appl. Phys. **93**, 8212 (2003).
[3] C. Fierz, S.-F. Lee, J. Bass, W. P. Pratt, Jr., and P. A. Schroeder, Physica B **165&166**, 453 (1990).
[4] V. V. Schmit, *The Physics of Superconductors* (Springer, New York, 1997).
[5] Z. Radovic, L. Dobrosavljevic-Grujic, A. I. Buzdin, and J. R. Clem, Phys. Rev. B **38**, 2388 (1998).
[6] Jun-Jih Liang, S. F. Lee, W. T. Shih, W. L. Chang, C. Yu, and Y. D. Yao, J. Appl. Phys. **92**, 2624 (2002).
[7] S. S. P. Parkin, Phys. Rev. Lett. **67**, 3598 (1991).
[8] C. Fierz, S.-F. Lee, J. Bass, W. P. Pratt, Jr., and P. A. Schroeder, J. Phys.: Condens. Matter **2**, 9701 (1990).
[9] G. L. Harding, A. B. Pippard, and J. R. Tomlinson, Proc. R. Soc. London, Ser. A **340** 1 (1974).
[10] A. B. Pippard Proc. R. Soc. London, Ser. A **391** 225 (1981).
[11] S. F. Lee, S. Y. Huang, and Y. D. Yao (unpublished).