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Analysis of diffusive interface resistance for measurements with perpendicular current in Fe/Nb multilayers

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In this study, we investigated the electron transport properties of interface between a ferromagnet and a superconductor with flowing current perpendicular to plan (CPP) at 4.2 K in Fe/Nb multilayers. The CPP resistance increased linearly with layer thickness and with bilayer number. We extracted the unit area resistance value of one pair of interface for superconducting and normal Fe/Nb by using a series resistor model. Hence, we can quantitatively analyze the interface resistance between Fe and Nb in the diffusive regime. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2176871]

There is much interest in studying electron transport properties of ferromagnetic/superconducting (F/S) interfaces. Recently, point contact technique was used to measure the spin polarization of various ferromagnets, including the predicted highly spin polarized half-metallic ferromagnets.[1] The results can be explained by the Andreev reflection and the transparency of the interface upon the injection of spin-polarized current from F into S. Spin effects play an important role in the Andreev reflection at the F/S interface. At small bias voltage, an incident electron in the spin-up band from a normal metal (N) is reflected by the interface as a hole in the spin-down band in order to form a Cooper pair. This conduction process is known as the Andreev reflection.[2] When the bulk scattering is negligible in a ballistic contact, the transport properties are directly connected to the probabilities of scattering at the interface. In a ferromagnet with different numbers of spin-up and spin-down conduction channels, only a fraction of the majority channels can be Andreev reflected. However, experimental studies of F/S contacts in the diffusive limit are more intriguing and are more complex in many unconventional proximity effects.[3] The resistance can either decrease or increase when cooling from above the critical temperature of superconductor.[4–6] Transport properties are governed by interplay between spin accumulation close to the interface and the Andreev reflection at the interface.

It is hard to quantitatively analyze the electron transport properties across the interface between S and F metals. We present here the resistance of Fe/Nb multilayers with current perpendicular to plane (CPP) measurement at 4.2 K in the diffusive regime. Our CPP samples were fabricated by dc magnetron sputtering onto Si(100) with three different *in situ* contact masks. General information can be found elsewhere.[7] The CPP sample is sandwiched between two thick circular electrodes which are in turn between two crossed long strips for four-point measurement. The thick superconducting leads assure uniform current throughout the whole multilayers sample. Each sample has N Fe/Nb repeated bilayers plus one layer of Fe, indicated as $(\mathrm{Fe/Nb})_N/\mathrm{Fe}$. The superconducting energy gap Δ of Nb is smaller than the energy of the exchange fields in Fe by several orders of magnitude. Thus, the proximity effect in ferromagnetic metals is negligible. All changes induced by the contact to a superconductor depend on the properties of the interface itself. The total resistance R_T was measured by superconducting quantum interference device (SQUID) based picovolt meter. Simple planar multilayers were also made for measuring temperature and magnetic field dependence of resistivity. X-ray diffraction showed crystalline structure of bcc (110) for Nb and Fe. Higher-order satellite peaks are observed to confirm a good coherence in the Fe/Nb multilayer system, as shown in Fig. 1.

Shukla and Prasad[8] calculated the interlayer exchange coupling between Fe layers when separated by Nb space layers using a self-consistent full-potential linear augmented plane-wave (FLAPW) method. They observed an oscillating exchange coupling as a function of Nb spacer thickness with a period of 0.6 nm. However, we found that the Fe layer was

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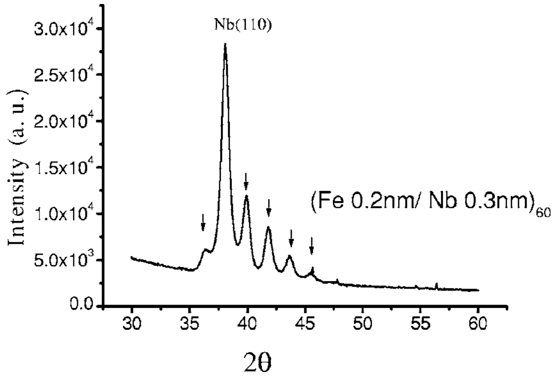

FIG. 1. High-angle x-ray diffraction of $[Fe(0.2\ nm)/Nb(0.3\ nm)]_{60}$ multilayer. Satellite peaks around Nb(110) are indicated by arrows.

not coupled across Nb in the Fe/Nb multilayer thin film with varying Nb thickness from 0.5 to 4 nm.[9]

Our sputtered bulk Nb has a superconducting transition temperature of T_c=9.2 K. When Nb films are sandwiched between fixed Fe thickness, T_c decreases with decreasing Nb thickness. Below a critical thickness d_{Nb}^{crit}, no superconductivity behavior could be found. This is due to a large suppression of the superconducting order parameter at S/F interface from the strong pair breaking by the ferromagnet at the interface. We have deduced the $d_{Nb}^{crit} \approx 34$ nm, the penetration depth $\xi_{FM}^{Fe}=1.2$ nm of the cooper pair into the ferromagnet, and the superconductor coherence length $\xi_{sc}=12$ nm from the analysis of our experimental data within Radović's model under the single mode approximation.[10,11] This means that when Nb thickness is thinner than $d_{Nb}^{crit} \approx 34$ nm, Nb is always normal, otherwise the Nb could become the superconductor in Fe/Nb multilayers.

In the present experiment, two series of samples were made with Nb thickness fixed at 15 and 80 nm separately, Fe thickness fixed at 20 nm, and increasing numbers of bilayers. Plots of the product of the sample area A and total resistance R_T against bilayer number N are given in Fig. 2. The specific CPP resistance AR_T is linearly proportional to the number of bilayers for both Nb thicknesses. The dash lines in Fig. 2 are least squares fit to each set of data. Since there is no antiferromagnetic coupling of Fe through Nb film, a one-band model could be applied. Therefore, the linear behavior of AR against N can be described as

$$AR_T = 2AR_{Fe/Nb(S)} + \rho_{Fe}t_{Fe} + N[\rho_{Fe}t_{Fe} + 2AR_{Fe/Nb(S)}], \quad (1)$$

for superconducting Nb and

$$AR_T = 2AR_{Fe/Nb(S)} + \rho_{Fe}t_{Fe} + N[\rho_{Fe}t_{Fe} + \rho_{Nb}t_{Nb} + 2AR_{Fe/Nb(N)}], \quad (2)$$

for for normal Nb. Here t is the thickness, ρ is the resistivity, and $R_{Fe/Nb(N),(S)}$ is the interface resistance between Fe and Nb layers for normal and superconducting states, respectively. According to individual fit, the equation is easy to be simplified as $AR_T=C_1+C_2N$ for normal Nb and $AR_T=(N+1)C_1$ for superconducting Nb, with $C_1=2AR_{Fe/Nb(S)}+\rho_{Fe}t_{Fe}$ and $C_2=2AR_{Fe/Nb(N)}+\rho_{Fe}t_{Fe}+\rho_{Nb}t_{Nb}$. Similar analysis on Co/Nb multilayers had been presented before.[7] There is mutual uncertainty between C_1 and C_2. We can perform a global fit to all data simultaneously since the two sets of data share the same parameters. As shown in Fig. 2, the straight line gives $C_1=7.1\pm1.3$ fΩ m^2 and $C_2=5.2\pm0.6$ fΩ m^2. The specific unit area resistance of one pair of interfaces can be derived to be $2AR_{Fe/Nb(S)}=5.9\pm0.3$ fΩ m^2 and $2AR_{Fe/Nb(N)}=2.8\pm0.4$ fΩ m^2 by putting bulk resistivities of 6.2 and 8 $\mu\Omega$ cm for 500 nm thick Fe and Nb at 10 K into Eqs. (1) and (2). From Pippard's model of partial quenching of Andreev reflection by impurities in the superconductor, the residual (S/N) boundary resistance can be written as $2AR \propto \rho_s l_a$, 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, and ρ_s is the bulk resistivity when S is in the normal state just above T_c.[12,13] The value of $2AR_{Co/Nb(S)}=6.3\pm0.9$ fΩ m^2 for Co/Nb multilayer reported before[7] is close to $2AR_{Fe/Nb(S)}=5.9\pm0.3$ fΩ m^2 for Fe/Nb multilayer. This is expected from Pippard's model due to that AR is only proportional to the coherence length and resistivity in superconductor film.

Instead of using bulk resistivity, we also varied the Fe and Nb thickness while the numbers of bilayers were fixed at 6 and 12, respectively, to treat the CPP resistivities as fitting parameters. The CPP resistance is linearly proportional to the thickness for both Fe layer and Nb layer. Using the one-band model, the linear behavior of AR against thickness can be written as

$$AR_T = 2AR_{Fe/Nb(S)} + 6AR_{Fe/Nb(N)} + 6\rho_{Nb}t_{Nb} + 7\rho_{Fe}d_{Fe}, \quad (3)$$

for varying Fe thickness (d_{Fe}) with Nb thickness fixed at 15 nm and

$$AR_T = 2AR_{Fe/Nb(S)} + 12AR_{Fe/Nb(N)} + 13\rho_{Fe}t_{Fe} + 12\rho_{Nb}d_{Nb}, \quad (4)$$

for varying Nb thickness (d_{Nb}) with Fe thickness fixed at 20 nm. As shown in Fig. 3(a), individual linear least squares fits of AR vs d_{Fe} and d_{Nb} samples yield a slope ρ_{Fe} of 6.2 and ρ_{Nb} of 12 $\mu\Omega$ cm, respectively. However, all the above equations share the same parameters. Therefore, we can perform a global fit to all data simultaneously to reduce the deviation.

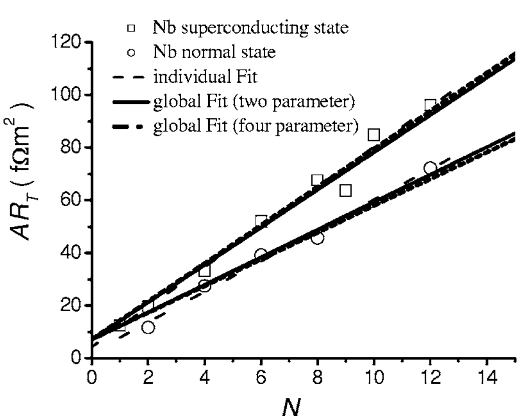

FIG. 2. Specific resistance AR_T vs bilayer number N of two sets of samples with Nb thicknesses fixed at 15 and 80 nm, respectively. The dashed lines are linear least squares fits to individual sets. The solid lines are global fit for two parameters and dash dot lines are global fit for four parameters to two sets of data simultaneously.

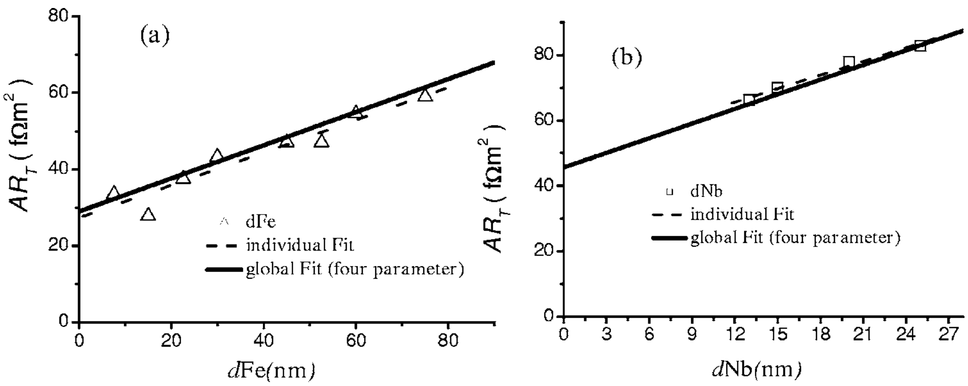

FIG. 3. (a) Specific resistance AR_T vs Fe thickness with Nb thickness fixed at 15 nm and $N=6$. (b) Specific resistance AR_T vs Nb thickness with Fe thickness fixed at 20 nm and $N=12$. The dashed lines are linear least squares fits to individual sets. The solid lines are global fit for four parameters to the data simultaneously.

We can rewrite Eq. (1) as $AR_T=g_1+Ng_2+(N+1)t_{\mathrm{Fe}}g_3+Nt_{\mathrm{Nb}}g_3$, Eq. (2) as $AR_T=(N+1)g_1+(N+1)t_{\mathrm{Fe}}g_3$, Eq. (3) as $AR_T=g_1+6g_2+7d_{\mathrm{Fe}}g_3+6t_{\mathrm{Nb}}g_3$, and Eq. (4) as $AR_T=g_1+12g_2+13t_{\mathrm{Fe}}g_3+6d_{\mathrm{Nb}}g_3$. Here g_1 is the $2AR_{\mathrm{Fe/Nb}(S)}$, g_2 is the $2AR_{\mathrm{Fe/Nb}(N)}$, g_3 is the ρ_{Fe}, and g_4 is the ρ_{Nb}. The results in Table I are the two-parameter and four-parameter best fit values by using global fit. From the studies of transport properties of normal metal-superconductor (N/S) structures, it is established that the difference between the superconducting and normal state conductance ($\delta G=G_s-G_N$) is negative for large S/N interface resistance ($R_{S/N}$) and changes sign with decreasing $R_{S/N}$.[14] In Table I, we can find that the $2AR_{\mathrm{Fe/Nb}(S)}$ is larger than $2AR_{\mathrm{Fe/Nb}(N)}$. The spin accumulation causes an additional voltage drop across the interface due to reduced spin transport into S. Therefore, the interface resistance of the F/S system should be larger than that of the F/N system. We also observed that the CPP resistivity of Nb is bigger than bulk resistivity. This probably shows that the conduction electron scattering at grain boundaries is the main scattering process in our sputtered samples.

TABLE I. The best derived values and parameters for the Fe/Nb multilayers.

Global fit	$2AR_S$ ($f\Omega$ m^2)	$2AR_N$ ($f\Omega$ cm)	ρ_{Fe} ($\mu\Omega$ cm)	ρ_{Nb} ($\mu\Omega$ cm)
Two parameters	5.9±0.3	2.8±0.4	6.2±0.6[a]	8±0.9[a]
Four parameters	6.0±0.4	2.0±0.9	6.2±0.8	12.5±1.3

[a]Bulk values measured in 500 nm films.

To summarize, we have presented the best fit by the one-band model to derive the absolute value of interface resistance in the diffusive CPP samples. The unit area specific resistance of Fe/Nb interface is $2AR_{\mathrm{Fe/Nb}(N)}=2.0\pm0.9$ fΩ m^2 for normal Nb and $2AR_{\mathrm{Fe/Nb}(S)}=6.0\pm0.4$ fΩ m^2 for superconducting Nb with bias voltage much less than the superconducting gap. We know that the spin accumulation leads to enhanced resistance whereas Andreev reflection can lead to decreased resistance. The diffusive interface resistance between F and S should take account of the competition between these two mechanisms.

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