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Superconducting critical temperature in FeN-based superconductor/ferromagnet bilayers

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Abstract

We present an experimental investigation of the superconducting transition temperatures, T_c, of superconductor/ferromagnet bilayers with varying the thickness of ferromagnetic layer. FeN was used for the ferromagnetic (F) layer, and NbN and Nb were used for the superconducting (S) layer. The results were obtained using three different-thickness series of the S layer of the S/F bilayers: NbN/FeN with NbN thickness, $d_{NbN} \approx 9.3$ nm and $d_{NbN} \approx 10$ nm, and Nb/FeN with Nb thickness $d_{Nb} \approx 15$ nm. T_c drops sharply with increasing thickness of the ferromagnetic layer, d_{FeN}, before maximal suppression of superconductivity at $d_{FeN} \approx 6.3$ nm for $d_{NbN} \approx 10$ nm and at $d_{FeN} \approx 2.5$ nm for $d_{Nb} \approx 15$ nm, respectively. After shallow minimum of T_c, a weak T_c oscillation was observed in NbN/FeN bilayers, but it was hardly observable in Nb/FeN bilayers.

Keywords : Proximity effect, NbN/FeN bilayer, Nb/FeN bilayer

1. INTRODUCTION

The superconducting critical temperature, T_c, as a function of the thickness of the ferromagnetic layer, d_F, reveals nonmonotonic behavior in ferromagnet/superconductor (F/S) bilayers [1] and F/S/F multilayers [2]. The most spectacular experimental result of F/S bilayer was the re-entrance of superconductivity [1, 3]. The competing orders between superconductivity and ferromagnetism affect each other by proximity effect. The proximity effect of ferromagnetic layer changes the properties of the superconducting layers by suppressing and oscillating the Cooper-pair wave function. As such, the superconducting transition temperature is seen to be affected.

In the experiments on Fe/V [4] and Gd/Nb [5] systems, the T_c showed nonmonotonic dependence with increasing d_F after the initial rapid drop. But Nb/Fe system did not reveal any nonmonotonic behavior [6]. Soon after, Fe/Nb/Fe system showed pronounced oscillatory behavior of T_c on the iron layers thickness with absolute amplitude of about 0.5 K [7]. Later in Nb/$Cu_{1-x}N_x$ bilayer system, a suppression of the superconducting pairing wave function showed a double suppression of superconductivity [1]. They ascribed the result to an experimental evidence for a quasi-one dimensional Fulde-Ferrell-Larkin-Ovchinnikov (FLLO) like state in the ferromagnetic layer; FFLO state explains that for ferromagnetic superconductors the superconducting order parameter may be modulated in real space by an exchange field, I, with $\Delta \sim \exp(ik_f r)$, where Δ is the energy gap, $k_f = v_F / 2I$ is the value of the wave-vector of FFLO pairs and v_F is the Fermi velocity [8, 9].

In V/Fe system, contrary to the previous results [4], T_c oscillations as a function of d_{Fe} were not observed [10]. Negative results were also published for the Nb/Fe [6].

Mühge *et al.* attributed a weak T_c oscillation to a modification of the repulsive interaction between the electrons in the magnetically "dead" Fe-rich interlayer when an exchange field in the Fe layer is present [7]. Magnetic dead layer reduces T_c due to the introduction of a strongly repulsive interaction for the Cooper pairs on one aspect. Conversely, it screens superconducting layer from the strongly pair-breaking exchange field of the ferromagnetic layer.

In the present work, we have studied the superconductivity of S/F bilayers covered by FeN layers with thickness, d_{FeN}, between 0 and 30 nm. In order to reduce the alloying effect at the interface, we have used the FeN layer for the magnetic layer and the NbN layer for the superconducting layer known for its hardness and wear resistance. We have also chosen Nb for the superconducting layer which has less hardness than the NbN layer.

2. EXPERIMENTAL

The S/F samples were prepared by magnetron sputtering on thermally oxidized Si substrates at room temperature. Both superconducting NbN and ferromagnetic FeN thin film were made by reactive methods. The base pressure of the sputtering chamber was lower than 3×10^{-7} Torr. The Nb targets were pre-sputtered for 5 minutes to remove contaminations and reduce the residual gas pressure in the sputtering chamber. Then, the superconducting layer was firstly deposited using dc magnetron sputtering. The average growth rates of superconducting layer were as follows: 5 Å/s for Nb and 3.6 Å/s for NbN. The Fe target was rf sputtered and the rate was 3.3 Å/s. The details of the fabrication conditions for NbN and FeN were discussed in published elsewhere [11].

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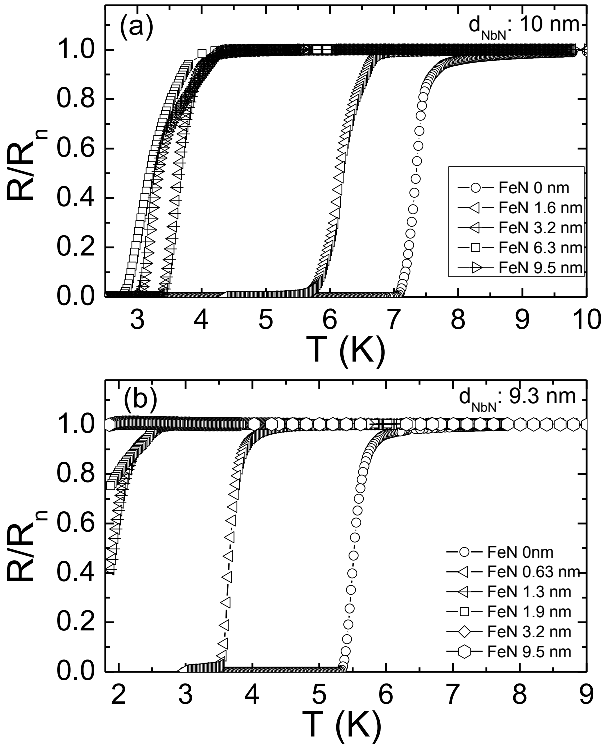

Fig. 1. (a) Resistive superconducting transitions of NbN/FeN bilayers for $d_{NbN} \approx 10$ nm at zero field with four different thicknesses of FeN ~ 1.6, 3.2, 6.3, and 9.5 nm. (b) $R(T)$ for $d_{NbN} \approx 9.3$ nm and five different thickness of FeN ≈ 0.63, 1.3, 1.9, 3.2, and 9.5 nm.

We fabricated 16 samples of different FeN thickness in each series. For a given run of deposition, we fabricated four samples of different d_{FeN} at each carousel by using a linear motion shutter and completed 16 samples by rotating sample holder platform which holds four carousels. Temperature dependence of resistance was measured by using a conventional DC four-probe method using a Quantum Design PPMS (Physical Property Measurement System). Mid-point temperature of the superconducting transition was defined as T_c for a given sample.

3. RESULTS AND DISCUSSION

Fig. 1 shows the temperature dependence of resistance, $R(T)$, of NbN/FeN bilayers with different d_{FeN} for two S/F series. The resistances are normalized to the residual normal-state values, R_n, just above the transition. T_c for pure superconducting NbN film was about 7.34 K for thickness $d_{NbN} \approx 10$ nm and 5.52 K for $d_{NbN} \approx 9.3$ nm, respectively. The transition temperature width of the bilayers was between 0.4 K and 1 K, which was determined by a change of the resistance from 0.1 R_n to 0.9 R_n.

The obtained T_c is plotted in Fig. 2 for two series of samples with variable d_{FeN} and fixed d_{NbN}. T_c of a thick NbN (10 nm) layer sharply dropped upon increasing the ferromagnetic FeN layer thickness till a certain thickness $d_{FeN} \approx 6.3$ nm, then exhibiting a weak oscillatory behavior with another shallow minimum at $d_{FeN} \approx 21$ nm. On the other hand, T_c of thinner NbN (9.3 nm) layer vanished above the range of $d_{FeN} \approx 3.2$ nm. In this case T_c is at least lower than the lowest temperature reached in PPMS. For convenience, T_c below 1.85 K was plotted as 0 K in the figure.

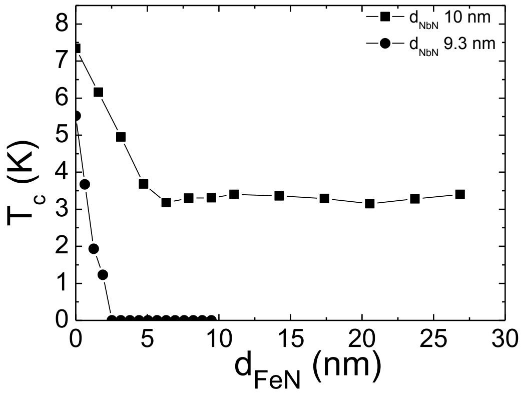

Fig. 2. Superconducting transition temperature T_c as a function of the FeN layer thickness, d_{FeN}, for NbN/FeN bilayers with $d_{NbN} \approx 10$ nm and $d_{NbN} \approx 9.3$ nm.

The present results without a pronounced minimum in $T_c(d_{FeN})$ is similar to other previously studied [10, 12]. Experimental results showed that Fe atoms diluted in Nb lose their magnetic moment in Nb/Fe bilayers [13]. The effective electron-electron interaction in the Fe-rich nonmagnetic interlayer is strongly repulsive, which stems from the coupling of the conduction electrons to the local paramagnetic fluctuations. This repulsive interaction suppresses T_c by the proximity effect to give a rise to the initial T_c suppression.

Fig. 3(a) shows the resistance $R(T)$ of Nb/FeN bilayers with different d_{FeN} in series. T_c was about 6.6 K for $d_{Nb} \approx 15$ nm. The transition temperature width was below 70 mK. On increasing the thickness of FeN layer, T_c of Nb/FeN bilayers showed a minimum value of 3.71 K at $d_{FeN} \approx 2.5$ nm. After this minimum value of T_c, the transition temperature steadily increased as shown in the figure.

The dependences of transition temperatures on the d_{FeN} for Nb/FeN and NbN/FeN bilayers are plotted to compare to each other in Fig. 3(b). A similar behavior, rapid decrease of T_c followed by gradual increase, was observed for Nb case, but the shallow minimum was detected at about $d_{FeN} \approx 2.5$ nm, much smaller than $d_{FeN} \approx 6.3$ nm for the NbN case. The d_{FeN} value of T_c minimum for NbN/FeN bilayers is similar to the result of using $Cu_{1-x}Ni_x$ as the ferromagnetic layer ($d_{Cu1-xNix} \approx 7$ nm), where clear T_c oscillation has been observed [1] whereas that of Nb/FeN bilayers is close to the other results with ferromagnetic layer thickness around 1 nm [2-5]. In the latter only a shallow T_c minimum has been detected.

Here we would focus on the difference in the d_{FeN} for a minimum value of T_c. NbN superconductor has a better wear resistance as well as a higher mechanical hardness than Nb superconductor. For Fe-rich interlayer at the S/F interface, the fact of T_c minimum occurrence at thicker ferromagnetic layer for NbN/FeN bilayers may imply that

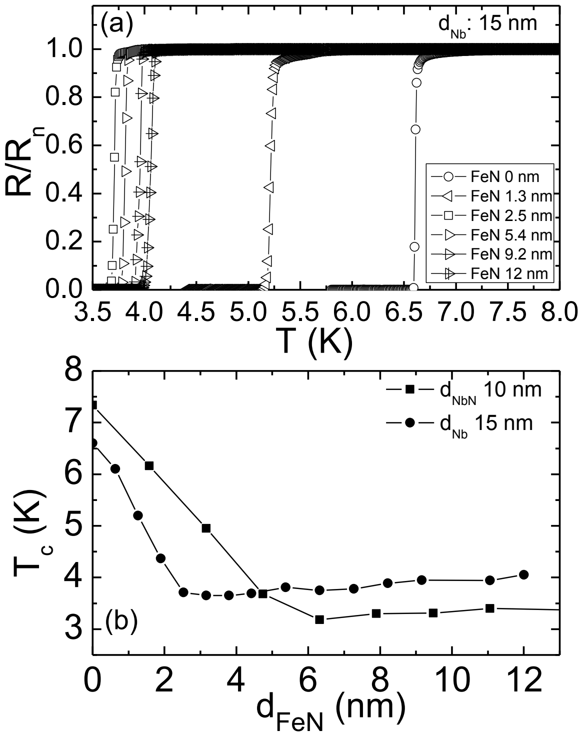

Fig. 3. (a) Resistance versus temperature of 15 nm thick Nb at zero field with five different thickness of FeN ~ 1.3, 2.5, 5.4, 9.5, and 12 nm. (b) Superconducting transition temperature T_c as a function of the FeN layer thickness d_{FeN} for NbN/FeN bilayers with $d_{NbN} \approx 10$ nm and $d_{Nb} \approx 15$nm.

the NbN/FeN bilayers have a thinner non-ferromagnetic interlayer at the interface compared to the Nb/FeN bilayers.

This fact also implies that the non-ferromagnetic interlayer not only reduces T_c by the introduction of a strong repulsive interaction for the Cooper pairs but also it screens the superconducting layer from the strong pair-breaking exchange field of the ferromagnetic layer.

4. SUMMARY

We have studied the superconducting transition in three series of S/F bilayer with a constant superconducting layer ($d_{NbN} \approx 9.3$ nm, $d_{NbN} \approx 10$ nm and $d_{Nb} \approx 15$ nm) while varying the thickness of FeN layer. We observed a nonmonotonic dependence of T_c on d_{FeN}, with a shallow minimum, however, a weak T_c oscillation was observed only in our sputtered NbN/FeN samples. Our work at least suggests that NbN is a better candidate for investigation of the proximity effect in bilayers with FeN as a ferromagnetic component.

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