Properties of superconductivity for decoupled ferromagnet/superconductor trilayers and multilayers in Fe/Nb system

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Abstract

The transition temperature $T_c$ and upper critical field $H_{c2}$ of sputtered Fe/Nb trilayers and multilayers have been determined by measurement of electrical resistivity. For a fixed Fe layer thickness, $T_c$ decreases with decreasing Nb thickness up to a critical thickness $d_{Nb}^{crit} \approx 34$ nm below which superconductivity vanishes. When the superconducting layers are thin ($d_{Nb} < 140$ nm) and decoupled by pair breaking in the ferromagnetic layers, the parallel critical field exhibits nonlinear temperature dependence, revealing a change in the superconducting dimensionality. The strong decrease of $T_c$ with decreasing Nb thickness as well as the temperature dependence of $H_{c2}$ can be well described by theoretical model.

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The interaction between superconductivity (SC) and ferromagnetism (FM) has attracted much interest. Because FM favors a parallel alignment of electron spins through the FM exchange field, whereas SC requires a coupling between antiparallel spin, both mechanisms are counteractive. Nevertheless, according to Fulde and Ferrel [1] and Larkin and Ovchinnikov [2] (FFLO), SC and FM may curiously coexist. It means that nonzero total momentum pairing still can occur while an exchange field is present. For example, the experimental results from Mühge et al. [3] found a nonmonotonic dependence of superconducting transition temperature $T_c$ on Fe layer thickness ($d_{Fe}$). Another research reported by Verbanck et al. [4] demonstrated a sudden drop of $T_c$ when they increased $d_{Fe}$ up to 1.5 nm for epitaxial Fe/Nb multilayer systems. However, in the study of coexistence of SC and FM, a thin FM layer, due to the reduction of the exchange energy, shows nonmagnetic behavior [3,4]. In order to learn about the proximity effect between SC and FM in the decoupled regime, we studied the critical temperature $T_c$ and upper critical field $H_{c2}(T)$ with a constant $d_{Fe} = 20$ nm, which is much large than that of the coupled regime of 1.2 nm [4] and a variety of Nb thicknesses. The dependence of $T_c$ on SC thickness and the temperature dependence of $H_{c2}(T)$ can be well described by the theory of Radović et al.[5] and Ginzburg–Landau theory, respectively. We also compare the Fe/Nb with the previously reported Co/Nb system [6,7].

The Fe/Nb samples were prepared by DC magnetron sputtering on Si(100) substrates. Twelve samples were fabricated in the same run to minimize any difference in preparation condition. In this paper, we will mainly discuss a series of samples as follows: Fe/Nb/Fe trilayers and 6 Fe/Nb repetitions multilayers denoted as (Fe/Nb)$_6$/Fe. The thickness of the Fe layer for both systems was kept 20 nm while that of SC layers varied. As shown in Fig. 1, the good

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quality and smooth interface can be verified by TEM image. Electrical resistance, $T_c$, and $H_{c2}$ were measured by four-point measurement.

Fig. 2 shows the $T_c$ as a function of the Nb thickness for the trilayers. With decreasing $d_{Nb}$, $T_c$ exhibits a continuous reduction down to a critical thickness $d_{sc}^{crit}$, below which superconductivity vanishes. The amplitude of the SC Cooper pair near the SC/FM boundary was subject to pair breaking by proximity effect. For the sample with the largest Nb thickness, the critical temperature is still lower than that of bulk Nb. For comparison, $T_c$ of a 560 nm single Nb film had been measured to be 9.2 K.

A microscopic theoretical model for the interpretation of experimental studies of FM/SC trilayers has been proposed by Radović et al. [5]. The reduced $T_c$ with decreasing $d_{sc}$ is associated with the pair-breaking effect within the single-mode approximation. In the framework of this model, the $T_c$ is given by

$$\ln t = \psi\left(\frac{1}{2}\right) - \Re \psi\left(\frac{1}{2} + \frac{\rho^*}{\tau}\right),$$

where $\psi$ is the digamma function, $\rho^*(T)$ is effective pair-breaking parameter and $t = T_c/T_{c0}$ is the reduced temperature with the bulk critical temperature $T_{c0}$. $\rho^*(T)$ in Eq. (1) can be calculated by Usadel’s equation [8] for the pair amplitude $F_{sc}$ in the superconductor

$$\frac{dF_{sc}}{dx} \bigg|_{bd} = \eta \frac{dF_{FM}}{dx} \bigg|_{bd} \quad \text{and} \quad F_{sc}|_{bd} = F_{FM}|_{bd},$$

where the interface transparency parameter $\eta$ characterizing the SC/FM interface. In the dirty limit, secular scattering, $\eta = \sigma_F/\sigma_S$, is the ratio of the normal state conductivities of the FM to that of SC layers, respectively. Solving Eq. (1) subject to the the boundary conditions (2) gives $T_c$ as a function of $d_{sc}$

$$K_{sc} d_{sc} \tan \left(\frac{K_{sc} d_{sc}}{2}\right) = \frac{2(1 + i)}{\varepsilon} \frac{d_{sc}}{\xi_{sc}} \tan h \left[2 \left(1 + \frac{1}{\xi_{FM}}\right) \frac{d_{FM}}{\xi_{FM}}\right].$$

Hence, $T_c$ depends on $d_{Nb}$, the coherence length $\xi_{SC}$, and the material parameter $\varepsilon = \xi_{SC}/\eta \xi_{FM}$. Here $\xi_{FM} = \sqrt{4/\hbar D_{FM}/I_0}$ is the penetration depth of the cooper pair into the ferromagnet and $D_{FM} = v_F l_{FM}/3$ is the diffusion constant in the FM layer with Fermi velocity $v_F$ and the mean free path $l_{FM}$. The $D_{FM}$ of Fe can be estimated by the Pippard relation [9] with the low temperature resistivity $\rho = 6.4 \mu \Omega \text{cm}$ for $d_{Fe} = 300 \text{ nm}$ and the coefficient of the specific heat $\gamma = 4.98 \times 10^{-3} \text{J K}^2 \text{ mole}$ [10]. The characteristic distance in Fe is derived to $\xi_{FM}^{Fe} = 1.2 \text{ nm}$ from the diffusion coefficient and splitting energy $I_0 = 1 \text{ eV}$ for Fe is slightly smaller than $\xi_{FM}^{Co} = 1.3 \text{ nm}$ for Co film that we have presented [6], since Fe has stronger exchange field and splitting energy than Co.

The solid line in Fig. 2 was obtained by fitting Eq. (1) to the data with parameters of $\varepsilon = 10$ and $\xi_{SC} = 12 \text{ nm}$. By extrapolating the fit to $T_c = 0$, we see that the critical thickness for superconductivity is about $d_{sc}^{crit} = 34 \text{ nm}$. It is larger than $d_{sc}^{crit} = 30 \text{ nm}$ for Co/Nb system [6] consistent with stronger pair breaking effect in Fe.

We also performed measurements of anisotropic upper-critical field $H_{c2}||$ and $H_{c2}⊥$ for Fe/Nb multilayers, where $H_{c2}||$ and $H_{c2}⊥$ denote the field parallel and perpendicular to layer planes, respectively. Fig. 3 shows $H_{c2}||$ versus reduced temperature $t$ for $d_{Nb} = 100, 120$ and 140 nm. The solid lines correspond to Ginzburg–Landau (G–L) relation. By using the G–L formulas for anisotropic superconductors, we can determine the dimensionality. For a 3D superconductor, the relation between $H_{c2}$ and reduce temperature $t$ is given by $H_{c2}|| (T) \propto (1 - t)$ and $H_{c2}⊥ (T) \propto (1 - t)$. However, in the case of two-dimensional (2D) superconductivity, the perpendicular coherence $\xi_{∥}$ is
limited by the layer thickness and becomes constant near $T_c$. In this case, the temperature dependence of $H_{c2}$ is expressed as

$$H_{c2} \propto (1-t)^{1/2}$$

and $H_{c2 \perp} \propto (1-t)$. It can be clearly seen the linear behavior of $H_{c2 \perp}$ for all thickness of Nb. Comparing Fig. 3(a) with Fig. 3(c), we found that the dependence of $H_{c2 \perp}$ on temperature changed from 2D to 3D, i.e., from a square-root dependence to a linear dependence. The extrapolation in Fig. 3 yields a coherence length $\xi_{GL}$ via $\xi_{GL}(T) = \pi \xi_{sc}(1 - t)^{-1/2}$. This gives $\xi_{sc} \approx 7$ nm which is the same with the value estimated by $\xi_{sc} = \sqrt{\hbar D_s}/2\pi k_B T = \sqrt{\xi_{BCS} l}/3.4$ with $l$ the electron mean free path, and the values obtained from the product $\rho l = 3.75 \times 10^{-6}$ $\mu \Omega \cdot cm^2$ for bulk Nb [7].

In summary, we have studied the proximity effect and the superconducting properties of Fe/Nb trilayers and multilayers. First, $d_{crit}^{SC}$ and $\xi_{sc}$ have been deduced from the analysis of experimental data within the Radović’s model under the single mode approximation. Second, a gradual transition from 2D to 3D superconductivity crossover, determined from the temperature-dependent $H_{c2}$, occurs around Nb thickness between 120 and 140 nm. Finally, our work showed that both $T_c$ and $H_{c2}$ as a function of Nb thickness were very well described by the theory for the decoupled multilayers.

References