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Journal of Magnetism and Magnetic Materials 304 (2006) e81–e83
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

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

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Available online 3 March 2006

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.

PACS: 74.45.+c; 74.70.−b; 74.78.Fk; 74.78.−w

Keywords: Proximity effect; Critical thickness; Dimensional crossover

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(1 0 0) 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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doi:10.1016/j.jmmm.2006.01.185

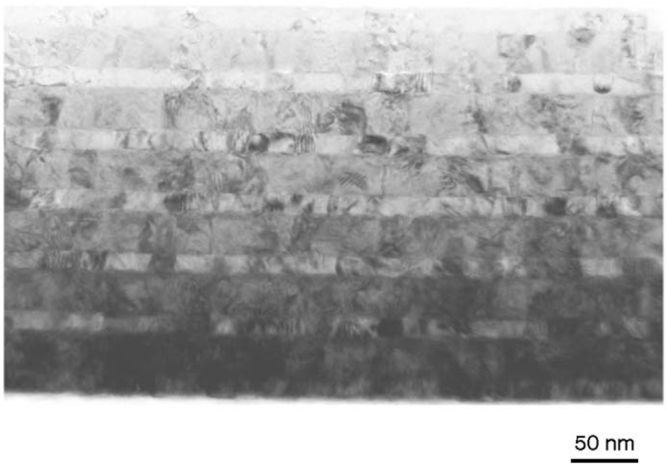

Fig. 1. TEM image of a $[Fe(20\,nm)/Nb(50\,nm)]_6/Fe(20\,nm)$ multilayer sample.

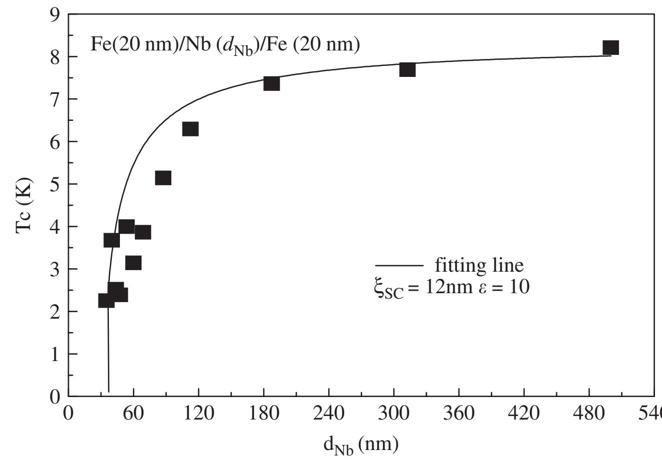

Fig. 2. Dependence of the superconducting transition temperature on the thickness of the Nb layer, the solid line is the best fit with Eq. (1).

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

$$\ln t = \Psi\left(\frac{1}{2}\right) - \mathrm{Re}\,\Psi\left(\frac{1}{2} + \frac{\rho *}{t}\right), \tag{1}$$

where ψ 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

$$\left.\frac{\mathrm{d}F_{SC}}{\mathrm{d}x}\right|_{bd} = \eta \left.\frac{\mathrm{d}F_{FM}}{\mathrm{d}x}\right|_{bd} \text{ and } F_{SC}|_{bd} = F_{FM}|_{bd}, \tag{2}$$

where the interface transparency parameter η 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}

$$K_{sc}d_{sc}\, \tan\left(\frac{K_{SC}d_{SC}}{2}\right) = \frac{2(1+\mathrm{i})}{\varepsilon}\frac{d_{SC}}{\xi_{SC}} \tan h\left[2(1+\mathrm{i})\frac{d_{FM}}{\xi_{FM}}\right]. \tag{3}$$

Hence, T_c depends on d_{Nb}, the coherence length ξ_{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 $\rho = 6.4\,\mu\Omega\,\mathrm{cm}$ for $d_{Fe} = 300\,\mathrm{nm}$ and the coefficient of the electronic specific heat $\gamma = 4.98 \times 10^{-3}\,\mathrm{JK}^2\,\mathrm{mole}$ [10]. The characteristic distance in Fe is derived to $\xi_{FM}^{Fe} = 1.2\,\mathrm{nm}$ from the diffusion coefficient and splitting energy $I_0 = 1\,\mathrm{eV}$ for Fe is slightly smaller than $\xi_{FM}^{Co} = 1.3\,\mathrm{nm}$ 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 $\xi_{SC} = 12\,\mathrm{nm}$. By extrapolating the fit to $T_c = 0$, we see that the critical thickness for superconductivity is about $d_{Nb}^{crit} = 34\,\mathrm{nm}$. It is larger than $d_{Nb}^{crit} = 30\,\mathrm{nm}$ 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 $H_{c2\perp}$ for Fe/Nb multilayers, where $H_{c2||}$ and $H_{c2\perp}$ 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 $H_{c2\perp}(T) \propto (1-t)$ However, in the case of two-dimensional (2D) superconductivity, the perpendicular coherence $\xi_\perp$ is

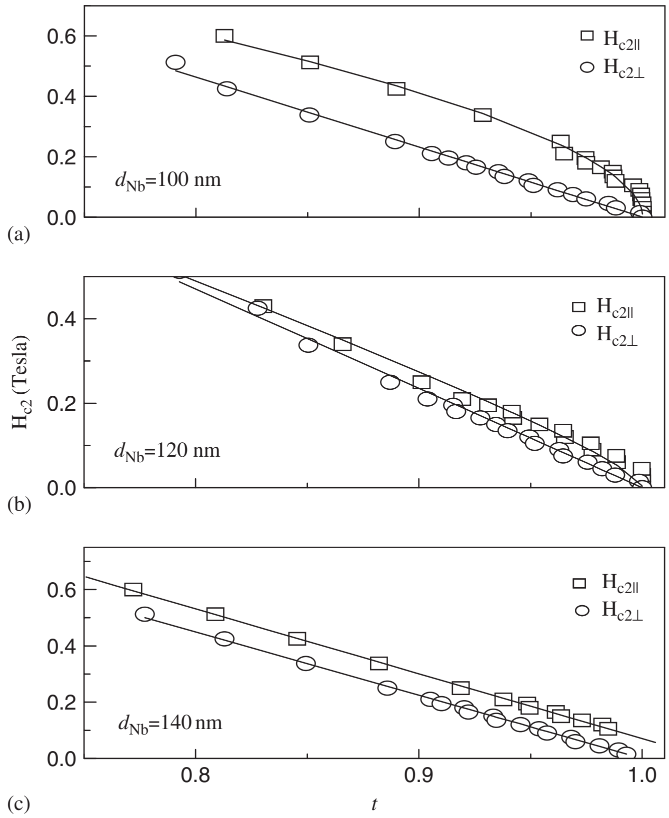

Fig. 3. H_{c2} versus reduced temperature t for [Fe (20 nm)/Nb (d_{Nb})]$_6$/Fe (20 nm) multilyers with $d_{Nb} = 100$ (a), 120 (b) and 140 nm (c).

limited by the layer thickness and becomes constant near T_c. In this case, the temperature dependence of H_{c2} is expressed as $H_{c2||}(T) \propto (1-t)^{1/2}$ and $H_{c2\perp}(T) \propto (1-t)$. 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 $H_{c2||}$ 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 $\xi_{GL}(0) = 10\,\text{nm}$ from the function $\xi_{GL}(0) = \sqrt{\phi_0/2\pi S T_c}$, where $S = -\mathrm{d}H_{c2}/\mathrm{d}T$. The superconducting coherence length ξ_{sc} is related to GL coherence length ξ_{GL} via $\xi_{GL}(T) = \pi\xi_{sc}(1-t)^{-1/2}/2$. This gives $\xi_{sc} \approx 7\,\text{nm}$ 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 $\rho l = 3.75 \times 10^{-6}\,\mu\Omega\,\text{cm}^2$ for bulk Nb [7].

In summary, we have studied the proximity effect and the superconducting properties of Fe/Nb trilayers and multilayers. First, d_{SC}^{crit} and ξ_{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.

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