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S. Y. Huang
Institute of Physics, Academia Sinica, Taipei, Taiwan 115, Republic of China and Institute of Electrophysics, National Chiao-Tung University, Hsinchu, Taiwan 300, Republic of China

J.-J. Liang
Department of Physics, Fu Jen Catholic University, Taipei, Taiwan 242, Republic of China

T. C. Tsai, L. K. Lin, and M. S. Lin
Institute of Physics, Academia Sinica, Taipei, Taiwan 115, Republic of China

S. Y. Hsu
Institute of Electrophysics, National Chiao-Tung University, Hsinchu, Taiwan 300, Republic of China

S. F. Lee[a)]
Institute of Physics, Academia Sinica, Taipei, Taiwan 115, Republic of China

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The behaviors of superconducting transition temperature T_c and upper critical field H_{c2} as a function of different superconductor thicknesses have been investigated in $Cu_{50}Ni_{50}$/Nb trilayers and multilayers. We deduced superconductor critical thickness, below which superconductivity vanishes, by analyzing the data in terms of proximity theory. The temperature dependence of H_{c2} measurement reveals the spatial dimensional crossover and the flux pinning mechanism in the superconductor. A strong pair-breaking effect was observed in the weak ferromagnetic $Cu_{50}Ni_{50}$ layers from both measurements. We attribute our observation to the high interface transparency between $Cu_{50}Ni_{50}$ and Nb. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2829607]

An artificial ferromagnet/superconductor (F/S) layered system is a suitable candidate for studying the coexistence of superconductivity and ferromagnetism by proximity effect. The Cooper pairs tend to leak out and remain superconducting in the adjacent F region. On the other hand, the electrons in the F region induce unequal spin population in the superconductor. They influence each other via the penetration of electrons through their common interface. The superconducting wave function not only decays in F, but also oscillates in a region of characteristic length ξ_F. The weak ferromagnetic layer of $Cu_{50}Ni_{50}$ is essential in achieving the appropriate exchange energy in a suitable window of the experimental phase space by a long magnetic coherence length, ξ_F. Various unusual phenomena occur in the CuNi/Nb system due to the oscillation of the S pairing wave function in F (see Refs. 1 and 2 for recent reviews). However, the quality of interfaces is one of the most important key factors.[3] In the present paper, we find that the properties of the interfaces strongly influence the temperature dependence of upper critical field H_{c2} and the thickness dependence of T_c. Nb is chosen as the superconductor and the $Cu_{50}Ni_{50}$ alloy as weak ferromagnet in studying the thickness dependence of T_c, the spatial dimensional crossover, and the flux pinning mechanism. Both measurements agree that the transparency of the $Cu_{50}Ni_{50}$/Nb interface is rather high. A comparison between weak and strong ferromagnetic films is given.

Several series of $Cu_{50}Ni_{50}$/Nb trilayer and multilayer samples were fabricated on Si(100) substrates using a sputtering system with a sample holder which allowed us to make 12 samples in the same run to obtain comparable quality samples for different F and S layer thicknesses. The detailed deposition conditions used for the present samples were similar to those described elsewhere.[4,5] The measurements of the magnetic moments were performed by a commercial superconducting quantum interference device magnetometer. In our sputtered $Cu_{50}Ni_{50}$ alloy, the magnetic moment was about 0.1 Bohr magneton per atom and the Curie temperature was about 100 K. In order to investigate the proximity effect between Nb and $Cu_{50}Ni_{50}$ in a decoupled regime, we will mainly discuss the series of samples as follows: (1) $Cu_{50}Ni_{50}/Nb(d_S)/Cu_{50}Ni_{50}$ trilayers with $Cu_{50}Ni_{50}$ thickness fixed at 50 nm and (2) $Cu_{50}Ni_{50}$/Nb multilayers denoted as $(Cu_{50}Ni_{50}/Nb(d_S))_6/Cu_{50}Ni_{50}$ with $Cu_{50}Ni_{50}$ thickness fixed at 20 nm. The thickness of the Nb layer for both systems varied. The critical temperature T_c and the critical field H_{c2} as a function of temperature were resistively measured in a ^{4}He cryostat on structured samples of 5 mm long and 1 mm wide.

T_c was determined by resistance measurements and was taken at 90% of the resistance just above the transition. The T_c for $Cu_{50}Ni_{50}/Nb(d_S)/Cu_{50}Ni_{50}$ trilayers as a function of d_{Nb} are shown in Fig. 1. With decreasing d_{Nb}, T_c exhibited a monotonically rapid reduction down to a critical thickness d_{crit}. The superconducting transition with $d_{Nb} < d_{crit}$ was not recorded at 1.7 K, the base temperature of our cryostat. The

a)Electronic mail: leesf@phys.sinica.edu.tw.

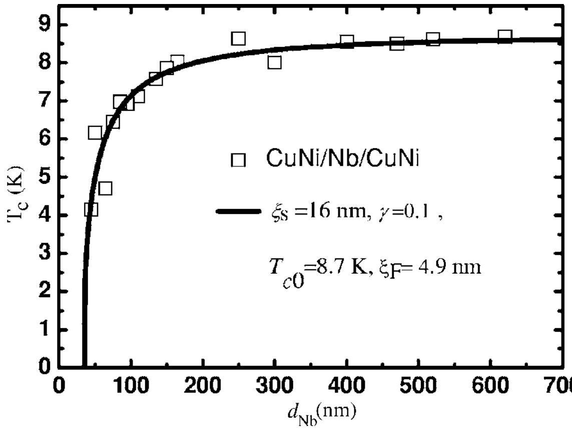

FIG. 1. Superconducting critical temperatures for $Cu_{50}Ni_{50}/Nb/Cu_{50}Ni_{50}$ trilayers as a function of d_{Nb}. The solid line is obtained from the theoretical fitting with parameters ξ_S=16 nm, γ=0.1, and T_{c0}=8.7 K.

decrease in T_c resulted from the suppression of the superconducting wave function at the F/S interface by the pair-breaking effect. We analyzed the behavior of $T_c(d_s)$ in the framework of the theoretical model developed by Radvoić *et al.*[6] In the single-mode approximation, the reduced critical temperature of our trilayers is associated with the pair-breaking effect from the following equations;[6] $\ln(T_c/T_{c0}) = \Psi(1/2) - \mathrm{Re}\,\Psi[(1/2)+(\rho^*/T_c)T_{c0}]$, where Re Ψ represents the real part of the digamma function, T_{c0} is the bulk critical temperature, and ρ^* is the effective pair-breaking parameter. The high interface transmission of boundary condition to evaluate T_c as a function of d_s is given by[7]

$$K_s d_s \tan\left(\frac{K_S d_S}{2}\right) = 2(1+i)\gamma\frac{d_S}{\xi_S} \times \tanh\left[2(1+i)\frac{d_F}{\xi_F}\right],$$

$$\text{with } \gamma = \frac{\rho_S \xi_S}{\rho_F \xi_F}, \quad \xi_F = \sqrt{\frac{4\hbar D_F}{I_0}}.$$

Here, $\rho_{S,F}$ are the low-temperature resistivities of S and F, D_F is the diffusion coefficient, and I_0 is the spin splitting energy of F. The simple physical meaning of γ is the strength of the proximity effect between the F and S metals. The diffusion coefficient D_F is related to the electron mean free path ℓ_F, the Fermi velocity ν_F, and the electronic specific heat coefficients γ_F by[8] $D_F = \nu_F l_{FM}/3 = (1/3\gamma_F \rho_F) \times (\pi k_B/e)^2$.

In this way, using $\gamma(Cu_{50}Ni_{50}) \approx 4.2\times 10^{-3}$ J/K^2 mole,[9] $\rho_F \approx 61$ $\mu\Omega$ cm, and $I_0 \approx 6$ meV, the $Cu_{50}Ni_{50}$ coherence length is evaluated to be ξ_F=4.9 nm. The result of the theoretical simulations obtained for the trilayer system with γ=0.1, ξ_S=16 nm, and T_{c0}=8.7 K is shown as the solid line in Fig. 1. By extrapolating the fit to T_c=0, the critical thickness is $d_{crit}(Cu_{50}Ni_{50})$=35 nm. For the purpose of comparison, the critical thicknesses were about 30 and 34 nm for Co/Nb/Co (Ref. 10) and Fe/Nb/Fe (Ref. 11) trilayers, respectively. It is found that the critical thickness is not smaller than those for the strong ferromagnet. For weak magnetic $V_{1-x}Fe_x$ system, the large critical thicknesses have also been observed.[3] We will now argue that this large thickness is due to the large interface transparency T_r.

Aarts *et al.*[3] proposed that the behavior of the critical thickness for the $F/S/F$ case is a function of the parameters γ and γ_b. The parameter γ_b describes the quality of the interface barrier. When γ is small as in our case, the "proximity leak" is large. It requires a low barrier (high T_r, small γ_b) to increase the critical thickness. Potensa and Marrows[12] reported γ_b=0.6, and Fominov *et al.* obtained a value of 0.3 when fitting the CuNi/Nb bilayer data.[13] These values for CuNi/Nb were much smaller than γ_b=1.6 for Co/Nb system obtained from direct interface resistance measurements.[14] Both measurements agree that the transparency of a CuNi/Nb interface is rather high. This conclusion is in agreement with the critical field H_{c2} data presented in this paper.

Another parameter to investigate the coupling phenomenon is the upper critical field H_{c2}, which gives the information on the coherence length and the dimensionality since H_{c2} reveals the role of the pair-breaking effect. From the Ginzburg-Landau (GL) theory, the perpendicular critical magnetic field for a superconducting film with thickness d_S shows linear temperature dependence, $H_{c2\perp} = [\phi_0/2\pi\xi_\parallel^2(0)] \times [1-(T/T_c)]$.

Here, ϕ_0 is the flux quantum, and $\xi_\parallel(0)$ ($\xi_\perp(0)$) is the zero temperature value of the GL coherence length parallel (perpendicular) to the sample plane. The behavior of the parallel critical field $H_{c2\parallel}(T)$ can be described by a similar expression where $\xi_\parallel^2$ is replaced $\xi_\parallel(0)$ $\xi_\perp(0)$. In the three-dimensional (3D) regime, the temperature dependence of $H_{c2\parallel}(T)$ is described by $H_{c2\parallel} = [\phi_0/2\pi\xi_\parallel(0)\xi_\perp(0)][1-(T/T_c)]$, while in the two-dimensional (2D) regime, the perpendicular coherence length $\xi_\perp$ is larger than the thickness of the films, and $H_{c2\parallel}(T)$ is described by Tinkham's expression[15]

$$H_{c2\parallel} = \frac{\sqrt{12}\phi_0}{2\pi\xi_\parallel(0)d_S}\sqrt{\left(1-\frac{T}{T_c}\right)}.$$

Samples with $(Cu_{50}Ni_{50}(20\text{ nm})/Nb(d_S))_6/Cu_{50}Ni_{50}(20\text{ nm})$, with d_S ranging from 20 to 600 nm, were measured. Figure 2 shows the temperature dependence of the $H_{c2\parallel}$ and $H_{c2\perp}$ for d_{Nb}=140, and $H_{c2\parallel}$ for d_{Nb}=160 and 180 nm. Data points for two samples with bigger d_{Nb} are relatively shifted by 0.05 in the x axis for clarity. The solid lines are theoretical curves by the GL relation. The $H_{c2\perp}$ follows a linear behavior for all thicknesses of Nb. It can be clearly seen that a gradual transition occurs from 2D to 3D behaviors as d_S increases from 140 to 180 nm, i.e., from a square-root behavior to a linear relation for the $H_{c2\parallel}$. The extrapolation yields a superconductor coherence length $\xi_{GL}(0)$=12 nm from the function $\xi_{GL}(0) = \sqrt{\phi_0/2\pi ST}$ where $S = -dH_{c2}/dT$.

For comparison, the dimension crossover is 100–140 nm for Nb/Fe (Ref. 11) and 145–185 nm for Nb/Co,[16] confirming that the large crossover thickness is related to the strong pair-breaking effect since $I_0(\mathrm{Co}) > I_0(\mathrm{Fe})$. The large dimension crossover thickness for $Cu_{50}Ni_{50}$ can be attributed to the high interface transparency

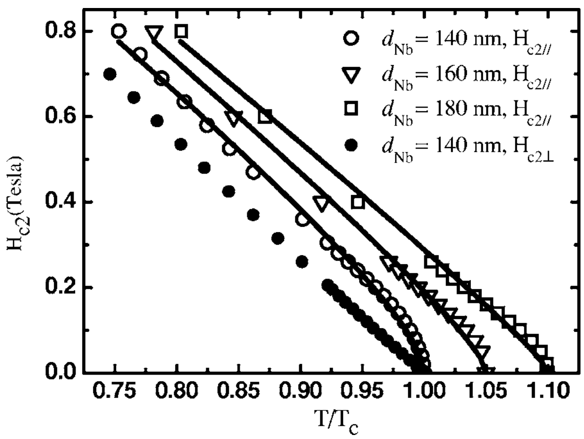

FIG. 2. Temperature dependence of the perpendicular (filled circles) upper critical fields for $Cu_{50}Ni_{50}/Nb$ multilayers with $d_{Nb}=140$ nm, and parallel fields (open circles, triangles, and squares) with $d_{Nb}=140$, 160, and 180 nm. Data for the $d_{Nb}=160$ and 180 nm are shifted to the right by $T/T_c=0.05$ and 0.1, respectively, for clarity. The lines are least-square fit to describe the 3D to 2D crossover using the Ginzburg-Landau relation.

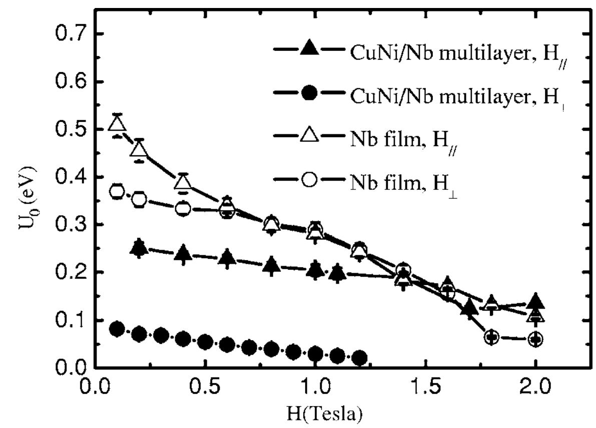

FIG. 3. Activation energy U_0 of flux flow versus parallel and perpendicular applied field for $(Cu_{50}Ni_{50}/Nb)_6/Cu_{50}Ni_{50}$ multilayer with $d_{Nb}=40$ nm and monolayer Nb with $d_{Nb}=240$ nm. Open symbols are for monolayer and solid symbols for multilayers. Data for a parallel field are in triangles and those for a perpendicular field in circles.

even in the weak ferromagnetic system. Angrisani Armenio *et al.* have observed that the temperature, where the 2D to 3D crossover occurred, moved toward a lower value for high interface transparency from the temperature dependent H_{c2} measurement with $d_{CuNi}=d_{Nb}=30$ nm.[17] Thus, the influence due to the barrier properties on the dimensionality, which is decided from the thickness of the *S* layer, also provides unambiguous evidence.

The temperature dependence of H_{c2} contains the information of the flux pinning mechanism in the superconductor, which can be revealed by analyzing the activation energy of the thermally assisted flux flow (TAFF). TAFF can be detected through the resistivity versus temperature curves for different applied fields. The activation energy U_0 is estimated by the Arrhenius law,[18] $\rho=\rho_0 \exp(-U_0/k_B T)$, where ρ_0 is a field-independent preexponential factor. For comparison, a monolayer of 240 nm Nb film and a 2D $(Cu_{50}Ni_{50}/Nb)$ multilayer with the same total Nb thickness were prepared. Figure 3 shows the activation energy of flux flows versus applied field *H*. The difference of activation energy between the parallel and perpendicular fields was relatively small in the pure Nb film, while for the $d_{Nb}=40$ nm multilayer, the U_0 for parallel field was four times the value for perpendicular field, which implied an easier TAFF due to vertex decoupling across $Cu_{50}Ni_{50}$ interlayers in the 2D system. In the MgB_2/Mg_2Si multilayer, U_0 for parallel field was significantly larger than the pure MgB_2 film due to the vortices trapping in the nonsuperconducting Mg_2Si layers.[19] Thus, in Fig. 3, the U_0 for parallel field showed the same level of flux pinning between our $Cu_{50}Ni_{50}/Nb$ multilayer, and pure Nb can be attributed to the high interface transparency between Nb and $Cu_{50}Ni_{50}$. Therefore, the H_{c2} measurement provides a lot of useful information to study the proximity effect in *F*/*S* system.

In summary, experiments on the proximity effect in the decoupled $Cu_{50}Ni_{50}/Nb$ layered structure have been performed by measurements of the thickness dependence of the superconducting transition temperature. The critical thickness and the strength of proximity effect have been derived from analyzing data within the proximity effect theory. We also studied the dimensionality crossover by the temperature dependent H_{c2} measurement and the flux pinning mechanism. The strong pairing-breaking effect observed in the weak ferromagnetic layer, which resulted in a strong influence on the critical thickness and the dimensional crossover, was due to the high interface transparency between $Cu_{50}Ni_{50}$ and Nb.

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