Physica B 194–196 (1994) 2405–2406
North-Holland

PHYSICA B

TRANSITION TEMPERATURE AND CRITICAL FIELDS OF Nb/Gd LAYERS

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The transition temperature and the critical fields of e⁻-beam evaporated Nb/Gd/Nb trilayers and Nb/Gd multilayers have been determined resistively and by dc-susceptibility. For constant thickness of the Gd layers we observe with decreasing thickness d_{Nb} of Nb layers a decrease of T_c and $H_{c2\perp}$ down to a critical thickness d_c, below which superconductivity is completely destroyed. This is due to pair breaking by the exchange field within the ferromagnetic Gd layers. The parallel critical fields mostly show the square-root like temperature dependence near T_c typical for 2D-superconductors. The interplay of orbital pair breaking by the external field and the exchange-field induced pair breaking leads to a nonmonotonic dependence of $H_{c\parallel}$ on d_{Nb} as predicted by recent theories.

Recently, studies of the proximity effect between superconducting (SC) and ferromagnetic (FM) films have received renewed interest. The main difference to the proximity effect at interfaces between a SC metal and a nonmagnetic normal (NC) metal is the very small penetration depth of Cooper pairs into the ferromagnet. Advances in UHV technology allow the preparation of well-defined layered structures with thickness in that region. Moreover, in recent theories the critical temperature and critical fields in SC/FM multilayers were computed beyond the Abrikosov-Gorkov spinflip-scattering model [1].

In this work we have chosen Nb, the elemental SC with the highest transition temperature T_c, and Gd, which in contrast to other rare-earth metals has a simple FM structure at all temperatures below T_{Curie}. The samples were grown at room temperature onto $(11\bar{2}0)$ sapphire substrates and have been characterized as described elsewhere [2]. Nb grows in (110) and Gd in (0002) direction. The Nb-layer thickness d_{Nb} was determined by small-angle X-ray diffraction. d_{Nb} was varied between 190 and 1500 Å while d_{Gd} was kept constant at 34 Å. We prepared Nb/Gd/Nb triple layers and Nb/Gd multilayers consisting of five bilayers. The outer films in the multilayers were made of Gd to suppress surface superconductivity.

The transition temperatures, determined resistively (ρ) by the midpoint of the SC transition, show a continuous depression with decreasing d_{Nb} down to a critical thickness d_c (Fig. 1). T_c was additionally determined by SQUID magnetometry (χ) The T_c depression is caused by the decrease of the SC order parameter near the SC/FM boundary by the proximity effect. The scales of the d_{Nb} axes for the triple layers and the multilayers differ by a factor of two, reflecting the expectation that samples in the triple-layer configuration should have the same T_c as multilayers with double d_{Nb}. T_c of the multilayers are somewhat higher than that of the triple layers, but qualitatively agree with this simple expectation. The $T_c(d_{Nb})$ data are analyzed in terms of a theory of Radovic et al. [1], which considers the case of completely decoupled SC layers. As shown by systematic variations of d_{Gd} [3] the effect of the magnetic interlayer(s) has nearly saturated at d_{Gd} = 34 Å. In this case only two independent parameters enter the theory, namely the SC-coherence length ξ_S and $g = \xi_M/\eta$, the ratio of the penetration depth of Cooper pairs into the ferromagnet ξ_M and the boundary-condition coefficient η. ξ_S was determined from $H_{c2\perp}$ of a 190-Å Nb single layer grown under identical conditions and from the resistivity (see Table 1). ξ_S = 78±5 Å and g = 235±10 Å have

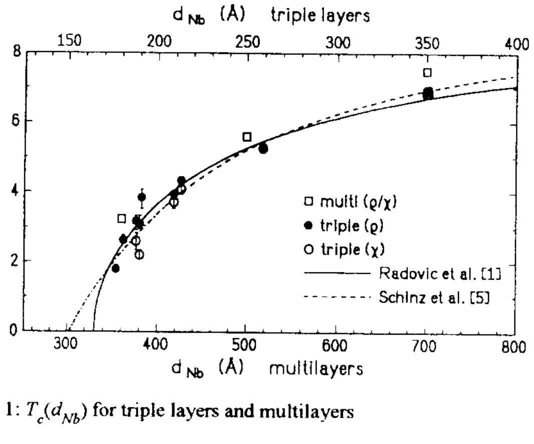

Fig. 1: $T_c(d_{Nb})$ for triple layers and multilayers

SSDI 0921-4526(93)1835-A

been determined by fitting the theoretical $T_c(d_{Nb})$ [1] curve to data of Fig. 1. Under the assumption that the mean free path in the Gd layers is roughly equal to d_{Gd} (as reasonable in such thin films) ξ_M can be estimated from $\xi_M = (4\hbar D_M/I_0)^{1/2}$ using $D_M \approx 1.3\ \mathrm{cm^2/sec}$ (electronic diffusivity), $I_0 \approx 0.31$ eV (exchange shift of Gd conduction (sub)bands) [4], yielding $\xi_M \approx 11$ Å and, with the above value of g, $\eta \approx 0.045$. Fig. 1 includes the fit of a recent GL-theory [5] where $\xi_{GL} = \pi/2\cdot\xi_S\ (1-T/T_c)^{-1/2}$

Figs. 2 and 3 show the critical field curves of our samples. Keeping g = 235 Å fixed, the theoretical fits to the data can be adjusted by small variations of ξ_S which are due to variations of the mean free path in different samples (Fig. 2). As T_c itself, the slopes of the perpendicular critical fields become continuously smaller with decreasing d_{Nb}. Since the normal component of the magnetic induction B is always continuous at interfaces, triple layers and multilayers again correspond each other with the above factor of two in d_{Nb}, and $H_{c2\perp}$ are approximately the same in corresponding samples. The upturn in the 700-Å sample is an effect also present in single Nb films and will be discussed elsewhere [6].

The situation in parallel field is quite different. The analogy between triple and multilayers breaks down because of surface superconductivity in the triple layers. Also, the depression of $H_{c\parallel}$ with decreasing d_{Nb} is <u>not</u> monotonic but enhanced for intermediate thicknesses (Fig. 3). The corresponding theoretical curves exhibit qualitatively the same behavior, but are systematically too small for low temperatures with the largest deviation ocurring for the 1500-Å film. This might be attributed to the nucleation of vortices, which is considered in [7]. Also, at lowest d_{Nb} linear instead of square-root behavior is found near T_c. The slightly different values of ξ_S (Table 1) determined from $H_{c2\perp}$ and $H_{c\parallel}$ are possibly due to a different averaging of thickness fluctuations in both cases.

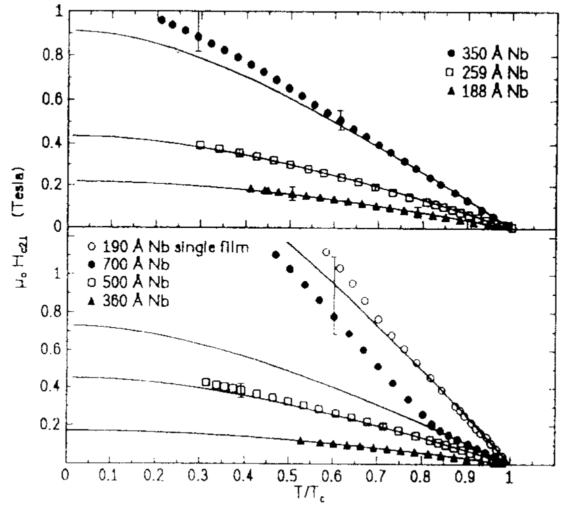

Fig.2: $H_{c\perp}$ of triple layers (top panel) and multilayers (bottom panel)

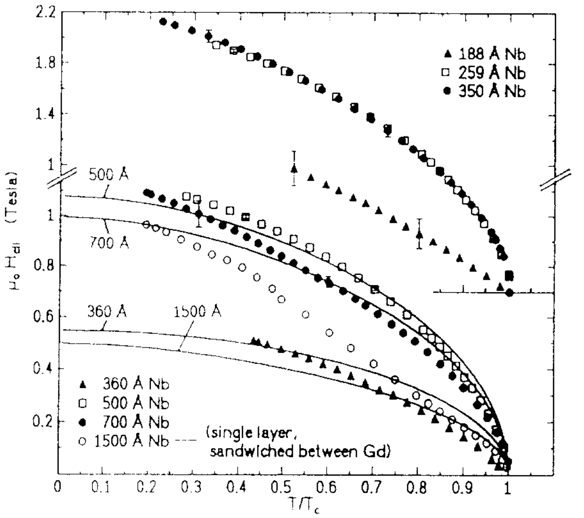

Fig.3: $H_{c\parallel}$ of triple layers (top panel) and multilayers (bottom panel)

d_{Nb} (Å)	190 single	360	500	700	1500 single
from ρ(10 K)	76	94	92	108	104
from $H_{c2\perp}$	72	79.5	86	88	93
from $H_{c\parallel}$	-	81.3	87	91	110

Table 1 : ξ_S of single and multilayers (in Å)

The nonmonotonic $H_{c\parallel}(d_{Nb})$ behavior is explained by the competition of two different depairing mechanisms i.e. exchange field of the Gd layer(s) and orbital effect of the external field, as described in [7].

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