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Proximity effect in superconductor/highly paramagnetic Nb/Pd systems

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Abstract

The behavior of the superconducting transition temperature T_c in layered systems made of niobium and highly paramagnetic palladium has been studied as a function of the layer thicknesses. The results have been analysed in the framework of the proximity effect theory, in order to determine the interface transparency T.

Keywords: Proximity effect; Interface transparency; Multilayer

1. Introduction

The proximity effect between a superconductor and another material has been intensively studied during the last decades [1,2]. However, this has often been done within approaches where an important parameter, the interface transparency T [3], is neglected. This parameter takes into account all effects which cause electrons to be reflected rather than transmitted at the interfaces, with the result that proximity effect is somehow screened. Interfaces between different materials are never completely transparent and this may be due to interface imperfections, lattice mismatches, fabrication methods [4,5], but also to intrinsic reasons such as the difference between Fermi velocities and the band structure of the two metals. Moreover, when the non-superconducting metal is magnetic, the splitting of the spin sub-bands as well as a spin-dependent impurity scattering also contribute to T [6]. Experimentally, T was usually treated as an adjustable parameter. In this article we present a study on Nb/Pd [7,8] systems (Pd is a highly paramagnetic metal), developed in the framework of the proximity effect theory in superconductor (S)/normal metal (N) multilayers, for arbitrary transparency of the interface [9]. The model is based on the Usadel equations with the boundary conditions derived by Kupriyanov and Lukichev [10]. These boundary conditions are expressed in terms of two parameters, γ and γ_b, given by

$$\gamma = \frac{\rho_s \xi_s}{\rho_n \xi_n}, \quad \gamma_b = \frac{R_B}{\rho_n \xi_n}. \tag{1}$$

Here $\xi_{s,n}$ and $\rho_{s,n}$ are the coherence lengths and the low temperature resistivities of S and N,

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respectively, while R_B is the normal-state boundary resistivity times its area. γ measures the strength of the proximity effect, while γ_b describes the effect of the boundary transparency T, to which is roughly related by

$$T = \frac{1}{1+\gamma_b}. \tag{2}$$

The value of the parameter γ has been determined experimentally, by measuring $\rho_{s,n} \equiv \rho_{Nb,Pd}$ and estimating $\xi_{s,n} \equiv \xi_{Nb,Pd}$. In this way, the interface transparency T becomes the only free parameter.

2. Sample preparation and structural properties

The samples were deposited on Si(1 0 0) wafers using a dual source magnetically enhanced dc triode sputtering system with a base pressure of 10^{-8} mbar and sputtering argon pressure of about 1.0×10^{-3} mbar. The substrates were let to pass alternatively over Nb and Pd target with a technique that allows to obtain a complete series in a single deposition run [11]. Nb and Pd were both deposited at typical rates of about 8 Å/s. We prepared three different sets of multilayers. Two sets, built as follows: $d_{Pd}/d_{Nb}/d_{Pd}$, were used to investigate the behavior of T_c as a function of the Nb layer thickness and to extract the value of T from the fitting procedure. Here d_{Pd} was fixed at around 1500 Å in order to represent a half-finite layer, while d_{Nb} was varied from 200 to 1300 Å.The third set was used, instead, to study the variation of T_c with d_{Pd}, in order to estimate the Pd coherence length, ξ_{Pd}. Now the samples were made up of five layers, $d_{Pd}^{out}/d_{Nb}/d_{Pd}^{in}/d_{Nb}/d_{Pd}^{out}$. The outer Pd layers, 300 Å thick, were deposited in order to create a symmetric situation for the Nb layers, with d_{Nb} fixed at 500 Å, while d_{Pd}^{in} was varied from 50 to 300 Å.

Extensive low- and high-angle X-ray diffraction analyses have been performed to structurally characterize the samples. High-angle scans clearly showed the Nb(1 1 0) and the Pd(1 1 1) peaks, from whose positions we estimated the lattice parameters, $a_{Nb} = 3.3$ Å for the bcc-Nb and $a_{Pd} = 3.9$ Å for the fcc-Pd, in agreement with the values reported in the literature [12]. Low-angle reflectivity measurements on samples previously fabricated have been performed to determine both Nb and Pd thickness and the value of the interfacial roughness (in the range 10–15 Å) [7,8].

The superconducting transition temperatures T_c were measured resistively using a standard dc four-probe technique. The values of the low temperature resistivities were estimated of about $\rho_{Nb} \approx 2.5$ μΩ cm and $\rho_{Pd} \approx 5$ μΩ cm, while the ratios $\rho_N(T = 300\ \mathrm{K})/\rho_N(T = 10\ \mathrm{K})$, with ρ_N being the normal-state resistivity, were about 2 for all the series, confirming the high uniformity of the transport properties of samples obtained in the same deposition run.

3. Superconducting properties and discussion

The value of γ_b, or that of the interface transparency, was obtained by a fitting procedure performed on the $T_c(d_{Nb})$ curve, in which T was the only free parameter. To do that, γ was determined experimentally, measuring the above values of $\rho_{Nb,Pd}$ and estimating $\xi_{Nb,Pd}$ as in the following.

To evaluate ξ_{Pd} we studied the behavior $T_c(d_{Pd}^{in})$, as shown in Fig. 1. Here the transition temperatures have been scaled according to $t^* = (T_c - T_c^{low})/(T_c^{high} - T_c^{low})$, where T_c^{low} and T_c^{high} are the

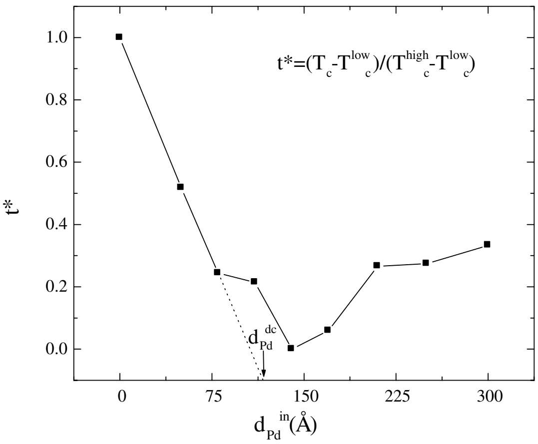

Fig. 1. Critical temperature $T_c(d_{Pd}^{in})$, scaled according to $t^* = (T_c - T_c^{low})/(T_c^{high} - T_c^{low})$. The arrow indicates the value of d_{Pd}^{dc}, the dotted line shows the way we determined it, while the solid one is a guide to the eye.

minimum and the maximum critical temperatures of the $d_{Pd}^{out}/d_{Nb}/d_{Pd}^{in}/d_{Nb}/d_{Pd}^{out}$ multilayers, respectively. The point of intersection between the dotted line and the d_{Pd}^{in} axis was defined as d_{Pd}^{dc}, the minimum Pd layer thickness needed to decouple two Nb layers [3].

This length is, in fact, related to ξ_{Pd} by the relation $d_{Pd}^{dc} \approx 2\xi_{Pd}$ [3]. The Pd coherence length determined in this way was about 60 Å. Finally, the experimental value of the Nb coherence length ξ_{Nb} was obtained by the slope $S = \mathrm{d}H_{c2\perp}/\mathrm{d}T|_{T=T_c}$ of the upper critical fields of the Pd/Nb/Pd trilayers, and was estimated to be $\xi_{Nb} \approx 64$ Å [8].

The dependence of the critical temperatures T_c on d_{Nb} in Pd/Nb/Pd trilayers is shown in Fig. 2. The solid line represents the model calculation obtained for $T = 0.46$. From this curve it was also possible to calculate the value of the critical Nb thickness, d_{Nb}^{cr}. This length is the minimum thickness of the Nb layer, between two Pd layers, needed to superconductivity to develop. In our case it was about 200 Å, so that we get the ratio $d_{Nb}^{cr}/\xi_{Nb} \approx 3$.

The value obtained for the interface transparency is relatively high, as expected by theoretical considerations. Electrons of both metals lie in the same d-bands [13–15] and the mismatch between the Fermi velocities is very low [14,16]. In addition, interface roughness and lattice mismatches

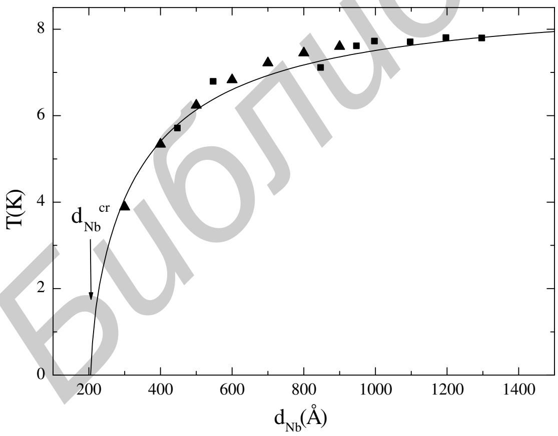

Fig. 2. Critical temperature T_c versus d_{Nb} for $d_{Pd}/d_{Nb}/d_{Pd}$ trilayers. Different symbols refer to different sample sets. The solid line is the result of the calculation with $T = 0.46$. The arrow indicates d_{Nb}^{cr}.

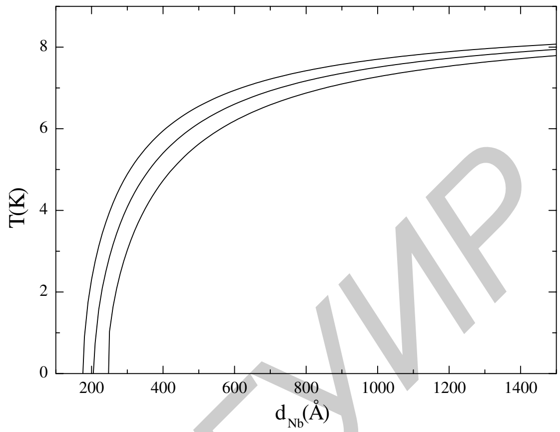

Fig. 3. The calculate change in the critical temperature $T_c(d_{Nb})$ for different values of T: $T = 0.42, 0.46, 0.50$, from left to right.

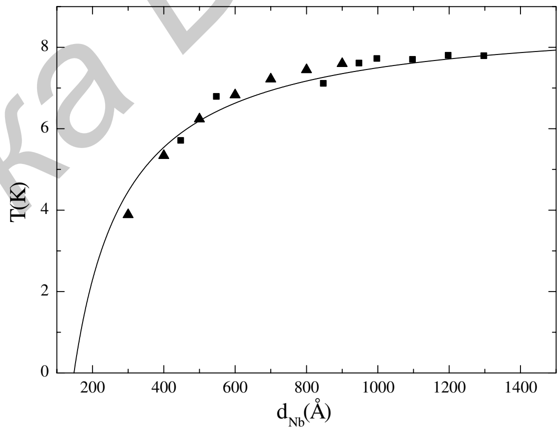

Fig. 4. Critical temperature $T_c(d_{Nb})$ for $d_{Pd}/d_{Nb}/d_{Pd}$ trilayers, as already shown in Fig. 2. The solid line is the calculated curve obtained from the Radovic theory [17] with $\eta = 0.09$ ($T = 0.18$).

also play a role, contributing to reduce the theoretically expected value of T [4,5,8]. The way different values of the interface transparency affect the theoretical behavior of the critical temperature $T_c(d_{Nb})$ is reported in Fig. 3.

Finally we also tried to fit the $T_c(d_{Nb})$ behavior by extending the Radovic et al. theory [17], valid for S/magnetic (M) systems, to the case of S/N systems with N being a normal metal with high spin susceptibility. Also in this case a single fitting parameter η is used, which can be shown to be related to the interface transparency T by the equation $\eta = T\rho_s\rho_n$ The best fit to the experimental data is obtained for $\eta = 0.09$, which correspond to $T = 0.18$, but the agreement is not satisfactory, as shown in Fig. 4. Nonetheless, we have to point out that Radovic theory applies to multilayered superconducting and magnetic systems. Moreover, as observed by Aarts et al. [3], Radovic model describes quite well the behavior of critical temperatures and critical fields, but does not explicitly incorporate the interface transparency.

4. Conclusions

In conclusion, we have estimated, in the framework of the proximity effect theory, the interface transparency T of layered Nb/Pd systems. The obtained value of T is relatively high, as expected by theoretical arguments.

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