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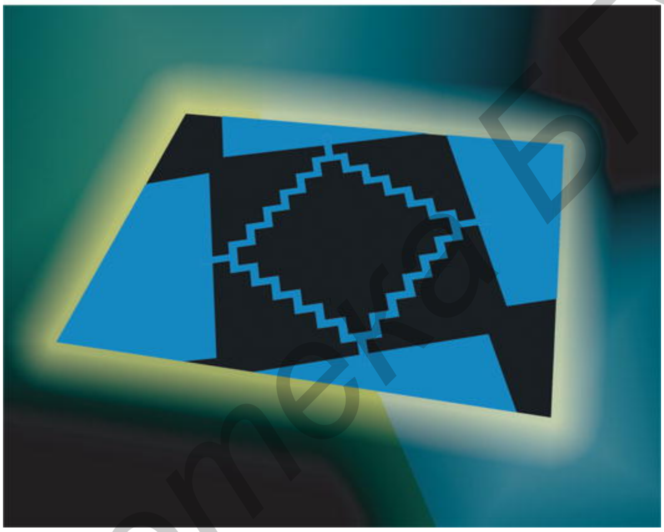

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Role of the external surfaces on the superconducting properties of superconductor/normal metal trilayers

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Abstract

Superconducting proximity effect is studied in superconductor/normal metal trilayers. The dependences of the superconducting transition temperature T_c versus Nb thickness in Cu/Nb/Cu systems and versus Cu thickness in Nb/Cu/Nb ones are described by different values of the microscopical parameters. We attribute this difference to the influence of the external surfaces of the Nb/Cu/Nb hybrids on the superconducting properties of the system.

Keywords: Proximity effect; N/S/N structure; S/N/S structure; Interface transparency

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1. Introduction

Physics of superconducting multilayers is a widely studied subject [1]. These systems are very interesting because, for example, it is possible to obtain layered systems with well-defined superconducting properties changing the constituting materials, the number of layers and their relative thicknesses. In particular, the above-mentioned parameters can be easily tuned in superconductor/normal metal (S/N) hybrids. These systems are superconducting due to the proximity effect which consists in the penetration of the Cooper pairs from the superconductor into the adjacent normal metal [2,3]. As a consequence, a superconducting state with a spatial non-homogeneous distribution of the Cooper pairs appears in the layered structure which results

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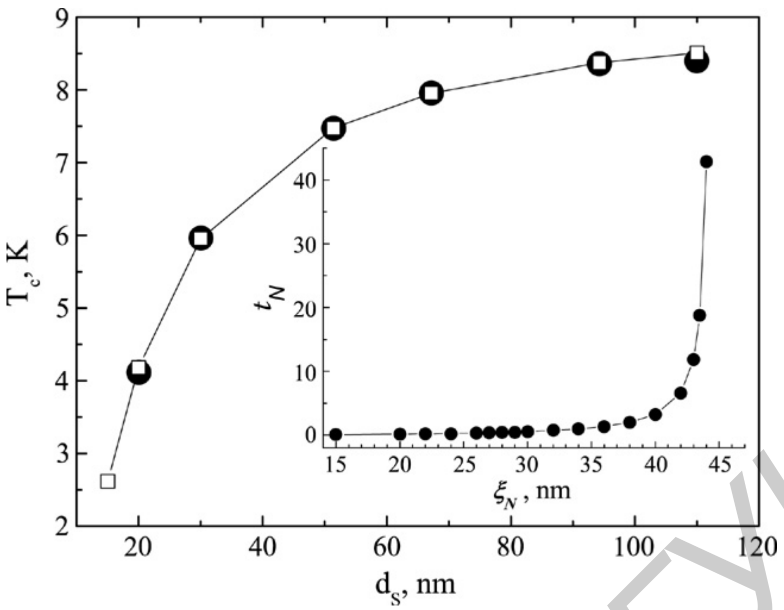


Fig. 1. Critical temperature, T_c, versus d_{S} for Cu/Nb/Cu structure with $d_{\mathrm{N}} = 150$ nm. Closed circles (open squares) correspond to the measured (calculated) values. The values of the used parameters are reported in the text. Inset: dependence of the S/N interface transparency t_{N} on the normal metal coherence length ξ_{N}.

in different experimental evidences which involve for instance the behavior of critical magnetic fields [4] and critical currents [5]. Recently the study of S/N multilayers has shown that the physical properties of these structures are strongly influenced by the position of their symmetry plane [6] and mainly determined by the external surfaces of the samples [6–8]. In other words, multilayers (samples with finite number of layers) and superlattices (samples with infinite number of layers) are characterized by different superconducting properties.

In this work, the problem of the influence of the external boundaries, namely, the top and bottom surfaces of the sample, on the critical temperature in N/S/N and S/N/S trilayers is examined. It is usually considered that such trilayers, fabricated in the same conditions, are characterized by the same parameters in the superconducting state. In particular, it is supposed *a priori*, that the critical temperature T_c of N/S/N structure with layer thicknesses d_{S} and d_{N} (the superconducting and the normal layer thicknesses, respectively) is equal to the critical temperature of S/N/S sample with layer thicknesses $d_{\mathrm{S}}/2$ and $2d_{\mathrm{N}}$ [2]. We show that it is not possible to theoretically describe the experimental $T_c(d_{\mathrm{S}})$ dependence for N/S/N and the $T_c(d_{\mathrm{N}})$ dependence for S/N/S samples using the same numbers.

2. Experimental results

Measurements were performed on Cu/Nb/Cu (N/S/N) and Nb/Cu/Nb (S/N/S) trilayers fabricated by MBE. The details of the sample preparation were published elsewhere [9]. For $T_c(d_{\mathrm{S}})$ measurements a set of Cu/Nb/Cu samples with Cu layers of fixed thickness ($d_{\mathrm{N}} = 150$ nm) and Nb layers with thicknesses in the range $d_{\mathrm{S}} = 20$–110 nm was prepared. The experimental $T_c(d_{\mathrm{S}})$ dependence is shown in Fig. 1 by closed circles. For $T_c(d_{\mathrm{N}})$ measurements a set of Nb/Cu/Nb samples with fixed Nb layer thickness ($d_{\mathrm{S}} = 22$ nm) and Cu layer thickness in the range $d_{\mathrm{N}} = 10$–160 nm was prepared. The experimental $T_c(d_{\mathrm{N}})$ dependence is shown in Fig. 2 by closed circles. The coherence length of the superconducting material, ξ_{S}, was determined by measuring the perpendicular upper critical field versus the temperature, $H_{c2\perp}(T)$. The value obtained for a single Nb film 100 nm thick was $\xi_{\mathrm{S}} = (6.4 \pm 0.2)$ nm.

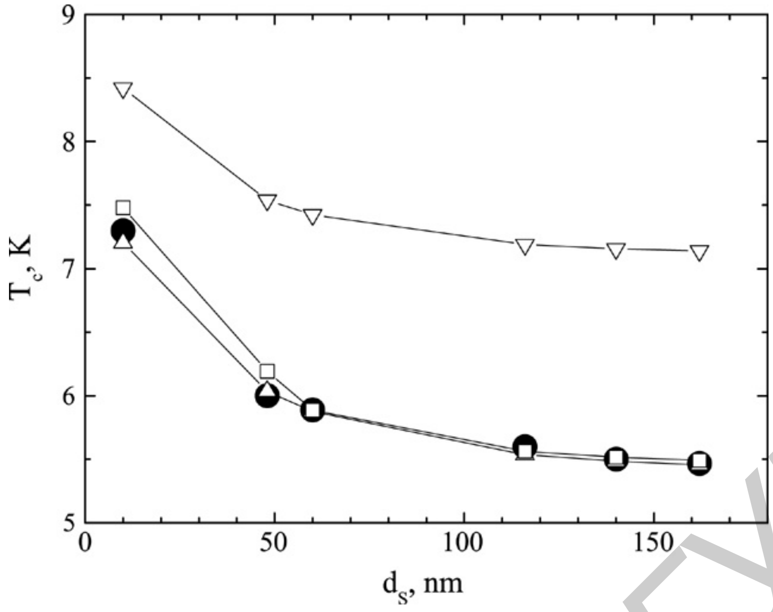
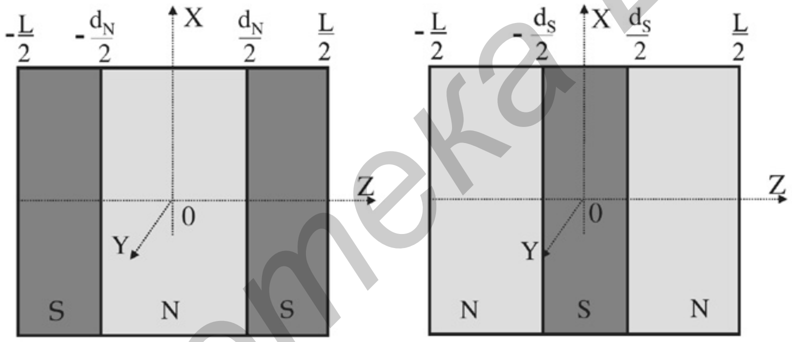


Fig. 2. Critical temperature, T_c, versus d_N for Nb/Cu/Nb structure with $d_S = 22$ nm. Closed circles correspond to the measured values. Open symbols correspond to the results of calculations, as described in the text.



a) b)

Fig. 3. Schematic drawing of the geometry of (a) S/N/S trilayers and (b) N/S/N trilayers.

3. Theoretical background

In this paper we describe the critical state of S/N multilayers in the framework of the microscopical theory in the diffusive approximation [2]. This approach allows us to extract the values of the microscopical material parameters of the S/N structures. The phenomenological Ginzburg–Landau equations, already used in the previous works [6–8], are, in fact, not suitable for quantitative analysis. We choose the system coordinate with the OZ axis oriented perpendicularly to the S/N layer's plane, and with XOY plane corresponding to the symmetry plane of the S/N structure. A schematic drawing of the geometry of the trilayered systems is shown in Fig. 3. In the absence of the external magnetic field, the microscopic equations in the diffusive limit can be written as [2,10]

$$\left(m + \frac{1}{2} - \frac{\hbar D(z)}{4\pi k_B T}\frac{d^2}{dz^2}\right) F_m(z) = N(z)V(z)\sum_{m'=0}^{m_D} F_{m'}(z) \quad (m = 0, 1, \ldots, m_D). \tag{1}$$

In Eq. (1) the following notations are used: $D(z)$, $N(z)$, $V(z)$ are step functions which take values of D_S, N_S, V_S in the superconducting layers and D_N, N_N, 0 in the normal ones. D_S, D_N are the superconducting and the normal metal diffusion coefficients, respectively; N_S, N_N are the densities of states at the Fermi level; V_S is the electron–phonon interaction constant in the superconductor; $m_D \equiv [\omega_D/2\pi k_B T - 0.5]$ (square brackets here denote the integer part); ω_D is the Debye frequency; k_B is the Boltzmann constant; $F_m(z)$ are the Gorkov quasiclassical anomalous Green functions.

The superconducting order parameter $\Delta(z)$ is determined by the Gorkov's condition of self-consistency:

$$\Delta(z) = 2\pi k_B T \cdot N(z)V(z) \sum_{m=0}^{m_D} F_m(z). \tag{2}$$

Eq. (1) are supplied by the conditions of joining of $F_m(z)$ functions at S/N interfaces [11]:

$$\begin{aligned} D(\pm z_\Gamma + 0)N(\pm z_\Gamma + 0)\frac{\mathrm{d}F_m(\pm z_\Gamma + 0)}{\mathrm{d}z} \\ = D(\pm z_\Gamma - 0)N(\pm z_\Gamma - 0)\frac{\mathrm{d}F_m(\pm z_\Gamma - 0)}{\mathrm{d}z} \end{aligned} \tag{3a}$$

$$D(\pm z_\Gamma - 0)\frac{\mathrm{d}F_m(\pm z_\Gamma - 0)}{\mathrm{d}z} = \frac{v_{FN} t_N}{2}\left(F_m(\pm z_\Gamma + 0) - F_m(\pm z_\Gamma - 0)\right), \tag{3b}$$

where $\pm z_\Gamma$ are the Z-coordinates of S/N interfaces (for N/S/N $z_\Gamma = d_S/2$ and for S/N/S $z_\Gamma = d_N/2$), $\boldsymbol{v}_{FN}$ is the Fermi velocity of normal metal, t_N is the transparency parameter of the S/N interface [12]. The boundary conditions for the $F_m(z)$ functions are:

$$\frac{\mathrm{d}F_m(-L/2)}{\mathrm{d}z} = \frac{\mathrm{d}F_m(L/2)}{\mathrm{d}z} = 0, \tag{4}$$

where L is the overall thickness of the S/N hybrid.

As a consequence of the solution to the Eqs. (1)–(4) we obtain a set of eigenvalues for the temperature T, the maximum of which corresponds to the critical temperature T_c of the S/N sample.

4. Results and discussion

The solution to the Eqs. (1)–(4) depends on five parameters: T_S, the critical temperature of the bulk Nb, the superconducting and the normal metal coherence lengths ξ_S and ξ_N,

$$\xi_S = \sqrt{\frac{\hbar D_S}{2\pi k_B T_S}}, \tag{5a}$$

$$\xi_N = \sqrt{\frac{\hbar D_N}{2\pi k_B T_S}}, \tag{5b}$$

the transparency parameter of S/N interface, t_N, and finally the parameter

$$p = \frac{D_N N_N}{D_S N_S} = \frac{\rho_S}{\rho_N}, \tag{6}$$

which determines the jump at the S/N interfaces of $F_m(z)$ first derivatives, as can be seen from

Eqs. (3a) and (3b). In Eq. (6) ρ_S and ρ_N are the low temperature ($T = 10$ K) resistivity values of the superconductor and the normal metal, respectively.

The value of the parameter p for a thin film can be only roughly estimated from resistivity measurements. In fact, the low temperature resistivity values increase as the film thickness is reduced, mainly due to the electron scattering at the film surfaces [13]. In multilayers surface effects are more relevant at the external boundaries of the sample, the scattering being weaker at the S/N internal interfaces. In our case, for Cu/Nb/Cu the value of the parameter p is determined quite unambiguously because the external Cu layers can be considered infinite ($d_N = 150$ nm) and because the resistivity of the internal Nb layer in our thickness range ($d_S > 20$ nm) can be considered as the resistivity of a bulk sample [14]. As a result, using $\rho_S = 3.6\ \mu\Omega \times \text{cm}$ and $\rho_N = 1.3\ \mu\Omega \times \text{cm}$ [9], for the Cu/Nb/Cu samples we get $p = 2.8 \pm 0.1$. On the other hand, for the Nb/Cu/Nb hybrids only a rough estimation could be done for the resistivities, resulting in a range of possible values for the parameter p: that is $p \approx 2.0 - 8.5$.

The parameter T_S can be accurately determined for N/S/N system from the asymptotic experimental $T_c(d_S)$ dependence. As a result, for Cu/Nb/Cu we have $T_S = (9.0 \pm 0.2)$ K. Consequently, from the expression (5a) it follows that $\xi_S = 6.4$ nm, in accordance with the value of the superconducting coherence length estimated from $H_{c2\perp}(T)$ measurements. On the other hand, for the Nb/Cu/Nb systems we do not directly measure the value of T_S. In this case we can only establish a lower limit for T_S, which corresponds to the measured T_c for the trilayers with $d_N = 0$. On the basis of Ref. [9] we get $7.5\text{ K} < T_S < 9.2$ K.

So while for the Cu/Nb/Cu system only two fitting parameters are still undetermined, t_N and ξ_N, for the Nb/Cu/Nb structure four parameters remain undetermined: t_N, ξ_N, p and T_S.

We first focus on the Cu/Nb/Cu trilayers. As it was shown in Ref. [15], in N/S/N structures the quantities t_N and ξ_N are linked. The $t_N(\xi_N)$ curve, reported in the inset of Fig. 1, contains, in fact, the values which reproduce the same $T_c(d_S)$ dependence. In Fig. 1 the open squares represent the calculated $T_c(d_S)$ dependence obtained for $t_N = 0.98$, corresponding to $\xi_N = 34$ nm. The good agreement with the experimental data is evident.

At this point we turn to the Nb/Cu/Nb trilayers. Initially, we tried to reproduce the experimental dependence $T_c(d_N)$ solving Eqs. (1)–(4) with the same parameters which we used for fitting the $T_c(d_S)$ curve. The theoretical $T_c(d_N)$ curve calculated for $t_N = 0.98$ (and, consequently, $\xi_N = 34$ nm), $p = 2.8$ and $T_S = 9.0$ K is shown by down open triangles. The disagreement with the experimental data is evident, the measured $T_c(d_N)$ dependence for S/N/S structure lying well below the theoretical prediction. As discussed above we believe that one of the main reasons of such discrepancy is related to the presence of the thin external Nb layers in the Nb/Cu/Nb system.

It is possible to reproduce the experimental $T_c(d_N)$ dependence by only changing the values of p and T_S. In Fig. 2 the result obtained for the Nb/Cu/Nb system with the parameters $t_N = 0.98$ ($\xi_N = 34$ nm), $p = 2.8$ and $T_S = 8$ K is shown by up triangles. In the same figure by open squares we show the calculated $T_S(d_N)$ dependence with $t_N = 0.98$ ($\xi_N = 34$ nm), $T_S = 9$ K and $p = 9.8$. In both cases the agreement between theory and experiment is satisfactory. However the value of p used to reproduce the last curve is out of the range of allowed values determined experimentally from resistivity measurements, as discussed in the previous section. In Fig. 4 we show the $T_S(p)$ curve (calculated using $t_N = 0.98$ ($\xi_N = 34$ nm) keeping fixed, as a first approximation, the value of ξ_S at 6.4 nm) which determines the range of values which accurately reproduce the experimental data for the structure Nb/Cu/Nb. In the inset of Fig. 4 we show the set of $T_c(d_N)$ curves which corresponds to the obtained $T_S(p)$ dependence. The difference between the calculated and the measured critical temperatures is less than 0.15 K. What it is worth to note

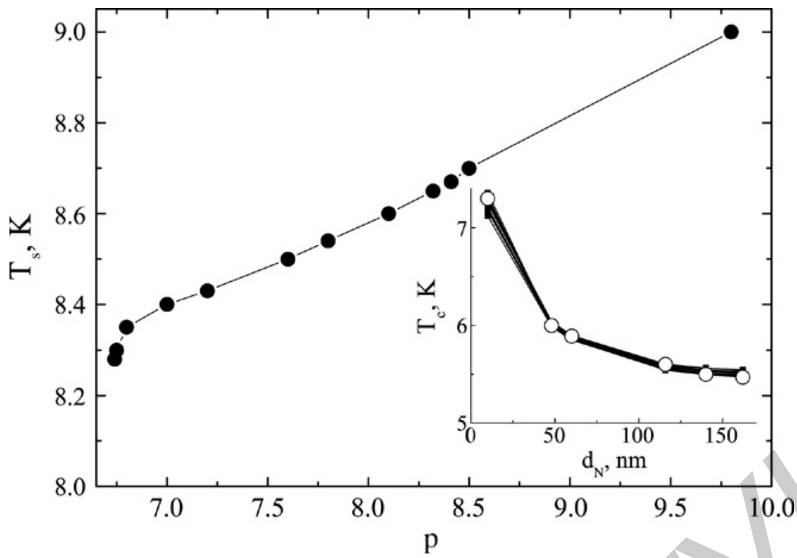


Fig. 4. Critical temperature of bulk Nb, T_S, versus p for Nb/Cu/Nb system. Calculations were performed using $\xi_S = 6.4$ nm. Inset: T_c versus d_N dependences for Nb/Cu/Nb trilayers. Open circles correspond to the measured values while solid lines correspond to the theoretical calculations from which the corresponding T_S and p values on the main plot were obtained.

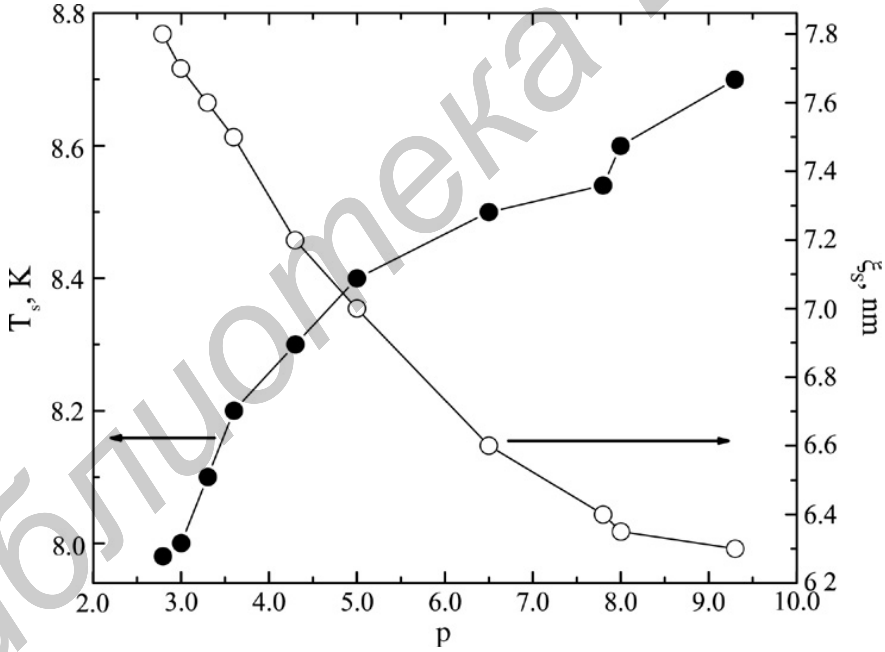


Fig. 5. T_S versus p for Nb/Cu/Nb system, left scale. ξ_S versus p for Nb/Cu/Nb system, right scale.

is that if we try to reproduce the $T_c(d_N)$ curve using the bulk $T_S = 9$ K we get an unphysical value for the parameter p. This discrepancy is still present even when considering the correct $\xi_S(T_S)$ dependence. In Fig. 5, in fact, the closed circles showing the $T_S(p)$ dependence have been calculated taking into account the relation (5a). The corresponding $\xi_S(p)$ dependence is shown in the same figure by open circles.

Finally, it is interesting to point out that even if we force T_S and p to change about 10% of their values in the Nb/Cu/Nb systems we cannot reproduce both $T_c(d_S)$ and $T_c(d_N)$ curves fixing the values of the other microscopical parameters.

5. Conclusions

The main purpose of this work was to examine the values of the parameters which describe the proximity effect both in S/N/S and in N/S/N trilayers. The $T_c(d_S)$ dependence in Cu/Nb/Cu samples was theoretically reproduced and a set of numbers was extracted, which however, did not describe the $T_c(d_N)$ behavior of Nb/Cu/Nb trilayers. This result is mostly due to the different properties of the internal S layers in Cu/Nb/Cu with respect to the external S layers in Nb/Cu/Nb samples.

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