Proximity effect and interface transparency in Nb/Cu multilayers

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The interface transparency $\mathcal{T}$ is quantitatively studied in Nb/Cu multilayers. The dependence of the critical temperature T_c on both the thickness of superconducting layers d_S in Cu/Nb/Cu trilayers and on the number of Nb/Cu bilayers N_b in $\mathrm{Cu}/[\mathrm{Nb}/\mathrm{Cu}]_{N_b}$ multilayers is considered. The experimental results are analyzed on the base of the exact solution of Usadel equations. We obtain that there is an infinite number of pairs of $(\mathcal{T},\xi_N)$ (ξ_N being the normal metal coherence length) which describes the measured $T_c(d_S)$ dependence with the same accuracy. This degeneracy is removed if the experimental $T_c(N_b)$ dependence is analyzed. This allows to unambiguously determine, without the need of an independent estimation of ξ_N, the value of $\mathcal{T}$ for our system. This general method turns out to be especially useful when dealing with superconducting/normal metal hybrids for which microscopic parameters are not well determined. *© 2009 American Institute of Physics.*
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When a superconductor (S) is brought into a close contact with a normal metal (N) to form S/N heterostructures, the superconducting behavior is determined by the proximity effect.[1–6] What essentially happens is that superconductivity propagates in N over a distance which is of the order of ξ_N, the normal metal coherence length, while the order parameter on the S side is depressed over a distance ξ_S, the superconducting coherence length. If the thickness of the superconducting layer d_S is smaller than ξ_S, superconductivity is completely suppressed.

Many studies have been devoted to investigate both the fundamental and applicative aspects of the proximity effect in S/N systems. The role of the barrier at the interface between the two metals has already been considered long time ago[3,7–9] but only more recently the quality of interface has been added to self-consistently model the interaction between S and N metals.[10,11] Interface transparency $\mathcal{T}$ can be connected with the boundary resistance that electrons encounter at the interface and this reduces the flow of Cooper pairs from the S to the N layer. The boundary resistance appears as a result of the mismatch between band properties of the two metals into contact and this determines the boundary conditions for the superconducting order parameter on the S/N interface.[12,13] From the experimental point of view, critical temperature[14,15] and critical magnetic field measurements[16] have been performed on S/N hybrids to obtain information on the transparency of the interface.[15,17] On the other hand, the microscopic parameters entering in the description of the proximity effect, such as $\mathcal{T}$ and ξ_N, are usually obtained as a result of a fitting procedure of the experimental data. One way to determine these quantities is to analyze the $T_c(d_S)$ data in N/S/N hybrids.[18,19] However, it has been shown that the experimental $T_c(d_S)$ dependence can be reproduced by an infinite number of pairs of $(\mathcal{T},\xi_N)$ when, as in the case of the samples used in this study, d_S and d_N (the thickness of the normal metal layer) are larger than ξ_S and ξ_N, respectively. This means that only when it is possible to obtain ξ_N by independent measurements, the curve $\mathcal{T}(\xi_N)$ unambiguously gives the value of the interface transparency.

In this work, to remove the above ambiguity, we propose to use the experimental asymptotic behavior of the T_c versus N_b dependence in a multilayered structure of the type $\mathrm{N}/[\mathrm{S}/\mathrm{N}]_{N_b}$ together with the results obtained for the $T_c(d_S)$ dependence for N/S/N trilayers. For N we choose Cu while Nb was taken as the superconducting metal. To obtain information on the interface transparency of this system, the experimental data have been interpreted using a theoretical model in which a matrix method has been developed to exactly solve the Usadel equations which describe the critical state of S/N multilayers,[18] using the boundary conditions developed in Ref. 12.

Nb/Cu multilayers were obtained by a dual-source magnetically enhanced dc triode sputtering technique on Si(100) substrates kept at room temperature at typical deposition rates equal to 0.7 nm/s for Nb and 0.6 nm/s for Cu. Details about sample preparation and characterization can be found elsewhere.[15,20] Low-angle x-ray diffraction measurements have confirmed the high-quality layering of the samples, which have a typical interfacial roughness of 2.5 nm.[15] Two sets of samples have been fabricated. In the first one we choose $N_b=1$ for all the samples to get Cu/Nb/Cu trilayers. In this case, d_N was kept constant to 150 nm while d_S varied in the range between 20 and 120 nm. This set of samples was used to determine the T_c versus d_S dependence. The critical temperature was determined at the middle of the resistive transition. The low temperature resistivity values ρ_{10} were typically around 3.0 $\mu\Omega$ cm for the trilayers of this series. For all of them $\beta_{10}\equiv\rho_{300}/\rho_{10}\approx 3.0$. As an example, in Fig. 1, the resistive transition for the Cu/Nb/Cu sample with $d_S=20$ nm is shown (open symbols). The width of the resistive transition curves ΔT_c, defined as $\Delta T_c=T(R=0.9R_{10})-T(R$

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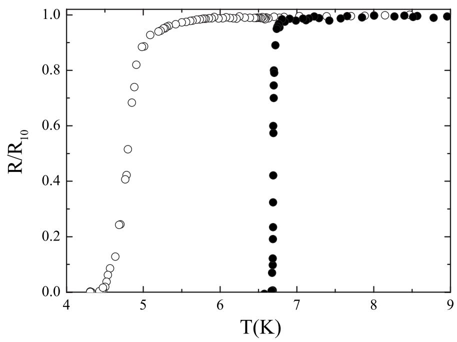

FIG. 1. Normalized resistive transition curves for the Cu/Nb/Cu trilayer with d_S=20 nm (open symbols) and for the $Cu/[Nb/Cu]_7$ multilayer (closed symbols).

$=0.1R_{10}$), is equal to 0.35 K. Here R_{10} is the value of the resistance at T=10 K. The second set consists of $Cu/[Nb/Cu]_{N_b}$ multilayers with N_b in the range 5–12 and $d_S=d_N$=20 nm. These multilayers have $\Delta T_c \approx 50$ mK, $\rho_{10} \approx 8.5$ $\mu\Omega$ cm, and $\beta_{10} \approx 1.8$. In Fig. 1 the resistive transition for the $Cu/[Nb/Cu]_7$ multilayer is shown by closed symbols.

Experimental data reported in Fig. 2, $T_c(d_S)$ dependence for Cu/Nb/Cu trilayers, and in Fig. 3, $T_c(N_b)$ dependence for $Cu/[Nb/Cu]_{N_b}$ multilayers, have been both interpreted using the same model developed in Ref. 18. This model, which describes the properties of S/N structures, contains five independent parameters. T_S, the critical temperature of the bulk superconductor, the coherence lengths ξ_S and ξ_N, the quantities $p \equiv \rho_S/\rho_N$, the ratio between the low temperature resistivities of the S and N metals, and $\gamma_b=[2l_N(1-\mathcal{T})]/(3\xi_N\mathcal{T})$,[21] where l_N is the low temperature electron mean free path in the normal metal. In the above relation $\mathcal{T}$ is the quantum mechanical transparency of the S/N interface which ranges in the interval [0,1]. T_S=8.8 K has been determined by measuring the critical temperature of a thick (d_S=150 nm) Nb film while for p we take $p \approx 2.55$.[15] The value of $\xi_S \approx 6.7$ nm has been obtained from upper critical magnetic field measurements on Cu/Nb/Cu trilayers.[15,22] The two remaining quantities, ξ_N and γ_b, are obtained as fitting parameters of the experimental dependence $T_c(d_S)$ for Cu/Nb/Cu

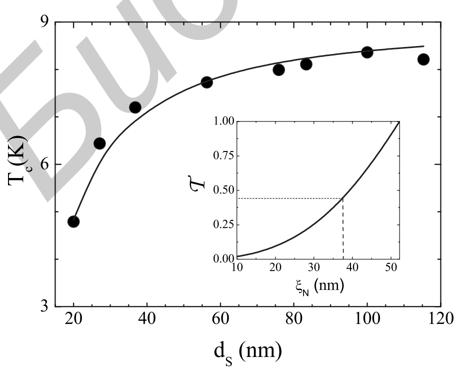

FIG. 2. Dependence of the superconducting critical temperature on d_S for Cu/Nb/Cu trilayers (closed symbols). The solid line is the fit to the experimental data using the theory developed in Ref. 18 with ξ_N=27 nm and γ_b=1.04. Inset: Dependence of the interface transparency $\mathcal{T}$ on the normal metal coherence length ξ_N, see the text for details. Broken lines identify the point with coordinates ξ_N=36 nm and $\mathcal{T}$=0.41.

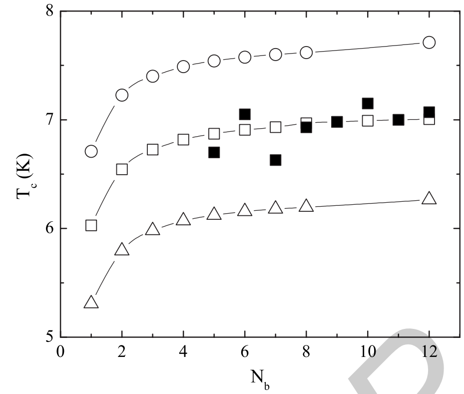

FIG. 3. Dependence of the superconducting critical temperature on N_b in $Cu/[Nb/Cu]_{N_b}$ multilayers (closed squares). Theoretical calculations refer to the following parameters: ξ_N=52.24 nm and γ_b=0 (circles), ξ_N=36 nm and γ_b=0.50 (open squares), and ξ_N=23 nm and γ_b=1.41 (triangles).

trilayers. However, all the theoretical curves obtained with any pair of γ_b and ξ_N values satisfying the simple relation

$$\gamma_b = \frac{\alpha(\xi_{N,\max} - \xi_N)}{\xi_N} \tag{1}$$

are indistinguishable and describe, with the same accuracy, the experimental data. The quantity α is order of unity and $\xi_{N,\max}$ is the largest value of the normal metal coherence length for which experimental data are theoretically reproduced using an ideal transparent interface: $\mathcal{T}$=1.[18]

In Fig. 2 the experimental points of the $T_c(d_S)$ dependence are shown by closed symbols. Among all the theoretical curves which reproduce the experimental data we show, for the sake of clearness, only the one obtained using ξ_N=27 nm and γ_b=1.04 ($\mathcal{T}$=0.20). In the inset of Fig. 2 is reported the $\mathcal{T}$ versus ξ_N dependence which represents all the pairs of these quantities for which the satisfactory agreement with the experimental data is obtained. The curve is obtained for α=1.11 and $\xi_{N,\max}$=52.24 nm in Eq. (1) and then using the relation between γ_b and $\mathcal{T}$ given in the text. As it follows from this result, the analysis of the $T_c(d_S)$ curve does not give a definite answer for the evaluation of the interface transparency (and of ξ_N). An independent way to experimentally determine the value of ξ_N could be implemented, for example, by measuring the T_c versus d_N curve in S/N/S structures. But, as it was shown in Ref. 19, such estimation of ξ_N is not correct due to the presence of surface effects. However, if we deal with materials for which microscopic parameters such as the Fermi velocity v_N^F or the electronic specific heat coefficient γ_N are known, the puzzle can be solved directly by calculating l_N and, consequently, ξ_N. For our samples we estimated $l_N \approx 20$ nm. This value has been obtained from the measured low temperature resistivity of a single Cu layer (ρ_N=1.8 $\mu\Omega$ cm) using the relation $\rho_N l_N = (1/v_N^F\gamma_N)(\pi k_B/e)^2$ (Ref. 24) with γ_N=124 J/K^2 m^3 (Ref. 25) and $v_N^F = 1.57\times10^6$ m/s.[26] As a consequence $\xi_N = (\hbar v_N^F l_N/6\pi k_B T_S)^{1/2} \approx 38$ nm and from the $\mathcal{T}(\xi_N)$ curve, we get $\mathcal{T}$=0.45. Here we wish to point out that in this case, it has been possible to remove the degeneracy in the $\mathcal{T}(\xi_N)$ values because for Cu both the values of v_N^F and γ_N are very well known. On the other hand, in the case of less studied materials, especially alloys and compounds, for which microscopic parameters such as v_N^F and γ_N are not precisely known, this procedure is hard to be applied and the problem can be solved only by measuring the $T_c(N_b)$ dependence. In our case this dependence was obtained from the series of $\mathrm{Cu}/[\mathrm{Nb}/\mathrm{Cu}]_{N_b}$ multilayers with N_b in the range 5–12. Experimental points are shown in Fig. 3 by closed symbols. In the same figure theoretical points obtained with the same model used above are shown for three different values of the pair (γ_b, ξ_N) by open symbols. Of course, in calculating these points, we have taken for T_S, p, and ξ_S the same values used when fitting the experimental data in Fig. 2. It is clear that in this case the results obtained are very different, and the theoretical curves strongly depend on the choice of the two fitting parameters. Experimental data are satisfactorily reproduced only with the pair $\gamma_b=0.50$ (which means $\mathcal{T}=0.41$) and $\xi_N=36$ nm. The obtained value of $\mathcal{T}$ is higher with respect to what is estimated when using the approximate solution of the microscopic Usadel equations for Nb/Cu hybrids ($\mathcal{T}=0.26$) (Ref. 15) and also with respect to what is obtained in the frame of a multichannel quasiclassical approach by Tagirov and García ($\mathcal{T}=0.33$) (Ref. 13) in fitting data of Ref. 15. However, $\mathcal{T}$ is smaller than the theoretical value ($\mathcal{T}=0.50$) which is obtained using a Fermi momenta mismatch model.[13] Moreover from the obtained values for $\mathcal{T}$ and ξ_N we estimate $l_N=19$ nm which actually coincides with the value we have obtained above from the measured resistivity using for v_N^F and γ_N the values reported in the literature. From the obtained γ_b value we can also calculate the specific resistance for the Nb/Cu interface which turns out to be equal to $0.33\ \mathrm{f}\Omega\ \mathrm{m}^2$. This value is in reasonable agreement with previous estimations performed on the same system with a different technique.[27]

In conclusion, an experimental method to satisfactorily evaluate the interface transparency $\mathcal{T}$ of Nb/Cu layered structures has been developed. The method consists in studying both the dependence of the critical temperature on the Nb layer thickness in Cu/Nb/Cu trilayers and on the number of bilayers N_b in $\mathrm{Cu}/[\mathrm{Nb}/\mathrm{Cu}]_{N_b}$ systems. The value of the interface transparency results from the fit of the experimental data in the framework of a theoretical model based on the exact solution of the Usadel equations. Further work is in progress to extend this method to the more complicated case of superconducting/ferromagnetic hybrids.

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