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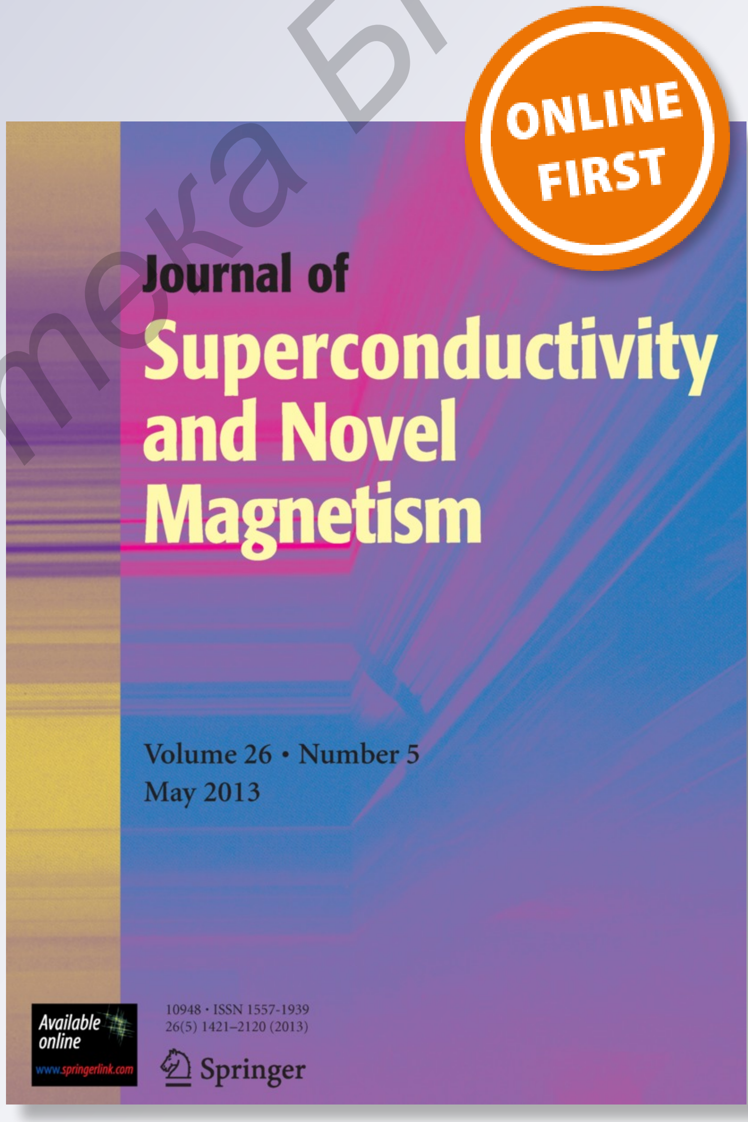

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ORIGINAL PAPER

Interface Properties of Superconductor-Based Heterostructures from Critical Temperature Measurements

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Abstract We report the experimental method of the evaluation of the specific boundary resistance, R_B, of superconductor (S)/non-superconductor (NS) interfaces by measuring the superconducting critical temperature, T_c, as a function of the thickness of the superconducting layer, d_S, in S/NS hybrids and of the number of S/NS bilayers, $N_{\rm bl}$, for a large number of $N_{\rm bl}$ in NS/[S/NS]$_{N_{\rm bl}}$ multilayers. Two types of systems have been studied. We choose Nb as the S material for both types and Cu for a normal metal (N) for the first one. In the second case, a weakly ferromagnetic alloy (F), $Cu_{0.38}Ni_{0.62}$, was chosen for NS. Analyzing the experimental results by solving exactly the Usadel equations, we were able to unambiguously determine the value of R_B for both the S/N and S/F hybrids. The results show that Nb/Cu is characterized by a lower value of the interfacial specific resistance with respect to the case of Nb/$Cu_{0.38}Ni_{0.62}$.

Keywords Proximity effect · Interface transparency · Specific boundary resistance · Usadel equations

1 Introduction

When a superconductor (S) is brought into a contact with a non-superconducting metal (NS) to form S/NS heterostructure, the superconducting behavior is determined by the proximity effect (PE). When NS is a normal metal (N), the superconducting order parameter exponentially decays inside N on the length ξ_N. When NS metal is a ferromagnet (F), a spatial oscillation of the superconducting order parameter is induced in the F-layer [1].

The role of the barrier at the interface between the two metals has already been considered a long time ago [2], but only more recently the quality of interface has been added to self-consistently model the interaction between S and NS metals [3]. Interface transparency τ can be connected with the boundary resistance R_B that electrons encounter at the interface and this reduces the flow of Cooper pairs from the S to the NS layer.

The microscopic parameters entering in the description of the PE, such as τ and the coherence length in N(F) metal, $\xi_{N(F)}$, are usually obtained as a result of the fitting procedure of the experimental data. One way to determine these quantities is to analyze the $T_c(d_S)$ data in S/NS hybrids [4]. However, it has been shown that the experimental $T_c(d_S)$ dependence can be reproduced by an infinite number of (τ, ξ_N) pairs [4]. This means that only when it is possible to obtain $\xi_{N(F)}$ by independent measurements, the curve $\tau(\xi_{N(F)})$ unambiguously gives the value of the interface transparency.

In the present study, to remove the above ambiguity, we propose to use the measured experimental asymptotic behavior of the T_c versus $N_{\rm bl}$ dependence in a multilayer structure of the type NS/[S/NS]$_{N_{\rm bl}}$ together with the results obtained for the $T_c(d_S)$ dependence for Cu/Nb/Cu trilayers (N/S/N system) and Nb/$Cu_{0.38}Ni_{0.62}$ bilayers (S/F system). To obtain information on the interface transparency of

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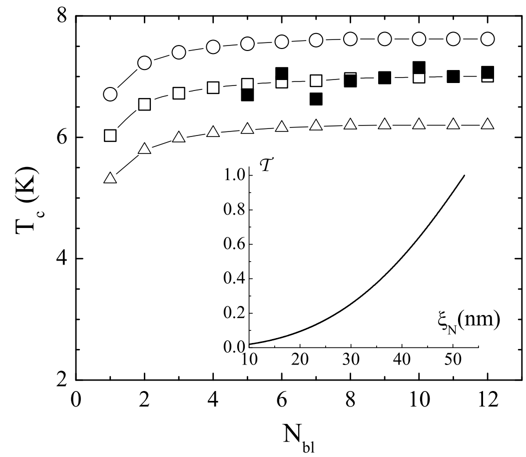

Fig. 1 Measured $T_c(N_{\mathrm{bl}})$ dependence for Cu/Nb multilayers with $d_S = d_N = 20$ nm (*closed symbols*). Theoretical calculations refer to the following parameters: $\xi_N = 52.24$ nm and $\tau = 1$ (*circles*), $\xi_N = 36$ nm and $\tau = 0.41$ (*open squares*), and $\xi_N = 23$ nm and $\tau = 0.13$ (*triangles*). *Inset*: $\tau(\xi_N)$ dependence

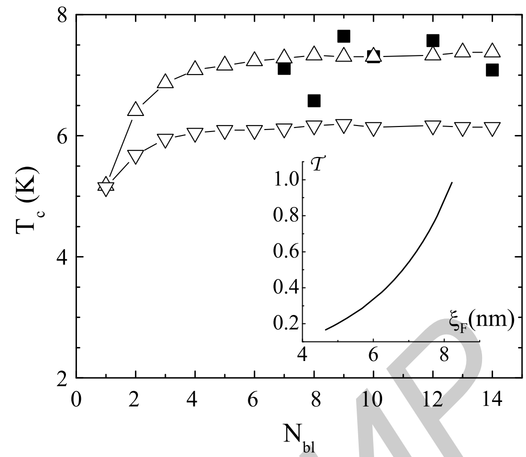

Fig. 2 Measured $T_c(N_{\mathrm{bl}})$ dependence for $Cu_{0.38}Ni_{0.62}$/Nb multilayers with $d_S = 15$ nm and $d_F = 5$ nm (*closed symbols*). Theoretical calculations refer to the following parameters: $\xi_F = 7.0$ nm and $\tau = 0.54$ (*up-triangles*), $\xi_F = 6.0$ nm and $\tau = 0.34$ (*down-triangles*). *Inset*: $\tau(\xi_F)$ dependence

these systems, the experimental data have been interpreted by solving exactly the Usadel equations [4, 5].

2 Results

Nb/Cu trilayers and multilayers were prepared by a dual-source magnetically enhanced *dc* triode sputtering technique on Si(100) substrates kept at $T = 300$ K. Nb/$Cu_{0.38}Ni_{0.62}$ hybrids were grown on Si(100) substrates in UHV *dc* diode magnetron sputtering in an Ar pressure of 1×10^{-6} Torr [6, 7].

In Fig. 1, we show the results for Nb/Cu. By analyzing the $T_c(d_S)$ for Cu/Nb/Cu trilayers with variable d_S and using two quantities, τ and ξ_N, as free parameters, we obtained that there is an infinite set of (τ, ξ_N) pairs which with the same accuracy describes the experimental data. In the inset to Fig. 1, we show the obtained $\tau(\xi_N)$ dependence. Only one point from this curve corresponds to the true value of τ. In order to take off this degeneracy, we measured the $T_c(N_{\mathrm{bl}})$ dependence for Nb/Cu multilayers. This result is present in the main plot of Fig. 1.

The same degeneracy between τ and ξ_F was obtained for the Nb/$Cu_{0.38}Ni_{0.62}$ system and was taken off by analyzing the $T_c(N_{\mathrm{bl}})$ dependence for multilayers. This result is shown in Fig. 2. In the inset to this figure, we show the degeneracy $\tau(\xi_F)$ curve obtained by fitting the $T_c(d_F)$ dependence for bilayers. In the main plot the $T_c(N_{\mathrm{bl}})$ dependences are present.

From the obtained τ and $\xi_{N(F)}$ values, it is possible to evaluate the R_B values for the studied systems [2]. We obtained $R_B = 0.33 \pm 0.02$ fΩ m^2 for Nb/Cu and $R_B = 1.1 \pm 0.6$ fΩ m^2 for Nb/$Cu_{0.38}Ni_{0.62}$.

3 Conclusions

We studied the $T_c(d_S)$ and $T_c(N_{\mathrm{bl}})$ dependences in S/N and S/F hybrids. The experimental data have been interpreted within the Usadel formalism. Due to the strong dependence of the theoretical $T_c(N_{\mathrm{bl}})$ curves on the pairs $(\tau, \xi_{N(F)})$ for large values of N_{bl}, we were able to evaluate the specific boundary resistance of these hybrids. We obtain that Nb/Cu interface is characterized by a lower value of R_B with respect to the case of Nb/$Cu_{0.38}Ni_{0.62}$.

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