

Transport properties of Nb/PdNi bilayers

C. Cirillo*, S.L. Prischepa¹, M. Salvato, C. Attanasio

Dipartimento di Fisica 'E.R. Caianiello' and INFM, Università degli Studi di Salerno, Baronissi (SA) I-84081, Italy

Abstract

The transport properties of superconductor/weak ferromagnet Nb/Pd₈₆Ni₁₄ sputtered bilayers have been studied. The critical thickness needed for superconductivity to develop is determined from the dependence of the transition temperature T_c on d_{Nb} .

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1. Introduction

In last years great interest has been devoted to the study of artificial layered structures consisting of superconducting (S) and magnetic layers (F), allowing the investigation of the interplay between two competing orders and revealing a rich variety of phenomena [1–4].

In these systems, the two different materials are coupled by proximity effect. Superconductivity is depressed in S over the coherence length ξ_S and a minimum thickness of the S layer is necessary to make superconductivity survive. This thickness is called superconducting critical thickness, d_S^{cr} . Superconductivity is also induced in F, but the exchange energy E_{ex} , which is here the main pair breaking mechanism, depresses superconductivity acting on the spins of the Cooper pairs. Moreover, due to the presence of this field, the superconducting order parameter does not simply decay in the ferromagnetic metal, but it also oscillates over a length scale given, in the dirty limit, by $\xi_F = \sqrt{\hbar D_F / E_{ex}}$, the coherence length in F [5]. Here, D_F is the diffusion coefficient.

The superconducting transition temperature, T_C , is the simplest parameter which reveals intriguing behaviour typical of the S/F structure, such as a nonmonotonic dependence, both in multilayers and bilayers, as a function of the F layers thickness, d_F . However, a clear comparison between the theoretical predictions [5–8] and the experimental results [1,9,10] is still controversial, because, at least in systems in

which F is a traditional ferromagnet, the oscillation are predicted and observed in a d_F range, where structural and magnetic properties are also critical [9–11].

For these reasons, we decided to study the Nb/PdNi system, where PdNi is a magnetic alloy, in which the exchange energy, controlled through the percentage of the magnetic component (Ni) in the metallic high paramagnetic matrix (Pd), is in the meV range [2]. These values lead to a ferromagnetic coherence length of the order of 50–100 Å, a thickness accessible to standard deposition techniques. Moreover, PdNi seems to be more intriguing than other weak ferromagnets, such as CuNi, because of the high values of the interface transparency measured in Nb/Pd systems [11,12].

This work is organized as follows: after a brief description of the sample preparation and structural characterization, we will focus on the behaviour of the superconducting transition temperatures of Nb/PdNi bilayers as a function of the Nb thickness.

2. Sample preparation and characterization

Nb/Pd₉₀Ni₁₀ bilayers were grown on Si(100) substrates by a dual source magnetically enhanced dc triode sputtering system with a movable substrate holder, in order to obtain 8 different samples in a single deposition run. The deposition conditions were similar to those of the Nb/Pd multilayers described earlier [13]. Two different sets of bilayers were prepared. They consist of a PdNi layer with constant thickness ($d_{PdNi} \approx 500$ Å) and a Nb layer with variable thickness ($d_{Nb} = 150$ – 1500 Å). These two series were used to determine $T_C(d_{Nb})$ behaviour and to estimate the Nb critical thickness. The superconducting transition temperatures T_C were resistively measured using a standard dc four-probe technique. The superconducting

* Corresponding author. Tel.: +39 89 965 256; fax: +39 89 965 275.

E-mail address: carla@sa.infn.it (C. Cirillo).

¹ State University of Computer Science and RadioElectronics, P. Brovka street 6, 220600 Minsk, Belarus

transition temperature was defined as the midpoint of the transition curve.

The measured values of the Nb and PdNi resistivities on samples deliberately fabricated, 2000 and 300 Å thick, were, respectively, $\rho_{\text{Nb}} = 6 \mu\Omega \text{ cm}$ and $\rho_{\text{PdNi}} = 24 \mu\Omega \text{ cm}$. The Nb critical temperature was $T_C = 9 \text{ K}$. Thus, the Nb coherence length was also determined through the dirty limit expression: $\xi_S = \sqrt{\hbar D_{\text{Nb}} / 2\pi K_B T_C}$. Here, D_{Nb} is the diffusion coefficient which is related to the low temperature resistivity ρ_{Nb} through the electronic mean free path l_{Nb} by $D_{\text{Nb}} = v_{\text{Nb}}^F l_{\text{Nb}} / 3$, in which $l_{\text{Nb}} = (1/v_{\text{Nb}}^F \gamma_{\text{Nb}} \rho_{\text{Nb}}) (\pi k_B / e)^2$ [14], where $\gamma_{\text{Nb}} \approx 7 \times 10^2 \text{ J/K}^2 \text{ m}^3$ is the Nb electronic specific heat coefficient [15] and $v_{\text{Nb}}^F = 2.73 \times 10^7 \text{ cm/s}$ is the Nb Fermi velocity [16]. We obtained $\xi_{\text{Nb}} \approx 83 \text{ \AA}$.

In the study of proximity effect, the control of interfaces properties is essential. For this reasons interface quality have been studied by X-ray reflectivity measurements, using a Philips X-Pert MRD high-resolution diffractometer. X-ray reflectivity analysis have been performed on bilayers deliberately fabricated with the appropriate thicknesses in the same conditions of the samples used in superconductivity measurements. The reflectivity profile of a Nb/PdNi bilayer with $d_{\text{Nb}} = 180$ and $d_{\text{PdNi}} = 237 \text{ \AA}$ is shown in Fig. 1 together with the simulation curve obtained using the Parrat and Nevot-Croce formalism [17,18]. The fit gives a roughness value of 12 Å. The film thicknesses obtained from the simulation were used for the final calibration of d_{Nb} and d_{PdNi} .

The onset of ferromagnetism in $\text{Pd}_{1-x}\text{Ni}_x$ alloys is around $x = 0.23$ [19]. In order to have a magnetic homogeneity a $\text{Pd}_{1-x}\text{Ni}_x$ target with $x = 10\%$ was used: This stoichiometry was not conserved in the samples as revealed by Rutherford Backscattering Spectrometry analysis, which gives a Ni concentration of $x = 0.14$. For $\text{Pd}_{90}\text{Ni}_{10}$ alloys the value of the exchange energy was estimated by saturation magnetization measurements, $E_{\text{ex}} = 15 \text{ meV}$ [2]. Using the values of the measured low temperature resistivity ρ_{PdNi} and of the Pd Fermi velocity $v_{\text{Pd}}^F = 2 \times 10^5 \text{ cm s}^{-1}$ [20], knowing the product

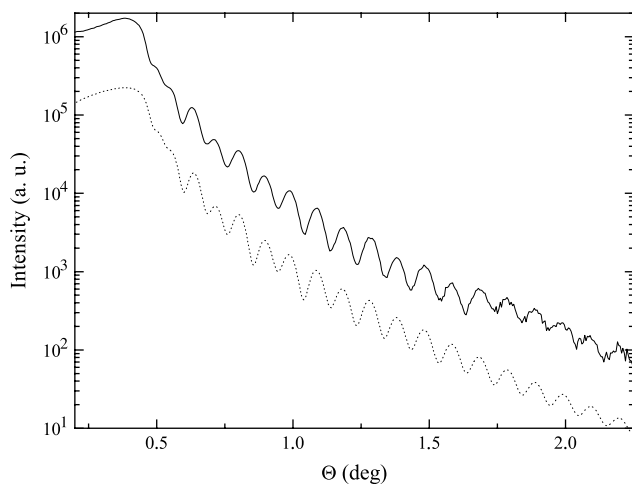


Fig. 1. Experimental (solid line) and calculated (dashed line) low-angle reflectivity profile for a Nb/PdNi bilayer. The numerical simulation is arbitrarily shifted downward for sake of clearness.

$\rho_{\text{Pd}} l_{\text{Pd}} = 4 \times 10^{-5} \mu\Omega \text{ cm}^2$ [21], we evaluated the diffusion coefficient $D_{\text{PdNi}} = v_{\text{Pd}}^F l_{\text{Pd}} / 3$, resulting in $\xi_F \approx 60 \text{ \AA}$.

It is well known that in metals electronic transport properties are closely related to magnetic ones. In particular electrical resistance measurements can give useful indications on the onset of magnetic ordering in metallic systems. For this reason we studied the critical behaviour of the electrical resistance of single PdNi films and of Nb/PdNi bilayers in the temperature range in which the magnetic ordering changes. From this measurements it is possible to estimate the Curie temperature of the alloy [24–26]. In Fig. 2a, the behaviour of the normalized electrical resistance, $R(T)R_{10 \text{ K}}$, of a series of Nb/PdNi bilayers is reported in the temperature range between 125 and 250 K. At high temperature, it is linear in T , but a broad maximum is present at $T \approx 185 \text{ K}$, which become more and more evanescent as the Nb thickness is increased. But is the singular behaviour of $R(T)$ first derivative, which better characterize the transition. In Fig. 2b, the temperature dependence of $r(T) = R(T) - R_{5 \text{ K}}$ and of dr/dT is presented for the Nb/PdNi bilayer with $d_{\text{Nb}} = 200 \text{ \AA}$: the lowest temperature at which the derivative shows a maximum can be taken as T_{Curie} [22–24]. In this case, the magnetic transition temperature can be approximately estimated as $T_{\text{Curie}} \approx 156 \text{ K}$, indicating that in the temperature range investigated for the superconducting measurements, the magnetic ordering is well established. The value obtained for the magnetic transition seems to be lower than the one derived by extraordinary Hall effect measurements [21]. Similar discrepancies have already been reported for other magnetic systems when T_{Curie} obtained by resistivity measurements is compared with the one obtained by saturation magnetization measurements [24].

3. Experimental results

The dependence of the critical temperatures T_C on d_{Nb} of Nb/PdNi bilayers is reported in Fig. 3. The transition temperature of the sample with $d_{\text{Nb}} = 150 \text{ \AA}$ is not reported since it was below 2 K, the lowest temperature reachable with our experimental setup. From this curve, we can extract $d_{\text{Nb}}^{\text{cr}} = 145 \text{ \AA}$ the minimum Nb layer thickness needed for superconductivity to develop. Comparing this result with the one obtained for Nb/Pd trilayers [11,12], and keeping in mind that the critical thickness of the bilayers is half of the corresponding trilayers, an higher value of $d_{\text{Nb}}^{\text{cr}}$ is found, indicating the stronger effect of the ferromagnet. This value is lower than the ones reported for traditional S/F systems [9,27], but higher than the one obtained for Nb/Cu $_{1-x}$ Ni $_x$ trilayers [4], where Cu $_{1-x}$ Ni $_x$ is another weak ferromagnet. This result may be due both to the weak ferromagnetism of the alloy and probably also to the good transparency of the Nb/PdNi interface. Also the ratio between the critical thickness and the Nb coherence length can be calculated, giving $d_{\text{Nb}}^{\text{cr}} / \xi_{\text{Nb}} = 1.75$, corresponding to 3.5 for the trilayers case. It depends both on interface transparency \mathcal{T} [28], and on the strength of the pairing, lowering with increasing ξ_F and decreasing \mathcal{T} . In S/F systems with $\mathcal{T} = 1$, d_s^{cr} / ξ_s has its theoretical upper limit close to 6 [28]. However, in classical S/

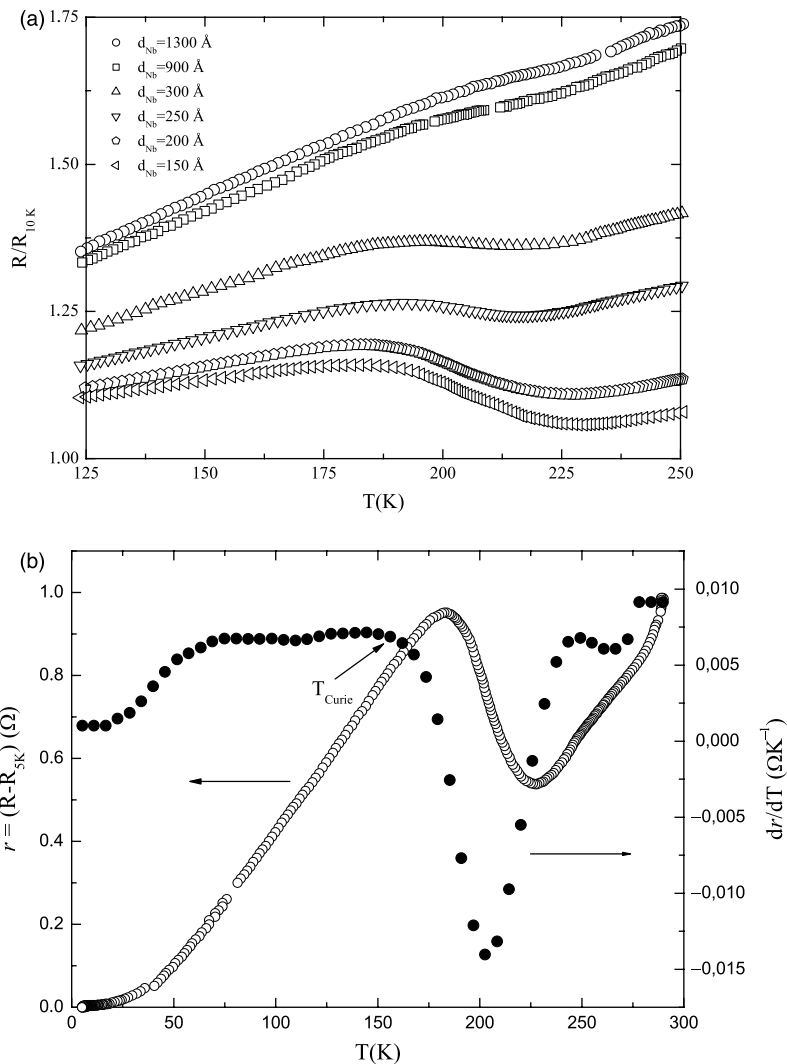


Fig. 2. (a) Normalized electrical resistance, $R(T)/R_{10\text{K}}$, of a series of Nb/PdNi bilayers. (b) Rescaled resistance $r(T) = R(T) - R_{5\text{K}}$ (open symbols) compared with its first derivative (solid symbols) for the Nb/PdNi bilayer with $d_{\text{Nb}} = 200\text{ \AA}$. The arrow indicates the value of T_{Curie} .

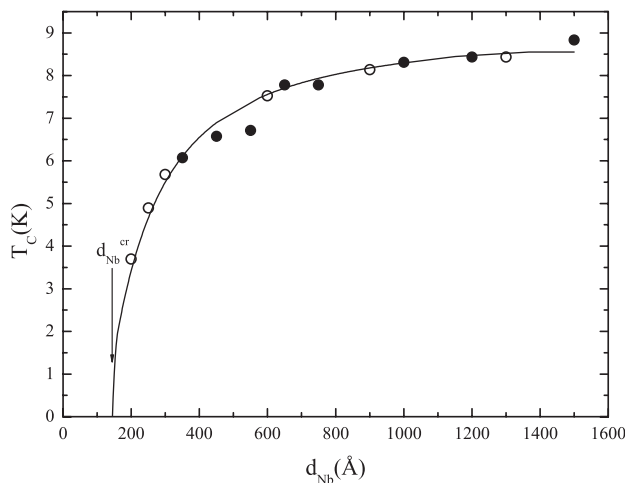


Fig. 3. Critical temperature T_{C} versus Nb thickness d_{Nb} . Different symbols refer to samples sets obtained in different deposition runs. The solid line is meant to guide the eye. The arrow indicates the value of $d_{\text{Nb}}^{\text{cr}}$.

F systems ξ_{S} is an order of magnitude larger than ξ_{F} and in this limit the $d_{\text{S}}^{\text{cr}}/\xi_{\text{S}}$ ratio is practically independent from \mathcal{T} [28]. Also for this reason, the study of S/F interface seems to be more interesting in the case of weak ferromagnet, having a larger value for the ferromagnetic coherence length.

In summary, we studied the transport properties of Nb/Pd86Ni14 bilayers grown by sputtering. In particular the attention was devoted to the dependence of the superconducting transition temperature on the thickness of the Nb layer with the thickness of the PdNi layer fixed at 500 \AA . As main conclusion we deduced the superconducting critical thickness, $d_{\text{Scr}} \sim 145\text{ \AA}$. This value is lower than the ones reported for traditional S/F systems (because of the weak ferromagnetism of the alloy), but higher than the one obtained for Nb/Cu1-xNix trilayers, with $x = 0.67, 0.59$ and 0.52 . Further studies on this system are still in progress, as the fabrication of bilayers with PdNi variables thickness which could give an estimation of the ferromagnetic coherence length and could eventually reveal an oscillatory behaviour of the superconducting critical

temperature. Moreover the interpretation of these results in the framework of recent theoretical model [7] could allow an evaluation of the interface transparency of the system.

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