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Resistive Transitions In S/F/S Trilayers

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Abstract. The phase transition of Nb/$Cu_{0.41}Ni_{0.59}$/Nb triple layers from the normal to the superconducting state has been studied experimentally by measuring the temperature dependence of the electrical resistance, $R(T)$. It is shown that the shape of the $R(T)$ curves is different depending on the $Cu_{0.41}Ni_{0.59}$ thickness. To explain the experimental data we developed a qualitative model which makes more evident the interconnection between the superconducting phase transition and the 0 to π crossover in SFS structures.

Introduction

In the last few years the problem of interplay between superconducting (S) and ferromagnetic (F) orderings attracted more and more attention [1,2]. This interest was stimulated by two factors: the experimental evidences of the non-monotonic dependence of the critical temperature T_c on the F layer thickness, d_F, in SFS [3] and FSFSF [4,5] heterostructures and the existence of Josephson π junctions [6,7], structures having in the ground state the phase difference φ between the order parameters of the two superconductors equals to π. Even if these two phenomena have always been considered as distinct manifestation of the π-phase, they are actually very closely connected.

In this paper we have studied the temperature dependence of the electrical resistance $R(T)$ in Nb/$Cu_{0.41}Ni_{0.59}$/Nb triple layers. The unusual shape of the measured $R(T)$ curves during the superconducting transition has been explained by developing a qualitative model which makes more straightforward the interconnection between the superconducting phase transition and the 0 – π transition in SFS structures.

Experimental Results

Nb/$Cu_{0.41}Ni_{0.59}$/Nb triple layers were deposited on Si(100) substrates in a UHV *dc* diode magnetron sputtering system with a base pressure less than 10^{-9} mbar and sputtering Argon pressure of 4×10^{-3} mbar. The Nb and the $Cu_{0.41}Ni_{0.59}$ layers were deposited at typical rates of 0.1 nm/s and 0.04 nm/s, respectively, measured by a quartz crystal monitor calibrated by low-angle reflectivity measurements. $Cu_{1-x}Ni_x$ is a weak ferromagnetic alloy, whose magnetic strength is controlled through the Ni content, which in our films was checked by Rutherford-backscattering analysis. The Curie temperature, T_{Curie}, and the magnetic moment per atoms, μ_{at}, for this Ni concentration in $Cu_{0.41}Ni_{0.59}$ thin films were estimated to be $T_{Curie} \approx 220$ K and $\mu_{at} \approx 0.12$ μ_B/at, respectively [8].

In order to study the dependence of the superconducting critical temperature as a function of the ferromagnetic layer thickness, $T_c(d_F)$, samples with constant Nb thickness, d_{Nb} = 14 nm, and variable $Cu_{0.41}Ni_{0.59}$ thickness (d_{CuNi} = 1 – 15 nm) were grown. To prevent Nb oxidation a thin, 1nm thick, Al capping layer was deposited on top of the structures. It fully oxidizes after contact with atmosphere and does not influence the superconducting properties of the upper electrode.

The high quality layering of our samples was confirmed by X-Ray Reflectivity measurements. In Fig. 1, the measured reflectivity profile (points) of a sample with d_{CuNi} = 3.8 nm is shown together with the simulation curve obtained with the Parrat and Nevot-Croce recursion relation [9]. The fit also gives information about the presence of interface roughness at different interfaces. In this case, the roughness of $Cu_{0.41}Ni_{0.59}$ film does not exceed 0.8 nm, which is typical for $Nb/Cu_{0.41}Ni_{0.59}$ system [10].

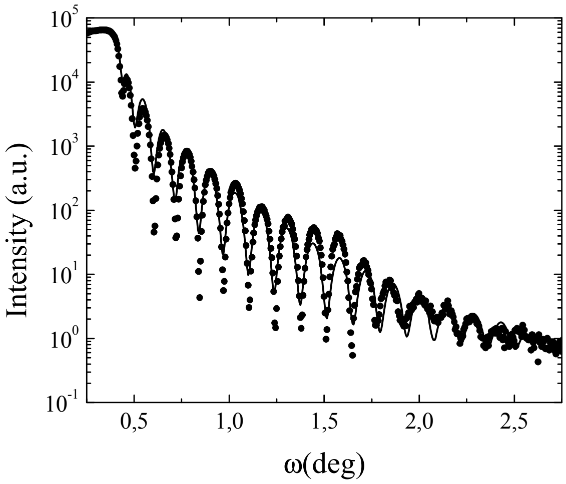

Fig. 1. Experimental (points) and calculated (line) low-angle reflectivity profile for $Nb/Cu_{0.41}Ni_{0.59}/Nb$ triple layer with d_{CuNi} = 3.8 nm.

The critical temperatures were resistively measured in a ^{4}He cryostat using a standard dc four-probe technique on unstructured samples. The critical temperature T_c was defined at the end of the transition curves. The dependence of T_c on d_{CuNi} is shown in Fig. 2. It can be seen that increasing d_{CuNi}, T_c exhibits first a rapid drop with minimum for $d_{CuNi} \approx 5$ nm. After this point T_c slightly increases with d_{CuNi} saturating at larger CuNi thickness. This overall $T_c(d_{CuNi})$ behavior is a signature of the so-called 0–π phase shift in S/F hybrids [2 - 4]. Apart from this standard behavior of $T_c(d_F)$ what is important to note is that some data scattering is present for our trilayers in the thickness range 2 nm< < d_{CuNi} < 8 nm. Moreover, as it is shown

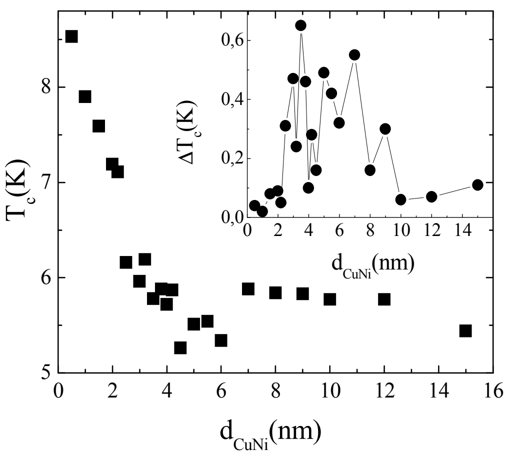

Fig. 2. T_c versus d_{CuNi} for Nb/CuNi/Nb trilayers. Inset: The width of the resistive transition ΔT_c versus d_{CuNi}.

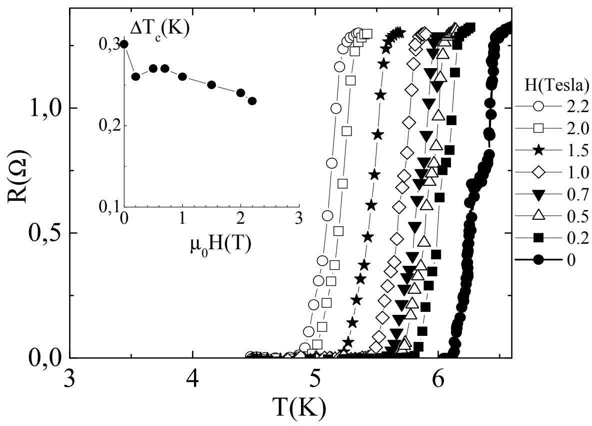

Fig. 3. The $R(T)$ transitions in parallel magnetic field H for trilayer with d_{CuNi} = =2.5nm. Inset: The width of the resistive transitionΔT_c versus H.

in the inset of Fig. 2, in this CuNi thickness range, the transition curves become broader and the width of the transition, ΔT_c, reaches values of 0.6 K. Outside this thickness range the transition curves are sharp, and $\Delta T_c \approx 0.1$ K. The broadening of the resistive transitions disappeares in the parallel magnetic field H. In Fig. 3 the $R(T,H)$ curves are shown for sample with d_{CuNi} = 2.5 nm. In the inset to this Figure we show the width of the $R(T)$ curves at different H values. It is clearly seen, that with H growth the form of $R(T)$ changes and transforms into a sharper transition.

Discussion

From the theory we know [1,2] that the appearance of a minimum in the $T_c(d_F)$ curve reveals the transition from 0- to π- phase. For this reason from our experimental data we claim that in our trilayers the π-phase sets in at $d_{CuNi} \approx 5$ nm and that it remains favored at least up to $d_{CuNi} = 15$ nm. For $d_{CuNi} \leq 2$ nm and $d_{CuNi} \geq 8$ nm, and therefore in the 0-phase and π-phase, respectively, the $R(T)$ curves show sharp phase transitions from normal to superconducting state. On the contrary, in the thickness interval 2 nm < d_{CuNi} < 8 nm, when we will show both the 0- and π- phases can be realized, the $R(T)$ dependencies are very broadened (see inset to Fig. 2). Indication of the broadening of the $R(T)$ curves for d_F close to the crossover 0-π point has been already observed in S/F multilayers [5], but to our knowledge it was never investigated in the literature.

To explain this effect we consider our trilayer as network of both SFS and SNS Josephson junctions (here N stands for normal metal). The wide $R(T)$ transitions are a consequence of the interaction between local 0 and π junctions in the network, which may be caused by fluctuations of the samples parameters. The possible physical reasons for this dispersion are the roughness of S/F interfaces (see Fig. 1) and the local fluctuations of Cu and Ni content in the $Cu_{0.41}Ni_{0.59}$ alloy [10]. Both of these values are usually of the order of the decay length of superconductivity into a ferromagnetic layer (several nanometers). For this reason the role of these interactions is much more important for thicknesses at which the entire sample goes from the 0 to the π phase, since, in this regime, i.e. for 2 nm < d_{CuNi} < 8 nm, small fluctuations in the F layer thickness or in the magnetic strength of the alloy can be critical. A schematic representation of a SFS trilayer in this thickness interval is shown in Fig. 4.

At the beginning of the superconducting phase transition superconductivity nucleates only in certain regions inside each S layer. Each Nb layer can be considered as formed by superconducting

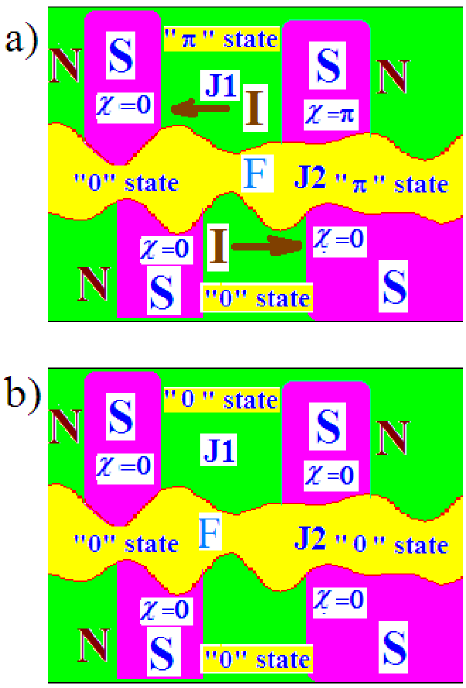

Fig. 4. Sketch of the unit cell of a SNS+SFS network, representing our SFS trilayers. Junction J1 (J2) corresponds to SNS (SFS) junction, respectively. The parameter χ represents the phase of the order parameter in each of the superconducting island. I is the circulating component of the superconducting part of the bias current. Presence of interface roughness is taken into account. For other details see the text.

islands, separated by N domains. For this reason they can be seen as a net of SNS junctions (marked as J1 in Fig. 4). The S layers are coupled via the F layer forming, in turn, a net of SFS junctions (marked as J2 in Fig. 4). So the entire trilayer can be seen as a SNS+SFS network. The ground state of J1 junctions corresponds to a phase difference between neighboring islands $\varphi = 0$, while the case $\varphi = \pi$ is a non-equilibrium state. It is reasonable to suppose that, due to the roughness of S/F interface and due to the variation of the in-plane material parameters, one of J2 contacts is in the 0-state and the other is in the π-state, as shown in Fig. 4a. At $T \approx T_c$, when the Josephson energy, E_N, associated to J1 is lower that E_F, the one related to J2, two junctions should be in the zero state and two in the π state. This situation is schematically shown in Fig. 4a. The application of a small measuring current generates Josephson superconducting currents having the opposite directions in the upper and bottom films since at least one of the SNS junction in the cell is at nonequilibrium state and behaves as a π contact.

When T decreases the average distance between S islands in Nb films becomes shorter resulting in an increase of E_N (while E_F remains practically constant). The increase of E_N results in increase of the circulating Josephson currents, which, in turn, makes the increase of the volume of S islands slower. These two competitive mechanisms make the $R(T)$ broader. If the temperature is further decreased E_N becomes larger than E_F. As a result all the junctions are in the 0-phase, with J2 in a nonequilibrium state, as shown in Fig. 4b. The spontaneous circulating currents are switched off. In the absence of this restraining mechanism the volume of superconducting islands rapidly increases and a sharp transition into superconducting state occurs in the overall system.

Conclusions

A model describing the observed unusual shape of the $R(T)$ curves in Nb/$Cu_{0.41}Ni_{0.59}$/Nb triple layers close to 0-π transition has been proposed. The model is based on the occurrence of SNS+SFS network in the system.

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