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Depairing currents in superconductor / ferromagnet Nb/CuNi trilayers close to T_c.

A. Rusanov, M. Hesselberth, S. Habraken and J. Aarts

Kamerlingh Onnes Laboratory, Leiden University, P.O. Box 9506, 2300 RA Leiden, The Netherlands

Abstract

In superconductor/ferromagnet (S/F) heterostructures, the exchange field h_{ex} of the F-layer suppresses the superconducting order parameter in the S-layer via the proximity effect. One issue in current research is the effect of a domain state, or, more generally, different directions of h_{ex}, on the superconductivity. We used a pulsed-current technique in order to measure the superconducting transport properties of $Cu_{1-x}Ni_x$/Nb/$Cu_{1-x}Ni_x$ ($x = 0.54$) F/S/F trilayers structured in strips of about 2 μm wide and 20 μm long as function of a small in-plane magnetic field. We find that the depairing current is tied to the magnetization behavior. In particular, we show that the suppression of superconductivity in the S-layer is smallest when the external magnetic field equals the coercive field H_c of the F-layers.

Keywords: Proximity effect, FSF-junctions, FS heterostructures, spintronics.

1 Introduction

The issue of the proximity effect between a superconductor and a ferromagnet is the focus of much current research. In principle, the superconductivity in the S layer is suppressed due to the pair breaking of the Cooper pair by the exchange field h_{ex} experienced in the ferromagnet. In the F-layer, a superconducting order parameter can still exist, but it becomes spatially modulated because the electrons which create a Cooper pair belong to different spin subbands. This leads to several effects observed experimentally, including oscillatory behavior of the superconducting transition temperature T_c as function of ferromagnetic layer thickness in F/S bi- or multilayers [1–3], and π-junctions in S/F/S Josephson junctions [4,5]. A different mechanism to influence the superconducting order parameter in the S-layer by the adjacent F-layers is by varying the relative directions of the magnetization (and therefore h_{ex}) in the two F-layers. It was predicted that, when the thickness of superconductor d_S is of the order of the superconducting coherence length ξ_S, the superconducting transition temperature is higher when the two magnetization directions are antiparallel than when they are parallel to each other [6]. The difference can even be enhanced by tuning the thickness of the F-layers d_F such that $d_F \approx \xi_F/2$ (with ξ_F the coherence length in the ferromagnet) [7]. A first observation of these so-called spin-switch effects was recently reported in ref. [8].

Basically, spin switching comes about when the Cooper pair samples different directions of h_{ex} simultaneously, which raises the question whether similar effects can be observed if the F-layers contain a domain structure rather than a homogeneous magnetization [9]. Two recent experiments reported an influence of the domain state on the transport properties of the superconductor. In Nb/Co bilayers it was found that the superconducting transition temperature T_c and critical current density J_c (defined using a voltage criterion) are higher at the coercive field of the Co layer [10]; a similar effect on J_c was observed in Co/Nb/Co trilayers, again using a voltage criterion [11]. Here we present results of a similar study, which differs in two ways from the ones cited above. We use F/S/F trilayers with S = Nb and F = $Cu_{0.46}Ni_{0.54}$, which is a very weak ferromagnet with a saturation magnetization M_s of about 0.1 μ_B (μ_B is the Bohr magneton) [12] to be compared to about 1 μ_B for Co. The experiment we perform is measuring the depairing current by a pulsed-current method. This quantity reflects the superconducting order parameter directly, and we showed before that it can be used in S/F systems [13]. We find that at least close to T_c the critical current of the trilayer as function of an in-plane magnetic field peaks at the coercive field H_{co} of the F-layer, which means that superconductivity is enhanced in the domain state.

2 Sample preparation and magnetic properties

Single F-films and F/S/F trilayers were DC-magnetron sputtered in an ultra high vacuum system with base pressure of about 10^{-9} mbar and sputtering argon pressure about $6{*}10^{-3}$ mbar. A $Cu_{1-x}Ni_x$ target was used with x = 0.50, which yielded a slightly different Ni concentration in the samples of x = 0.54. We will call this alloy CuNi. The thickness of the F-layers was chosen to be 9 nm,

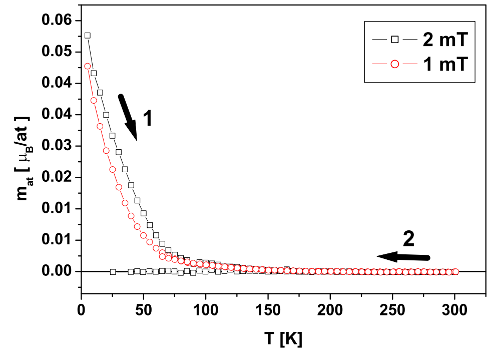

Fig. 1. Magnetization M as a function of temperature T for a CuNi/Nb/CuNi trilayer after saturation at 5 K in the fields indicated. Arrows denote the measurement sequence. The Curie temperature is around 110 K.

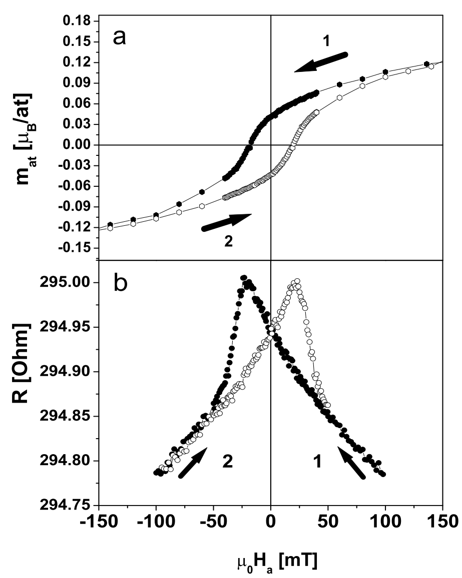

Fig. 2. Dependence of (a) magnetization M and (b) resistance R on magnetic field H_a for a CuNi/Nb/CuNi trilayer at 5 K. Filled symbols are used for the field sweep from positive to negative field (denoted 1), open symbols for the opposite direction (denoted 2). The coercive field H_c is around 22 mT.

which is about 0.5 ξ_F [4]. The S-layer thickness was chosen at 23 nm in order to have the superconducting transition temperature around 4 K [12]. Electron beam lithography was used to pattern the samples for 4-point measurements, with the bridge between the voltage contacts 2 μm wide and 20 μm long. The patterned samples were Ar-ion etched. Unstructured samples were measured by SQUID-magnetometry in order to determine M_s, H_{co} and the Curie temperature T_{Curie}. Fig. 1 shows the typical dependence of the magnetization M on temperature T for a single F-layer, using a standard procedure: the sample was magnetized at 5 K to its saturation in a field of 0.7 T, then the field was set to a small value (typically of about 0.1 mT), and $M(T)$ was measured up to 300 K and back down to 5 K. T_{Curie} was defined at the temperature where irreversibility sets in when cooling down. The dependence of M on applied field H_a at 5 K of a single F-layer is given in Fig. 2a. It shows a hysteresis loop typical for a ferromagnet with H_{co} about 25 mT. To determine possible differences in H_{co} between structured and unstructured samples caused by the sample shape anisotropy, we measured the magnetoresistance $R(H_a)$ of a structured samples at 5 K. With H_a in the plane of the film, but perpendicular to the bridge and therefore the current, $R(H_a)$ behaves as shown in Fig. 2b. Two peaks are found at H_{co}, due to the anisotropic magnetoresistance effect. The slight difference in aspect ratio A for the structured (A = 10) and the unstructured (A = 5) samples does not lead to a significant difference in H_{co}.

3 Superconducting properties and discussion

For the determination of the critical current I_c at different temperatures a pulsed-current method was used. Current pulses of about 3 ms with growing amplitude were sent through the sample below T_c = 4.0 K (shown in the onset of Fig. 3). Each pulse was followed by a long pause of about 7 s. The voltage response of the system was observed on a oscilloscope triggered for the time of a single pulse. To improve the signal resolution a differential amplifier combined with low-noise band filters was used. Two typical current (I)–voltage (V) characteristics are shown in Fig. 3, taken at temperatures 3.9 K (reduced temperature $t = T/T_c$ = 0.98) and 3.7 K (t = 0.93). One can see a clear jump from the superconducting into the normal state at I_c, which we designate the depairing current [13]. For all samples, down to t = 0.98 a small onset voltage was observed below I_c, probably because of vortex motion. In order to be sure that this has no influence on the depairing current, the sample temperature was probed during every current pulse. A significant increase was found only when I_c was reached.

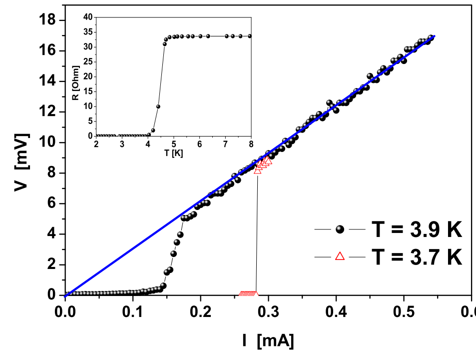

Fig. 3. Current (I) versus voltage (V) characteristics of a CuNi/Nb/CuNi trilayer shaped as 2 μm wide bridges at the temperatures indicated. The line shows the normal (ohmic) resistance. The transition from the normal to the superconducting state, shown in the inset, occurs at T_c = 4.0 K.

The dependence of I_c as function of H_a at T = 3.8 K is shown in Fig. 4. Upon lowering H_a from the positive high field side, I_c rises and reaches its maximum value at a negative value of about −20 mT, quite close to H_{co}. It then decreases again. When increasing H_a from a large negative field, a similar maximum occurs at +20 mT, with clearly hysteretic behavior. Clearly, the suppression of superconductivity in the S-layer by the proximity effect is less for the case when a domain

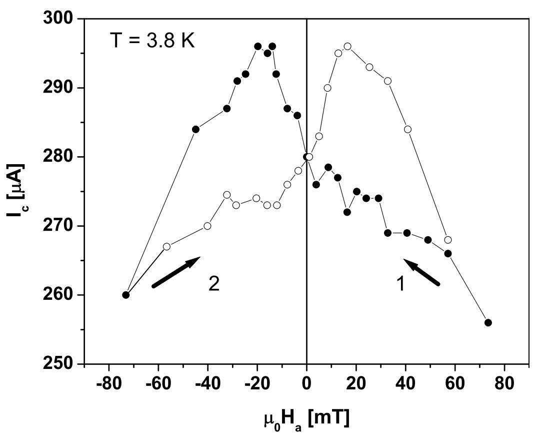

Fig. 4. Depairing current I_c of the CuNi/Nb/CuNi trilayer as function of applied magnetic eld H_a at T = 3.8 K. Filled symbols are used for the eld sweep from positive to negative eld (denoted 1), open symbols for the opposite direction (denoted 2).

structure is present in the outer F-layers, which is similar to the ndings in refs. [10,11]. Note that the result does not imply the existence of a coupling between the F-layers: the variation of exchange eld directions in the domain walls might be su cient to reduce the suppression. The scatter in the data points in Fig. 4 may be caused by the changing domain structure; either a varying suppression of the order parameter or an induced vortex state [14] could result in a slightly di erent current distribution at each point. The main result of a peak in I_c around H_{co} is also found for the case of thick (50 nm) ferromagnetic layers. This seems to exclude the possibility that e ects of inducing an inhomogeneous order parameter in the F-banks play a role, at least in this temperature regime.

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