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LETTER TO THE EDITOR

The long range influence of a superconductor on the electron transport in ferromagnetic wires

P Nugent, I Sosnin[1] **and V T Petrashov**

Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK

E-mail: i.sosnin@rhul.ac.uk

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Abstract

The resistivity of a ferromagnetic wire with an extension in contact with a superconductor has been measured at various temperatures and magnetic fields. The distance from the ferromagnet to the superconducting contact was fabricated to be 250–400 nm, much larger than the coherence length in the ferromagnet, which was a few nanometres; nevertheless, we found that the resistivity increases at the superconducting transition. The result was obtained for different ferromagnets and superconductors. We establish that the resistivity increase is not due to a redistribution of magnetic domains as a result of the screening of magnetic flux by the superconductor, as suggested recently.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The electrical resistivity of a normal metal (N) in contact with a superconductor (S) is modified by the superconducting proximity effect [1]. The superconducting correlations penetrate the normal metal up to the electron phase breaking length, L_ϕ. In contrast, when a ferromagnet (F) is in contact with a conventional superconductor with singlet pairing, the proximity effect is strongly suppressed due to the spin ordering in F, so that the penetration depth is limited by the ferromagnetic coherence length $L_F = \sqrt{\hbar D/k_B T_C}$. For Ni this length is a few nanometres. Nevertheless, the influence of the superconductor was reported to penetrate the Ni wire over a length as large as 1 μm [2]. At the time the result was a mystery since it appeared to contradict the theory of the proximity effect. Some later experiments also reported anomalous resistivity behaviour in F/S systems with measuring current going through the F/S interface [3–5]. It was shown experimentally [6] that the anomalous resistivity may originate at the F/S interface, as predicted theoretically [7]. An alternative explanation by Bergeret *et al* [8] proposed the

[1] Author to whom any correspondence should be addressed.

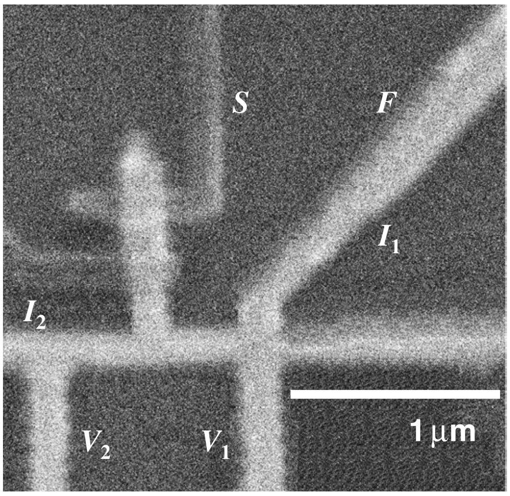

Figure 1. SEM micrograph of a measured sample. Current contacts are labelled I_1 and I_2; voltage contacts are labelled V_1 and V_2. The ferromagnetic wire has an extension which contacts the superconductor, the shape of which is irrelevant.

appearance of the triplet superconducting order parameter at the F/S interface, a hypothesis that has not yet been verified experimentally. In a recent experiment by Dubonos *et al* [9], the change of magnetization propagates into multi-domain ferromagnetic samples over distances of 1 μm, as a result of redistribution of magnetic flux due to Meissner screening by a superconductor in structures similar to that of [2]. The resistivity of a ferromagnet depends on the local direction of magnetization with respect to measuring electrical current (which leads to well-known anisotropic magnetoresistance, AMR). The question is, could this magnetic domain reshuffling upon the superconducting transition [9] explain the results of [2]?

In order to answer this question we carried out a detailed experimental study in a number of F/S nanostructures of geometry similar to that used in [2] to provide statistical data and exclude spurious effects. With careful control of fabrication parameters we have achieved good reproducibility of results, and established that the anomalous long range influence of superconductors in hybrid F/S nanostructures is a genuine effect.

2. Sample fabrication

The samples were fabricated using e-beam lithography and standard processing. The geometry of the structures is shown in figure 1. I_1 and I_2 are current leads; V_1 and V_2 are voltage leads. The superconductor was placed on the extension of the F-wire so that the measuring current does not pass through the F/S interface. The fact that the superconductor is a loop is of no importance in the reported experiment. The superconductor was 60 nm thick Al or Pb film. The Pb film was made with stabilizing Au layers by *in situ* evaporation of 19 nm Pb, followed by 1 nm Au both repeated three times. The ferromagnet was a 40 nm thick Ni/Cu alloy film of various concentrations fabricated by thermal co-evaporation of Ni and Cu at the same time with the specified rates to obtain needed concentration. The resulting concentration of the film was measured using x-ray spectroscopy in a scanning electron microscope with an accuracy better than 2%. The homogeneity of the alloy films produced by co-evaporation was checked by x-ray microanalysis and by dc-extraction magnetometry on ferromagnetic alloys, and was

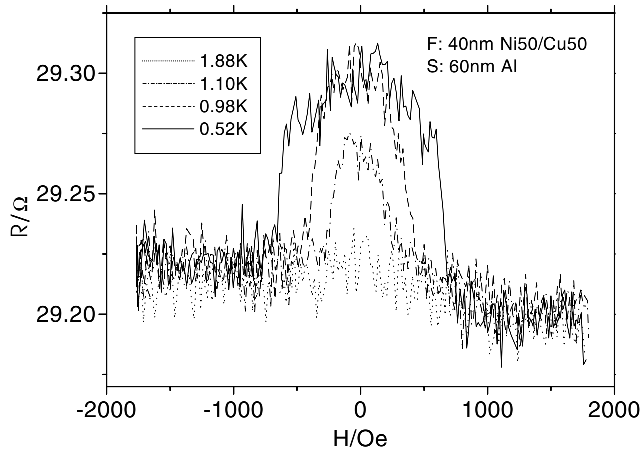

Figure 2. Magnetoresistance of the Ni50/Cu50 sample shown in figure 1 at different temperatures.

found to be better than 2%. To obtain clean interfaces between the layers, the contact area was Ar^+ plasma etched before the deposition of the second layer.

3. Experimental data

The measurements were carried out in a ^{3}He cryostat in the temperature range 0.28–1.5 K in magnetic fields up to 1 T applied perpendicular to the substrate. A four-point Wheatstone bridge was used with lock-in amplifier at the frequency 17.7 Hz to measure the magnetoresistance of the samples. The resistivity of the F-wire was measured using all-ferromagnetic electrodes, which had no contact with the superconductor.

Figure 2 shows the magnetoresistance of the sample shown in figure 1 recorded at different temperatures. The sample is $50 \pm 2\%$ Ni/$50 \pm 2\%$ Cu alloy film as a ferromagnet and 60 nm of Al as a superconductor. At the onset of superconductivity at about 1.2 K the resistance of the F-wire, which is 250 nm away from the F/S contact in this case, increases by about 0.1 Ω over the total resistance of 29.2 Ω, a relative change of 0.3%. This effect can be reversibly suppressed by the application of a magnetic field above the critical field of the superconductor. The Curie temperature estimated by the AMR measurements is about 50 K. The amplitude of the AMR signal did not change between 0.28 and 10 K. It can be seen in figure 2 that the amplitude of the effect observed is much bigger than that of the AMR. In order to compare the two we have measured the AMR accurately on a longer F-wire on the same chip. The result at 0.28 K is shown in figure 3. The AMR effect is about 0.03% and it is at least ten times smaller than the long range influence effect in question. Note that there is strong hysteresis for fields less than 1 kOe due to irreversible domain movement, which was not seen in the measurements presented in figure 2.

In order to distinguish between the domain wall movement and the long range mechanism we have repeated the same experiments using Pb as the superconductor. For Pb the critical field H_{c2} of the superconducting transition is much larger than 1 kOe, which corresponds to uniform magnetization rotation on the magnetization curve. We present results from the sample where the ferromagnet was 40 nm of Ni65 $\pm$ 2%/Cu35 $\pm$ 2% alloy and the superconductor was 60 nm of Pb (Au stabilized). The distance from the measured F-wire to the F/S interface was about

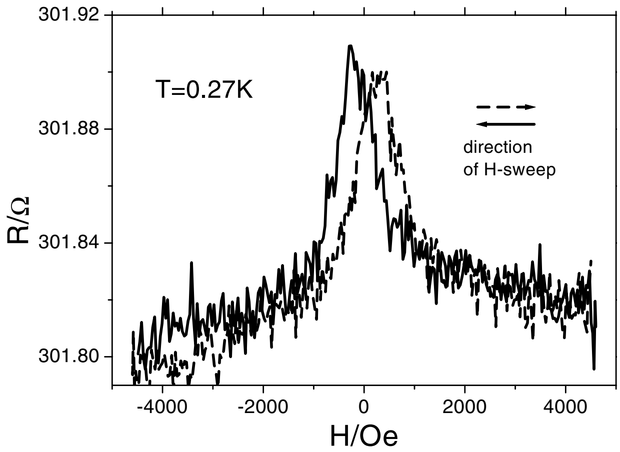

Figure 3. AMR on long F-wire Ni50/Cu50 from the same sample presented in figures 1 and 2.

300 nm. Figure 4 shows the results in this case. The AMR signal can now be seen on the same structure (top panel) as well as on the control long wire on the same chip (bottom panel). The effect of the long range superconducting influence is again about ten times bigger than the AMR. More importantly one can now see the jump in magnetoresistance in the range of magnetic fields where the sample is magnetized *uniformly*. This excludes any influence of the domain reshuffling effect on our measurements, since there are no domains in the sample at this field. All samples showed the increase in resistance with T_{Curie} in range of 50–200 K.

In non-ferromagnetic samples of the same geometry as above and with a lower Ni concentration (5–10%), no influence of the superconductor has been detected, corresponding to a strong suppression of L_ϕ. In samples with Ni concentration less than 5%, the nonlocal influence becomes the same as in the ordinary proximity effect with the resistance of wire smaller in the superconducting state. These results on paramagnetic Ni/Cu sample will be reported in detail elsewhere [10].

4. Analysis and discussion

There are two arguments against the domain reshuffling mechanism explanation proposed in [9]. First, the magnitude of our effect may exceed by more than an order in magnitude the total effect of anisotropic magnetoresistance. The change of resistivity due to domain reshuffling can only be a fraction of the total AMR amplitude because stray field redistribution is unlikely to magnetize the sample uniformly perpendicular to the current as in actual AMR measurements. Second, by choosing a superconductor with high critical field H_{c2} we demonstrate that the effect exists even when the ferromagnet is magnetized uniformly and there are no magnetic domains in the sample at all.

Also, in this geometry the measuring current does not go through the F/S interface; therefore, there are no anomalies due to non-equilibrium effects at the interface.

Conductance suppression in mesoscopic N/S structures has been addressed in several theoretical papers [11–13]. It was shown that the resistance change due to the superconducting proximity effect can be of either sign and is very sensitive to the quality of the N/S interface. However, the attenuation of the singlet superconducting correlations over the distance $L = 250$ nm is estimated to be $\exp(-L/L_F)$, which is about 2×10^{-6}, even for

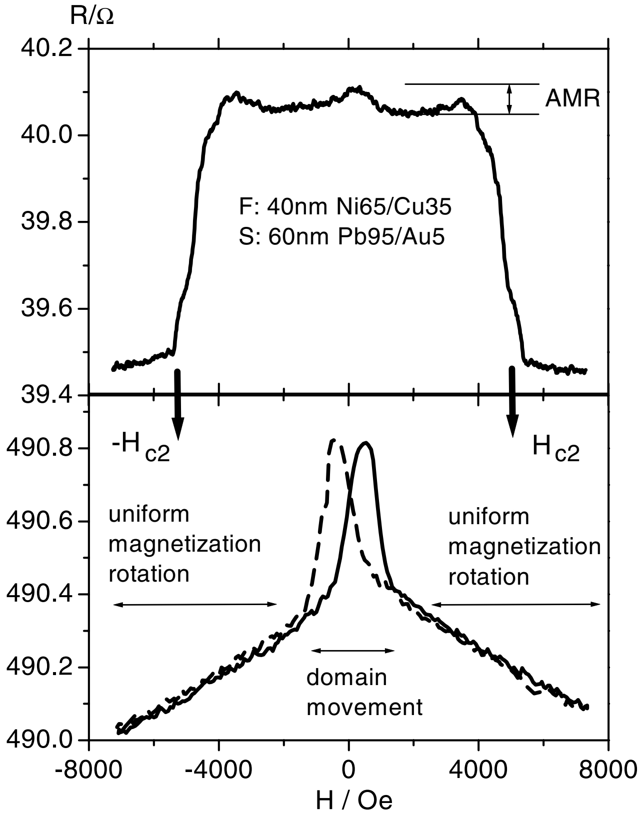

Figure 4. Top panel: long range influence of a superconductor (Pb) on F-wire Ni65/Cu35. Bottom panel: AMR on a long F-wire from the same Ni65/Cu35 sample.

the sample with the lowest Curie temperature in this series (50 K) where $L_F = 17$ nm. Such a strong attenuation rules out the possibility of a normal proximity effect.

Having excluded the above mechanisms, we conclude that the most likely explanation is that there are triplet pair correlations generated at the F/S interface that penetrate the F-wire over distances of few hundred nanometres [8]. These correlations may appear at the F/S interface due to inhomogeneous magnetic field [8] or as a result of spin–orbit interaction in the presence of a contact potential difference [14]. The mechanism of conductance suppression in the F-wire can be similar to the ones considered in [11–13] for N-wires.

Further work to establish the dependence of the conductance changes in F/S nanostructures on the interface quality is under way.

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