Long Range Proximity Effect in Hybrid Ferromagnetic/Superconducting Nanostructures

V. T. Petrashov, I. A. Sosnin, C. Troadec

Department of Physics, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, U.K.

We find that the dependence on temperature and magnetic field of the electrical resistance of diffusive ferromagnetic nano-wires measured with superconducting electrodes changes drastically with the distance, \( L \), between the ferromagnet/superconductor contacts, however is remarkably similar for the wires with the same \( L \) ranging from 300 nm to 1000 nm, prepared under identical conditions. The result gives an evidence for the long-range superconductor-induced changes in transport properties of ferromagnetic nano-wires.

PACS numbers:74.50.+r, 74.80. Fp, 85.30. St.

1. Introduction

Recent experimental discoveries of large superconductor-induced changes in the resistance of disordered ferromagnetic nano-wires suggesting long-range superconducting proximity effect\(^1\)\(^-\)\(^4\)\(^,\)\(^5\)\(^,\)\(^6\) have stimulated a significant number of theoretical investigations\(^7\)\(^-\)\(^12\) since according to the existing views superconducting correlations cannot penetrate in the bulk of ferromagnetic materials. One of the explanations of the effects put forward by authors of [13] is based on the properties of the \( F/S \) interfaces without taking into account proximity induced changes in the bulk of ferromagnetic conductors. Experiments enabling to separate the bulk and interface effects in hybrid \( F/S \) nanostructures are in order.

So far we concentrated on experimental separation of the bulk and interface contributions using measurements with \( F \)-wires of different thickness and residual resistance. Recently\(^\uparrow\) we reported new results on the depen-
V. T. Petrushov et al.

dence of the proximity effects in diffusive mesoscopic $F/S$ structures on applied magnetic field. In this paper we focus on the study of the proximity effects in diffusive $F$-wires of very similar electrical properties, geometry and crystalline structure however with different distance, $L$, between $F/S$ contacts. We find that the dependence of the effects on temperature and magnetic field being drastically different in wires with different $L$, is remarkably similar for different wires with the same $L$ in the range from 300nm to 1000 nm, giving a direct experimental evidence for the long-range nature of the proximity effect in diffusive ferromagnetic wires. We discuss a new mechanism for the long-range effect based on the analysis of the topologies of actual Fermi-surfaces in ferromagnetic metals.

2. Experimental

The structures were made using "lift-off" e-beam lithography technique. The first layer was Ni wire (electrodes 1-7) in contact with Al wires of the second layer (electrodes 2-6 and 8-12) (see Fig. 1). We have developed a technique of plasma cleaning of the surface of Ni film followed by the deposition of Al without breaking vacuum with the resistance of down to $5 \times 10^{-2}$ $\Omega$ for 100x100 $\text{nm}^2$ contacts. We measured the resistance of Ni

Fig. 1. SEM picture of one of the measured samples. Contacts 1-7 are Ni 40nm; contacts 2-6 and 8-12 are Al 40nm for one sample and Al 80nm for the other. Both samples are of exactly the same geometry.
Long Range Superconducting Proximity Effect

wires with distance $L$ between $F/S$ contacts in the range from 300 nm to 1000 nm, in the temperature range from 0.28K to 6K in magnetic fields up to 5T applied perpendicular to the substrate. All the measured Ni wires were deposited simultaneously and had thickness of 40 nm, width of 200 nm and the value of $\rho$ of 14 $\mu\Omega\text{cm}$ corresponding to the diffusion constant, $D$, of about 40 cm$^2$/s. The Al wires were 100 nm wide. Two batches of samples with Al thickness of 40 nm and 80 nm were prepared under identical conditions with the deposition of Ni, the spinning of the resist and the baking made simultaneously. The values of $\rho$ and $D$ for Al were 0.8 $\mu\Omega\text{cm}$ and 200 cm$^2$/s, correspondingly. We used commercially available materials of purity 99.999% from Advent Ltd.

3. Results

Fig. 2. Temperature dependence of the resistance of the two samples with various length, $L$, between superconducting electrodes. Current and potential leads are marked according to Fig. 1.
The results of measurements of the dependence of the resistance on temperature for 8 Ni structures are shown in Fig. 2. For all the results presented on Fig. 2 and 3 we used Ni wires as current leads and Al wires as potential leads. It is seen that the structures with different distance, $L$, between the $F/S$ contacts show completely different dependence. Remarkably, the curves for the structures with the same $L$ are similar. The drop in the resistance reaches $-3 \, \Omega$ for the sample with $L=1000\,\text{nm}$ and 40nm thick Al that is an order in magnitude larger, than the total contact resistance of $0.18 \times 2 \, \Omega$ in the normal state. The amplitude of the effect is larger for samples with 40 nm thick Al probes. That can be accounted for by the higher transparency of $F/S$ interfaces for that sample, where the resistance of contacts in normal state was $0.2 \, 0.02 \, \Omega$. The voltage-current characteristics of all of the inter-

Fig. 3. Magnetoresistance of the structures of Fig. 2.
Long Range Superconducting Proximity Effect

faces from Ni40nm/Al40nm sample, were $N$-shaped in the superconducting state suggesting strong non-equilibrium effects (Fig. 5 left). The resistance of the contacts for Ni40nm/Al40nm structures had a scatter in the range from 0.1 $\Omega$ up to 1.0 $\Omega$ with linear $V$ vs. $I$ curves (Fig. 5 right). Nevertheless, an obvious correlation between the temperature-dependent resistance of samples with the same $L$ persisted despite such a significant difference in the properties of contacts.

![Graph](image)

Fig. 4. Magnetoresistance of the Ni 40nm/Al 40nm structure with $L=300$nm measured using different combinations of current and potential leads. Curves are shifted for clarity.

Figure 3 shows magnetoresistance curves for the samples of Fig. 2 measured using the same combinations of leads at $T = 0.28$ K.

The behaviour of the resistance at the onset of superconductivity at critical magnetic fields correlates with that at critical temperature. The difference between the resistance in the normal limit at high field and that in zero field coincides with the difference of the resistance above critical temperature and that at $T = 0.28$ K for all samples, however the dependence on magnetic field is more complicated. Singularities in the shape of sharp
peaks and dips appear in the vicinity of 100 G.

We find that the results of measurements depend strongly on the combination of potential and current leads, as expected. Figure 4 shows the magnetoresistance of one of the samples measured using different leads. The difference in the measured resistance is significant. It is much larger than the resistance of the contacts in normal state. The distribution of the electrochemical potentials in our system depends on the current leads used with the potential leads of different materials sensing different electrochemical potentials. We believe that these non-equilibrium effects may result in an N-shaped voltage-current characteristic of the contact seen on Fig. 5 left.

Fig. 5. Magnetoresistance and voltage-current characteristics of one the interfaces from Ni 40nm/Al 40nm sample (left) and Ni 40nm/Al 80nm (right) sample. Solid and dashed lines correspond to two different combination of current and potential leads.

We have extensively studied the sharp singularities and found that they
Long Range Superconducting Proximity Effect

are the result of the changes taking place due to magnetic field in the vicinity of \( F/S \) contacts. Figure 5 shows the results of measurements of two contacts for two different samples. Note that there is a voltage drop between the ends of the selfsame Al wire crossing Ni wire. That means, first, that there are normal regions in Al wire. We believe that Al can go normal due to reciprocal exchange proximity effect\(^1\) in the vicinity of the \( F/S \) contact. Second, there should exist parallel to the Al wire component of current in the \( F/S \) contact. The latter may take place in asymmetric contacts with non-uniform distribution of the barrier resistance at the \( F/S \) interface. Direct measurements (see Fig. 5) confirm the existence for such an asymmetry. An additional asymmetry is introduced in the same magnetic fields as sharp singularities in the magnetoresistance.

4. Discussion

The existing theories are based on idealized isotropic models of the Fermi-surfaces of ferromagnetic metals. In a ferromagnet with the exchange field energy, \( h_0 \), the Andreev reflected quasiparticles acquire a momentum of \( Q = 2h_0/v_F \), where \( v_F \) is the Fermi velocity\(^1^1\), resulting in an exponential decay of the superconductor-induced wave functions in diffusive conductors over microscopic distances, \( \xi_m = \sqrt{\frac{\hbar D}{2\pi k_B T_0}} \), where \( T_0 \approx h_0/k_B \) is the Curie temperature, \( D \) is the diffusion constant. Hence the amplitude of long-range effects in diffusive \( F/S \) systems with small superconducting gap, \( \Delta \ll h_0 \), is predicted to be negligibly small. We emphasize\(^1^7, 1^8, 1^9\) that in real metals the exchange interaction is anisotropic with the value of \( Q \) strongly depending on the position of the Andreev reflected electrons on the Fermi-surface. The value of \( Q \) may vanish for certain electron pairs with opposite spins and directions of momentum (mixed spin regions at the Fermi surface) electron\(^2^0\). Such electrons may be Andreev-reflected with no effects of the exchange interaction and hence originate the long-range proximity effects in hybrid \( F/S \) nanostructures. The amplitude of the superconducting condensate functions on the \( F \)-side should depend on both, the number the mixed spin electrons and their life times. The latter in principle can be larger than the averaged over the Fermi surface transport relaxation time (see e.g.\(^1^8\) and references therein).

One more effect which deserves consideration is the variation in the exchange interactions at the ferromagnet/vacuum and ferromagnet/substrate interfaces.
5. Summary

We summarise the results of the present work that cannot be accounted for by existing theories without assuming long-range proximity effects in ferromagnetic wires.

a) Large drops in the resistance, $\Delta R$, of up to 3 Ω at normal state barrier resistance of 0.2 Ω. The theory predicts $\Delta R < 0.1$ Ω for this case.

b) Strong correlation of the proximity induced effects with distance between $F/S$ contacts in the range of up to 1000 nm, even though interfaces themselves were quite different.

c) Strong non-equilibrium effects with N-shaped $V-I$ curves for $F/S$ contacts.

d) Sharp singularities of large amplitude in the magnetoresistance of $F$-wires with $S$-contacts.

6. Acknowledgments

We acknowledge financial support from the EPSRC (Grant Ref: GR/L94611).

REFERENCES

1. V.T. Petrashov, V.N. Antonov, S.V. Maksimov, and R.Sh. Shaikhaidarov, JETP Lett. 59, 551 (1994).
2. M.D. Lawrence and N. Giordano, J. Phys. Cond. Matt. 8, L563 (1996).
3. M. Giroud, H. Courtois, K. Hasselbach, D. Mailly, and B. Pannetier, Phys. Rev. B 58, 11872 (1998).
4. V.T. Petrashov, I.A. Sosnin, I. Cox, A. Parsons, and C. Troadec, Phys. Rev. Lett. 83, 3281 (1999).
5. M. Giroud, K. Hasselbach, H. Courtois, D. Mailly, and B. Pannetier, in Mesoscopic Superconductors and Hybrid Structures, COST-TMR-CCP9 Workshop, 16-19 December 1999, Lancaster, UK.
6. M.D. Lawrence and N. Giordano, J. Phys. Cond. Matt. 11, 1089 (1999).
7. M.J.M. de Jong and C.W.J. Beenakker, Phys. Rev. Lett. 74, 1657 (1995).
8. E.A. Demler, G.B. Arnold, and M.R. Beasley, Phys. Rev. B 55, 15174 (1997).
9. F.J. Jedema, B.J. van Wees, B.H. Hoving, A.T. Filip, T.M. Klapwijk, Phys. Rev. B 60, 16549 (1999).
10. V.I. Fal’ko, C.J. Lambert, A.F. Volkov, JETP Lett. 69, 532 (1999).
11. F. Zhou and B. Spivak, preprint, cond-mat/9906177.
12. A.A. Golubov, preprint, cond-mat/9907194.
13. W. Belzig, A. Brataas, Yu.V. Nazarov, G.E.W. Bauer, cond-mat/0005188.
14. V.T. Petrashov, I.A. Sosnin, I. Cox, A. Parsons, and C. Troadec, preprint, cond-mat/0005437.
Long Range Superconducting Proximity Effect

15. V.V. Schmidt, *The Physics of Superconductors*, P. Muller and A.V. Ustinov (Eds), Springer, 1997.

16. P.M. Tedrow, J.E. Tkaczyk, A. Kumar, Phys. Rev. Lett. **56**, 1746 (1986).

17. G. Lonzarich in *Electrons at the Fermi surface*, ed. M. Springford, Cambridge University Press, 1980.

18. Int. Conf. on Electron life times in metals, J. Phys. Cond. Matt. **19**, 3 (1975); A.K. Geim, V.T. Petrashov, and M. Zolotarev, Sov. Phys. JETP **91**, 2101 (1986).

19. R. Gersdorf, Phys. Rev. Lett. **40**, 344 (1978).

20. C.S. Wang and J. Callaway, Phys. Rev. B **15**, 298 (1977).