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Mesoscopic superconductors in proximity to nanomagnets

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Abstract. We report a study of electron transport through mesoscopic superconducting (aluminium) wires with ferromagnetic (nickel) and superconducting electrodes in the temperature range of 0.28–1.5 K in magnetic fields up to 5 T. We observe spectacular changes in the differential voltage-current characteristics, dV/dI vs I , when the measuring current is injected from the ferromagnetic electrodes: the dV/dI curves become non-symmetric with respect to the current direction and show the regions with negative differential resistance. The peaks corresponding to the superconducting transition split into two with separation depending on the external magnetic field and the polarisation of current. We attribute the effects to the nonequilibrium spin polarization induced by the current from the ferromagnetic electrode and the effects of the saturation magnetisation leading to the Zeeman splitting of the quasiparticle spectrum in the adjacent superconductor.

Introduction

Properties of a ferromagnetic/superconductor interface have been extensively studied over the past years. In early experiments by Tedrow and Meservey with low transparency interfaces, the tunneling from ferromagnetic (F) into superconductor (S) was used to calculate density of states for spin-up and spin-down electron bands in the ferromagnet [1]. The model employed the Zeeman splitting of quasiparticle spectrum in the superconductor. Recently, major experimental efforts have been applied to study F/S systems with high transparency clean interfaces. It was found that the superconducting correlations penetrate in the ferromagnet over surprisingly large distance [2–4]. By matching Andreev reflection coefficients at the interface, it was possible to extract the spin polarization of the current [5]. On the other hand, spin accumulation in non-magnetic media over the distance of spin-relaxation length imposes a nonequilibrium magnetic moment, which depends on amplitude and sign of spin polarisation [6]. In our experiment with clean interfaces we observed the Zeeman splitting in the critical current of superconducting transition due to strong magnetic field from the ferromagnet. The geometry of electrodes allowed us to vary the polarisation of measuring current. We found the value of the splitting depending on the polarisation. The essential difference of our experiment is the presence of strong gradient of magnetic field. For the first time the effect of the magnetic field gradient in mesoscopic systems was observed.

1 Experimental

The samples were fabricated using standard e-beam lithography. The geometry of the structures is shown in Fig. 1. The width of the wires was about 100 nm. The first layer was a 40 nm thick Ni film in contact with golden pads made using photo-lithography. The length-to-width ratio for the Ni wire was about 20. The second layer was 55 nm thick Al film with small area of the interface to Ni of about $100 \times 100 \text{ nm}^2$. Before the deposition of the second layer, the contact area was Ar⁺ plasma etched to obtain a clean interface between

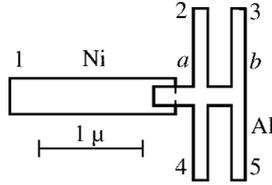


Fig. 1. Sample geometry. 1—Nickel electrode; 2–5—Aluminium electrodes. The voltage U_{23} is measured as a function of current I_{45} or I_{15} applied to part ab .

the two metals. A special study of the interface quality using SIMS spectra showed that total amount of oxygen between the layers correspond to less than 8% of one monolayer.

The measurements were carried out in the temperature range from 0.28 K to 1.5 K and in magnetic fields up to 5 T applied perpendicular to the substrate. The voltage U_{23} was measured as a function of current I_{45} or I_{15} applied to part ab . To change the ratio of spin polarised to non-spin polarised current, additional current I_{bias} was supplied between points 1, 4. The resistivity, ρ , of the Ni and Al films was about $50 \mu\Omega\text{cm}$ and $1.3 \mu\Omega\text{cm}$, with the diffusion constants, D , equal to $14 \text{ cm}^2/\text{s}$ and $106 \text{ cm}^2/\text{s}$, respectively, calculated using ρl value for Ni, $1.5 \times 10^{-11} \Omega\text{cm}^2$ [13a] and Al, $3.2 \times 10^{-12} \Omega\text{cm}^2$ [13b]. The critical temperature of the Al wires was about 1.0 K. We believe that this lower-than-usual value was due to the proximity to the ferromagnetic conductors.

2 Results

Figure 2(a) shows experimental normal/superconducting phase diagrams of an Al wire, obtained by measuring differential resistance versus applied dc current at different external magnetic fields. The peaks on the diagrams correspond to critical current of a superconducting transition. Figure 2(b) shows results of calculation of critical current, taking into account Zeeman splitting and angular dependence of critical magnetic field. The fit is in excellent agreement with experiment.

Figure 3 presents the effect of bias current applied to electrodes 1 and 4. It is seen, that the peaks can split in two with the distance between them depending on I_{bias} . When the direction of I_{bias} and I_{45} or I_{15} in electrode 4 coincide, the spin-polarization of the resulting current through ab does not change. Hence position of peaks A depend very little on bias current. On the contrary, when I_{bias} and $I_{4,5}$ or $I_{1,5}$ in electrode 4 are of opposite direction, so that spin polarization in ab increases as I_{bias} increases. As a result of that we see strong critical current suppression with larger splitting (peaks B on Fig. 3).

3 Discussion

To understand main features of experimental phase diagram, it is important to take into account that nanomagnet can produce rather strong and nonuniform magnetic field next to the mesoscopic superconductor. In this case, external magnetic field is not only directly influence the superconductor but also change the direction of magnetisation in the ferromagnet, which in turn affects the superconductor. To simulate this situation, we take the following model. Our Ni nanomagnet is a single-domain ferromagnetic with easy axis along the wire, i.e. pointing onto the superconductor. External magnetic field is then perpendicular to easy axis. As it increases, the saturation magnetisation vector rotates toward the direction of external field while staying the same in absolute value. The effective magnetic field, H^* , acting on the superconductor from the nanomagnet we take equal to component of induction inside ferromagnet normal to the interface and neglect H inside the ferromagnet.

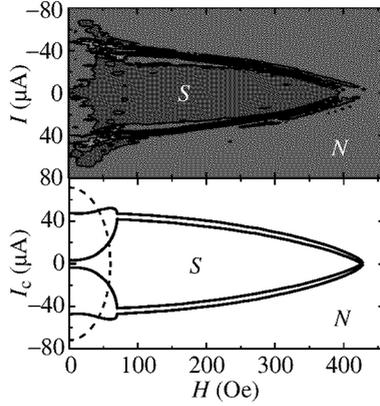


Fig. 2. (a) The current-magnetic field normal/superconducting phase diagram taken at $T = 0.27$ K. Colour represents value of dV/dI in arbitrary units. Measuring current is I_{15} . (b) Calculated dependence of reduced critical current.

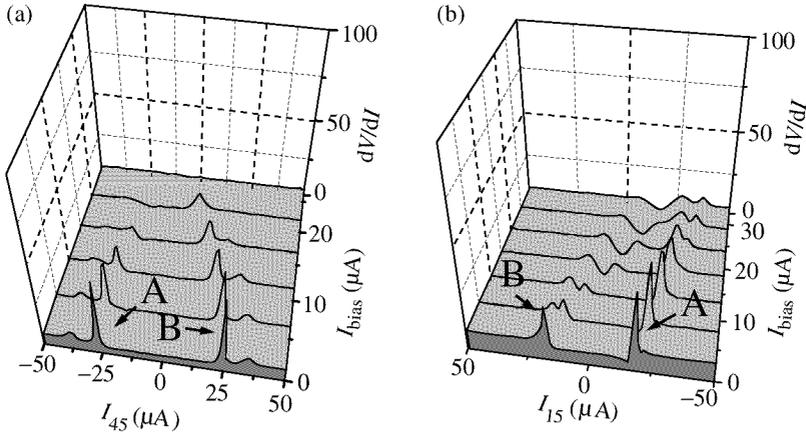


Fig. 3. (a) dV/dI vs I_{45} , (b) dV/dI vs I_{15} . Curves taken at $T = 0.27$ K, $H = 200$ Oe. Bias current applied to electrodes 1 and 4. Peaks A: direction of I_{bias} and I_{45} , I_{15} in electrode 4 is the same; peaks B, opposite.

The angular dependence of critical magnetic field $H_c(\theta)$ we take [7]

$$\left| \frac{H_c(\theta) \cos(\theta)}{H_{c\perp}} \right| + \left(\frac{H_c(\theta) \sin(\theta)}{H_{c\parallel}} \right)^2 = 1 \quad (1)$$

The dependence of the superconducting gap (Δ) on the magnetic field close to the transition we approximate as,

$$\Delta(H) = \Delta_0 \left[1 - \left(\frac{H^*(H)}{H_c} \right)^2 \right]^{1/2} \pm \mu_B H^*(H), \quad (2)$$

where the second term is due to the Zeeman splitting of the quasiparticle spectrum. We take that critical current $I_c(H) \propto \Delta^{3/2}(H)$ (see for example [7]). The result of this fitting is

shown as solid lines in Fig. 2. We used the following parameters in calculation: $\Delta_0 = 1.7$ K, $H_{c\perp} = 430$ Oe, $H_{c\parallel} = 1800$ Oe, $H_{rot}=70$ Oe, $B_s = 6000$ Gs. Though the model describes well the main features of the phase diagrams, it does not account for additional peaks marked in Fig. 2. We believe that the origin of these could be a strong gradient of magnetic field, causing an additional force equal to acting in opposite directions on electrons with opposite spins. This results in different effective electric field acting on spin-up and spin-down electrons, leading to additional peaks on the phase diagram. However, to calculate this effect one need to know exactly the distribution of magnetic field. The experiments to measure this distribution directly using Lorentz microscopy are under way.

4 Conclusion

We measured normal/superconducting phase diagram of a mesoscopic superconductor in proximity to a nanomagnet. We observed a Zeeman splitting of quasiparticle spectrum in the superconductor. The position of the peaks on the diagrams corresponded to critical current of a superconducting transition. The proposed model, taking into account the effect of magnetic field of a nanomagnet and angular dependence of a critical field, explains well the main features. However, additional peaks are probably due to strong gradients of magnetic field. Using bias current, that allowed us to change the polarisation of measuring current, we showed that the splitting depends on spin polarisation, what supports our model.

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