Conductivity of mesoscopic structures with ferromagnetic and superconducting regions

V. T. Petrashov, V. N. Antonov, S. V. Maksimov, and R. Sh. Shaĭkhaĭdarov
Institute of Problems of the Technology of Microelectronics and Highly Pure Materials, Russian Academy of Sciences, 142432 Chernogolovka, Moscow Region, Russia

(Submitted 10 March 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **59**, No. 8, 523–526 (25 April 1994)

The effect of superconducting islands, deposited on the surface of ferromagnetic (nickel) structures with conductors with transverse dimensions of 0.02–0.08 μm, on the conductivity of these structures has been studied experimentally. In the course of the superconducting transition of the islands, the resistance of the nickel may either decrease or increase. The influence of the superconductor extends over distances greater than 2 μm, i.e., more than 30 times the length $L_c = \hbar v_F / k_B T_c$, over which the superconducting correlations are destroyed in a ferromagnet (v_F and T_c are the Fermi velocity and Curie temperature).

In this letter we are reporting an experimental study of the conductivity of some "hybrid" structures consisting of mesoscopic ferromagnetic (F) and superconducting (S) regions. We have found that the superconductors may cause either a significant decrease or an increase in the resistance of the F regions. We have found that the influence of the superconductors extends over distances significantly longer than the coherence length of the electrons in the ferromagnet. A corresponding effect has been observed in nonmagnetic (silver) structures[1] and has been called an "anomalous proximity effect." The results of the present study indicate that the anomalous proximity effect may occur in the absence of a superconducting correlation and in the absence of weakly localized states in normal regions.

Thin-film ferromagnetic structures of two types were studied. The structures of the first type, whose geometry was proposed in our earlier paper,[1] have an H-shaped part and extensions up to 2.0 μm long (Fig. 1), on which superconducting stripes S are deposited at various distances L from point 1. The resistance of the part of the structure between points 1 and 2, R_{12}, was measured by the four-contact method. The length of this region was 0.2 μm. The width of the current and potential leads was 0.08–0.1 μm at points 1 and 2, and their length was on the order of 10 μm. They terminated in 3×5-μm areas. The structures were made of nickel, while the S stripes were made of tin and lead.

The structures of the second type were like those used in Ref. 2: nickel rings 0.3 μm in diameter with extensions oriented perpendicular to the current lines (a transverse or T geometry[2]). Lead and tin stripes were deposited on the extensions. In all the structures, the nickel conductors had a width of 0.08–0.1 μm and a thickness of 0.02 μm. The tin and lead stripes were 1.0, 0.2, and 0.05 μm in length, width, and thickness, respectively. The error in the determination of the dimensions was 5–10%. The

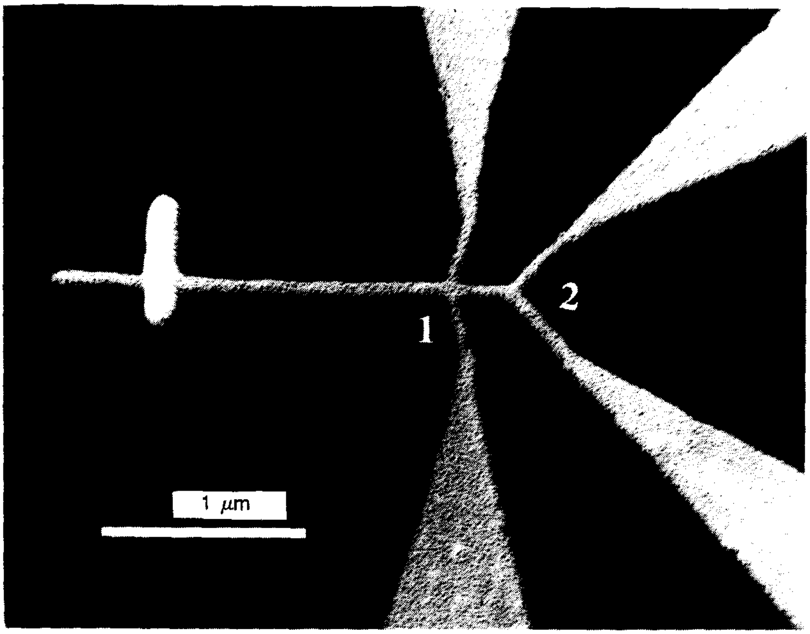

FIG. 1. Electron micrograph of a test sample. The sample was an H-shaped nickel structure with an extension. The bright stripe deposited perpendicular to the extension is made of tin. Points 1 and 2 are the points to which the current and potential leads (the flaring parts of the structure) were applied. The length of the scale marker is 1 μm.

structures were fabricated by electron-beam lithography. Silicon coated with the native oxide was used as a substrate. The films were deposited by vacuum deposition, with the substrate held at room temperature. We took particular care to create clean interfaces, with a controllable composition, between the normal metal and the superconductor. The measurements were carried out at temperatures of 1.3–4.2 K at frequencies of 30–300 Hz in magnetic fields up to 10 kG, oriented perpendicular to the films.

Figure 2 shows some representative plots of the resistance R_{12} versus the magnetic field for various temperatures, for samples with tin stripes at various distances from point 1. These structures were fabricated simultaneously and lay on a common substrate. In the temperature region 4.2–3.65 K the resistance in a zero field and the magnetoresistance behave as in control structures without superconductors, and they are essentially independent of the temperature. The magnetic-field dependence is similar to that observed in ordinary wide ferromagnetic films with an easy axis lying in the plane of the film and oriented perpendicular to the applied magnetic field.[3] The magnetoresistance of some of the structures exhibits a hysteresis, which is usually interpreted as meaning that the angle between the easy axis and the normal to the film deviates from the value $\pi/2$. Behavior of this sort is usually attributed to a magnetic anisotropy.[3,4] As the temperature is lowered further, the resistance R_{12} of the structure

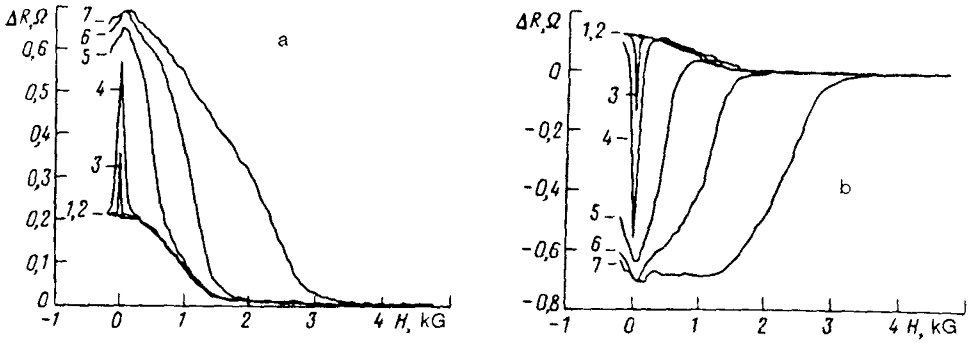

FIG. 2. Resistance of the region of the nickel structure between points 1 and 2 (see Fig. 1) versus the magnetic field at various temperatures. *1*—$T=4.22$ K; *2*—3.65; *3*—3.5; *4*—3.35; *5*—3.1; *6*—2.7; *7*—1.3 K. a) The tin stripe is at a distance $L=1.0$ μm from point 1, and the total resistance is $R=450$ Ω in a field $H=5$ kHz; b—$L=0.3$ μm, $R=350$ Ω.

with $L=1.0$ μm in a zero magnetic field increases sharply near $T=3.5$ K, which corresponds to the transition of the tin stripe to a superconducting state, and the resistance of the structure with $L=0.3$ μm drops sharply (Figs. 2a and 2b). At a total resistance on the order of 400 Ω, the change in resistance is 0.1–0.2%. The increments in the resistance of the structures due to the effect of the superconductor fade away as the magnetic field is raised above the critical field of the superconductor. In several structures, the amplitude of the effect reached 1–1.5%. In the interval $0.1 < L < 2.0$ μm, studied in these experiments, we did not see any tendency for a decrease in the amplitude due to an increase in L. The error within which we were able to position the superconducting stripes at the desired places was on the order of ± 0.1 μm. Determining whether the sign and magnitude of the effect are random or are governed by the position of the superconductor will require acquiring a statistical base of data or substantially improving the precision with which the various layers are brought into coincidence in the course of the lithography.

The behavior of the conductivity of the singly connected nickel structures with islands of a superconductor away from the classical current lines is thus qualitatively the same as the behavior of corresponding silver structures[1] near the superconducting transition of the islands: The sign of the change in the resistance of the conductors can be either positive or negative. The influence of the superconductors extends over "macroscopic" distances, greater than 2 μm, in both the nickel and silver conductors.

The results of the effect of the superconductors on the magnetoresistance of the ferromagnetic and nonmagnetic rings turned out to be different. While "giant" oscillations arise in the magnetoresistance in the nonmagnetic mesoscopic rings, with a period corresponding to the "superconducting" flux quantum,[3,5] $\Phi_0=\hbar c/2e$, in the small ferromagnetic rings with superconducting boundaries we observed no such oscillations with this period in the temperature range studied. In a few of the rings we observed some oscillations superimposed on a monotonic variation of the magnetoresistance, but those oscillations cannot be linked with the Little–Parks or Aharonov–Bohm effect, since their periods cannot be associated with the quantum of flux through the rings.

There are also differences between the singly connected ferromagnetic and nonmagnetic structures. These differences arise in weak magnetic fields, far from the superconducting transition of the islands. The nickel structures do not exhibit the sharp structural features near a zero field which have been observed in silver structures.[1] In addition, the change in conductance is more than an order of magnitude smaller than the changes in the conductance of silver conductors[1] for the same geometry and the same temperature.

Several conclusions can be drawn from these results. First, the existence of an anomalous proximity effect in small nickel conductors is apparently unrelated to Cooper pairs or to weakly localized (singlet) electronic states. In a ferromagnet, they should be destroyed over distances on the order of $L_c \sim \hbar v_F/I$, where v_F is the Fermi velocity, $I \sim k_B T_c$ is an energy parameter of the exchange field,[6] and T_c is the ferromagnetic ordering temperature. For our nickel films we have $T_c = 620$ K, so we have $L_c \sim 0.07$ μm. This figure is smaller by a factor of 30 than the distances over which the effect of the superconductor is observed. Experimental evidence that weak localization makes a negligible contribution comes from the absence of the characteristic magnetoresistance[7] and also the oscillations mentioned above. The absence of the Aharonov–Bohm effect, associated with weakly localized, triplet states,[8] from the nickel rings may mean that the diffusion length of the spin–orbit scattering, L_{so}, over which such states are stable, is much shorter than the circumference of the rings in our films: $L_{so} \ll 1$ μm. In order to observe the effect, it will apparently be necessary to use rings with a diameter smaller than 0.3 μm; it may also be necessary to use initial nickel of higher purity, without heavy impurities.

Although there is as yet no theory for mesoscopic ferromagnetic systems with superconducting regions, the observed effects can be explained in a qualitative way on the basis of changes in the electronic interference pattern due to the onset of Andreev reflections of interfering electrons. This possibility was demonstrated by numerical analysis in Ref. 9 for nonmagnetic mesoscopic conductors. That study made use of the Landauer formula as generalized to the case with Andreev reflections.[10] This explanation presupposes that the distance over which the electrons involved in the interference retain their coherence is greater than 2 μm in our nickel conductors at liquid-helium temperatures. In other words, this distance is on the same order of magnitude as the phase relaxation length in nonmagnetic metals. One possible way to experimentally confirm this point might be to observe $\hbar c/e$ Aharonov–Bohm oscillations in nickel rings in stronger fields.

We wish to thank C. Lambert, D. E. Khmel'nitskiĭ, V. F. Gantmakher, and the participants of a seminar of the Institute of Problems of the Technology of Microelectronics and Highly Pure Materials, Russian Academy of Sciences, for a useful discussion of these results. We also thank the International Science Foundation for financial support of our project, Ph2–000785.

[1] V. T. Petrashov *et al.*, JETP Lett. **58**, 49 (1993).
[2] V. T. Petrashov *et al.*, Phys. Rev. Lett. **70**, 347 (1993).
[3] V. A. Buravikhin *et al.*, *Physics of Magnetic Films* [in Russian] ed. by L. V. Kirenskiĭ (Irkutsk, 1967), No. 1, p. 3.
[4] G. G. Lonzarich, *Electrons at the Fermi Surface*, ed. by M. Springfield (Cambridge Univ. Press, Oxford, 1980).
[5] V. T. Petrashov *et al.*, Phys. Scripta T **42**, 136 (1992).
[6] S. V. Kuplevakhskiĭ and I. I. Fal'ko, JETP Lett. **52**, 957 (1990).
[7] G. Bergman, Phys. Rep. **107**, 1 (1984).
[8] B. L. Al'tshuler *et al.*, Solid State Commun. **48**, 841 (1983).
[9] C. J. Lambert and V. C. Hui (in press).
[10] C. J. Lambert, J. Phys. Cond. Matt. **3**, 6579 (1991).

Translated by D. Parsons