Anomalous proximity effect in mesoscopic conductors

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It has been observed experimentally that a normal mesoscopic conductor coupled by a normal bridge to a superconductor with small dimensions can undergo a transition to states with either elevated or depressed conductivity if the bridge is considerably longer than the coherence length of the normal metal. The changes in the conductance are $\Delta G = \pm 2\times 10^3$ (e^2/h).

A thin layer of a normal metal bordering a superconductor should itself go superconducting as the result of superconducting correlations (a "proximity effect" [1-3]). The experiments which we are reporting here reveal that, upon the formation of superconducting regions in mesoscopic systems, normal regions can go into states with either an elevated or depressed conductivity. The superconductor is influential over distances considerably greater than the coherence length of the normal metal, $L_T = \sqrt{\hbar D/k_B T}$, where D is the diffusion coefficient of the normal electrons.

We studied normal thin-film structures having an H-shaped region and branches bc of length 1.2 μm (see the inset in Fig. 1), on which superconducting stripes S were deposited at various distances L from point b. The resistance of region ab, 0.2 μm long, was measured by the four-contact method. The structures were made of silver, and the stripes S of aluminum. The width and thickness of the silver conductors were 0.1 and 0.05 μm, respectively. The length, width, and thickness of the aluminum stripes were 0.3, 0.2, and 0.05 μm. The error in the determination of the transverse dimensions was about 0.01 μm, and that in the determination of the thickness about 0.002 μm. The structures were fabricated by electron-beam lithography. The substrate was silicon covered by the native oxide. The films were deposited by vacuum deposition; the substrate was held at room temperature. A special effort was made to create clean interfaces, with a controlled 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.

Figure 1 shows an example of the temperature dependence of the resistance of region ab of the silver structure for the case $L = 0.2$ μm. As the temperature is lowered, the resistance R_{ab} increases sharply near $T \approx 1.45$ K, which corresponds to the transition of the aluminum stripe into a superconducting state. At a total resistance $R_{ab} \approx 2.9$ Ω, the increase amounts to $\approx 30\%$. An increase in the resistance is also observed when the magnetic field is lowered below the critical field of the superconductor (more on this below). This behavior is not described by the theory of the

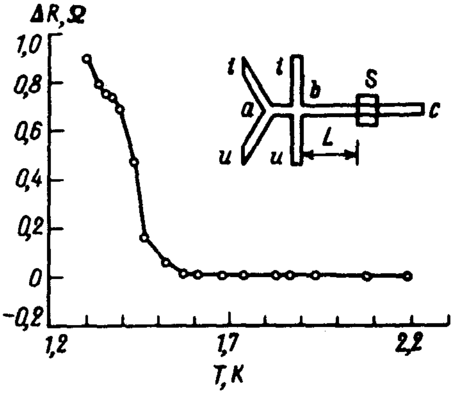

FIG. 1. Representative temperature dependence of the resistance R_{ab} of region (see the inset, which shows the geometry of the samples). The structure *uaiibcu* is a normal metal (silver); the stripe S is aluminum; *i*—*i* are current contacts, *u*—*u* are potential contacts. Here we have $R_{ab}=2.9\ \Omega$ at $T=4.2$ K; $L=0.2\ \mu$m.

ordinary proximity effect,[1-3] which predicts a decrease in the resistance of a normal conductor in contact with a superconductor.

We studied structures with bridges of various lengths L connecting the superconductor to the region through which a current flowed. Measurements were carried out simultaneously on three structures on a common substrate, which had been fabricated simultaneously. We found that the effects in structures with different values of L were different, even in sign. Figure 2 shows R_{ab} as a function of the magnetic field for $L=0.2$, 0.6, and 1.0 μm. At $L=0.2$ and 1.0 μm the resistance R_{ab} increases, while at $L=0.6\ \mu$m it decreases, when the aluminum stripe goes superconducting. Figure 3, a and *b*, shows the resistance R_{ab} as a function of the magnetic field in the weak-field region for various lengths L. The curve labels correspond to Fig. 2.

In addition to the transitions to states with an elevated resistance, there is another unexpected result: the strong influence of the superconductor over distances much greater than the coherence length of the normal metal, L_T. The resistivity ρ of a wide silver film fabricated at the same time as the structures was $0.8\times10^{-6}\ \Omega\cdot$cm. Knowing ρ and the value $\rho l\approx5.6\times10^{-12}\ \Omega\cdot\text{cm}^2$ for silver, we find a diffusion coefficient $D=\frac{1}{3}v_F l\approx23$ and $L_T\approx0.1\ \mu$m at $T=1.3$ K (here l and v_F are respectively the mean

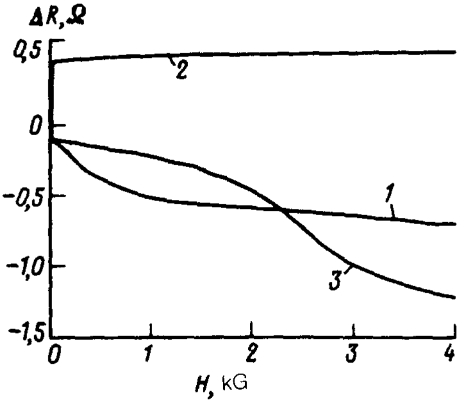

FIG. 2. The resistance R_{ab} (see Fig. 1 and its caption) versus the magnetic field for various lengths L. *1*—$L=0.2\ \mu$m, $R_{ab}(4.2\ \text{K})=2.9\ \Omega$; *2*—0.6, 2.0; *3*—1.0, 2.3.

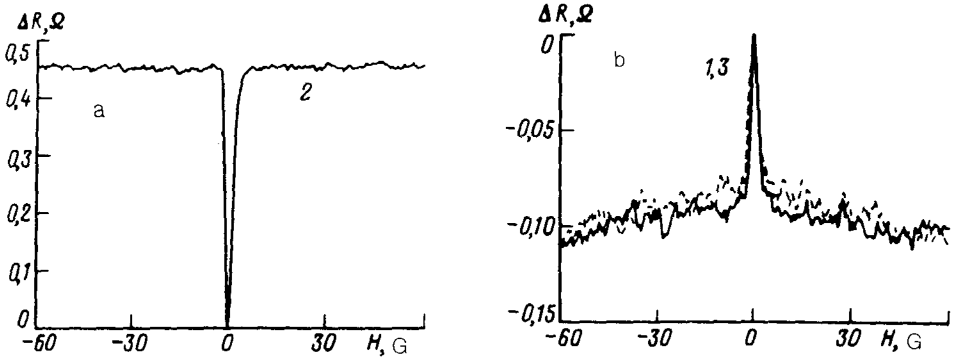

FIG. 3.

free path and the Fermi velocity). The distance over which the influence of the superconductor is seen (Fig. 2) is thus greater than L_T by a factor of 10; in this particular experiment, the effect was greater when the superconductor was far away than when it was close by (Fig. 2).

At currents on the order of 1.5 μA, transitions to states with a lowered differential resistance are observed on the current-voltage characteristics of the structures with $L=0.2$ and 1.0 μm, while transitions to states with an elevated differential resistance are seen on the characteristics for the structures with $L=0.6$ μm. These effects correspond to the signs of the effects due to the magnetic field and the temperature.

At present, the theory of systems which include both mesoscopic normal regions and mesoscopic superconducting regions is still in its infancy, and it can offer at best a qualitative explanation of the increase in the resistance of a normal mesoscopic conductor upon the appearance of superconducting branches. The probability for transitions to states with an elevated or depressed conductivity depends on the parameter $\eta=N_{\rm eff}/N_{\rm max}$, where $N_{\rm eff}$ and $N_{\rm max}$ are respectively the effective and maximum possible number of conduction channels for the given conductor.[4] The effective number of conduction channels, $N_{\rm eff}$, is found from the known formula (Ref. 5, for example) for the conductance G:

$$G=(2e^2/h)N_{\rm eff}.$$

The maximum number of channels is given by $N_{\rm max}=k_F^2S/\pi^2$, where S is the cross-sectional area of the conductor, and k_F is the Fermi wave vector. In the limiting case, in which the effective number of conducting channels is equal to the maximum number, $N_{\rm eff}=N_{\rm max}$, the number of channels can only decrease as a result of changes in the electron interference pattern upon the appearance of superconducting regions.[4] At $\eta\approx 1$ (this case corresponds to a pure, ordered conductor) the probability for an increase in the resistance is at a maximum. At $\eta\approx 0$ (corresponding to the case of a high degree of disorder) the probability for a decrease in the resistance is at a maximum. At $\eta\approx 0.1$, according to the calculations of Ref. 4, the two directions of the change in the conductivity are equiprobable. The quantity η can be calculated easily.

For our silver samples ($k_F \approx 0.6 \times 10^8$ cm^{-1}, $S \approx 5 \times 10^{-11}$ cm^2, $N_{\text{max}} \approx 1.8 \times 10^4$, $G \approx 0.3$ S, and $N_{\text{eff}} \approx 3.9 \times 10^3$) we find $\eta \approx 0.22$. This value corresponds to the situation in which resistance-increasing transitions are more likely. This conclusion agrees with our results. On the other hand, the magnitude of the observed effect corresponds to $\Delta N_{\text{eff}} = \pm 2 \times 10^3$, implying a violation in our system of the rule $\Delta N_{\text{eff}} = \pm 1$ for the change in the conductance of mesoscopic conductors.[6,7]

It can thus be regarded as an established fact that the influence of the superconducting regions on the normal regions in mesoscopic systems extends over distances much greater than the coherence length of the normal electrons and that the sign of the change in the conductance ΔG of the normal regions upon the superconducting transition can be either positive or negative. The magnitude of the change in conductance can reach $\Delta G = 2 \times 10^3 (2e^2/h)$. In order to answer the question of whether the sign of the effect (a) is governed by the distance between the regions and the geometry of the system or (b) depends on the particular realization of the random potential of the conductors, i.e., is random, will require further experiments.

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