Resistance of mesoscopic *S–N–S* junctions

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As the dimensions of metallic conductors are reduced, the resistance of the conductors begins to increase, while the magnetoresistance changes sign when the contacts go into a superconducting state. An explanation is proposed on the basis of a quantization of the energy of electrons by virtue of Andreev reflection from *N–S* interfaces.

Conductors with sufficiently small dimensions can be thought of as essentially electron interferometers. The size of the quantum correction to their conductivity should be highly sensitive to the nature of the electron scattering at the conductor–contact interface, since this interface plays a role analogous to that played by a mirror

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in an optical interferometer. We are talking here about "mesoscopic" conductors, whose largest dimensions are comparable to the phase relaxation length of conduction electrons, $L_\varphi = (D\tau_\varphi)^{1/2}$, and the coherence length $L_T = (\hbar D/kT)^{1/2}(\tau_\varphi^{-1}$ is the sum of the frequencies of all scattering processes which disrupt the phase of the electrons, and D is the electron diffusion coefficient). In thin-film samples at liquid-helium temperatures, L_φ and L_T are in the interval 0.1–2 μm, so the fabrication of metallic electron interferometers with "mirrors" of various materials will require multilayer submicron lithography in which the different layers are aligned with each other with a precision at the submicron level.

We are reporting a solution of that problem in this letter. We studied the effect of the temperature and a magnetic field on the conductivity of thin silver and bismuth conductors with widths $L_y = 0.07$–0.3 μm, a thickness $L_z = 0.04$ μm, and lengths $L_x = 0.1$–1.0 μm. The current and potential contacts were made of aluminum and lead. It was found that when these contacts go into a superconducting state, the resistance of conductors which are sufficiently short and thin increases sharply, and the positive weak-localization magnetoresistance goes negative, acquiring an absolute value more than an order of magnitude greater than the weak-localization value before the transition. The behavior of the resistance of short samples might be explained in terms of a spatial quantization of the energy of the electrons in the normal phase of a sample as a result of the finite motion of these electrons due to Andreev reflection from N–S interfaces in the absence of phase relaxation and spin flip upon Andreev reflection.

The insets in Figs. 1 and 3 show the geometry of the samples. The substrate was high-purity silicon covered with its native oxide. Lift-off electron-beam lithography

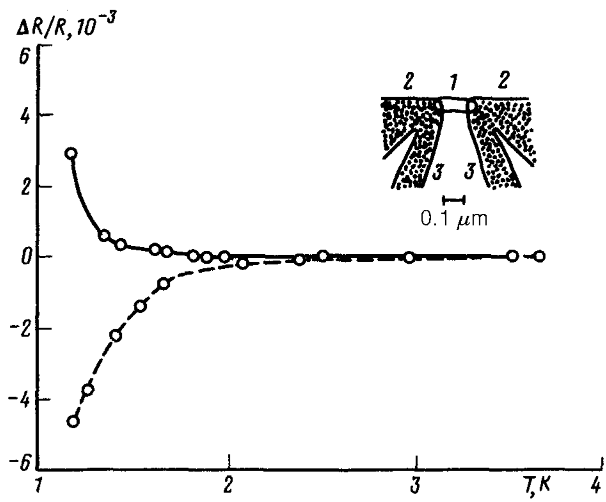

FIG. 1. Solid line—Temperature dependence of the resistance of a submicron bismuth sample with aluminum contacts; dashed line—temperature dependence of the resistance of the contacts. Inset: 1) Sample; 2,3) current and potential contacts.

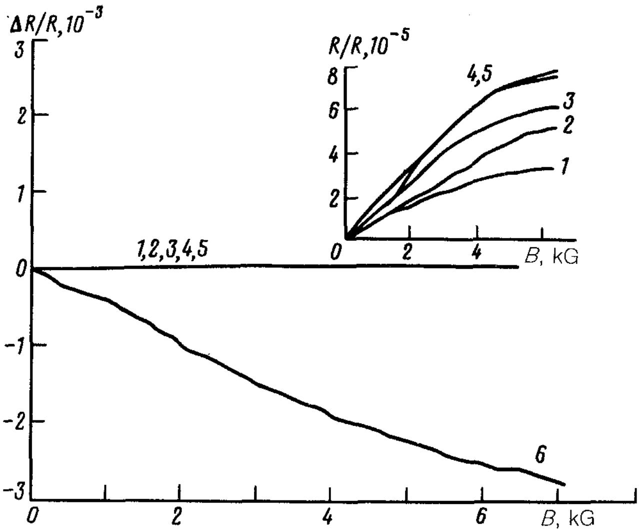

FIG. 2. Magnetic-field dependence of the resistance of a submicron bismuth sample with aluminum contacts at various temperatures: 1—4.2 K; 2—3.1 K; 3—2.9 K; 4—2.6 K; 5—2.2 K; 6—1.3 K.

was used with a negative vacuum electron-beam resist and ion etching.[2] The films were vacuum-deposited and had resistances $R_\square$ (Ag) = 0.3–0.5 Ω and $R_\square$ (Bi) = 100–300 Ω. The measurements were carried out at temperatures of 1.3–4.2 K in magnetic fields up to 5 kG at frequencies of 30–300 Hz.

Figure 1 shows a representative plot of the resistance of a short bismuth conductor (see the inset in Fig. 1) with aluminum current and potential contacts in a zero magnetic field. Also shown here is the temperature dependence of the resistance of the contacts. We see that the resistance of the bismuth conductor *increases* when the contacts start to go into a superconducting state. Figure 2 shows the behavior of the resistance of the same sample as a function of the magnetic field at various temperatures. Before the contacts go superconducting we see the usual positive magnetoresistance associated with a weak-localization effect. When the superconducting transition of the contacts begins, this increase in the magnetoresistance comes to a halt, and the magnetoresistance decreases. It proceeds to change sign. The absolute value of the negative magnetoresistance at $T = 1.3$ K is roughly 40 times the maximum value of the positive magnetoresistance (see Fig. 2 and the inset there).

Similar results were found on the silver samples.

The changes in the resistance of "long" conductors ($L_x \geqslant 1$ μm), when the contacts go superconducting, are of the opposite sign: The resistance in a zero magnetic field decreases. The magnetoresistance increases sharply without changing sign. This behavior can be explained at a quantitative level by the onset of a proximity effect.

The effects described above correspond to the very beginning of the superconducting transition of the contacts. To see a broader picture we used some samples

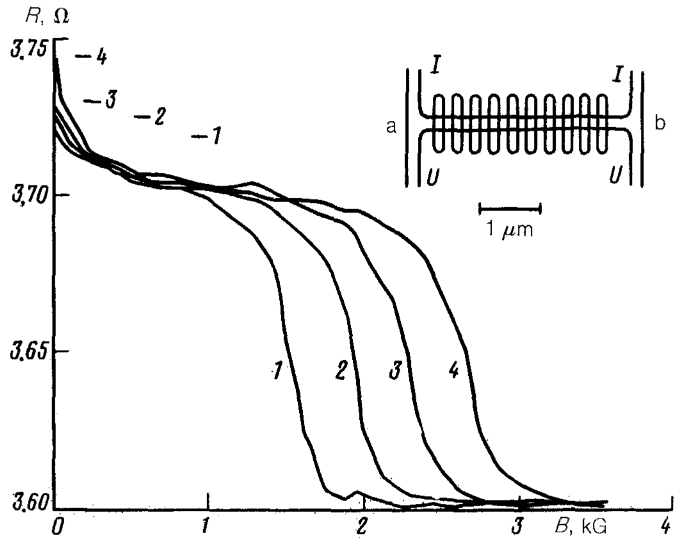

FIG. 3. Magnetic-field dependence of the resistance of a silver strip on which lead strips have been deposited.

fabricated with contacts made of a lead film with $T_c = 6.2$ K. It was found that effects characteristic of short conductors could be observed by depositing some closely spaced superconducting strips (at least two) on top of, and in the direction perpendicular to, a narrow strip of a normal metal (see the inset in Fig. 3). Because of the proximity effect, the sample breaks up into alternating short S and N regions.

Figure 3 shows the magnetic-field dependence of the resistance of a silver strip (see the inset) with $L_y = 0.2$ $L_z = 0.04\,u$m, a length of 3.5 μm, and ten parallel strips of lead oriented perpendicular to the silver strip. The width of the lead strips is 0.13 μm, their thickness is 0.1 μm, their length is 1.0 μm, and the distance between them is 0.26 μm. Results are shown for several temperatures. When the lead strips go superconducting, the resistance of region *a–b* of the sample *increases*. There are two intervals of the magnetic field in which the resistance changes most rapidly: the region in which the lead goes superconducting (this is a region of relatively strong fields, $B_c \approx 1$–3 kG) and a weak-field region, $B < 1$ kG. The magnetoresistance depends on the temperature in different ways in these two regions: In fields $B \approx B_c$, the total change in the resistance depends only weakly on the temperature, while in weak fields the temperature dependence is fairly strong.

These results can be explained in a consistent way as follows.

When the N–S interfaces form, the longitudinal energy of an electron in an N region is quantized because of the finite motion of the electrons imposed by Andreev reflection.[1] As a result, all three components of the energy are quantized.[3] The quantization is important if the distances between the quantum levels, $\Delta\epsilon$, are greater than both kT and kX, where T is the temperature, and X is the Dingle temperature, which characterizes the collisional broadening of the levels. According to Refs. 1, 3, and 4, we have

$$\Delta\epsilon = \pi\hbar v_F / L_i \quad i = x, y, z, \tag{1}$$

$$X = \hbar / 2\pi k\tau, \tag{2}$$

where v_F is the Fermi velocity, and τ^{-1} is the total electron collision rate.

The dimensions of our short samples were $L_i \approx 0.1\ \mu$m and corresponded to a value $\Delta\epsilon \approx 250$ K. The collision rate can be estimated by noting that in the case of silver we have[5] $\rho v_F \tau = R_\square L_z v_F \tau = 5.36 \times 10^{-12}\ \Omega \cdot \text{cm}^2$ ($R_\square = 0.3\ \Omega$, $v_F = 10^8$ cm/s). Calculating τ from this relation, and substituting it into (2), we find $X \approx 30$ K. We thus conclude that maxima should arise in the density of states in short normal regions. If the Fermi level lies between maxima, the resistance of the sample will be higher than in the absence of quantization. If rigid boundaries lead to a quantization, the sign of the change in the resistance should be random in the various regions. We carried out about ten experiments on short samples; in all cases the resistance was found to increase upon the appearance of N–S interfaces. We believe that this result can be explained on the basis that the N–S interfaces are mobile and must assume the positions which minimize the energy of the electrons of the superconductor–(normal metal) system. A peak in the density of states should tend to shift below the Fermi level, as in the case of a Peierls transition. The proximity effect is in a sense blocked; the N–S interfaces cannot move arbitrarily close together, since the effect would be to increase the energy of the electrons in the normal region.

The reason why the magnitude of the change in resistance does not depend on the temperature at magnetic fields $B \approx B_c$ may be that the relation $X \gg T$ held in our case.

The effect of the quantization becomes negligible at $\Delta\epsilon < kX$, i.e., at sample lengths $L_0 > 0.8\ \mu$m, according to (1). In samples with $L_x > L_0$ there should be not transition to a state with a higher resistance; this conclusion agrees with experiment.

The behavior of the magnetoresistance in weak fields can be explained in terms of a weak-localization effect on the basis of the theory of Ref. 6, under the assumption that no phase relaxation of the electrons or spin flip occurs as a result of Andreev reflection. In this case the theory predicts a weak-localization correction $(\Delta R / R^2)_{\text{loc}} = (e^2/\pi\hbar)[\coth(L/L_\varphi + L_\varphi/L_x]L_\varphi/L_x$. For short N silver regions ($L_x \approx 0.1\ \mu$m) we find $\Delta R / R^2 = 7 \times 10^{-3}\ S$ at $T = 1.3$ K; from this figure we find $L_\varphi/L_x \approx 19$. This is a completely realistic relation, since measurements on long silver samples with normal contacts yielded $L_\varphi \approx 1.5\ \mu$m. Other boundary conditions fail to explain the large magnitude and the sign of the weak-localization magnetoresistance of our short samples.

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