Phase controlled mesoscopic ring interferometer

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The conductance oscillations in a normal metal mesoscopic ring, to which a superconducting wire is attached at two points was measured. The oscillations are due to a phase transfer from the superconducting condensate to normal electrons via Andreev reflections at the normal metal-superconductor interfaces. The phase difference between the interfaces was controlled by varying a subcritical current through the superconductor and, alternatively, by applying a magnetic field. New components were found in the spectrum of oscillations. © *1994 American Institute of Physics.*

Several new phenomena[1–7] have recently been observed in mesoscopic structures that consist of normal (N) and superconducting (S) regions. They have been attributed to the Andreev reflections[8] of normal electrons at the $N-S$ boundary. Such a reflection transforms an electron on the N side to a Cooper pair on the S side plus a hole that retraces the electron orbit on the N side (and vice versa for a hole to the electron transformation). An extra phase equal to the macroscopic phase, ϕ, of a superconductor is acquired by an electron in the Andreev reflection and, correspondingly, a hole acquires an extra phase $-\phi$. If the interfering quasiparticles are reflected from two different superconductors or two different points of a single superconductor with phases equal to ϕ_1 and ϕ_2, then the resulting interference and, for example, the conductance of the mesoscopic conductor between the superconductors, will depend on the phase difference $\Delta\phi=\phi_1-\phi_2$. The first experimental manifestation of such a relationship between the phases of normal electrons and those in a superconductor was reported in Ref. 2. A new component was found in the spectrum of magnetoresistance of a normal mesoscopic ring with superconducting "mirrors." The new component corresponds to half a "superconducting" flux quantum, $\Phi_0/2=h/4e$, and it can be explained in terms of the interference of electrons with phase shift $\Delta\phi$. New nonlinear phenomena due to the electron retardation effects can also be observed when $\Delta\phi$ changes mainly during the diffusion of quasiparticles between the superconductors.[2]

Recently[5] we have designed an experiment which enabled us to vary $\Delta\phi$ in a wide range by creating a condensate phase gradient in a single superconductor to which a normal mesoscopic structure was attached. The phase gradient was controlled by passing a subcritical current through the superconductor. It was shown that the conductance of a mesoscopic body varies periodically as a function of $\Delta\phi$. A similar result was obtained in Ref. 7 where the normal structure was shunted by several Josephson junctions.

In this paper we report the results of an experimental study of the conductance of a

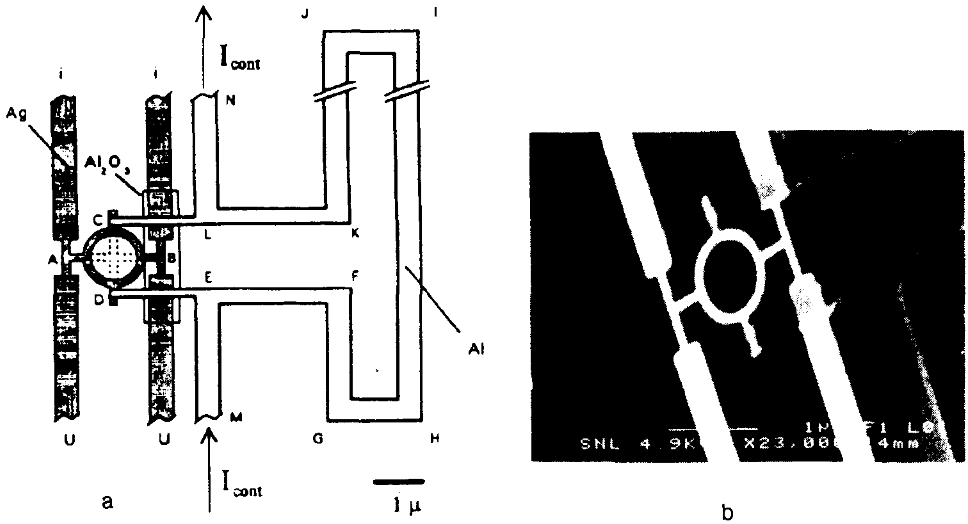

FIG. 1. a) The geometry of the experiment $i-i$ and $U-U$ are the current and the potential leads for measuring the resistance between points A and B (R_{AB}) of the silver structure. The dashed line shows the geometry of the structure, where the ring was replaced by a cross (see text); dc current source is connected to M and N to control the phase difference between points C and D of the aluminum wire. b) A SEM micrograph of one of the samples. The diameter of the ring is equal to 1 μm.

normal metal mesoscopic ring interferometer with two interfaces to a superconducting wire. The phase difference $\Delta\phi$ between the $N-S$ interfaces was controlled by passing a supercurrent in the attached superconductor and/or by applying a magnetic field. The $\Delta\phi$ periodic conductance oscillations were observed. New components in the spectrum of oscillations were found.

The experimental configuration is shown in Fig. 1. The normal conductor has the shape of a ring with four stubs. The stubs A and B of the ring are connected to the current leads ($i-i$) and the potential leads ($U-U$). The ends of the other stubs, C and D, are connected to a superconducting wire (MEFGHIJKLN). A subcritical control current, I_{cont}, can be passed through this superconducting wire, and thus create a phase difference between the points C and D. A comparison was made with the measurements of the conductance of the structure, where the normal part was singly connected and had a shape of a cross, shown in Fig. 1 by the dashed line.

The structure was defined using the technique described by us previously.[2,5] The substrate was a high-purity silicon covered with native oxide. The first layer, the normal part of the structure, was made of silver. The thickness of the film was 50 nm, the widths of the silver wires were 100 nm, and their lengths, AB and CD, for the cross-like structure were 2 μm. The diameters of the rings were 1 μm. The second, insulating layer was made of Al_2O_3 of thickness about 10 nm. The third layer, the superconducting part of the structure, was made of aluminum that had a thickness of 25 nm. Two different wire widths, 500 and 800 nm were used to form the rectangular loop. The distances between the centers of the wires forming the loop (GHIJ) were 34 μm and 1.4 μm for all

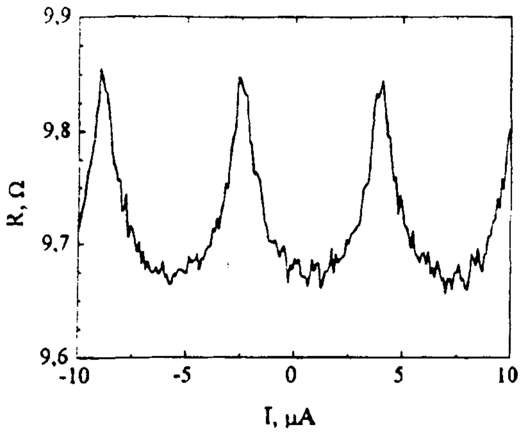

FIG. 2. The resistance R_{AB} as a function of the current through the superconducting Al part of the cross-like structure shown in Fig. 1 (dashed line), $T=20$ mK.

structures. The lengths of the connectors CK and DF were 4.8 μm and the distance between them was 1.6 μm (edge to edge). The distances EF and LK were 2.5 μm. The widths of CL and DE were 200 nm. The sheet resistance of the silver film was 0.5 Ω. This corresponds to a diffusion coefficient of electrons, $D=10$ cm^2/s and a coherence length $L_T=(hD/2\pi k_B T)^{1/2}$ of about 100 nm at $T=1$ K. The phase-breaking length of electrons, $L_\phi=(D\tau_\phi)^{1/2}$, where $1/\tau_\phi$ is the sum of the phase breaking scattering rates, was estimated to be about 1 μm from a weak localization magnetoresistance curve of a co-evaporated Ag film. There was a good electrical contact between the Ag film and the superconducting Al, the resistance was on the order of a few ohms. The measurements were performed at temperatures between 0.02 and 1.2 K. The resistance R_{AB} of the normal conductor, AB (see Fig. 1) was measured as a function of temperature; the control current of density less than 10^5 A/cm^2 passed through MN. A magnetic field of up to 2 kG was applied perpendicular to the substrate. A four-probe ac technique was used. Frequencies of 30–300 Hz and a lock-in technique were used to measure R_{AB}. A dc source was applied to the points M and N to supply the control current. In the experiments described here, the resistance drops in the range from $<1\%$ to 30% were observed in different samples. Both drops and rises were noted in the previous experiments.[2–4]

Figure 2 shows a typical example of the dependence of R_{AB} on the control current at a temperature of 20 mK for a cross-like sample. Periodic oscillations are seen. The magnetic field in the vicinity of the silver conductor (AB), which was induced by the current, was negligible.

The dependence of R_{AB} of the same sample on the magnetic field at zero current in the superconductor is shown in Fig. 3. Figure 4 shows the conductance oscillations of the ring structure. Drastic difference is seen in the magnetoresistance of the two systems. The oscillations as a function of the control current were similar with the two systems. The magnetoresistance oscillation period is $\Delta B=0.37$ G for the cross-like structure. This corresponds to a flux quantum $\Delta BS=\Phi_0=h/2e$ with S equal to the area enclosed by the centers of the Al loop wires that are connected to the points C and D of the normal structure. The spectrum of the magnetoresistance oscillations of the ring structure contains high-frequency oscillations with a period $\Delta B=0.37$ G, modulated by much lower

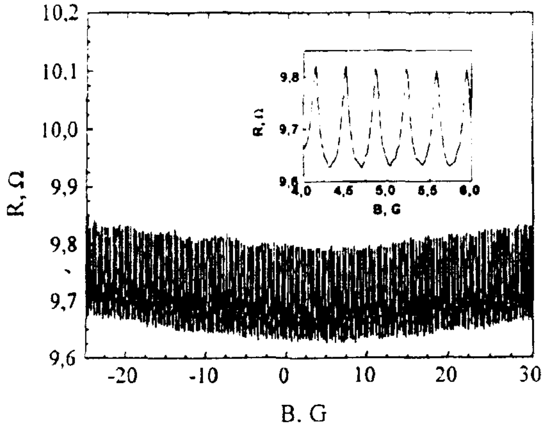

FIG. 3. Resistance R_{AB} versus the magnetic field for the cross-like normal structure (the dashed line in Fig. 1).

frequencies. The lower modulation envelope has a period of $\Delta B = 28$ G, which corresponds to a flux quantum $\Delta B S_\tau = \Phi_0 = h/2$, with S_τ equal to the area enclosed by the center line of the silver ring. The upper modulation envelope has a period of $\Delta B = 14$ G, which corresponds to a flux quantum $\Delta B S_\tau = \Phi_0/2 = h/4e$. As can be seen from Fig. 4 (inset a), the high-frequency oscillations have a strong second-harmonic component near the maximum of the lower modulation envelope line. The positions of the extrema of the R_{AB}-versus-B curve depend periodically on the current in the superconducting wire. We did not compensate for the magnetic field of the earth or for the remanent field in our cryostat. This circumstance may explain the asymmetry of the curves in Figs. 2–4 with respect to $B = 0$. Special measurements showed that the resistance R_{AB} has a minimum at $\Delta B = 0$ and $I = 0$.

The measurements showed that the oscillation period with magnetic field, ΔB, does not depend on the width of the Al wires but is determined, within 5%, by the area S defined by the centers of the Al wires. This result is in contrast with the period with

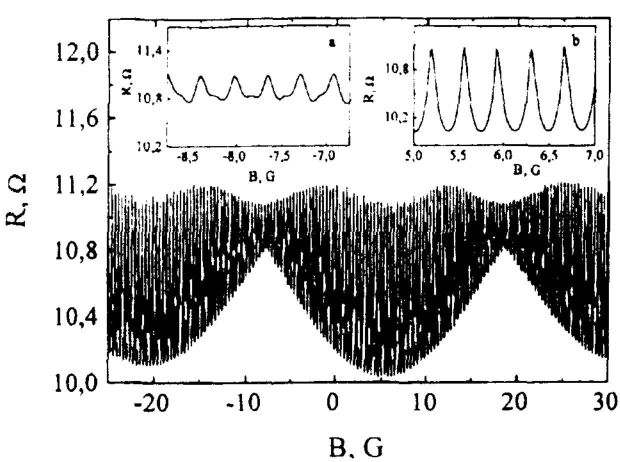

FIG. 4. Resistance R_{AB} versus the magnetic field for the ring interferometer $T = 20$ mK (compare with Fig. 3).

control current, ΔI. Structures with the same S but different widths of the Al wires give different ΔI. For the loops with Al wire widths of 800 nm and 500 nm, the periods ΔI are 6.4 μA and 2.3 μA, respectively.

The main features of our results can be interpreted as support of a model in which the phase-dependent Andreev reflected charge carriers contribute to the conductance of a mesoscopic conductor. Such an effect has been analyzed theoretically.[9–13] We observed oscillations at temperatures of up to 1 K at a coherence length $L_T=0.1$ μm, when the "usual" proximity effect was negligible.

The superconducting phase gradient in a superconducting wire at a current density **j** can be written as follows:[14]

$$\nabla\phi_{CD}=\left(\frac{2\pi m}{eh}\right)\frac{2}{n_s}\mathbf{j}+\left(\frac{4\pi e}{hc}\right)\mathbf{A}, \tag{1}$$

where $n_s/2$ is the density of Cooper pairs, m is the electron mass, and **A** is the vector potential which depends on the applied field and current. The phase difference between the points C and D in the absence of an external magnetic field can be written

$$\Delta\phi_{CD}=2\pi\frac{L_{\text{eff}}}{\Phi_0}I. \tag{2}$$

L_{eff} is the effective self-inductance of the superconductor. This inductance is the sum of the "kinetic" inductance, which corresponds to the first term on the right-hand side of Eq. (1), and the "geometric" inductance given by the second term. I is the current and $\Phi_0=h/2e=2\times10^{-15}$ Wb.

In a magnetic field, additional phase difference, $\Delta\phi_{CD}$, appears. This phase difference is given by the second term in (1) with an externally induced vector potential. For high-frequency oscillations the phase difference $\Delta\phi_{CD}$ is approximately given by

$$\Delta\phi_{CD}=2\pi\frac{\Phi}{\Phi_0}, \tag{3}$$

where Φ is the flux through the area of the Al loop which is connected to C and D. The flux is enhanced by the Meissner effect in the relatively broad wire, and the period in B is given approximately by the area S (introduced above), which is enclosed by the center contour of the loop. Knowing the periodicity of the superconducting phase, we can calculate the effective inductance, L_{eff}, of the superconducting loop using Eq. (2). L_{eff} depends on the width of the superconducting wire (at a constant S) and is 2×10^{-10} H and 5.6×10^{-10} H for the two loops with wire widths of 800 and 500 nm, respectively, consistent with the results of our previous work.[5]

According to the numerical calculations[11] for disordered conductors, which is the case in our experiment, the conductance oscillations, averaged over a random disposition of the scatterers, should have a period of 2π, instead of the π periodicity predicted in Ref. 9. While our experiments confirm 2π periodicity for high-frequency oscillations, there are still some discrepancies between our experimental results and the predictions. The theory[11] predicts decay of the 2π Fourier component of the conductance oscillations at high quasiparticle energies, which experimentally may manifest itself through the existence of a crossover temperature, at which the conductance switches from 2π to π periodicity. We have not observed such a crossover in the temperature range from $T=0.02$ K up to $T\sim 1$ K. In addition, the $h/4e$ component on the low-frequency side of the oscillation spectrum (corresponding to π periodicity) decays more rapidly with increasing temperature than the $h/2e$ component. Furthermore, the conductance extremum at $\Delta\phi=0$ is predicted to be sample-specific in disordered conductors.[11] Experimentally, in all our structures which were investigated, the conductance had a maximum at zero phase difference.

We have not yet developed a clear-cut theory of the observed general oscillation picture in our ring interferometer.

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[1] For a review, see T. M. Klapwijk, Physica B **197**, 481 (1994).
[2] V. T. Petrashov *et al.*, Phys. Rev. Lett. **70**, 347 (1993); Physica B **194–196**, 1105 (1994).
[3] V. T. Petrashov and V. N. Antonov, JETP Lett. **54**, 241 (1991).
[4] V. T. Petrashov *et al.*, JETP Lett. **58**, 49 (1993).
[5] V. T. Petrashov *et al.*, submitted to Phys. Rev. Lett. (1994); *Internat. Confer. on the Physics and Technology of Metallic Nanostructures (Metallic Nano-Electronics)*, Chernogolovka, 12–15 September 1994.
[6] H. Pothier *et al.*, to be published.
[7] P. G. N. de Vegvar *et al.*, Phys. Rev. Lett. **73**, 1416 (1994).
[8] A. F. Andreev, Zh. Eksp. Teor. Fiz. **46**, 1823 (1964) [Sov. Phys. JETP **19**, 1228 (1964)].
[9] B. Z. Zpivak and D. E. Khmelnitskii, JETP Lett. **3**, 412 (1982).
[10] B. L. Altshuler and B. Z. Spivak, Zh. Eksper. Teor. Fiz. **92**, 609 (1987) [Sov. Phys. JETP **65**, 343 (1987)].
[11] V. C. Hui and C. J. Lambert, Europhys. Lett. **23**, 203 (1993); C. J. Lambert and S. J. Robinson, Physica B **194–196**, 1641 (1994).
[12] H. Nakano and H. Takayanagi, Phys. Rev. B **47**, 7986 91993).
[13] A. Kadigrobov *et al.*, to be published.
[14] A. A. Abrikosov, *Osnovy Teorii Metallov*, Nauka, Moscow, 1987 [*Fundamentals of the Theory of Metals*].

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