Phase Memory Effects in Mesoscopic Rings with Superconducting "Mirrors"

V. T. Petrashov and V. N. Antonov

Institute of Microelectronics Technology, Russian Academy of Sciences, Chernogolovka, Moscow District, 142432 Russia

P. Delsing and R. Claeson

Department of Physics, Chalmers University of Technology, S-412 96 Gothenburg, Sweden

(Received 4 August 1992)

We find a drastic difference between the magnetoresistance of normal-metal (Ag) mesoscopic rings with superconducting boundaries (mirrors) and that of plain rings. The amplitude of $h/2e$ Aharonov-Bohm oscillations is enhanced more than 100 times in rings with mirrors in the measuring leads. Rings with mirrors in stubs perpendicular to the current flow show $h/4e$ and $h/2e$ oscillations and evidence of a superconducting transition. The results are interpreted as due to a phase coupling between the superconductors via normal electrons, and to a confinement of quasiparticles to the ring by Andreev reflections.

PACS numbers: 72.15.Lh, 71.55.Jv, 72.20.My

As the dimensions of a conductor are reduced, the magnitude of the quantum contributions to its conductance becomes very sensitive to the properties of the interfaces to the environment. Such is the case in "mesoscopic" conductors, for which the largest extension is comparable to or less than the characteristic lengths: the phase-breaking length $L_\phi=(D\tau_\phi)^{1/2}$ and the normal-metal coherence length $L_T=(hD/k_BT)^{1/2}$ (τ_ϕ^{-1} is the sum of the scattering rates where the phase of an electron is disrupted; D is the electron diffusion constant). The phase memory of the electron is maintained throughout such a conductor.

Not only the interfaces parallel to the direction of the current but also the interfaces to the leads to the conductor become important [1]. Their role is analogous to that played by mirrors in an optical interferometer. L_ϕ and L_T are of the order of 0.1–2 μm in metallic thin films at liquid-helium temperatures. Hence, the fabrication of electron interferometers with "mirrors" requires multilayer lithography with a submicron precision of the alignment of different layers. A variety of mirrors can be envisioned. Here we specialize in normal-metal–superconductor (N/S) interfaces that lead to substantial quantum corrections [2,3]. We will present experimental evidence for electron phase memory effects in disordered mesoscopic rings of normal metal with superconducting boundaries, or mirrors. Three types of rings are compared. They contain (a) no superconducting mirrors [see inset in Fig. 1(a)], (b) superconducting mirrors in the measuring leads with N/S interfaces perpendicular to the current flow [longitudinal (L) mirrors, see the inset of Fig. 1(b)], and (c) superconducting mirrors in stubs to the ring, perpendicular to the line joining the measuring leads [transverse (T) mirrors, Fig. 1(c)]. In the latter case, there should be no potential difference between the two mirrors if they are symmetrically located. Drastic differences were observed in the magnetoresistance of the three systems. The amplitude of the $h/2e$ Aharonov-Bohm type oscillations in the magnetoresistance was enhanced up to 400 times in the rings with L mirrors as compared to those without mirrors. This was not anticipated by the existing theory. Furthermore, relatively large $h/4e$ oscillations (as well as $h/2e$) were seen in the magnetoresistance of rings with T mirrors. This we believe is due to a phase shift of a quasiparticle, which is Andreev reflected at an N/S interface, equal to the phase of the superconductor [2,3]. This may be the first experimental manifestation of a relationship between the microscopic phase of a normal electron and the macroscopic phase of a superconductor. Another difference between rings with Al T and L mirrors is that the former seem to go superconducting, while the latter do not.

Silver rings and connecting leads were patterned using lift-off and electron-beam lithography; see the insets of Fig. 1 for the geometry. A copolymer of polymethylmethacrylate (PMMA) and polymethacrylic acid (PMAA) formed the bottom layer and pure PMMA the top one of the two-layer resist. The substrate was high-purity silicon covered by its native oxide. Each set of samples contained three rings of practically the same dimensions: the widths of the wires were 90–200 nm, the thickness 50 nm, and diameters $2r=0.6$–1.0 μm. Two of the rings were equipped with superconducting mirrors (S mirrors). These were formed by a proximity effect using strips of a superconductor across the leads to the ring; see insets of Figs. 1(b) and 1(c). Both Al and Pb-Au alloys were used as the superconductor. The thicknesses were 50 and 40 nm, respectively. The superconducting transition temperature T_c of Al was 1.3 K, and of Pb-Au, 6.2 K, both on top of Ag. All films were deposited by thermal evaporation onto the substrate which was held at room temperature. The superconducting strips were defined using a lift-off method based on the same resists as above for Ag. The resistance of the underlying Ag structure and its degradation at room temperature depended strongly on the baking temperature of the resist during the second lithography step. The silver films had sheet resistance $R_l(\mathrm{Ag})=0.3$–10 Ω. Here we will

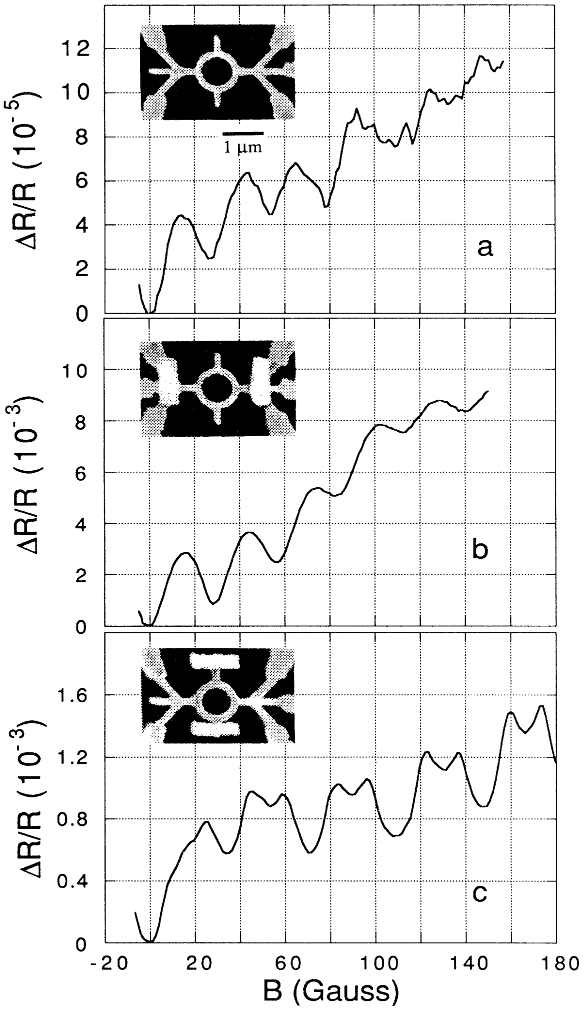

FIG. 1. The insets give SEM pictures of the samples: (a) the bare ring of Ag, (b) with "L" mirrors in the measuring leads, (c) with "T" mirrors in the side arms. Superconducting strips are of Al. The magnetoresistances at $T = 20$ mK are given in the graphs. Note the large difference in scales among (a)–(c). The resistances at $B = 0$ are (a) 51, (b) 63, and (c) 67 Ω. The inner and outer diameters of the rings are 0.8 and 1.1 μm.

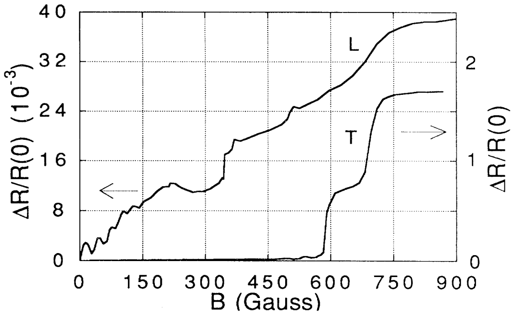

FIG. 2. The magnetoresistance over an extended field range for rings with "L" and "T" mirrors of Al (same as in Fig. 1). The plots were taken at 20 mK.

present results from the high-resistance batches. The measurements were performed at temperatures of 0.02–1.2 K, our samples had $L_\phi \approx 1$–2 μm and $L_T = 0.1$–0.8 μm. We used frequencies of 30–300 Hz. The magnetic field, which ranged up to 0.2 T, was perpendicular to the substrate.

Rings without S mirrors showed the usual dependence of the resistance on magnetic field. A typical example is shown in Fig. 1(a). At low fields, oscillations with a period of the flux quantum dominate, $\Delta BS = \Phi_0 = h/2e$ [$S = \pi r^2$, where in this case, r is the average radius, $r = (r_i + r_o)/2$, $2r_i \approx 0.8$ μm and $2r_o \approx 1.1$ μm being the inner and outer diameters], $\Delta B \approx 28$ G. The oscillation amplitude, $\Delta R/R$, is of the order of a few times 10^{-5}. For $B > 200$ G, the h/e oscillations and "universal" conductance fluctuations dominate.

The rings with superconducting strips across the current leads, the L mirrors, showed qualitatively similar behavior but with a strongly enhanced amplitude; see Fig. 1(b) for Al strips. At low fields, the $h/2e$ oscillations are amplified about 100 times as compared to those of Fig. 1(a). The enhancement was even stronger, about 400 times, with Pb-Au strips. The main increase in the $h/2e$ amplitude occurred as the temperature was lowered through the superconducting transition temperature. Well below T_c, the oscillation amplitude increased similarly with and without L mirrors, less than a factor of 2 between 600 and 20 mK. At magnetic fields of $225 < B < 285$ G, the magnetoresistance (dR/dB) was negative. Additional features may, partly, be attributed to changes in superconductivity with magnetic field. Several discontinuities, which were sample dependent, were registered; see Fig. 2. These features are quite different in the samples with superconducting strips across the stubs outside the direct path of current flow.

The total decrease in the resistance of a sample with T mirrors is much larger than for the L mirrors, about 60% instead of 1%; the remainder is assumed to be due to the leads. Fewer features are seen in the high-field range; see Fig. 2. The superconducting transition leads to two major resistance steps at about 600 and 700 G at $T = 20$ mK for that sample. The relatively high critical field is due to the small extensions of the film (in two directions) as compared to the penetration depth. The discontinuities occur at lower fields with increasing temperature and are almost independent of the measuring current in the range 0.05–5 μA. The curves displayed here were taken in this low-current, linear regime.

The most conspicuous difference between the samples with L and T mirrors is seen in the low-field magnetoresistance. Relatively large oscillations are seen for both, but the period for a T mirror ring is not only $\Delta BS' = \Phi_0$ [as in Fig. 1(b)] but also $\Delta BS' = h/4e = \Phi_0/2$. In this case $\Delta R/R \approx -(\cos 2\pi BS'/\Phi_0 + \beta \cos 4\pi BS'/\Phi_0)$

with $\beta \approx 1$ and S' corresponding to the inner diameter of the ring, $2r_i$ [see Fig. 1(c)]. The total amplitude of the oscillations increases with increasing magnetic field, in contrast to the L mirror case for which it decreases. The relative contribution of the $h/4e$ component is smaller at high magnetic fields. Neither $h/4e$ oscillations nor indications of superconductivity were seen in rings with a single T mirror, while $h/2e$ oscillations and positive magnetoresistance were enhanced within 1 order in magnitude. Rings with one of the strands crossed by a superconducting strip never showed any enhanced oscillations. The total number of samples measured was more than 20.

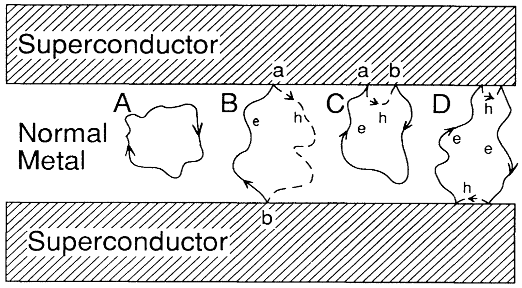

FIG. 3. Trajectories contributing to quantum corrections to the conductance of a normal metal between two superconductors. The time-reversed paths are not shown.

An obvious remark is that the observed phenomena could be due to induced superconductivity by a "usual" proximity effect: Little-Parks resistance oscillations [4], or Maki-Thompson-Larkin [5] fluctuations of the order parameter. These are based upon the "leakage" of Cooper pairs from S to N over a distance of the order of L_T. We think they give contributions to the electron transport in the rings, e.g., the single-mirror case. However, for two mirrors there is a pronounced difference between the L- and T-mirror cases which would not be expected from a "usual" proximity effect. (It is true that the T-mirror strips are located somewhat closer to each other than the L ones, but the difference is no larger than 10%.) There are also the $h/4e$ oscillations, the negative dR/dB in the region $225 < B < 285$ G for the L-mirror configuration of Fig. 2, as well as the enhancement of negative magnetoresistance and the increase of the resistance of short conductors when the mirrors become superconducting as reported in Ref. [6]. These phenomena occur also well below T_c and are rather temperature independent at the lowest temperatures. We, hence, try to explain the phenomena in the context of Andreev reflections of normal quasiparticles at N/S boundaries.

Contributions to the quantum interference corrections of the resistance of the normal part of the circuit can be qualitatively described considering different types of closed diffusion trajectories. The most important, we believe, are shown in Fig. 3. Normal-electron trajectories of kind A lead, together with their time-reversed, conjugate trajectories, to weak localization effects and to $h/2e$ oscillations [7]. Trajectories of type B were considered theoretically [2,3]. Andreev reflections at points a and b transform an electron on the N side to a Cooper pair on the S side and a hole on the N side, and vice versa hole to electron. An extra phase of $-\chi_1$ (or $-\chi_2$, depending on which N/S interface the Andreev reflection takes place) is supposed to be acquired [2]; χ_1 and χ_2 are the phases of the two superconducting banks. Correspondingly, a hole that is reflected into an electron will obtain an extra phase χ_1 (or χ_2). Interference between two such trajectories depends on a phase shift $2\phi = 2(\chi_1 - \chi_2)$, resulting [2,3] in a period of $2\phi = 2\pi$ instead of the usual superconducting period of $\phi = 2\pi$. In the presence of a magnetic field and Josephson coupling between the superconductors, there are phase shifts from the flux Φ enclosed in the ring, $2\pi\Phi/\Phi_0$, and from the Andreev reflections, $2\phi = 2\pi\Phi/\Phi_0$. This adds up to a flux periodicity of $\Phi_0/2 = h/4e$. Trajectories like C and D differ from B as a reflection of an electron to a hole to an electron does not result in additional phase shift due to the superconducting phase (unless the latter fluctuates rapidly in time), and they do not lead to coupling between the superconducting banks.

For a ring with T mirrors an enhancement of weak localization due to "coherent confinement" is not expected. Instead, we suppose the electron transport is dominated by the contribution of B-type trajectories. They would provide phase-coherent coupling of the superconductors by normal electrons and an extra "supercurrent" (keeping the terminology of Ref. [3]). The critical current of the ring oscillates as a function of magnetic field, as in a two-junction superconducting interferometer, with the additional periodicity of $h/4e$. This leads to oscillations in the resistance of the structure. As the magnetic field inside the silver ring is partially screened by superconducting currents, the effective area of the hole would be S' as observed [cf. Fig. 1(c)].

In the case of L mirrors there is a potential difference V between the superconductors. This will lead to a variation in ϕ with time according to the Josephson relation. To observe the coupling between the superconductors through B-type orbits, the period of phase oscillations should be much larger than the time of diffusion of an electron between the superconductors [2], τ_f. In our case, with a distance between superconductors of $L \approx 2$ μm, $\rho l = 5.6 \times 10^{-12}$ $\Omega\,\mathrm{cm}^2$ (ρ is the resistivity and l is the electron mean free path), and sheet resistance $R_\square = 6$ Ω, we calculate the diffusion constant $D \approx 6$ cm^2/s and $\tau_f = L^2/D \approx 5 \times 10^{-9}$ s. This is much larger than the inverse of the doubled Josephson frequency (taking into account the π periodicity; $2\omega_J \approx 4 \times 10^{10}$ rad/s with an estimated potential drop over the ring $V \approx 7$ μV). Hence, $2\omega_J \tau_f \ll 1$ was not fulfilled and coherence effects due to normal-metal electron phase memory should be suppressed. The mirrors prevent normal electrons from diffusing into the measuring probes and losing the phase memory. The weak-localization correction to the conductance should be strongly enhanced by N/S boundaries in mesoscopic conductors; cf. Fig. 1(b) for experimental results. The mechanism should lead to an enhancement of both contributions to the weak localization [8], having total spin $J=0$ (singlet contribution) and $J=1$ (triplet). This may explain the relatively strong negative component in the magnetoresistance of the rings with L mirrors (225–285 G) and of short SNS strips [6]. The Maki-Thompson-Larkin mechanism would lead to an enhancement of only the singlet contribution, giving a positive magnetoresistance.

Our simple physical picture gives a qualitative description of several of the observed phenomena: the difference between L and T mirrors, the enhanced oscillations of magnetoresistance, the additional $h/4e$ period for T mirrors, and the negative magnetoresistance. However, several questions remain to be answered. One concerns the magnitude of the enhancement of weak localization and $h/2e$ oscillations. The maximum enhancement predicted by the theory of weak localization [1] is of the order of 10 for samples with $2\pi r/L_\phi \approx 1$ (which is close to the length ratio in our samples). Such a large enhancement was calculated when the boundary conditions were changed from one extreme to another, from a total loss of phase memory of electrons going into wide banks to free boundary conditions [9]. In our case there was an enhancement of up to 400 of weak-localization effects due to superconducting mirrors in the narrow leads, much more than expected. Another question concerns the characteristic lengths governing the extra supercurrent. While the relevant characteristic length for weak localization and for magnetoresistance oscillations is L_ϕ, the characteristic length for the extra supercurrent is $L_T/2$ according to [3]. Why then do supercurrents in the rings with T mirrors survive at temperatures up to 1 K where $L_T \approx 0.1$ μm? A more detailed understanding is needed.

We thank A. F. Andreev, D. E. Khmelnitskii, and C. J. Lambert for stimulating discussions. We thank B. Nilsson and L. G. Majstrenko for technical help in using the facilities of the Swedish Nanometer Laboratory and of the Quantum Electron Kinetics Laboratory of IMT. The work was supported by Russian and Swedish Academies of Sciences and the Swedish Natural Science Research Council.

[1] B. L. Altshuler, A. G. Aronov, and A. Yu. Zuzin, Zh. Eksp. Teor. Fiz. **86**, 709 (1984) [Sov. Phys. JETP **59**, 415 (1984)].

[2] B. Z. Spivak and D. E. Khmelnitskii, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 334 (1982) [JETP Lett. **35**, 412 (1982)].

[3] B. L. Altshuler, D. E. Khmelnitskii, and B. Z. Spivak, Solid State Commun. **48**, 841 (1983); B. L. Altshuler and B. Z. Spivak, Zh. Eksp. Teor. Fiz. **92**, 609 (1987) [Sov. Phys. JETP **65**, 343 (1987)].

[4] W. A. Little and R. Parks, Phys. Rev. **133**, A97 (1964).

[5] A. I. Larkin, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 239 (1980) [JETP Lett. **31**, 219 (1980)].

[6] V. T. Petrashov and V. N. Antonov, Pis'ma Zh. Eksp. Teor. Fiz. **54**, 245 (1991) [JETP Lett. **54**, 241 (1991)]; V. T. Petrashov, V. N. Antonov, and M. Persson, Phys. Scr. (to be published).

[7] B. L. Altshuler, A. G. Aronov, and B. Z. Spivak, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 101 (1981) [JETP Lett. **33**, 94 (1981)].

[8] G. Bergmann, Phys. Rep. **107**, 1 (1984).

[9] P. Santhanam, Phys. Rev. B **35**, 8737 (1987); **39**, 2541 (1989); V. Chandrasekhar, P. Santhanam, and D. E. Prober, Phys. Rev. B **44**, 11 203 (1991).

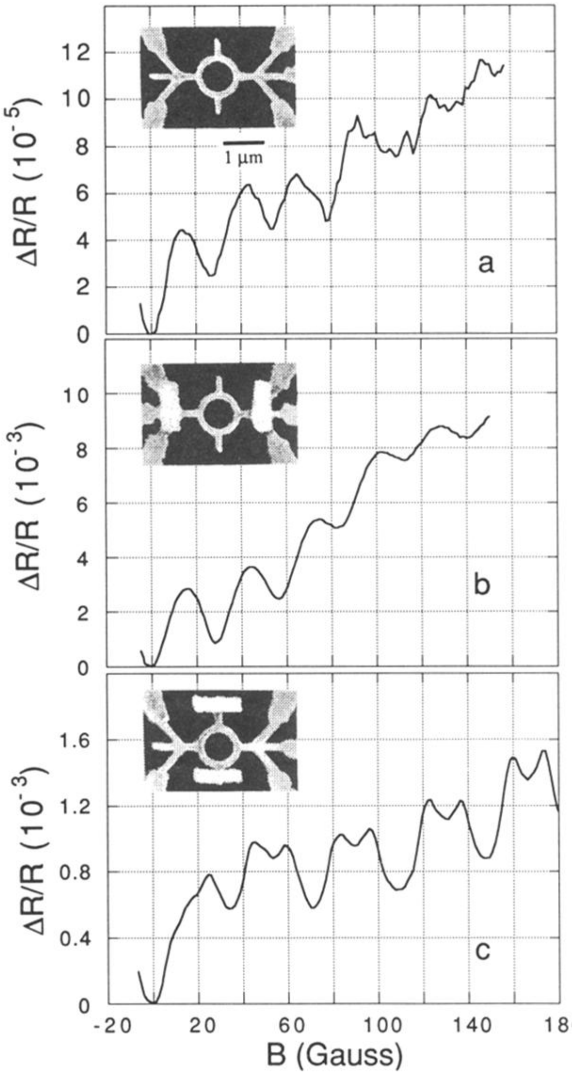

FIG. 1. The insets give SEM pictures of the samples: (a) the bare ring of Ag, (b) with "L" mirrors in the measuring leads, (c) with "T" mirrors in the side arms. Superconducting strips are of Al. The magnetoresistances at $T=20$ mK are given in the graphs. Note the large difference in scales among (a)–(c). The resistances at $B=0$ are (a) 51, (b) 63, and (c) 67 Ω. The inner and outer diameters of the rings are 0.8 and 1.1 μm.