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PHASE CONTROLLED MESOSCOPIC RING ITERFEROMETR

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We report measurements of conductance oscillations in a normal metal mesoscopic ring to which a superconducting wire is attached at two points. The oscillations are due to 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 sub-critical current through the superconductor and, alternatively, by applied magnetic field. New components were found in the spectrum of oscillations.

Several new phenomena [1-7] have recently been observed in mesoscopic structures consisting of normal (N) and superconducting (S) regions. They have been ascribed to 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 retracing the electron orbit on the N side (and vice versa for a hole to electron transformation). An extra phase equal to the macroscopic phase, ϕ, of a superconductor is acquired by an electron in an Andreev reflection and, correspondingly, a hole obtains an extra phase $-\phi$. If the interfering quasi-particles are reflected from two different superconductors or two different points of a single superconductor with phases equal to ϕ_1 and ϕ_2, the resulting interference and, e.g., the conductance of the mesoscopic conductor in 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 corresponded to half a "superconducting" flux quantum $\Phi_0/2 = h/4e$ and it could be explained by an interference of electrons with phase shift $\Delta\phi$. New non-linear phenomena due to electron retardation effects could also be observed when $\Delta\phi$ changed essentially during the diffusion time of quasiparticles between the superconductors [2].

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

In this paper we report an investigation of the conductance of a normal metal mesoscopic ring interferometer with two interfaces to a superconducting wire. The phase difference $\Delta\phi$ between N/S interfaces was controlled by passing supercurrent in an attached superconductor and/or by applying magnetic field. $\Delta\phi$-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 to the ring are connected to the current $(i-i)$ and potential $(U-U)$ leads . The ends of the other stubs, C and D, are connected to a superconducting wire (MEFGHIJKLN). A sub-critical 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 normal part was singly-connected and had a shape of a cross, shown in Fig. 1 by dashed line.

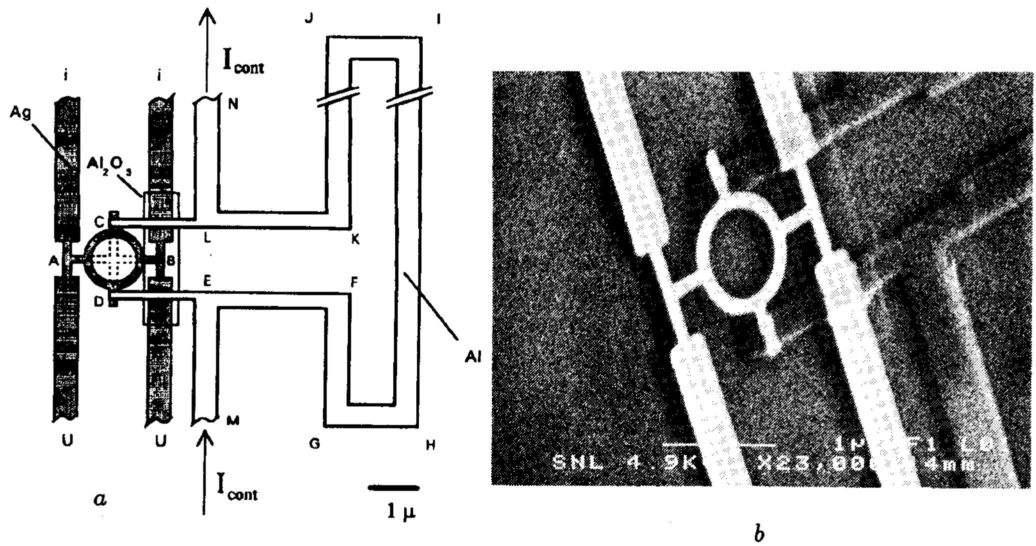

Fig.1. a) The geometry of the experiment. $i-i$ and $U-U$ are current and potential leads to measure the resistance between the points A and B (R_{AB}) of the silver structure. Dashed line shows the geometry of the structure, where the ring was replaced by cross (see text); dc current source is connected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

The structure was defined using the technique described by us previously [2,5]. The substrate was high-purity silicon covered by its 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, while their lengths, AB and CD, for the cross-like structure were 2μm. The diameters of the rings were 1μm. 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 aluminium that had a thickness of 25 nm. Two different wire widths were used to form the rectangular loop, namely 500 and 800 nm. The distances between the centres of the wires forming the loop (GHIJ) were 34μm and 1.4μm for all structures. The lengths of the connectors CK and DF were 4.8μm and the distance between them was 1.6μm (edge to edge). The distances EF and LK were 2.5μm. The widths of CL and DE were 200 nm. The sheet resistance of the silver film was 0.5Ω. This corresponds to a diffusion coefficient of electrons, $D = 10\text{cm}^2/\text{s}$ 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 about 1μm 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 of 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, control current with a density less than $10^5\,\mathrm{A/cm^2}$ through MN. 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, resistance drops ranging from less than 1% to 30% were observed in the different samples. Both drops and rises were noted in the previous experiments [2-4].

Fig. 2 shows a typical example of the dependence of R_{AB} on 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), that was induced by the current, was negligible.

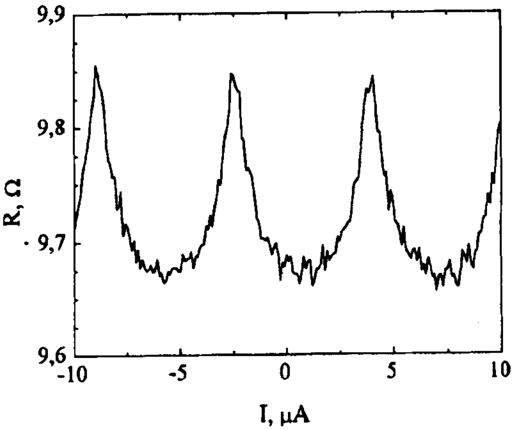

Fig.2. The resistance R_{AB} as a function of the current through the superconducting Al part of the cross-like structure given in Fig. 1 (dashed line), $T = 20$ mK

The dependence of R_{AB} of the same sample on magnetic field at zero current in the superconductor is shown in Fig 3. Fig. 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 control current were similar for both 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 centres 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 the period of $\Delta B = 0.37$ G, modulated by much lower frequencies. The lower modulation envelope has a period of $\Delta B = 28$ G, which corresponds to a flux quantum $\Delta BS_r = \Phi_0 = h/2e$ with S_r equal to the area enclosed by the centre line of the silver ring. The upper modulation envelope has a period of $\Delta B = 14$ G, which corresponds to a flux quantum $\Delta BS_r = \Phi_0/2 = h/4e$. As is seen from Fig. 4, inset (a), the high frequency oscillations have strong second harmonic component near the maximum of lower modulation envelope line. The positions of the extrema of the R_{AB} vs. B curve depended 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 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 minimum at $\Delta B = 0$ and $I = 0$.

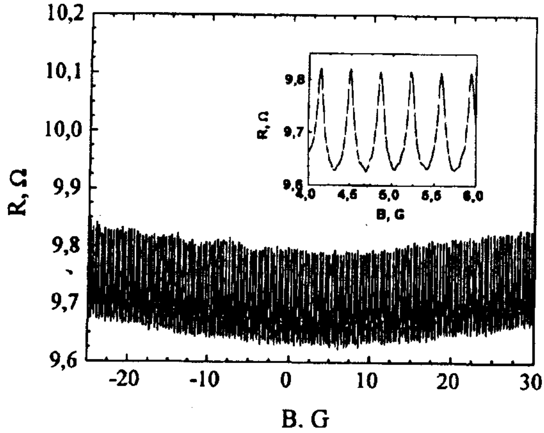

Fig. 3. The resistance R_{AB} versus magnetic field for the cross-like normal structure (dashed line in Fig. 1)

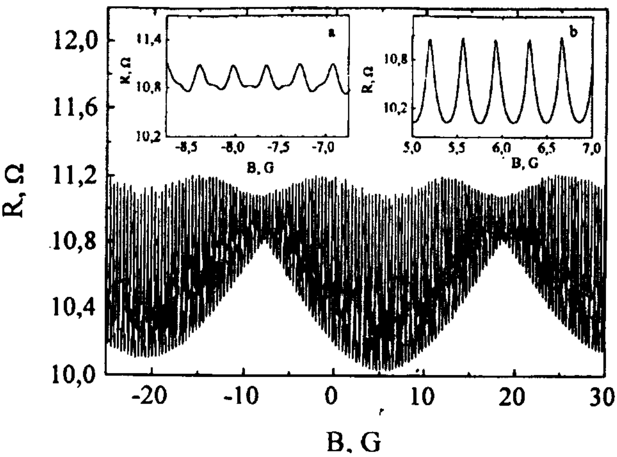

Fig.4. The resistance R_{AB} versus magnetic field for the ring interferometer $T = 20$ mK (compare with Fig. 3.)

The measurements showed that the period of the oscillations with magnetic field, ΔB, did not depend upon the width of the Al wires but was given, within 5%, by the area S defined by the centres of the Al wires. This is in contrast to the period with control current, ΔI. Structures with the same S but different widths of the Al wires gave different ΔI. For the loops with Al wire widths of 800 nm and 500 nm, the periods ΔI were 6.4μA and 2.3μA respectively.

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

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

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

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

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

L_{eff} is the effective self-inductance of the superconductor. It is the sum of a "kinetic" inductance, corresponding to the first term in the right hand side of eq. (1), and a "geometric" inductance given by the second term. I is the current and $\Phi_0 = h/2e = 2\cdot10^{-15}$ Wb.

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

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

Φ is the flux through the area of the Al loop connected to C and D. The flux is enhanced by the Meissner effect in the relatively broad wire and the period in B should be given approximately by the area S (introduced above) 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 constant S) and equals $2\cdot10^{-10}$ Henry and $5.6\cdot10^{-10}$ Henry for the two loops with wire widths of 800 and 500 nm, respectively, which coinsides with the results of our previous work [5].

According to numerical calculations [11] for disordered conductors, which is the case in our experiment, the averaged over a random disposition of the scatterers conductance oscillations should have a period of 2π instead of π periodicity predicted in [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 conductance oscillations at high quasiparticle energies, which experimentally may manifest through the existence of a cross-over temperature, at which the conductance switches from 2π to π periodicity. We have not observed such a cross-over in the temperature range from $T = 0.02$ K up to $T \sim 1$ K. Moreover, the $h/4e$ component in the low frequency side of the oscillation spectrum (corresponding to π-periodicity) decays more rapidly with increasing temperature than $h/2e$-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 maximum at zero phase difference.

A clear-cut theory of the observed general oscillation picture in our ring interferometer is at the moment absent.

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