Pis'ma v ZhETF, vol.64, iss.11, pp.789 - 793

THERMAL EFFECT IN PHASE-PERIODIC CONDUCTANCE OF DISORDERED MESOSCOPIC N/S STRUCTURES

V.T.Petrashov[1], *R.Sh.Shaikhaidarov*$^+$, *I.A.Sosnin*$^{+2)}$

Department of Physics, Royal Holloway, University of London
Egham, Surrey TW20 0EX, U. K.

$^+$*Institute of Microelectronics Technology RAS*
142432 Chernogolovka, Moscow District, Russia

Submitted 31 Oktober 1996

We report measurements of the temperature dependence of the amplitude of phase-periodic conductance oscillations in disordered (diffusive) normal metal (Ag) structures attached to a superconducting (Pb) wire at two points. The amplitude of oscillations exceeds the value of e^2/h by orders of magnitude and reaches its maximum at a temperature corresponding to the Thouless energy. The results support the recent theory [7], taking into account the characteristic energy dependence of the change in the diffusion coefficient of quasiparticles in a normal conductor due to Andreev reflections. The lineshape of the oscillations as a function of superconducting phase difference is found to be extremely sensitive to the quality of N/S interfaces and shows hysteresial behaviour in the interferometers with specially prepared clean interfaces.

PACS: 74.50.+r

In recent years a range of new phenomena has been discovered during experiments on coherent, mesoscopic, normal (N) metal structures in proximity to superconducting (S) islands and/or boundaries [1-6].

The conductance of a normal mesoscopic disordered conductor, to which a superconducting wire is attached at two points, oscillates when the condensate phase difference between the contact points is varied [5]. One of the striking features of the observed oscillations is their unexpectedly large amplitude exceeding the value of e^2/h by several orders of magnitude. In contrast to this, the standard theory predicts that the zero temperature conductance of a disordered system with diffusive electron transport is not affected by penetrating superconductivity and the oscillation is a small mesoscopic effect with "universal" amplitude of order e^2/h. Recently Nazarov and Stoof [7] have proposed an explanation of experimentally observed "giant" oscillations, taking into account the characteristic energy dependence of the change in the diffusion coefficient, D, of quasiparticles in a normal conductor due to Andreev reflections. While the change is negligible at zero energy and at high energy, the value of ΔD at a point separated by a distance L from the N/S interface can reach its maximum value ΔD of the order of D at a quasiparticle energy of the order of hD/L^2. Since the energy interval for propagating quasiparticles is determined by the temperature, this leads to a thermal effect with a maximum in the temperature dependence of the amplitude of oscillations at T^* of the order of the Thouless energy, hD/k_BL^2. The amplitude is predicted to decrease when lowering the temperature below T^*. An alternative mechanism, taking into account particle-hole symmetry breaking due to a small but

---

[1] e-mail: v.petrashov@rhbnc.ac.uk

[2] e-mail: sosnin@ipmt-hpm.ac.ru

finite bias voltage across the structure, has been suggested [8]. That mechanism leads to strong non-linear effects with the maximum of amplitude of oscillations at voltages V of the order of hD/ek_BL^2 across the structure. In this paper we report the first experimental observation of the non-monotonous temperature dependence of the amplitude of phase-periodic oscillations in diffusive Andreev interferometers. The maximum of the amplitude is reached in the temperature range predicted [7]. These results, together with the results of our measurements of voltage-current characteristics of the structures, suggest that the thermal effect mechanism is dominant in real mesoscopic structures. The lineshape was found to depend strongly on the temperature and the quality of the N/S interfaces. In the interferometers with specially prepared clean N/S interfaces we have observed a hysteresial dependence of the resistance on the condensate phase difference, which may be explained using the model suggested [9].

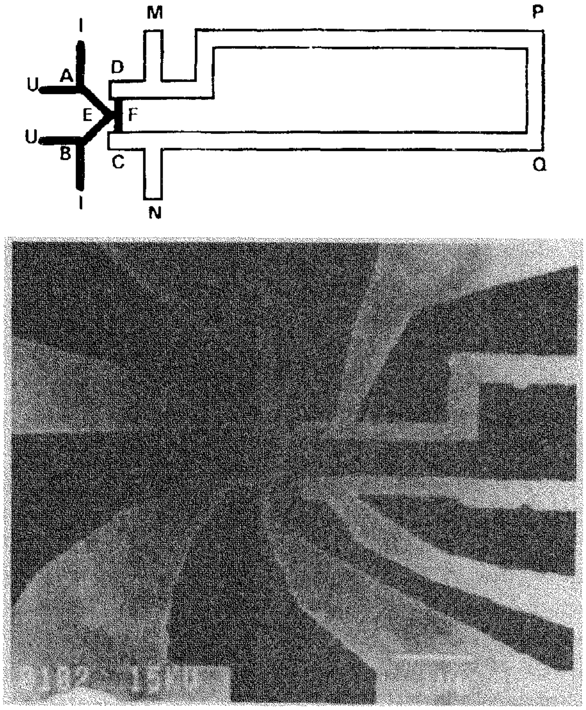

Fig.1. The geometry of the experiment. I-I and U-U are current and potential leads to measure the resistance across A and B of normal (black part) wire. A dc current source is connected to M and N to control the phase difference between C and D. The phase can also be controlled by a magnetic flux through the loop D-P-Q-C

The experimental configuration is shown in Fig. 1. The normal conductor AEB is connected to current leads (I-I) and potential leads (U-U). The conductor has a T-shaped part $DFCE$ which is connected to a superconducting wire $MPQN$. A subcritical control current, I, can be passed through this wire creating a superconducting condensate phase difference, $\Delta\varphi$, between the points C and D. Alternatively, $\Delta\varphi$ can be created by applying a magnetic field perpendicular to the structure.

The structures were fabricated using electron beam lithography and the lift-off technique. A two layer PMMA/PMAA resist was used. The substrate was silicon covered by its native oxide. The normal part of the structure was made of silver. The film thickness was 60 nm, the width of the wire was about 100 nm. The length of normal wire bridging the parts D and C of the superconductor

(Pb) was 400 nm. Two sets of structures of the same geometry and materials were made. The first set was prepared using standard technological procedures [1]. To develop PMMA and PMAA layers, the solutions of toluene in isopropanol and of ethylcellosolveacetate (ECA) in ethanol were used. Prior to the deposition of superconductor (Pb), the structures were cleaned with Ar^+ ions. For the fabrication of the second set, an additional rinsing in deionised water before the ion etching has been included. The measurements were performed at liquid helium temperatures $1.3 < T < 4.2$ K. The resistance across the points A and B, R_{AB}, was about 2.5 Ohm, the resistance of the N/S barrier did not exceed $0.1R_{AB}$ for all structures. The diffusion coefficient $D = 90\,\mathrm{cm}^2/\mathrm{s}$ and a coherence length $\xi_N = 85$ nm at $T = 1.3$ K was calculated using the value of $\rho l = 5.36 \cdot 10^{-12}$ Ω cm^2 (see ref. in Ref. [5]) for silver. The phase breaking length, L_φ, estimated from weak localisation magnetoresistance of co-evaporated films was 1.2 μm.

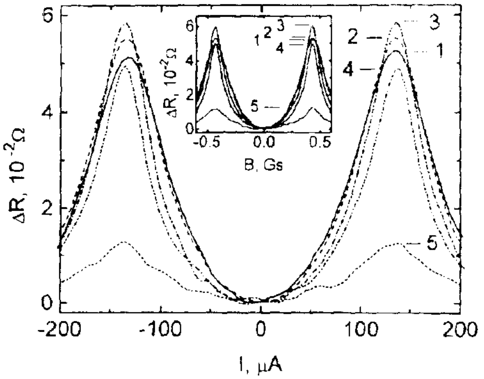

Fig.2. The dependence of the oscillating part of the resistance R_{AB} of Ag/Pb structure shown in Fig.1 on the control current through MN at different temperatures. 1 – T=4.0K, 2 – T=3.6K, 3 – T=3.2K, 4 – T=2.8K, 5 – T=1.3K. The inset shows the dependence of R_{AB} on magnetic field

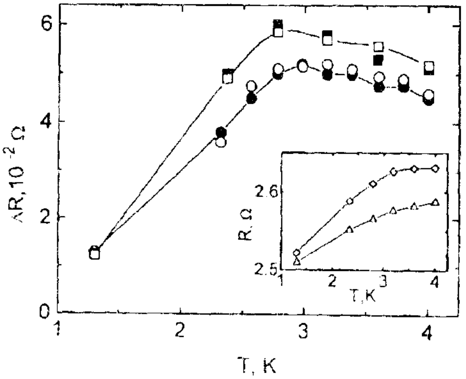

Fig.3. Temperature dependence of the amplitude of oscillations for two structures. Black symbols – for the amplitude vs. control current, empty symbols – for the amplitude vs. magnetic field. Inset: temperature dependence of the resistance R_{AB} (see text) for one of the structures at $\Delta\varphi = \pi$ (upper curve), and $\Delta\varphi = 0$ (lower curve)

Fig.2 shows the dependence of the oscillating part of the resistance of the normal structure, R_{AB}, on the control current through MN at different temperatures for a structure made in the standard way. The applied current through AB did not exceed 1 μA. The resistance R_{AB}, oscillates with a period of $\Delta I = 280$ μA. Similar oscillations are seen as a function of magnetic field (see inset in Fig.2). The oscillation period is $\Delta B = 0.86$ G. This corresponds to a flux quantum $\Delta BS = \varphi_0 = h/2e$ with S equal to the area enclosed by the centres of Pb loop wires that are connected to the points C and D. That means that we observe 2π-periodicity of oscillations, which is consistent with the results obtained at much lower temperatures [4,5]. In both cases the lineshape of oscillations is nonsinusoidal. Fig.3 shows the temperature dependencies of the amplitude of oscillations vs. current and vs. magnetic field for two structures. It is seen that the dependencies are non-monotonous and coincide for the oscillations with magnetic field and current. The position of the maximum was found to be sample-dependent, with a tendency to move to lower temperatures with increase in the sample resistivity. We have also found that the position of the maximum was sensitive to thermocycling of the sample and moved to lower temperatures after each warming up to room temperature, followed by cooling to helium temperature. The I-V curves of the normal parts of all structures were linear up to $500\,\mu$A, the highest current we could achieve. The temperature dependence of the absolute value of the resistance R_{AB}, at different superconducting phase differences for one of the samples is shown in the inset of Fig. 3. The upper and lower curves correspond to $\Delta\varphi = \pi$ and $\Delta\varphi = 0$, respectively. The dependence at $\Delta\varphi = \pi$ saturates at T=3.5 K, while at $\Delta\varphi = 0$ the resistance increase continues up to temperatures higher than T=3.4 K.

While the precision of direct measurements of the N/S barrier resistance, R_b, was not high enough to see the difference between the structures, we have observed drastic changes in the line shape and in the position of the oscillation amplitude maximum for the structures treated with de-ionised water before the ion etch. The position of the maximum shifted to temperatures higher than 4.2 K. An asymmetry in the line shape at temperatures lower than 2.5 K has appeared with hysteresial behaviour of the dependence of R_{AB}, as a function of phase, $\Delta\varphi$, near 1.3 K (see Fig.4). The amplitude of oscillations and the line shape of oscillations at temperatures higher than 2.5 K was close to that shown in Fig.2. The I-V curves were linear in the temperature range investigated.

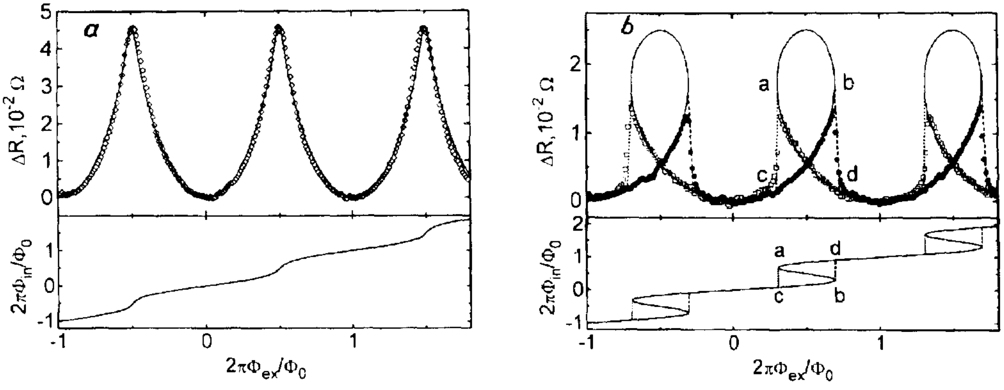

Fig.4. Oscillating part of the resistance, R_{AB}, as a function of phase in the interferometer with clean N/S interfaces at different temperatures (upper parts of figures (a) and (b)), symbols – experiment, solid lines - calculations using equations (1) and (2); (a) T=3.75 K, (b) T=1.3 K; black circles – ΔR vs. external magnetic flux, Φ_{ex}, during the flux increase from $-\Phi_0$ to $+\Phi_0$, squares – the dependence for change of flux in opposite direction. The lower parts of figures show the dependence of phase difference between points C and D (see Fig.1 and eq. (1)) vs. external flux

Our results on the temperature dependence of the amplitude of oscillations are consistent with the prediction of the theory of the thermal effect. The effect arises from the energy dependent change of the diffusion coefficient D, of quasiparticles due to Andreev reflections. In structures similar to ours, the theory predicts maximum in the temperature dependence of the amplitude of oscillations at T^* of the order of hD/k_BL^2, where L is the distance between the point E and the nearest superconductor (see Fig.1). For our structure with $L = 4 \cdot 10^{-5}$ cm an estimate gives T^*=2.6 K, which is in excellent agreement with the theory of Nazarov and Stoof. As for particle-hole symmetry-breaking we believe that voltages across the structure were too low to observe the effect. That conclusion is supported by the I-V characteristics measurements and estimates of the voltages.

To explain the result shown in Fig.4 we have to take into account that the supercurrent can flow between the points C and D with an associated critical current. The phase difference, $\Delta\varphi$, between the points C and D is given by:

$$\Delta\varphi = \varphi_B - 2\pi(\mathcal{L}I_c/\Phi_0)\sin(\Delta\varphi), \tag{1}$$

where $\varphi_B = 2\pi\Phi_{ex}/\Phi_0$, $\Delta\varphi = 2\pi\Phi_{in}/\Phi_0$, Φ_{ex} is the applied magnetic flux, Φ_{in} is the resulting flux, and $\mathcal{L}$ is the selfinductance of the loop. If we assume that the actual relation between the oscillating part of the resistance and the phase is given by [9]

$$\Delta R = -R_0\cos(\Delta\varphi) \tag{2}$$

the experimental dependence ΔR (Φ_{ex}/Φ_0) can be nicely explained (see Fig.4).

In conclusion, the thermal effect gives an excellent account for the phase-periodic conductance oscillations in normal metal/superconductor mesoscopic structures in the case of the classical proximity effect. The lineshape of the oscillations including hysteresial behaviour can be explained with the screening effects being taken into account.

We thank B. J. Van Wees, C. Lambert, A. Zaikin, A. Volkov, and Yu. Nazarov for stimulating discussions. This work is supported by INTAS-94-3862 Grant, the Russian National Nanostructure programs (grants 1-20 and 104D/57) and Russian Fund for Fundamental Research (grant 95-02-05495), and Nanotechnology Initiative of Royal Holloway College of the University of London.

---

1. V.T.Petrashov, V.N.Antonov, P.Delsing, and T.Claeson. Phys. Rev. Lett. **70**, 347 (1993).
2. V.T.Petrashov, V.N.Antonov, S.V.Maksimov, and R.Sh.Shaikhaidarov. Pis'ma Zh. Teor. Fiz. **58**, 48 (1993), [JETP Lett. **58**, 49 (1993)].
3. H.Pothier et al. Phys. Rev. Lett. **73**, 2488 (1994).
4. V.T.Petrashov, V.N.Antonov, P.Delsing, and T.Claeson. Pis'ma Zh. Teor. Fiz. **60**, 589 (1994), [JETP Lett. **60**, 606 (1994)].
5. V.T.Petrashov, V.N.Antonov, P.Delsing, and T.Claeson. Phys. Rev. Lett. **74**, 5268 (1995).
6. P.G.N. de Vegvar, T.A.Fulton, W.H.Mallison, and R.E.Miller, Phys. Rev. Lett. **73**, 1416 (1994).
7. Yuli V.Nazarov and T.H.Stoof. Phys. Rev. Lett. **76**, 823 (1996).
8. A.Volkov, N.Allsopp, C.J.Lambert. J. Phys. Condens. Matter **8**, L1-L6 (1996).
9. B.J. Van Wees, S.G. den Hartog, and A.F.Morpurgo, Phys. Rev. Lett. **76**, 1402 (1996).