Segment of an inhomogeneous mesoscopic loop as a dc power source

S.V. Dubonos, V.I. Kuznetsov, and A.V. Nikulov
Institute of Microelectronics Technology and High Purity Materials,
Russian Academy of Sciences, 142432 Chernogolovka, Moscow District, RUSSIA.

A dc voltage changed periodically with magnetic field is observed on segments of asymmetric aluminum loop without any external dc current at temperatures corresponded to superconducting transition. According to this experimental result a segment of the loop is a dc power source. A possibility of a persistent voltage on segments of an inhomogeneous normal metal mesoscopic loop follows from this result.

Introduction

It is known that the persistent current (i.e. a direct current in the thermodynamic equilibrium state) can flow along a mesoscopic loop because of the quantization of the momentum circulation $\int dl p = \int dl (mv + (q/c)A) = m \int dl v + (q/c)\Phi = n2\pi\hbar$ The persistent current $I_p = sj_p$ in normal metal mesoscopic loops was predicted more than 30 years ago [1] and was observed not so long ago [2]. It is known also that a potential difference $V = (\langle \rho >_1 - \langle \rho >_2) l_s j$ should be observed on a segment $l_s$ of an inhomogeneous conventional loop at a current density $j$ along the loop if the average resistivity along the segment $\langle \rho >_1 = \int l_s dl \rho / l_s$ differs from the one along the loop $\langle \rho >_2 = \int l_s dl \rho / l$. Therefore a possibility of a persistent voltage can be assumed at a segment of an inhomogeneous mesoscopic loop at $j_p \neq 0$.

The latter, i.e. $j_p \neq 0$, can be only if the mean free path of electrons is not smaller than the length $l$ of loop circumference and the temperature is lower than the energy difference between adjacent permitted states $p^2(n = 1)/2m - p^2(n = 0)/2m = 2\pi^2\hbar^2/ml^2$. This difference is not large for electrons. For example, at $l \approx 4 \mu m$, the $2\pi^2\hbar^2/ml^2$ value corresponds $T \approx 1 K$. Therefore it is enough difficult to observe the persistent current in normal metal loop [2].

It is more easier to observe the persistent current in superconducting loop since the mean free path of superconducting pairs is infinite and the energy difference between adjacent permitted states is much higher than in normal metal loop. First experimental evidence of the persistent current at non-zero resistance - the Little-Parks experiment [3] was made as long ago as 1962. In the present work the dc voltage proportional to the $I_p$ is observed on segments of an asymmetric superconducting loop in accordance with the analogy with a conventional inhomogeneous loop.

1. EXPERIMENTAL DETAILS

The dependencies of the dc voltage $V$ on the magnetic flux $\Phi \approx BS$ of some round symmetric and asymmetric Al loops (see Fig.1) with a diameter $2r = l/\pi = 1, 2$ and $4 \mu m$ and a linewidth $w = 0.2$ and $0.4 \mu m$ at the dc measuring current $I_m$ and different temperature close to $T_c$ were measured. Here $B$ is the magnetic induction produced by a superconducting coil; $S = \pi r^2$ is the area of the loop. The Al microstructures Fig.1 are prepared using an electron lithograph developed on the basis of a JEOL-840A electron scanning microscope. The sheet resistance $R_s \approx 0.5 \Omega/\square$ at $4.2 K$, the resistance ratio $R(300K)/R(4.2K) \approx 2$ and the midpoint of the superconducting resistive transition $T_c \approx 1.24 K$.

2. EXPERIMENTAL RESULTS

The voltage oscillations corresponded to the conventional Little-Parks oscillations were observed on the contacts $V_3$ of the symmetric loop [4]. These resistance oscillations $R_1(\Phi/\Phi_0) = V_3/I_1$ observed in the temperature region of the superconducting transition (i.e. at $T \approx T_c$) are explained by the $T_c$ oscillations $T_c(\Phi/\Phi_0)$ because of the oscillation of the persistent current $I_p(\Phi/\Phi_0)$ [5]. Here $\Phi_0 = 2\pi \hbar c / q = \pi \hbar c / e$ is the flux quantum for superconducting pair, $q = 2e$. The voltage $V_3 = 0$ at the
measuring current \( I_1 \equiv I_m = 0 \) whereas the voltage oscillations \( V(\Phi/\Phi_0) \) are observed on the contacts \( V_2 \) and \( V_3 \) of the asymmetric loop at \( I_2 \equiv I_m = 0 \) Fig.2.

The apparent (with amplitude \( \Delta V \geq 0.1 \mu V \)) oscillations without an external dc current were observed in a narrow temperature region \( \Delta T \approx 0.01 K \) corresponds to the bottom of the resistive transition. Its amplitude increases (up to \( \Delta V \approx 1.2 \mu V \)) with temperature lowering down to the lowest temperature \( \approx 1.23 K \) we could reach.

3. POWER SOURCE

The observation of the voltage oscillations in the asymmetric loop and its absence in the symmetric loop conform to the analogy with a conventional loop. Although the oscillations \( I_p(\Phi/\Phi_0) \) [5] take place in the both cases in the symmetric loop \( < \rho >_s = < \rho >_l \) and therefore \( V = 0 \) at \( I_m = 0 \). The difference of \( < \rho >_s \) from \( < \rho >_l \) in the asymmetric loop is caused by the additional potential contacts \( V_3 \).

There is an important difference from the conventional loop where the potential difference appears in accordance with the Ohm’s law \( E = -\nabla V - (1/c)dA/dt = \rho P \). The voltage on Fig.2 is observed without the Faraday’s voltage \( dA/dt = (1/l)d\Phi/dt = 0 \) and consequently the electric field \( E = -\nabla V \) and the persistent current \( I_p \) should have opposite directions in a segment because \( \int dl \nabla V = 0 \), i.e. according to the result presented on Fig.2 a segment of the asymmetric loop is a dc power source at \( \Phi \neq n\Phi_0 \) and \( \Phi \neq (n + 0.5)\Phi_0 \). The power \( W_{load} = V^2R_{load}/(R_{load} + R_s)^2 \) can be obtained on a load with the resistance \( R_{load} \). Because the resistance of the segment \( R_s \leq R_{sn} \approx 15 \Omega \) then \( W_{load} = V^2/4R_s \geq 2 \times 10^{-14} Wt \) at \( R_{load} = R_s \) and \( V \approx 1 \mu V \).

4. WHAT ENERGY IS TRANSFORMED IN THE POWER \( V I_p \)?

It should be noted that already the classical Little-Parks experiment is evidence of the dc power source. According to this experiment the persistent current \( I_p \neq 0 \) is observed at non-zero resistance \( R_l > 0 \) along the loop and consequently an energy dissipation with the power \( R_l I_p^2 \) takes place. The persistent current is maintained in spite of this dissipation because of reiterated changes of the momentum circulation of superconducting pairs at switching of the loop between superconducting states with different connectivity [6].

Because of the quantization the momentum circulation of pair \( \int dl p = 2m \int dv + (2e/c)\Phi \) changes from \( (2e/c)\Phi \) to \( n2\pi\hbar \) at each closing of superconducting state. The reiterated changes \( n2\pi\hbar - (2e/c)\Phi = 2\pi\hbar(n - \Phi/\Phi_0) \) with an average frequency \( \omega \) is equivalent of the action of the average force \( \int F = 2\pi\hbar(\pi - \Phi/\Phi_0)\omega \) which maintains the circulating current instead of the Faraday’s voltage. \( \pi \) is the thermodynamic average of the quantum number \( n. \ \pi - \Phi/\Phi_0 = (n - \Phi/\Phi_0)_{min} \) when \( \Phi \) is not close to \( (n + 0.5)\Phi_0 \) and \( \pi - \Phi/\Phi_0 = 0 \) at \( \Phi = (n + 0.5)\Phi_0 \), where the integer number \( n \) \( (n - \Phi/\Phi_0)_{min} \) corresponds to a minimum possible value \( |n - \Phi/\Phi_0| \).

The quantum force \( F_q \) is not localized in principle in any loop segment [6], i.e. \( F_q = \int dl F (l/l) \). Therefore a potential difference \( V = (\pi\hbar\omega/e)(\pi - \Phi/\Phi_0)(l/l) \) should be observed on a segment \( l_s \) remaining in superconducting state when other segment is switched in normal state with the frequency \( \omega \). This relation explains the observed voltage oscillation Fig.2. Loop segments are switched in normal state at \( T \approx T_C \) by thermal fluctuations and an external electric noise. Consequently the energy of thermal fluctuations or an external electric noise is transformed in the power \( V I_p \) observed in our work.

5. CONCLUSION

The observation of the voltage oscillations Fig.2 is evidence of a possibility of an analogous observation on segments of inhomogeneous normal metal mesoscopic loop. There is an important question: thermal fluctuations or an external noise induce the dc voltage. The temperature dependence of the amplitude \( \Delta V(T) \) observed in our work is evidence of the latter. But it is enough obvious that thermal fluctuations can also induce the dc voltage on segments of inhomogeneous mesoscopic loops [6].

Acknowledgements

This work was financially supported by the Presidium of Russian Academy of Sciences in the Program “Low-
Dimensional Quantum Structures

[1] I. O. Kulik, *Pisma Zh. Eksp. Teor. Fiz.* 11, 407 (1970) (*JETP Lett.* 11, 275 (1970)).

[2] L. P. Levy et al. *Phys. Rev. Lett.* 64, 2074 (1990); V. Chandrasekhar et al. *idid.* 67, 3578 (1991); E. M. Q. Jariwala et al. *idid.* 86, 1594 (2001).

[3] W. A. Little and R. D. Parks, *Phys. Rev. Lett.* 9, 9 (1962).

[4] S. V. Dubonos, V. I. Kuznetsov and A. V. Nikulov, [physics/0105059](physics/0105059).

[5] M. Tinkham, *Introduction to Superconductivity*. McGraw-Hill Book Company (1975).

[6] A. V. Nikulov, *Phys. Rev. B* 64, 012505, (2001)