Quantum oscillations of the rectified voltage and the critical current of asymmetric mesoscopic superconducting loops

V.L. Gurtovoi, S.V. Dubonos, A.V. Nikulov, N.N. Osipov, and V.A. Tulin
Institute of Microelectronics Technology and High Purity Materials, Russian Academy of Sciences, 142432 Chernogolovka, Moscow District, RUSSIA.

The current-voltage curves and magnetic dependence of the critical current of asymmetric superconducting loops are measured. It was found that sign and value of the asymmetry of the current-voltage curves changes with value of magnetic field, periodically for single loop and system of identical loops. The obtained results allow to explain the quantum oscillation of the dc voltage, observed below superconducting transition in the previous works, as rectification of ac current or noise.

Introduction

The Bohr’s quantization \( \oint dl p = n 2 \pi \hbar \) postulated for the explanation of the stable electron orbits in atom is the cause of various quantum phenomena [1] on the mesoscopic level. One of the most wonderful phenomena is the persistent current \( I_p \) observed in normal metal [2], semiconductor [3] and superconductor [4,5] mesoscopic loop \( l \). Its value and sign vary periodically with value of magnetic flux \( \Phi \) inside the loop since the canonical momentum \( p = mv + qA \) and therefore permitted values of velocity circulation \( \oint dl v = 2 \pi \hbar (n - \Phi/\Phi_0) \), where \( \Phi_0 = 2 \pi \hbar / q \) is the flux quantum. For the first time the persistent current \( I_p(\Phi/\Phi_0) \propto n - \Phi/\Phi_0 \) was predicted [4] and observed [5] in superconductor structure. Later the like periodical dependence \( I(\Phi/\Phi_0) \propto n - \Phi/\Phi_0 \) was predicted [6] and observed [2,3] in non-superconducting mesoscopic structures. Recently the quantum oscillations of the dc potential difference \( V_{dc}(\Phi/\Phi_0) \propto I_p(\Phi/\Phi_0) \) were observed on segments of asymmetric superconducting loops [7,8]. It is important to investigate the cause of this phenomenon in order to clear up a question: "Could a like one be observed in normal metal or semiconductor asymmetric mesoscopic loops?"

It was found that the quantum oscillations \( V_{dc}(\Phi/\Phi_0) \) can be observed without an evident power source near superconducting transition [7], whereas at a lower temperature they can be induced by an external ac current when its amplitude exceeds a critical value [8]. It was assumed in [8] that the asymmetry of the current-voltage curves and its periodical change with magnetic field are the cause of the \( V_{dc}(\Phi/\Phi_0) \) observed in the both cases. In order to verify this assumption the current-voltage curves of asymmetric aluminum loops and its change with magnetic field are investigated in the present work.

1. EXPERIMENTAL

Investigated structures with thickness \( d = 40 - 70 \, \text{nm} \) consisted of asymmetric aluminum round loops (rings) with semi-ring width \( w_n = 200 \, \text{nm} \) and \( w_w = 400 \, \text{nm} \) for narrow and wide parts, respectively, Fig.1. They were fabricated by thermally evaporated on oxidized Si substrates, e-beam lithography and lift-off process. Two single loops with diameter \( d = 4 \, \mu m \), width of the current stripe, see Fig.1, \( w_{con} = 0.6 \, \mu m \) and \( w_{con} = 0.7 \, \mu m \), two systems of identical 20 loops with \( d = 4 \, \mu m \), \( w_{con} = 0.4 \, \mu m \) and \( w_{con} = 1 \, \mu m \) and two systems of double loops with different diameter \( d = 4 \, \mu m \) and \( d = 3 \, \mu m \) were investigated. For this structures, the sheet resistance was \( 0.2 \div 0.5 \, \Omega/\Omega \) at 4.2 K, the resistance ratio \( R(300K)/R(4.2K) = 2.5 \div 3.5 \), and critical temperature was \( T_c = 1.24 \div 1.27 \, K \).

The current-voltage curves and magnetic dependencies of the critical current \( I_{c+}, I_{c-} \) measured in opposite directions on the loop, shown on Fig.1, and systems of such loops were investigated. Magnetic field direction was perpendicular to the ring’s plane. All signals were digitized by a multi-channel 16-bit analog-digital converter card.

FIG. 1: An SEM photo of the asymmetric aluminum round loop (ring) used for the measurements. \( w_{con} \) is the width of the Al stripes used as current contacts.
2. RESULTS

Three types of the current-voltage curves are observed: 1) smooth and reversible one; 2) irreversible, with smooth transition into the resistive state; 3) irreversible, with jump increase of the resistance of the whole structure at \( I = I_{c+} \) or \( I_{c-} \). The first type is observed near superconducting transition \( T_c \), the second one in an intermediate region of temperature and the third one at low temperature. We have found that the critical current \( I_{c+}, I_{c-} \) both of single loops and systems of identical loops is periodical function of magnetic field with period corresponding to the flux quantum \( \Phi_0 \), Fig.2. The magnetic dependencies of the critical current \( I_{c+}(\Phi/\Phi_0) \) and \( I_{c-}(\Phi/\Phi_0) \) measured in opposite directions are similar, Fig.2, for all investigated structures. The anisotropy of the magnetic periodical dependencies \( I_{c,an} = I_{c+} - I_{c-} \) Fig.2, is a consequence of a shift \( \Delta \phi \) of these dependencies one relatively another, \( I_{c+}(\Phi/\Phi_0) = I_{c-}(\Phi/\Phi_0) + \Delta \phi \).

The similarity of the magnetic periodical dependencies of anisotropy of the critical current \( I_{c,an}(\Phi/\Phi_0) \) and the dc voltage \( V_{dc}(\Phi/\Phi_0) \) induced by an external ac current, Fig.2, corroborates the explanation [8] of the quantum oscillations of the dc voltage observed on segments of asymmetric superconducting loops as a consequence of rectification of the ac current [8] or noise [7]. The similarity of the magnetic dependencies \( V_{dc}(B) \) and \( -I_{c,an}(B) \) is observed also on double loops with different diameter, Fig.3, although these dependencies are not periodical in this case [9].

The rectified voltage \( V_{dc} = \Theta^{-1} \int_0^\infty dt V(I_{ext}(t)) \) appears when the amplitude \( I_0 \) of the external current \( I_{ext}(t) = I_0 \sin(2\pi ft) \) exceeds either \( I_{c+} \) or \( I_{c-} \) and its absolute value \( |V_{dc}| \) decreases when \( I_0 \) exceeds both \( I_{c+} \) and \( I_{c-} \). The amplitude \( V_A \) of the quantum oscillations \( V_{dc}(\Phi/\Phi_0) \) has a maximum value [8,9] \( V_{A,max} \) at \( \min(I_{c+},I_{c-}) < I_{0,max} < \max(I_{c+},I_{c-}) \). Our measurements have shown that the relation \( V_{A,max}/I_{0,max} \) is high at a low temperature \( T < 0.98T_c \), where the current-voltage curves of the third type are observed: \( V_{A,max}/I_{0,max} \approx 0.8 \Omega \) for a single loop with the resistance in the normal state \( R_n = 3.3 \Omega \) and \( V_{A,max}/I_{0,max} \approx 20 \Omega \) for a systems of identical 20 loops with \( R_n = 92 \Omega \). The high efficiency of rectification is conditioned by the irreversibility of the current-voltage curves and it decreases near superconducting transition.

The conclusion that the potential difference \( V_{dc}(\Phi/\Phi_0) \) observed at \( T < T_c \) on asymmetric superconducting loop is result of rectification of an ac current or noise does not exclude a like phenomenon in normal metal or semiconductor asymmetric loops. The asymmetry of the current-voltage curves and \( I_{c+}(\Phi/\Phi_0), I_{c-}(\Phi/\Phi_0) \) is consequence of the persistent current \( I_p(\Phi/\Phi_0) \) which is observed not only at \( T < T_c \) but also at \( T \approx T_c \) and even \( T > T_c \) [5] where \( R_I > 0 \). One can expect \( V(\Phi/\Phi_0) = R_{asym}I_p(\Phi/\Phi_0) \) at \( I_p \not= 0 \) and \( R_I \not= 0 \) by analogy with the case \( V = R_{asym}I_p(I_0-I_s/l) \) of conventional circular current \( I = R_I^{-1}\int pt\,dl/E \) induced by the Faraday’s voltage \( \int pt\,dl/E = -\partial\Phi/\partial t \) in an asymmetric loop with the segment resistance \( R_{ls}/l \not= R_1/l \).

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