Quantum Oscillations of the Critical Current of Asymmetric Aluminum Loops in Magnetic Field

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Abstract. The periodical dependencies in magnetic field of the asymmetry of the current-voltage curves of asymmetric aluminum loop are investigated experimentally at different temperatures below the transition into the superconducting state $T < T_c$. The obtained periodical dependency of the critical current on magnetic field allows to explain the quantum oscillations of the dc voltage as a consequence of the rectification of the external ac current and to calculate the persistent current at different values of magnetic flux inside the loop and temperatures.

Keywords: Mesoscopic superconductor loop, persistent current, quantum oscillations.

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INTRODUCTION

The persistent current $I_p = s2e_n v_s$ should flow along circumference of a superconductor loop $l$ with thin section $s < \lambda L^2$ at $\Phi \neq n\Phi_0$ since the state with zero velocity of superconducting pairs $v_s = 0$ is forbidden when the magnetic flux $\Phi$ inside $l$ is not divisible by the flux quantum $\Phi_0 = h/2e$ [1]. Its equilibrium value and sign $<I_p> = s2e_n <v_s> \propto <n> - \Phi/\Phi_0$ vary periodically with $\Phi$ [1]. The Little-Parks resistance oscillations $R_l(\Phi/\Phi_0)$ [2] observed in the loop [3] is experimental evidence of $I_p \neq 0$ at non-zero resistance $R_l > 0$. According to an analogy with the conventional circular current a dc potential difference $V(\Phi/\Phi_0) \propto I_p(\Phi/\Phi_0) \propto <n> - \Phi/\Phi_0$ may be expected to be observed on segments of asymmetric superconductor loop at $R_l > 0$. Such quantum oscillations of the dc voltage were observed on segment of asymmetric aluminum loops [4,5] and much before on a double Josephson point contact [6]. The dc voltage $V(\Phi/\Phi_0)$ observed near the critical temperature $T_c$ [4,6] can be induced by switching of the loop between superconducting states with different connectivity [7,8]. The quantum oscillations $V(\Phi/\Phi_0)$ induced at lower temperatures by an external ac current [5] may be interpreted as a result of the rectification because of asymmetry of the current-voltage curves sign and value of which are periodical function of $\Phi$. The results of measurements of this periodical change of the asymmetry of the current-voltage curves with value of magnetic flux $\Phi$ inside asymmetric aluminum loop at different temperatures are presented in this work.

FIGURE 1. SEM image of a typical asymmetric aluminium rings.

EXPERIMENTAL DETAILS AND RESULTS

Microstructures consisting of asymmetric Al rings with semi-ring width $w_n = 200$ nm and $w_w = 400$ nm for the narrow and wide parts, respectively, see Fig.1,
were investigated. 4 μm diameter single asymmetric superconductor ring (ASR) and 20 ASR structures, see Fig.1, were fabricated by e-beam lithography and lift-off process of film d = 45-50 nm in thickness, thermally evaporated on oxidized Si substrates. For these structures, the sheet resistance was 0.23 Ω/□ at 4.2 K, the resistance ratio R(300K)/R(4.2K)=2.7, and the critical temperature was T_c = 1.24-1.27 K.

Current -Voltage Curves

The structure as a whole jumps into the resistive state R > 0 (at a low temperature T < 0.995T_c) when the current density exceeds the critical value j_c in any of its segment and the irreversibility of the current-voltage curves is observed at T < 0.99 T_c. The value of its segment and the irreversibility of the current- voltage curves is observed at T < 0.99T_c. The value of the external current I_ext corresponding to this jump to the state with R > 0 is measured as the critical current |I_{ext}|c of the structure.

![FIGURE 2. Quantum oscillations of the critical current |I_{ext}(Φ/Φ_0)| of system of 18 asymmetric Al loops with w_{ext} = 400 nm < w_n + w_w measured in opposite directions |I_{ext}|c, |I_{ext}|c at T = 0.978 T_c. The quantum oscillations of the dc voltage V(Φ/Φ_0) induced by the external ac current with the frequency f = 40 kHz and the amplitude 7 μA are shown also.](image)

Periodical Dependence of |I_{ext}(Φ/Φ_0)|

Our measurements have revealed the periodical magnetic dependencies |I_{ext}(Φ/Φ_0)| of both single rings and systems of rings with both w_{con} < w_n + w_w, see Fig.2, and w_{con} ≥ w_n + w_w. These periodical dependencies may be explained as a consequence of superposition of the external I_{ext} and persistent I_p(Φ/Φ_0) currents. The current density in the narrow j_n and wide j_w semi-rings is determined by both the I_{ext} and I_p currents: j_n = I_{ext}/d(w_n + w_w) ± I_p/dw_n and j_w = I_{ext}/d(w_n + w_w) ± I_p/dw_w [5]. The summation “+” takes place when the direct I_{ext} and circular I_p currents have the same direction in the semi-rings, see Fig.1. The current density mounts the critical value j_c first of all in the narrow semi-rings at |I_{ext}|c = d(w_n + w_w)/(j_c - I_p/w_w), in the wide ones at |I_{ext}|c = d(w_n + w_w)/(j_c - I_p/w_w) or in the stripes connecting the rings at |I_{ext}|c = d w_{con} j_c depending on the I_{ext} and I_p directions and the j_p/w_w values.

Our results of the measurement of |I_{ext}(Φ/Φ_0)| are evidence of the periodical dependence not only value but also sign of I_p(Φ/Φ_0) since the |I_{ext}(Φ/Φ_0)| value depends on the I_{ext} direction, |I_{ext}|c+, |I_{ext}|c- of the current-voltage curves are asymmetric, at some Φ/Φ_0 values, see Fig.2. For example |I_{ext}|c+ (at the right I_{ext} direction) has a minimum value at Φ/Φ_0 = 0.2 ± n whereas |I_{ext}|c- (at the left I_{ext} direction) the minimum is observed at Φ/Φ_0 = 0.8 ± n, see Fig.2. This means that the persistent current has the clockwise direction at Φ/Φ_0 = 0.2 ± n and the counter-clockwise one at Φ/Φ_0 = 0.8 ± n since the minimum of |I_{ext}|c is observed when the I_{ext} and I_p have the same direction in the narrow semi-rings, see Fig.1. The experimental dependencies |I_{ext}(Φ/Φ_0)|, |I_{ext}(Φ/Φ_0)| obtained in our work allow to explain the quantum oscillations of the dc voltage V(Φ/Φ_0) as consequence of the rectification and to calculate the I_p(Φ/Φ_0;T) dependencies at T < T_c.

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