Quantum oscillations of the critical current of asymmetric superconducting rings and systems of the rings

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The quantum oscillations in magnetic field of the critical current of asymmetric superconducting rings with different widths of the half-rings are shifted to opposite sides for measurement in the opposite direction. The value of this shift found before equal half of the flux quantum for single ring with radius 2 μm has smaller value at lower critical current and for system of the rings with smaller radius.

Introduction

Quantum mechanics was developed for description of paradoxical phenomena observed on the atomic level with typical size < 1 nm = 10⁻⁹ m. In our everyday word with typical size > 0.1 nm = 10⁻⁴ m quantum phenomena are not observed. One may say that nanostructures appertain to a region of boundary between the quantum and classical worlds. For example, according to the Bohr’ quantization of the angular momentum of electron rψ = mνω = ħn postulated in 1913 the energy difference between permitted states Eₙ₊₁,n = mv²/2 - mvω/2 ≈ h²/2m² ≈ 5.510⁻²¹ J ≈ k_B 400 K at the orbit radius r ≈ 1 nm and Eₙ₊₁,n ≈ k_B 0.0004 K at r ≈ 1 μm = 1000 nm. Therefore atom orbits with r < 1 nm are stable at the room temperature T ≈ 300K whereas the persistent current, the quantum phenomena connected with the Bohr’ quantization, can be observed in semiconductor [1] and normal metal [2] ring with r ≈ 1 μm only at very low temperature T < 1 K. In the rings with radius r ≈ 10 nm made recently [3] this phenomenon was observed up to T ≈ 4.2 K.

The persistent current is observed because of the influence of the magnetic vector potential A on the phase ϕ of the wave function Ψ = |Ψ|exp iϕ the gradient of which ∇ϕ is proportional to the canonical momentum ħ∇ϕ = p = mv + qA of a particle with the mass m and the charge q. The minimum permitted value of the velocity ħ/m = 0.66 × 10⁻²⁵ m/s, therefore atom orbits with r ≈ 1 μm only at very low temperature T < 1 K. In the rings with radius r ≈ 10 nm made recently [3] this phenomenon was observed up to T ≈ 4.2 K.

1. QUANTUM OSCILLATIONS OF THE PERSISTENT CURRENT

The energy difference between permitted states of any real superconductor ring ΔEₙ₊₁,n >> k_BT since superconducting condensate moves as whole and superconducting pairs cannot change the integer quantum num-

FIG. 1: Magnetic field dependencies of the critical current of a single asymmetric ring with radius r ≈ 2 μm and widths of the half-rings w₁ = 0.3 μm and w₂ = 0.2 μm measured in the positive Iₚ⁺ (solid lines) and negative Iₚ⁻ (black squares) directions at T = 0.986T_c (I_c(T) = 4.3 μA); T = 0.990T_c (I_c(T) = 2.5 μA) and T = 0.996T_c (I_c(T) = 0.6 μA). T_c = 1.294 K. The Φᶜ/Φ₀ dependence for T = 0.996T_c is vertically shifted on -0.1 μA. The period of oscillations in magnetic field H₀ = Φ₀/S = 1.44 Oe corresponds to the rings area S = πr² = 14.4μm² and the radius r ≈ 2.1 μm.

for the permitted value of the persistent current corresponding to minimum energy E₀ ∝ (n - Φ/Φ₀)² changes between -1/2 and 1/2 with the Φ variation from (n + 0.5)Φ₀ to (n + 1 + 0.5)Φ₀ and jumps from 1/2 to -1/2 at (n + 0.5)Φ₀ [6]. The state with minimum energy gives predominant contribution to the thermodynamic average value T_p. This value equals zero T_p = 0 not only at Φ = nΦ₀ but also at Φ = (n + 0.5)Φ₀ where the persistent current I_p have equal magnitude and opposite direction in the two states n - Φ/Φ₀ = ±1/2. In agreement with (1) the magnetization M ∝ T_p [5] and

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the rectified voltage $V_{dc} \propto |T_p| [7,8]$ equal zero at $\Phi = n \Phi_0$ and $\Phi = (n + 0.5) \Phi_0$. The Little-Parks oscillations of the resistance $\Delta R \propto |T_p|^2 \propto (n - \Phi/\Phi_0)^2$ have minimum at $\Phi = n \Phi_0$ and maximum at $\Phi = (n + 0.5) \Phi_0 [9]$.

2. SHIFT OF THE CRITICAL CURRENT OSCILLATIONS MEASURED ON ASYMMETRIC RINGS

The magnetic dependencies of the critical current $I_c = I_{c,0} - 2 |I_p|$ measured on symmetric ring [10] agree also with the persistent current oscillations (1) predicted with the universally recognized quantum formalism. The maximum of $I_c(\Phi/\Phi_0)$ are observed at $\Phi = n \Phi_0$ and minimum at $\Phi = (n + 0.5) \Phi_0$ [10]. But we have discovered that the $I_{c,+}(\Phi/\Phi_0)$ and $I_{c,-}(\Phi/\Phi_0)$ oscillations of the critical current measured on asymmetric rings with different widths of the half-rings are shifted to opposite sides for measurement in the opposite direction [10]. This shift results to the anisotropy of the critical current $I_{c,n}(\Phi/\Phi_0) = I_{c,+}(\Phi/\Phi_0) - I_{c,-}(\Phi/\Phi_0) = I_c(\Phi/\Phi_0 + \Delta \phi/2) - I_c(\Phi/\Phi_0 - \Delta \phi/2) \neq 0$ explaining the rectification effect [8] observed on asymmetric superconducting rings [7]. But the observation of the $I_{c,+}(\Phi/\Phi_0)$, $I_{c,-}(\Phi/\Phi_0)$ maximums at $\Phi = (n \pm \Delta \phi/2) \Phi_0$ and their minimums at $\Phi = (n + 0.5 \pm \Delta \phi/2) \Phi_0$ is in an irreconcilable contradiction with the prediction (1) of the universally recognized quantum formalism. Because of possible fundamental importance of this contradiction we have measured the shift observed on ring with different radius and on system with different number of rings.

Our previous measurements [10] of single ring with radius $r \approx 2 \mu m$ and widths of the half-rings $w_w = 0.25 \mu m, w_n = 0.2 \mu m; w_w = 0.35 \mu m, w_n = 0.2 \mu m; w_w = 0.4 \mu m, w_n = 0.2 \mu m$ have shown that the value of the shift $\Delta \phi \approx 0.5$ independently of the value of the ring anisotropy $w_w/w_n$ in the interval 1.25 - 2 and of the critical current value $I_c(T)$. More careful measurements have confirmed this result for the critical current $I_c(T) > 10 \mu A$. But at the higher temperature, where the $I_c(T)$ is lower, we have found a weak decrease of the shift value: $\Delta \phi \approx 0.4$ at $I_c(T) \approx 8 \mu A; \Delta \phi \approx 0.35$ at $I_c(T) \approx 4.3 \mu A; \Delta \phi \approx 0.3$ at $I_c(T) \approx 2.5 \mu A; \Delta \phi \approx 0.25$ at $I_c(T) \approx 0.6 \mu A$. Fig 1.

A more visible decrease of the shift is observed at measurement of system of 110 rings with radius $r \approx 1 \mu m$: $\Delta \phi \approx 0.3$ at $I_c(T) \approx 4.1 \mu A; \Delta \phi \approx 0.16$ at $I_c(T) \approx 2.8 \mu A; \Delta \phi \approx 0.1$ at $I_c(T) \approx 1.6 \mu A; \Delta \phi \approx 0.08$ at $I_c(T) \approx 0.7 \mu A$. Fig 2. Only insignificant discrepancy is observed between the magnetic dependencies $I_{c,+}(\Phi/\Phi_0)$, $I_{c,-}(\Phi/\Phi_0)$ of the critical current measured in opposite directions on system of 667 asymmetric ring with radius $r \approx 0.5 \mu m$, Fig 3.

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