Quantum oscillations of rectified dc voltage as a function of magnetic field in an "almost" symmetric superconducting ring

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(Dated: February 2, 2008)

The interest to asymmetric rings [1] was also due to that such but extremely thin-wall rings biased by a microwave current at $T < 0.5 T_c$ could be used in a novel superconducting flux qubit with quantum phase-slip centers [2].

In this work, we report an experimental investigation of ac voltage rectification in a superconducting thin-film asymmetric ring with a specially created circular asymmetry was recently reported [1]. Unlike previously proposed rectifiers which contained superconducting loops with tunnel or point contacts [2], the asymmetric structure proposed in [1] is the simplest and most efficient ac voltage rectifier with a high magnetic-field-dependent output signal.

Time-averaged rectified dc voltage $V_{dc}(B)$ was observed in a circular-asymmetric ring [1] threaded by a magnetic flux and biased by a low-frequency sinusoidal current (without a dc component) with an amplitude close to the critical one at temperatures slightly below $T_c$. $V_{dc}(B)$ is an odd function with respect to $B$ and is periodically dependent on $B$ with the period $\Delta B = \Phi_0/S$, where $\Phi_0$ is the superconducting magnetic flux quantum and $S$ is the effective ring area [1]. The experimental results in [1] provide indirect arguments for the $V_{dc}(B)$ voltage in a single asymmetric ring is directly proportional to the ring circulating current $I_R$. It can then be supposed that $V_{dc}(B)$ functions measured at various parameters can be used instead of $I_R$ functions to describe the quantum state of an asymmetric structure.

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In this work, we report an experimental investigation of ac voltage rectification in a ring where circular asymmetry was not specially created. The rings studied were slightly geometrically distorted, the distortion arose during structure fabrication and was about 10% of the ring major wire width. In spite of a weak circular asymmetry of the rings, the observed rectification effect was fairly large.

The sample studied was a thin-film aluminum structure $d = 50$ nm thick. It was fabricated by thermal Al deposition onto a silicon substrate, using the lift-off process of electron beam lithography with proximity effect correction. An atomic-force microscopy (AFM) image of the structure in an $8.26 \times 8.26 \, \mu m^2$ window is shown in Fig. 1. The ring with a 10% wire widening in the upper ring part is in the center of the structure. The width of all narrow wires, except the widened part, is $w_n = 0.43 \pm 0.02 \, \mu m$, the width of the widened part is $w_w = 0.48 \pm 0.02 \, \mu m$ (Fig. 1). The areas of the inner and outer ring contours are $S_{in} = 8.3 \, \mu m^2$ and $S_{en} = 13.2 \, \mu m^2$, respectively. The averaged geometrical area of the ring is, then, $S_g = 10.75 \, \mu m^2$. The structure resistance in the normal state at $T = 4.2 \, K$ is $R_{4.2} = 26 \, \Omega$, the ratio of the room to helium temperature resistance is $R_{300}/R_{4.2} = 2$, the electron effective mean free path is $l = 10 \, nm$, $T_c = 1.360 \, K$, and the superconducting coherence length is $\xi(0) = 110 \, nm$. 

The semiconductor was an $n$-type GaAs. The structure was annealed at $T = 400 \, K$ for 1 hour to ensure the stability of its resistance. The $I_R$ vs $\Phi_0$ characteristics were measured in the temperature range from 4.2 to 10 K. The superconducting resistance versus the magnetic field $B = B_{dc}$ measured in the normal state at $T = 300 \, K$ is $R_{300}(B) = \Phi_0^2/(2 \pi B)$.

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FIG. 1: AFM image of the structure in a 8260 × 8260 nm² window. The outer diameter of the ring is 4.1 μm.


\[ V_{dc}(B) \text{ in the structure at a sinusoidal current of } \nu = 1.23 \text{ kHz with } I_0 = 2.4 \text{ \(\mu\)A at } T = 1.335 \text{ K.} \]

\[ \text{FIG. 2: } V_{dc}(B) \text{ in the structure at a sinusoidal current of } \nu = 1.23 \text{ kHz with } I_0 = 2.4 \text{ \(\mu\)A at } T = 1.335 \text{ K.} \]

\[ \text{FIG. 3: Fourier spectrum of the function } V_{dc}(B). \text{ The symbols } S_{-2}, S_{-1}, S_1, \text{ and } S_2 \text{ refer to satellite frequencies.} \]

\[ V_{dc}(B) \text{ oscillations were experimentally studied in structures similar to that in Fig. 1 at various amplitudes of bias bias alternating current (without a dc component) close to the critical amplitude at temperatures slightly lower than } T_c. \text{ The magnetic field perpendicular to the structure surface was slowly varied during } V_{dc}(B) \text{ measurements. The } V_{dc}(B) \text{ curve measured in the structure of Fig. 1 biassed by a sinusoidal current of } \nu = 1.23 \text{ kHz with the amplitude } I_0 = 2.4 \text{ \(\mu\)A at } T = 1.335 \text{ K is shown in Fig. 2. The amplitude of the } V_{dc}(B) \text{ oscillations behaves non-monotonically and is maximum at } 17 \text{ Gauss. In fields higher than } 40 \text{ Gauss, these oscillations become virtually imperceptible. As } I_0 \text{ increases, the highest maximum of the } V_{dc}(B) \text{ oscillations shifts towards lower fields, because the amplitude of the oscillations depends both on bias current and magnetic field.} \]

\text{For a detailed analysis, the fast Fourier transformation (FFT) of the } V_{dc}(B) \text{ curve is calculated. Fig. 3 shows the FFT spectrum obtained using } 2^{12} \text{ uniformly distributed points in the range from } -150 \text{ to } +150 \text{ Gauss. The fundamental frequency of the ring } f_R \text{ is the inverse value of the fundamental oscillation period, i.e. } f_R = 1/\Delta B_R = S/\Phi_0. \text{ The fundamental frequency value expected from the ring averaged geometrical area } S_g \text{ is } f_g = 0.52 \text{ Gauss}^{-1}. \text{ Indeed, the FFT spectrum exhibits a peak at } f_R = 0.62 \text{ Gauss}^{-1} \text{ close to the geometric value } f_g (\text{Fig. 3).} \]

\[ \text{Apart from the fundamental frequency } f_R, \text{ the spectrum contains its higher harmonics } f_{Rm} = m f_R, \text{ where } m = 2, 3, 4, \ldots. \text{ Moreover, additional satellite peaks around the fundamental frequency and higher harmonics are observed at frequencies } f_{Sn} = f_R + n \Delta f \text{ and } f_{Sm} = m f_R + n \Delta f \text{ (} n = \ldots, -3, -2, -1, 1, 2, 3, \ldots\text{), respectively. For this curve (Fig. 2), the low-frequency value is } \Delta f = 0.03 \text{ Gauss}^{-1} \text{ and corresponds to the magnetic field } B_c = 33 \text{ Gauss. It is seen that } \Delta f \text{ determines the low-frequency background, with higher-frequency quantum oscillations superimposed on it. As external parameters and the sample geometry change, } B_c \text{ behaves like a field suppressing the superconducting order parameter in the ring wires but is of slightly smaller value. So, satellite frequencies arise due to a combined effect of bias alternating and circulating currents and are dependent on the magnetic depairing factor.} \]

\[ \text{Thus, rings of geometrical inhomogeneity up to } 5\% \text{ of the major wire width were fabricated. Some structures had the narrowings (widenings) by } 10\% \text{ with respect to the wire width. In these structures, the effect of ac voltage rectification was well observable. Since the magnetic-field-dependent electron quantum transport in almost symmetric superconducting loops is usually studied, using a modulation of the measuring dc current by a weak bias ac current, the side effect of ac voltage rectification, which can arise in the structures but was previously disregarded, should be taken into consideration.} \]

\[ \text{We are grateful to V. L. Gurtovoi, A. V. Nikulov, and V. A. Tulin for helpful discussions. The work was supported by the program "Organization of Calculations Based on New Physical Principles" (Department of Information Technologies and Computer Systems, RAS) and the program "Quantum Macrophysics" (Presidium of RAS).} \]

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