Physica C 492 (2013) 11–17

Contents lists available at SciVerse ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Unusual quantum magnetic-resistive oscillations in a superconducting structure of two circular asymmetric loops in series

V.I. Kuznetsov *, A.A. Firsov

Institute of Microelectronics Technology and High Purity Materials, Russian Academy of Sciences, Chernogolovka, Moscow Region 142432, Russia

ARTICLE INFO

Article history:
Received 10 March 2013
Received in revised form 26 April 2013
Accepted 6 May 2013
Available online 16 May 2013

Keywords:
Quantum magnetic-resistive oscillations
Rectified direct voltage
Superconducting asymmetric circular loops
Nonlinear coupling
Quantum states

ABSTRACT

We measured both quantum oscillations of a rectified time-averaged direct voltage $V_{rec}(B)$ and a dc voltage $V_{dc}(B)$ as a function of normal magnetic field B, in a thin-film aluminum structure of two asymmetric circular loops in series at temperatures below the superconducting critical temperature T_c. The $V_{rec}(B)$ and $V_{dc}(B)$ voltages were observed in the structure biased only with an alternating current (without a dc component) and only with a direct current (without an ac component), respectively. The aim of the measurements was to find whether interaction (nonlinear coupling) exists between quantum magnetic-resistive states of two loops at a large distance from each other. The distance between the loop centers was by an order of magnitude longer than the Ginzburg–Landau coherence length $\xi(T)$. At such distance, one would not expect to detect any interaction between the quantum states of the loops. But we did find such an interaction. Moreover, we found that $V_{dc}(B)$ functions (like $V_{rec}(B)$ ones) can be used to describe the quantum states of the loops.

1. Introduction

Asymmetric superconducting loops without tunnel contacts are interesting for a prospective technological application [1] and fundamental studies of unusual quantum magnetic-field-dependent oscillations of both rectified direct voltage [1] and critical superconducting currents [2,3]. A superconducting asymmetric circular loop and the asymmetric loops in series are very efficient rectifiers of ac voltage [1].

Rectification effect can be interpreted as follows. If a superconducting loop is threaded with a magnetic flux Φ and biased by an alternating sinusoidal current (with a zero dc component) and if, in addition, the sum of bias ac and magnetic-filed-periodically-dependent loop circulating current exceeds the critical current value in a certain loop part, then an alternating voltage, with the period equal to the current period, appears across the loop. In a strictly symmetric circular loop, the time-averaged value of alternating voltage is zero because of the positive voltage corresponding to certain half-periods is cancelled out by the negative voltage corresponding to other half-periods. In a superconducting asymmetric circular loop [1], the difference between circulating current densities in two semi-loops disturbs the symmetry between positive and negative voltages, and a nonzero time-averaged (rectified) direct voltage $V_{rec}(B)$ appears as a function of magnetic field B.

$V_{rec}(B)$ voltage oscillates with the period $\Delta B = \Phi_0/S$, here Φ_0 is the superconducting magnetic flux quantum and S is the effective loop area [1]. In a single asymmetric loop, $V_{rec}(B)$ is the sign-alternating function of B. $V_{rec}(B)$ voltage changes its sign in fields corresponding to integer and half-integer values of a normalized magnetic flux Φ/Φ_0 [1].

$V_{rec}(B)$ oscillations [1] are quite unusual. They radically differ from oscillations in the Little–Parks (LP) effect [4]. As compared to the LP oscillations [4], in low fields, the amplitude of the $V_{rec}(B)$ oscillations can reach a giant magnitude that can be calculated by the expression $I_cR_N/2\pi$ (for a bias sinusoidal current) [1]. Here, I_c is the critical superconducting current in the zero field and R_N is the structure resistance in the normal state. The maximum amplitude of voltage oscillations $V_{rec}(B)$ corresponds to the maximum amplitude ΔR (from peak to peak) of resistance oscillations that can reach R_N. For aluminum loops [1], the ΔR amplitude derived from $V_{rec}(B)$ oscillations can exceed the amplitude of magnetoresistance oscillations expected on the basis of the LP effect more than by one order of magnitude.

$V_{rec}(B)$ oscillations reach their extreme values (maxima and minima) at Φ/Φ_0 close to $\pm(n + 1/4)$, where n is an integer, while $R(B)$ oscillations in the LP effect reach their extreme values at $\Phi/\Phi_0 = n + 1/2$.

In a single asymmetric circular loop and identical asymmetric loops in series, a nonzero rectified voltage $V_{rec}(B)$ appears because of a difference between critical superconducting currents $I_{c+}(B)$ and $I_{c-}(B)$ measured [2,3] for arbitrarily positive and negative half-waves of a bias ac.

* Corresponding author. Tel.: +7 4965244022.
E-mail address: kvi@iptm.ru (V.I. Kuznetsov).

0921-4534/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physc.2013.05.003

$I_{c+}(B)$ and $I_{c-}(B)$ oscillations were unexpectedly found to be unusual. It was revealed that in low fields the curves $I_{c+}(B)$ and $I_{c-}(B)$ are shifted from one another with a π phase shift (corresponds to magnetic-field shift of $\Phi_0/2$) [2,3]. Note that according to contemporary theoretical conceptions this incomprehensible π phase shift can be hardly expected in the studied asymmetric structures [1–3].

Moreover, like $V_{rec}(B)$ oscillations these $I_{c+}(B)$ and $I_{c-}(B)$ oscillations reach their extreme values at Φ/Φ_0 close to $\pm(n + 1/4)$. Some other striking features of $V_{rec}(B)$, and $I_{c+}(B)$, and $I_{c-}(B)$ oscillations were also found in asymmetric loops [2,3].

Unlike LP oscillations, the unusual quantum $V_{rec}(B)$, $I_{c+}(B)$, and $I_{c-}(B)$ oscillations [1,3] in an asymmetric circular loop cannot be explained in the framework of the simple Ginzburg–Landau (GL) quasi-one-dimensional model [5], using only the requirement of superconducting fluxoid quantization [6]. Thus, experimental studies of the unusual quantum oscillations [1–3,7,8] in simple superconducting circular-asymmetric structures generate many unsolved questions.

Besides the rectification of ac voltage, an asymmetric loop is interesting for other applications. Earlier [1,7,8], it was assumed that the quantum states of a single superconducting asymmetric circular loop placed in the normal magnetic field B at T below T_c can be described by the oscillating superconducting circulating current of the loop $I_R(B)$. In order to determine the time-averaged quantum states, the loop was periodically switched from superconducting state to resistive state and back by a bias alternating current (without a dc component) with an amplitude close to the critical current value. As a result of the multiple switching, the rectified direct voltage $V_{rec}(B)$ appears in the loop [1]. At certain values of the magnetic field, $V_{rec}(B)$ can be directly proportional to $I_R(B)$ in a single asymmetric circular loop [1]. Therefore, measurements of $V_{rec}(B)$ can allow the readout of the time-averaged quantum states of the loop [1]. Moreover, the oscillating $V_{rec}(B)$ voltage recorded at the different current values can describe quantum magneto-resistive states of the loop (the states depend both on the magnetic field and the bias ac). Quantum magneto-resistive states of the two directly connected asymmetric circular loops [7,8] can be described by quantum magneto-resistive states of each loop and coupling between the states of the loops.

In addition, an asymmetric loop of high-resistance material with an extremely small wall narrowing could be used as an element of a superconducting flux qubit [9,10] with quantum phase-slip centers [11,12]. Two successive loops of this kind could be an analog of two successive flux qubits.

For certain technological applications, it is necessary to know both the strength and mechanism of coupling between quantum states of loops. Earlier, an interaction (nonlinear coupling) was revealed between quantum magnetic-resistive states of two different superconducting directly connected asymmetric circular loops forming a figure-of-eight-shaped structure [7,8]. To determine the quantum state of each loop and coupling between the loops, rectified voltage $V_{rec}(B)$ was measured in a figure-of-eight-shaped structure pierced with a magnetic flux and biased with a low-frequency current (without a dc component) and with an amplitude close to critical, at T slightly below T_c [7,8]. Possible mechanisms of the interaction between the loops can be magnetic coupling and electro-dynamic coupling through a bias ac.

We assume that electro-dynamic coupling between two successive loops that occurs through a bias ac is a nonlocal phenomenon with the nonlocal superconducting length [13–15] close, by the order of magnitude, to the Ginzburg–Landau coherence length $\xi(T)$ [6]. Note that the nonlocal length estimated from Ref. [16] can reach the value several times exceeding $\xi(T)$.

Nonlinear coupling between quantum magnetic-resistive states of two asymmetric loops in series should become weaker with an increasing distance between them. It can be assumed that the most long-scaled electro-dynamic coupling should almost disappear if the spacing between loop centers increases to $10\xi(T)$.

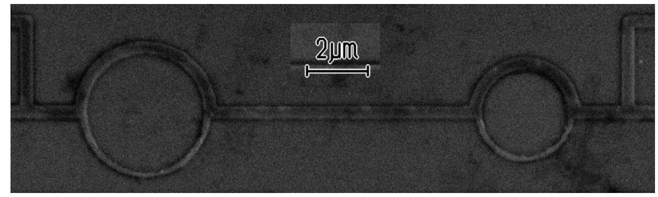

Fig. 1. SEM image of the structure. The scale bar: *2* μm.

The aim of this work was to find the largest distance between the loops at which the coupling between quantum magnetic-resistive states of the loops would still occur. For this purpose, we experimentally studied the quantum magnetic-resistive behavior of two different superconducting aluminum asymmetric circular loops connected in series with a wire of a length (Fig. 1) close to the penetration depth of a nonuniform electric field into a superconductor [5,17] Λ_E.

Like the authors of Refs. [7,8], we measured the rectified direct voltage $V_{rec}(B)$ in the structure (Fig. 1) versus normal magnetic field B and a bias sinusoidal low-frequency current (without a dc component) at temperatures T slightly below T_c in order to determine the quantum magnetic-resistive states of two loops in series and the coupling between the loop states. In addition, we measured a dc voltage $V_{dc}(B)$ as a function of B and bias dc (without an ac component) through the structure.

One more goal was to test whether $V_{dc}(B)$ oscillations can be used to describe the quantum magnetic-resistive states of an asymmetric structure. We also made a comparison of $V_{rec}(B)$ and $V_{dc}(B)$ oscillations.

2. Samples and experimental procedure

A 45 nm thick structure of two loops connected in series was fabricated by thermal sputtering of aluminum onto a silicon substrate using the lift-off process of electron-beam lithography. Fig. 1 displays a scanning electron microscopy (SEM) image of the structure. It consists of two different successive asymmetric circular loops with the distance between the loop centers $L = 12.5$ μm. The average widths of all narrow and wide wires in the sample central part are $w_n = 0.22$ μm and $w_w = 0.41$ μm, respectively. The circular asymmetry permits the observation of nonzero rectified voltage $V_{rec}(B)$ in the structure [1,7,8]. The minimum area of the loop is the internal area within the inner loop border. The minimum areas of the larger and smaller loops are $S_{Lmin} = 11.57$ μm^2 and $S_{Smin} = 6.34$ μm^2, respectively. From the structure geometry, the average areas of the larger and smaller loops are $S_{Lg} = 13.93$ μm^2 and $S_{Sg} = 7.92$ μm^2, respectively.

The structure has the following parameters. The critical superconducting temperature $T_c = 1.355 \pm 0.001$ K was determined from the midpoint of normal-superconducting transition $R(T)$ in a zero field. The total normal-state resistance measured between two vertical wires at $T = 4.2$ K is $R_N = 32\ \Omega$. The ratio of room-temperature to the helium-temperature resistance is $R_{300}/R_{4.2} = 2$. Sheet resistance is $R_S = 0.69\ \Omega$, the resistivity is then $\rho = 3.105 \times 10^{-8}\ \Omega$ m. From the expression [1,18] $\rho\ l = (6 \pm 2) \times 10^{-16}\ \Omega$ m^2, we determine the electron mean free path $l = 19$ nm. The superconducting coherence length of pure aluminum at $T = 0$ is $\xi_0 = 1.6$ μm. Hence, the structure is a "dirty" superconductor, because $l \ll \xi_0$. Therefore, for this structure the temperature-dependent superconducting G–L coherence length at temperatures slightly below T_c is determined from the expression [6,19] $\xi(T) = \xi(0)(1 - T/T_c)^{-1/2}$, where $\xi(0) = 0.85(\xi_0 l)^{1/2} = 0.15$ μm. In the studied temperature range, $\xi(T) = 0.85 - 1.2$ μm. For this structure, the theoretical estimation