EVIDENCE OF LITTLE–PARKS OSCILLATIONS IN AN ARRAY OF μm–SIZED MoC LOOPS WITH NANOWIRES, DETECTED BY GIGAHERTZ RESONATOR RESPONSE METHOD

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1. Introduction

The single-valuedness of the complex superconducting order parameter in superconductors results in fluxoid quantization. As a consequence, when the magnetic flux Φ threading a superconducting loop differs from $n\Phi_0$, where n is an integer number and $\Phi_0 = h/2e$ is the superconducting flux quantum, circulating super–current is induced in the loop[1]. The fluxoid quantum number n is chosen in order to minimize the kinetic energy of the persistent current in the loop. This means, that the current and thus the critical temperature of the loop is a periodic function of the magnetic flux. The first experimental evidence was given in 1962 by Little and Parks (LP), by measuring the resistive transition of a thin-walled superconducting cylinder in an axial magnetic field, where the measured resistance exhibited a series of parabolic variations in critical temperature with magnetic field[2].

In 2011, a microwave resonator method for observation of LP oscillations at temperatures much lower than the critical temperature (~1/10 T_c) was published by the group of Bezryadin[3]. In this experiment, a pair of parallel MoGe nanowires were incorporated into a superconducting coplanar waveguide (CPW) resonator at the point of the current antinode to create a superconducting loop. A CPW resonator is essentially a thin-film Fabry–Perot resonator for GHz radiation[4]. Depending on the DC external magnetic field, Meissner currents develop in the loop, changing the resonance frequency of the resonator as a periodic set of parabolas observed in the transmission of the resonator. These parabolas correspond to the states of the wire loop having different fluxoid numbers n.

In this paper, we report on the observation of LP oscillations in an array of loops fabricated in the middle of Molybdenum Carbide (MoC) CPW resonator at temperatures well below T_c (~T_c/300). In this resonator –nanowire device, each loop contains a pair of nanowires with approximate dimensions ~ 50nmx500nm. MoC is a highly disordered superconductor with high sheet resistance and thus high kinetic inductance[5,6]. High kinetic inductance can be used for photon detection experiments or possible implementation of quantum phase slip qubits[7] and parametric cryogenic amplifiers[8]. Moreover, this material can play an important role in the study of the still open and intriguing question of superconducting insulator transition[9]. The resonator-nanowires device consisting of 20 nanowires exhibits reasonably high quality factor (~2000 at 6GHz) which demonstrates feasibility of the MoC films for nanofabrication.

2. MoC thin film preparation, structure design and fabrication

The MoC film was deposited by magnetron reactive sputtering of molybdenum onto a negatively biased (Us=-400V) sapphire c-cut substrate in an argon acetylene atmosphere. The partial pressure of acetylene and Ar gas was set to 3×10^{-4} mbar and 5.4×10^{-3} mbar, respectively. The temperature of the substrate during deposition was 200 °C. The film thickness was set by tuning the sputtering time according to the sputtering rate of 10 nm/min. The roughness of the films obtained from AFM topography of surface, is about 0.3 nm. The details are given in Ref. [5]. The CPW resonators were patterned by optical lithography. The center conductor width of our half-wave resonator design is w=50 μm, the separation from the ground plane is s =30μm, corresponding to 50 Ω impedance. The length of the resonator is l=24 000 μm, corresponding to fundamental frequency of 2.5 GHz at 0 K temperature for 300 nm thick film on sapphire dielectric layer with 450μm. The loaded quality factor of this design is 35 000. However, for 10 nm thick film, the sheet resistance is increased to $R_s \approx 180$ Ω and due to the increase in kinetic inductance of the resonator, the fundamental mode resonance frequency is shifted to 1.5 GHz. The details of the design and characterization CPW resonator on 10 nm thick films can be found in Ref. [6].

In the middle of the resonator, an array of 10 loops 10μm x10μm with separation of 10 μm were patterned by electron-beam lithography, followed by dry etching. Each loop contains a pair of parallel nanowires with design size of 50nm x500nm. The actual size of the nanowires, estimated from scanning electron microscope images, ranges from 45 nm to 80 nm in width and the length ranges from 280 nm up to 320 nm.

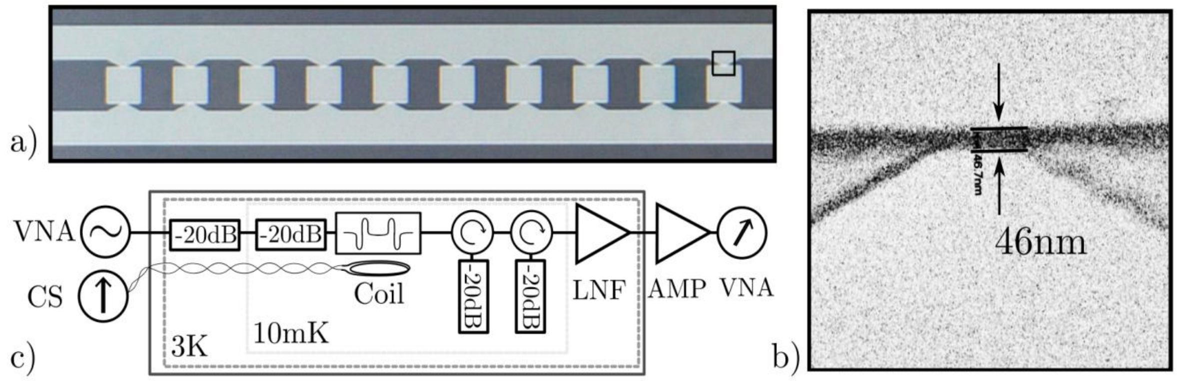

Fig.1: *a) Scanning electron microscope image of the array of 10x10um sized loops fabricated in the middle of the MOC CPW resonator center conductor. Each loop contains a pair of parallel nanowires. b) Enlarged view of a single nanowire. c) Scheme of the experimental set-up for transmission measurement of the resonator-nanowire device in* He^3-He^4 *dilution refrigerator.*

3. Experimental set-up

The transmission measurements of the resonator were carried out in a cryogen-free dilution refrigerator with base temperature of 13 mK. The sample was glued and wire-bonded to a printed circuit board with 50 μm aluminum wires and enclosed in a copper box. The scheme of the RF experimental set-up is in Fig. 1c). The input line, where probing signal was applied (VNA N5242A), is filtered by a set of thermally anchored attenuators placed at 3 K stage and mixing chamber stage (10 mK) of the refrigerator. The output line contains two cryogenic circulators installed between the sample and low noise cryogenic amplifier (LNF) placed on 3 K plate in order to isolate the sample from the 3 K thermal noise (Fig. 2a). The cryogenic amplifier amplifies the signal and isolate its input from room temperature low-noise amplifier (AMP) which amplifies the signal for the vector network analyzer. The external DC magnetic field was provided by a single superconducting coil fixed to the sample holder. The DC transport properties of the nanobridges were carried out in a ^{3}He refrigerator at temperatures ranging down to 340 mK by classical four probe measurement method [10].

4. Results

The critical temperature transition of the 10 nm thin MoC film with R_s =180 Ω was T_c= 6 K, while the critical temperature of the nanowires was slightly suppressed to a value of T_c= 3 K. This value agrees with the one estimated from the measurement of the temperature dependence of the resonator–nanowires transmission spectrum. At 13 mK, the transmission spectra of the resonator, measured at different probing powers, revealed 3 resonant peaks with strong power dependence (nonlinearities and bifurcations [11]).

These resonant peaks at frequencies $\omega_1 \sim 2\pi\times 1.15$ GHz, $\omega_2 \sim 2\pi\times 3.488$ GHz and $\omega_3 \sim 2\pi\times 5.916$ GHz and with quality factors $Q_1 \sim 2800$, $Q_2 \sim 2700$ and $Q_3 \sim 2000$ correspond to the 1st, 2nd and 3rd harmonics of the λ/2 resonator.

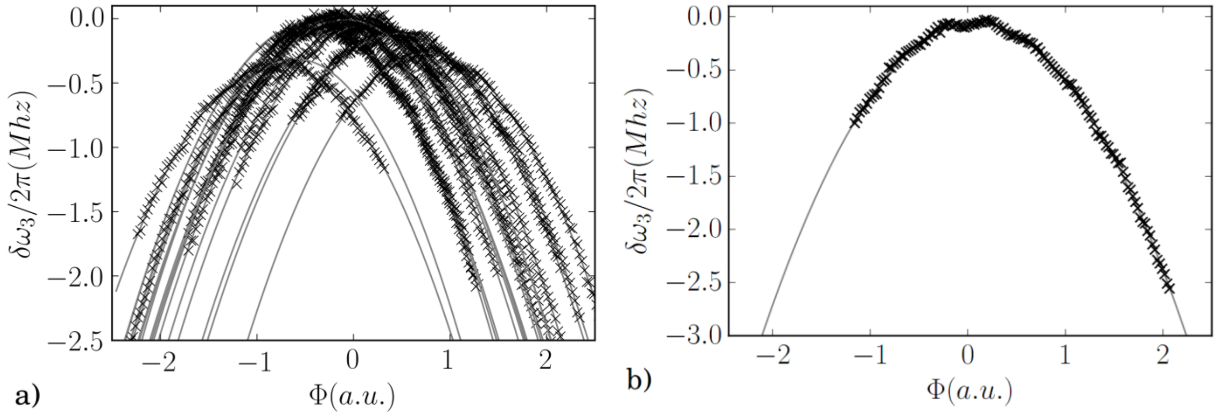

Fig.2: a) The magnetic field dependence of the resonance frequency shift at 3rd harmonic of the resonator defined as $\delta\omega_3 = \omega_3(\Phi) - \omega_{3max}$*, where* ω_{3max} *is the maximal value of the resonant frequency at zero bias. A series of distorted parabolas is visible. Ramping the magnetic field, the shift of the resonant frequency follows a parabolic shift and at certain field jumps to another parabola, corresponding to a different state of the persistent currents in the superconducting loops with nanowires. The crosses correspond to the measured data and solid lines are parabolic fits. b) Detail of a single branch of the resonant frequency shift and its parabolic fit.*

The resonance frequency of the 1st harmonics is shifted from the expected value of 2π×1.5 GHz for a resonator on 10 nm thick film due to the kinetic energy contribution of the nanowires to the total inductance of the resonator.

The resonant frequencies and quality factors were obtained by Lorentz fit of the resonator's transmission spectra. The resonant frequencies of the resonator show a strong dependence on external magnetic field, see Fig 2a). Starting from zero bias and increasing the external applied magnetic field, the resonant frequency is decreasing, following parabolic magnetic field dependence. At certain magnetic field, the resonant frequency jumps to a different parabola. By ramping the magnetic field subsequently, multiple jumps occur and set of distorted parabolas is revealed (fig. 2b)). We argue, following Ref.[3], that the transition from one branch to the next one corresponds to a Little-Park's phase slip event, and the periodic oscillations are due to the oscillation of the Meissner current magnitude in the loops, effectively changing the resonators inductance.

5. Conclusion

In this paper we have presented the fabrication of a resonator-nanowire device consisting of a CPW resonator fabricated on a 10 nm thick MoC film and an array of μm sized MoC loops in the resonator's centre conductor with each containing a pair of 50nm x500nm nanowires. Three resonant peaks with strong nonlinear characteristics were identified, demonstrating the functionality of the resonator. Characterizing the resonant frequency of the resonator with respect to external magnetic field, a periodic, parabolic shift of the resonator frequency due to the oscillation of the Meissner current magnitude in the loops is demonstrated. These oscillations resemble the famous LP experiment. A multi–loop system exhibits a set of parabolic frequency shifts similar to those observed for a single loop in Ref. [3].

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