SWITCHING EFFECT IN SQUIDS COUPLED BY JOSEPHSON JUNCTION

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1. Introduction

While nowadays efficiencies of state-of-art single photon detectors in infrared (IR) range go up to 73% [1], construction of a microwave single photon detector with similar properties is a technological challenge. The problem of detection of a single microwave photon arises from low microwave photon energy, which is proportional to its frequency. In comparison to the energy of an IR photon ($\sim10^{-19}$ J or equivalently ~10000 K), the energy of a microwave photon is several orders of magnitude smaller $\sim10^{-24}$ J or equivalently ~500 mK. To efficiently distinguish between individual photons (those we want to detect), one should decrease dark count rate arising from thermal photons. This requires microwave photon detectors working at cryogenic temperatures below 100 mK. This approach has already been employed in IR single photon detectors based on kinetic inductance of superconductors [1].

Recently, there were several proposals [2][3] and also realization [4] of a microwave single photon detection with superconducting qubits. A promising approach seems to be also exploiting of hysteretic behaviour of an underdamped Josephson junction (JJ) studied theoretically and experimentally in references [5] and [6].

In this paper, a switching characterization of a system consisting of two superconducting quantum interference devices (SQUIDs) coupled by a Josephson junction (JJ) is presented. We argue that the hysteretic switching between distinguishable states of SQUIDs can be used as an ultrasensitive microwave detector.

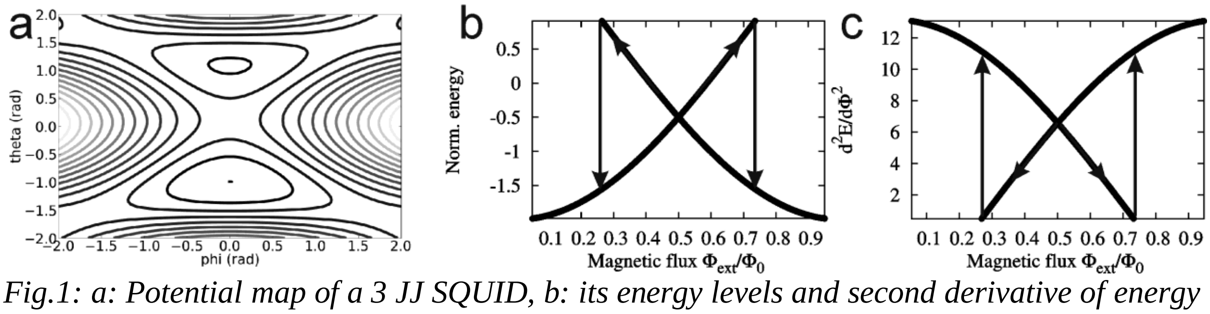

Fig.1: a: Potential map of a 3 JJ SQUID, b: its energy levels and second derivative of energy with respect to magnetic flux. The arrows show the direction of field sweep

2. Model

Two superconductors separated by a thin layer of a dielectric material can be modelled as a parallel connection of a capacitor with energy $E_C=CV^2/2$ and an ideal JJ with energy $E_J=\Phi_0 I_C/(2\pi)(1-\cos(\varphi))$, where C is the capacity of the capacitor, V is the voltage on its electrodes, $\Phi_0=h/(2e)$ is the magnetic flux quantum, h is the Planck constant, e is the charge of the electron, I_C is the critical current of the junction and φ is the gauge-invariant phase of superconducting wavefunction. System with N junctions enclosed in a superconducting ring (SQUID) is described by Lagrangian [7]:

$$L(\varphi_i,\dot{\varphi}_i)=\frac{\hbar^2}{2(2e)^2}\sum_{i=1}^{N}C_i\dot{\varphi}_i^2+\frac{\Phi_0}{2\pi}\sum_{i=1}^{N}I_{Ci}(1-\cos(\varphi_i)), \quad (1)$$

where the gauge-invariant phases φ_i satisfy condition:

$$\sum_{i=1}^{N}\varphi_i=2\pi\frac{\Phi_{ext}}{\Phi_0}\mathrm{mod}(2\pi). \quad (2)$$

For small loops (~5x5μm^2), the external flux Φ_{ext} is equal to net flux penetrating the loop (magnetic flux generated by superconducting current circulating in the loop is negligible). The aforementioned Lagrangian is identical to the Lagrangian of a particle with N-1 degrees of freedom (due to conditions (2)) in potential determined by Josephson energy. Treating the system semi-classically, stable ground state and metastable excited state can be found as a global and a local minimum of the potential for given external flux Φ_{ext}, respectively. In the figure 1a, a potential of 3 JJ SQUID with 3 identical JJs is shown (in coordinate system rotated by 45 degrees, φ_1, $\varphi_2 \rightarrow \varphi$, θ) for Φ_{ext}/Φ_0 =0.48. There are two distinguishable potential minima corresponding to the ground state (loop current flowing in one direction) and metastable state (loop current flowing in the opposite direction).

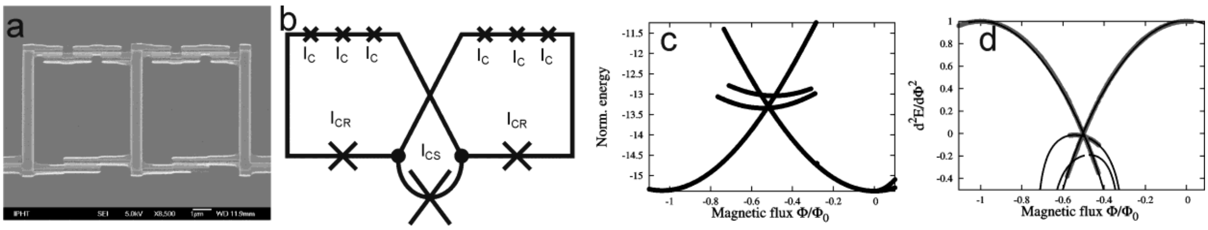

Fig.2: a: SEM image of 2 coupled SQUIDs and b: its electrical equivalent schematics, where the crosses denote JJs. c: Simulated energy levels for parameters fitted from measured data. d: Measured (normalized) transmission – gray solid lines and fit by theory described in main text – black thin solid lines.

For particular JJ parameters, SQUID becomes hysteretic and its state depends on the SQUID history (magnetic flux applied before), see figure 1b. SQUID escape rate Γ from the metastable state depends on the external magnetic flux Φ_{ext}, on the potential landscape - on the shape of the potential valleys, where minima are situated and on the height of the barrier between them. A SQUID is the most stable for $\Phi_{ext}/\Phi_0=(2n+1)/2$ (degenerate points, both states have the same energy), where n is an integer. The switching probability P after time τ can be found from equation [8][9]:

$$P=1-\exp(-\Gamma\tau), \quad (4)$$

At high temperatures, the escape rate Γ is determined by thermal activation, while at lower temperatures, quantum tunneling dominates [8][9].

3. Sample design and fabrication

The investigated sample is a system of two SQUIDs strongly coupled by JJs to a half wavelength superconducting coplanar waveguide resonator. Two-SQUID structure consists of 9 JJs overall, two of them couple SQUIDs to the resonator and one JJ shared by both SQUIDs serves as a ferromagnetic coupling [10] between them, see figure 2a,b. The resonator quality factor and the resonance frequency of the 1st mode were designed to 10000 and 7.5 GHz, respectively.

The niobium resonator was prepared by e-beam lithography and dry etching of 200 nm thick film on a silicon substrate. The aluminium SQUIDs in the middle of the resonator were prepared by shadow evaporation technique.

4. Measurement and results

Properties of the resonator are influenced by presence of the SQUIDs in its current antinode (in the middle of the resonator). The state of the SQUIDs can be determined by measurement of relative resonance frequency detuning of the resonator [11]:

$$\frac{\delta f_0}{f_0} \approx \frac{\Delta L}{L_0} = \frac{1}{2}\frac{M^2}{L_0}\frac{\partial^2 E}{\partial \Phi^2}, \qquad (5)$$

where ΔL is the change of the resonator inductance due to SQUIDs, L_0 is the inductance of the resonator, M is the effective mutual inductance between the SQUIDs and the resonator. Thus, by probing resonance frequency of the resonator, one acquires information about the energy levels (states) of the SQUID system.

Resonance frequency of the resonator as a function of applied flux was measured by a vector network analyzer. Bias flux was applied by a coil integrated into the sample holder, which was thermally anchored to the mixing chamber of a dilution refrigerator with base temperature of 10 mK. Results shown in the figure 2d were fitted by Lagrangian (1) and using condition (2) for two superconducting rings. From the fit, homogeneity of magnetic field is determined to be 93%, ratio between I_C and I_{CR} is 1.25 and ratio between I_C and I_{CS} is found to be 0.13, see figure 2b.

The system with 2 SQUIDs has 4 distinguishable states corresponding to 4 combinations of loop currents flowing in clockwise (CW) and counter clockwise (CCW) directions. In the experiment, only three states (see fig. 2d) were observed due to inhomogenetiy of the magnetic field penetrating the SQUIDs, which caused that the one state with opposite currents in the loops is preferred.

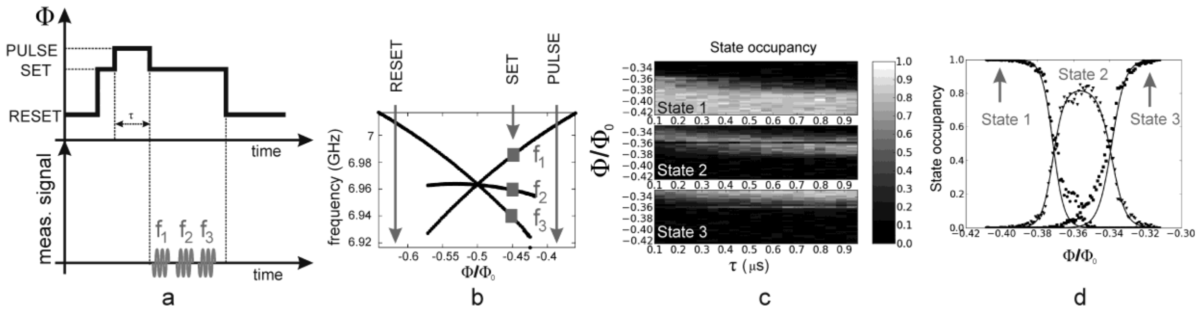

Fig.3: a: Pulse measurement sequence (see main text for details). b: resonator transmission spectrum with frequencies corresponding to working point. c: probability to find system in particular state as a function of pulse duration and amplitude. d: cross-section of (c) for fixed pulse length τ=600ns. Points depict measured data, while solid lines are fit by (4).

Metastable states with high escape rates were investigated by pulse measurements (see figure 3a) in which hysteretic behaviour of the system was exploited. Working point ("SET" in fig.3a) is set by the bias coil, so the three observable states are stable enough to perform transmission measurement. At first, the system is reset to the state with both currents circulating CCW (ground state for $-1<\Phi_{ext}/\Phi_0<0.5$, however third excited state for $0.5<\Phi_{ext}/\Phi_0<0$) by application of short current pulse to on-chip bias-flux line. Subsequently, another current pulse with opposite polarity is applied to the same line, enabling the system to switch to one of the lower energy metastable states (currents circulating in opposite directions) or to ground state (both currents circulating CW). Using this method, metastable states with lifetime > 100 ns were investigated.

In the figure 3c, the probability to find SQUID system in particular state after pulse sequence shown in fig. 3a are displayed.

5. Summary

In summary, quantitative characterization of coupled 2 SQUID system was presented. Three out of four states of the system were observed and discussed. Switching from higher energy to lower energy states was investigated by pulsed measurements.

Presented device could be used as a sensitive detector by measuring its state occupancy by methods shown above, while superconducting cavity is excited by microwaves. As stated in ref. [6], amplitude of current generated by a single microwave photon in the cavity with frequency in GHz range, seems to be sufficient to induce switching of a state of one of the coupling JJs in SQUIDs.

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