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Oscillation of Critical Current by Gate Voltage in Cooper Pair Transistor

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Cooper pair transistor에서 gate voltage에 의한 임계전류의 진동

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Abstract

We measured the critical current of a Cooper pair transistor consisting of two Josephson junctions and a gate electrode. The Cooper pair transistors were fabricated by using electron-beam lithography and double-angle evaporation technique. The Gate voltage dependence of critical current was measured by observing voltage jumps at various gate voltages while sweeping bias current. The observed oscillation was 2*e*-periodic, which shows the Cooper pair transistor had low level of quasiparticle poisoning.

Keywords : Cooper pair transistor, critical current, Josephson junction, quasiparticle, tunneling

I. Introduction

Using nanoscale Josephson junctions, solid state circuits that can prepare and manipulate coherent superposition of charge states was demonstrated [1, 2]. This phenomenon can be used to construct solid-state quantum computers and quantum current standards whose speed is not limited by incoherent tunneling. However, the tunneling of quasiparticles leads to decoherence, which is called “quasiparticle poisoning.”

In RCSJ model of a Josephson junction, total current I is carried by three parallel channels; a Josephson junction, a resistance R and a capacitance C. The supercurrent channel is described by Josephson relation

$$I_s = I_{co} \sin\varphi \tag{1}$$

where φ is the phase difference of the two side of the junction. For ideal tunnel junctions at temperatures far below T_c, I_{co} is given by [3]

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$$I_{co} = \pi\Delta/2eR_n \qquad (2)$$

where Δ is the BCS energy gap at 0 K.

The behavior of the Josephson junction under current bias can be described by the so-called “tilted washboard” model [4, 5], in which a particle of mass $(\hbar/2e)^2C$ moves along the φ axis in an effective potential

$$U(\varphi) = -E_J \cos \varphi - (\hbar I/2e)\varphi \qquad (3)$$

where the Josephson coupling energy $E_J = (\hbar/2e)I_{co}$.

The particle, which denotes the status of the Josephson junction, tunnels out of the potential well and moves along the tilted washboard as the bias current exceeds a certain critical current. Since the tunneling is an inherently stochastic process, the particle starts moving at slightly different currents, which requires repeated measurements to obtain the critical-current distribution of the Josephson junction.

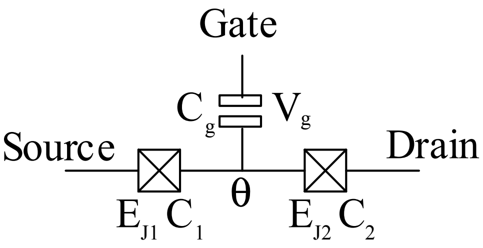

Fig. 1. Schematic of a Cooper pair transistor. The phase of the superconducting island is θ, C_g is the gate capacitance and V_g is the gate voltage.

When two small-capacitance Josephson junctions are connected in series, the Hamiltonian of the system, consisting of the Coulomb energy from the charges on the capacitances and the Josephson coupling energies, can be written as the following [6]

$$H = \frac{(Q-Q_g)^2}{2C_\Sigma} - 2E_J\cos(\varphi/2)\cos(\theta) \qquad (4)$$

where Q is the charge of the island, Q_g (= C_gV_g) is the gate charge, C_Σ (= $C_1 + C_2 + C_g$) is the total capacitance, φ is the phase difference across the whole device, and θ is the phase of the island, which is conjugate to the charge of the island. Since the charge of the island can be controlled by the gate voltage, Eq. (4) implies that Cooper pair transistor can be effectively considered as a gate-tunable single Josephson junction [7].

Without quasiparticle tunneling, the gate voltage dependence of the switching current in the Cooper pair transistor would be $2e$-periodic because the charge of the superconducting island Q should be the multiples of $2e$.

II. Experimental setup

The Cooper pair transistor in our study was fabricated by e-beam patterning of resists followed by double-angle evaporation of aluminum. A thin insulating layer (AlO_x) was formed by exposure of bottom aluminum layer to oxygen between the serial evaporations of aluminum.

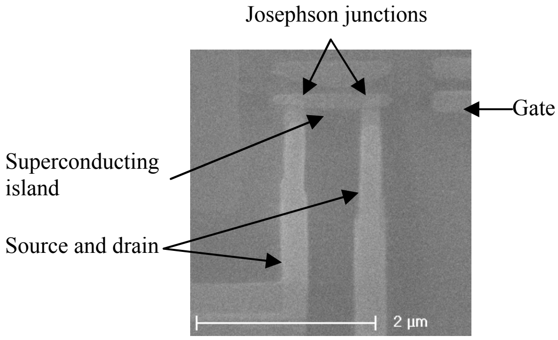

Fig. 2. Scanning electron micrograph of the Cooper pair transistor. The superconducting island was about 1.2 µm x 0.2 µm.

Figure 2 shows SEM picture of the Cooper pair transistor. Both of the Al layers were about 15 nm thick and the junction area was about 0.2 × 0.15 µm^2. The normal state resistance of the two junctions in series was 12 kΩ. Superconducting gap Δ = 200 µeV was extracted from *I-V* measurements.

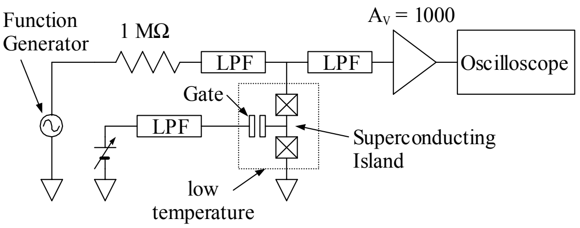

Fig. 3. Experimental setup for I_c measurement of the Cooper pair transistor. A triangular wave from the function generator was applied to the Cooper pair transistor through a resistor and a low pass filter (LPF). As the current through the device exceeded the critical current, a voltage jump occurred. The Cooper pair transistor was at 50 mK.

Figure 3 shows the schematic experimental setup to measure the switching current of the Cooper pair transistor. A triangular wave of frequency 11 Hz from a function generator passed through a 1 MΩ resistor, which made the function generator behave like a current source. The current-biased Cooper pair transistor switched from zero voltage state to non-zero voltage state when the current exceeded a certain critical current of Josephson junctions. The voltage signal, amplified by 1000 times, was fed to an oscilloscope. The stored data from the oscilloscope were later analyzed automatically by a computer program to find switching current. To reduce external interference, we placed low pass filters between room temperature electronics and the sample.

III. Results and discussion

Figure 4 shows the measured *I-V* characteristics of the Cooper pair transistor at 50 mK, which obtained from more than 1000 measurements at $V_g = 0$. The voltage remains close to zero until the current reaches about 10 nA, then the voltage switched on. When the voltage decreases, the *I-V* curve follows retrapping current, which make the *I-V* curve hysteretic.

By averaging observed switching currents at a certain gate voltage, we can obtain mean switching current as a function of gate voltage as shown in Fig. 5. The period of switching current oscillation was 75 mV. To find out whether this gate voltage period is *e*-periodic or 2*e*-periodic, we applied magnetic field of 0.5 T so that superconductivity was destroyed, and measured oscillation of current as a function of gate voltage, which comes from Coulomb blockade phenomenon. The measured period 37 mV is one half of switching current oscillation period, which confirms switching current oscillation is 2*e*-periodic.

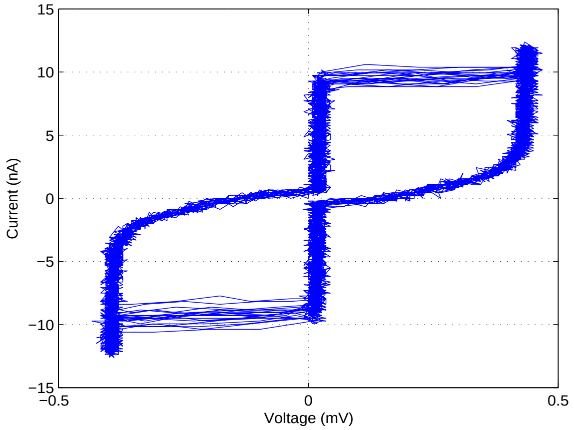

Fig. 4. *I-V* characteristics of the Cooper pair transistor. As current approaches 10 nA, the Cooper pair transistor switches to finite voltage state. When current starts to decrease, *I-V* follows retrapping current curve, which makes *I-V* curve hysteretic.

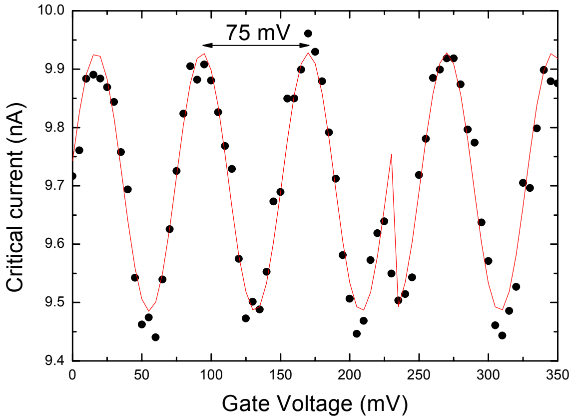

Fig. 5. Plot of mean switching current as a function of gate voltage shows quasi-sinusoidal oscillation whose period is 75 mV. The discontinuity at $V_g \approx 225$ mV may come from phase slip of Josephson junction.

In summary, we found that the gate voltage dependence of the switching current in Cooper pair transistor was 2*e*-periodic, which indicated that the tunneling probability of unpaired quasiparticles was low in our sample. Further study is needed to probe the relationship between quasiparticle tunneling and switching current oscillation [8].

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