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High-speed Measurement Method of Quantized Energy Levels in Josephson Junctions Using SFQ Circuits

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Abstract

A single flux quantum (SFQ) circuit has been designed to demonstrate an energy levels quantization in a Josephson Junction. The high-speed operation of SFQ circuits realizes applying a high-speed ramped bias current to a Josephson junction, which allows the noiseless experiment at higher temperature. A high-speed ramped bias current ($dI/dt = 2000 \text{ A/sec}$) is applied to a Josephson junction using the proposed circuit. Although the energy levels quantization has not been observed yet, the obtained escape rate was high enough to observe the energy levels quantization. The proposed circuit indicates the effectiveness of SFQ circuits as experimental apparatuses.

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1. Introduction

To build a practical quantum computer, an integration of a large number of quantum bits (qubits) is required. A Josephson junction is very attractive candidate for practical qubits because the junctions are easily fabricated with conventional superconducting LSI manufacturing technologies.

A Josephson junction current-biased close to its critical current has a few numbers of quantized energy levels resulting from plasma oscillation modes [1] and behaves as a quantum bit [2]. The Rabi oscillation has been observed in this Josephson junction qubit, in which the decoherence time was estimated to be about 5 microseconds [3].

The quantization of the energy levels in the Josephson junction can be observed by measuring escape rate of the junction [4]. The escape rate is obtained from the switching current distribution in a junction current-biased slightly lower than its critical current.

Macroscopic quantum effects like the energy levels quantization is observable at a temperature below a “crossover temperature” T_0 ,

$$T_0 \cong \frac{\hbar \omega_{j0}}{2k_B}, \quad (1)$$

where $\hbar$ is the Plank constant divided by 2π , k_B is the Boltzman constant, and ω_{j0} is the plasma frequency of the Josephson junction where no bias current is applied to the junction, and denoted as the following formula:

$$\omega_{j0} = \left(\frac{2\pi I_0}{\Phi_0 C} \right)^{\frac{1}{2}}, \quad (2)$$

where I_0 is the critical current of the junction, Φ_0 is flux quantum ($= h/2e$), and C is the junction's capacitance.

Silvestrini et al. indicated the observation of energy levels quantization is possible

using a high-speed ramped bias current to avoid a thermal diffusion which prevents a quantum behavior, and observed the clear energy levels quantization at 1.4 K in a Josephson junction, while the crossover temperature is 200 mK [4][5].

We have proposed an SFQ circuit to observe the quantized energy levels in the Josephson junction. SFQ circuits have the characteristics of high-speed operations and low power consumption [6]. The designed circuit applies higher sweeping speed of ramped bias current to a Josephson junction and enables us to observe the energy levels quantization at higher temperature. This circuit system allows the Josephson junction well isolated from the environment because we do not have to provide high frequency signals from room temperature electronics.

2. Experimental

Fig. 1 shows a schematic diagram of the proposed circuits. The persistent current in the superconducting loop containing J_1 , L_Q , and J_Q increases slightly when an SFQ pulse is inputted because the loop has large inductance. Assuming the inductance of L_Q is 20.7 nH, the current applied to J_Q increases by about 100 nA whenever an SFQ pulse is inputted to the loop. The high-speed ramped bias current can be applied to J_Q by an SFQ clock generator which generates high frequency SFQ pulses. The similar technique has been proposed by Feldman et al [7].

The measurement is started by inputting a START pulse to the clock generator. The high-frequency SFQ clock pulses are inputted to the superconducting loop containing J_Q and to an SFQ counter which counts the number of SFQ pulses. The high-speed ramped bias current applied to J_Q switches it to the finite voltage state at a current value slightly lower than that of its critical current. The clock generator is stopped when J_Q switches to

the voltage state, which produces STOP pulses for the clock generator. The switching current is measured by the SFQ counter because the number of SFQ pulses is proportional to the current applied to J_Q . The measurements of switching current are performed repeatedly without turning off the bias current I_1 because small resistances R_1 and R_2 initialize the internal state of the circuit after J_Q and J_2 are switched. The distribution of the switching current is obtained by measuring the switching current many times.

The circuit was designed using the NEC 2.5 kA/cm² Nb standard process [8]. The crossover temperature of the Josephson junction was estimated to be about 1.4 K by substituting the junction's capacitance into eq. (2) and using eq. (1). Clock generator and counter were designed using the CONNECT cell library [9]. Fig. 2 shows input/output circuitry. The counter is composed of ten T1 flip-flops. The outputs of the counter are read out serially using a 10-bit shift register.

Fig. 3 shows simulation results of the proposed circuit. Fig. 3 (a) indicates that a ramped bias current is applied after the START signal is inputted, and the STOP signal is inputted to the clock generator when J_Q switches to the voltage state. The frequency of the clock generator is about 17 GHz. The sweeping speed of ramped bias current (dI/dt) is about 1500 A/sec. The sweeping speed reaches up to $dI/dt = 2000$ A/sec by increasing DC bias voltage of the circuits. Fig. 3 (b) indicates the self-resetting function of the circuit, which shows the measurements can be performed repeatedly at the repetition frequency of 1 MHz.

3. Results and Discussion

The experiment was performed at 4.2 K. Fig. 4 shows the tested result of one measurement, where the frequency of the clock generator is set to 20 GHz. Fig. 4 (b) indicates the number of SFQ pulses generated is $(0101111001)_2$ at the time the clock generator stopped.

A distribution of the switching current was obtained by repeating the measurements. The calculated escape rate of the junction reached up to 10^{10} sec^{-1} . This value is high enough to observe the energy levels quantization. The clear macroscopic quantum effect has not been observed yet because the number of measurements was not enough to measure the precise escape rate.

4. Conclusion

We have proposed an SFQ circuit to demonstrate an energy levels quantization in a Josephson junction. The circuit was designed based on NEC Nb standard fabrication technology. High-speed operation of SFQ circuits realizes the high-speed sweeping of bias current, which enables us to observe the macroscopic quantum effect at higher temperature. The test result indicates the obtained escape rate reaches up to 10^{10} sec^{-1} , which is high enough to observe the energy levels quantization. The clear macroscopic quantum effect has not been observed. The automated measurement system is being prepared and the experiment is continuing.

References

- [1] J. Clarke et al., SCIENCE 239 (1988) 992.
- [2] J. M. Martinis et al., Phys. Rev. Lett. 89 (2002) 117901.

- [3] Y. Yu et al., SCIENCE 296 (2002) 889.
- [4] P. Silvestrini et al., Phys. Rev. B 41 (1990) 7341.
- [5] P. Silvestrini et al., Phys. Rev. Lett. 79 (1997) 3046.
- [6] K. K. Likharev, and V. K. Semenov, IEEE Trans. Supercond. 5 (1995) 2447.
- [7] M. J. Feldman, Physica B 284-288 (2000) 2127.
- [8] S. Nagasawa et al., IEEE Trans. Appl. Supercond. 1 (1993) 3.
- [9] S. Yorozu et al., Physica C 378-381 (2002) 1471.

Figure Captions

Fig. 1. A schematic diagram of the proposed circuit to measure the escape rate of a Josephson junction. J_Q and J_2 denote unshunted junctions. $J_Q = 100 \mu\text{A}$, $J_I = 216 \mu\text{A}$, $J_2 = 100 \mu\text{A}$, $I_I = 50 \mu\text{A}$, $L_Q = 18.1 \text{ nH}$, $L_I = 7.5 \text{ pH}$, $R_I = 0.2 \Omega$, and $R_2 = 0.2 \Omega$.

Fig. 2. A block diagram of input/output circuitry. A TRG signal is to output a stored data in the counter to a 10-bit shift register, and a READ signal is to read out the tested result from the shift register. A TRGOUT signal is to confirm the TRG input.

Fig. 3. The simulation result.

Fig.4. The test result of one measurement. For START, TRG, and READ, rising edges correspond to the input of SFQ pulses. For OUT, and TRGOUT, transitions are the output of SFQ pulses.

Fig. 1

Fig. 2

(a)

(b)

Fig. 3

(a)

(b)

Fig. 4