Extended Abstracts of the 1998 International Conference on Solid State Devices and Materials, Hiroshima, 1998, pp. 208-209

Characterization of Small Superconducting Rings and Its Possible Application to New Single Flux Quantum Devices

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1. Introduction

In superconducting rings, the fluxoid is quantized in units of the superconducting flux quantum, $\Phi_0=h/2e$. So far, the fluxoid number n has been determined by magnetization measurement. In this paper, we study the magnetic response of small superconducting rings by measuring the energy gap and determine n by the voltage. Besides, we propose possible devices which control a single flux quantum by applying a voltage.

2. Characterization of Small Superconducting Rings

Figure 1 shows a SEM picture of one of our samples. An aluminum ring with perimeter of 2.6 μm is connected to two Al leads (source and drain) through small tunnel junctions with area of 0.01 $(\mu m)^2$ and tunneling resistance of ≈ 100 kΩ. The samples are fabricated using electron-beam lithography and our original metal deposition technique (improved shadow deposition technique) where no redundant metal stays on the ring. This new technique enables us to study small tunnel junction devices with a ring.

In the current-voltage characteristics of this sample, quasiparticle current sets in at the gap voltage, $V_g = 2(\Delta_{ring} + \Delta_{lead})/e + V_C$. Here Δ_{ring} and Δ_{lead} are the superconducting energy gaps of the ring and the leads respectively, and V_C is the offset voltage by Coulomb blockade. Thus, the voltage for a small current is sensitive to the change in Δ_{ring}. Figure 2 shows magnetic field dependence of the source-drain voltage at $I = 0.1$ nA. When the applied magnetic field B increases (bold line), the voltage repeats a moderate change (in most cases a decrease) followed by a jump. This voltage variation is due to the change of supercurrent in the ring; the supercurrent flows in order to shield the applied magnetic field, and consequently, decreases the superconducting energy gap of the ring. When the supercurrent reaches its critical value, magnetic flux penetrates into the ring and the supercurrent suddenly decreases, which causes the jump in voltage. When B is swept repeatedly up and down, we can obtain many curves as shown by the dots in Fig. 2. Each interval of the tops of adjacent curves is near Φ_0/A (A is the area of the ring), showing that n changes by one for one voltage jump. Thus, we can assign n for each curve as shown in the figure. By using this result, we can determine the fluxoid number in a small superconducting ring as shown in Fig. 3.

The magnetic field where flux penetrates in the ring depends on the biasing current I. The transition from the n=0 state to n=1 occurs at 7.86 mT and 5.97 mT for I = 0.1 nA and 10 nA, respectively. From this, we can estimate the shielding current for one flux quantum (current at A in Fig. 2) at about 14 nA.

3. Possible Application to New Single Flux Quantum Devices

By using the above properties, it may be possible to make a new kind of single flux quantum device. This circuit is more advantageous than the existing Josephson-junction logic circuit, because the former uses voltage as an input signal while the latter uses current. It uses a superconducting single electron transistor (S-SET) as a superconducting switch. A S-SET consists of two superconducting small tunnel junctions connected in series, whose central island is electrostatically coupled to a gate electrode. Figure 5 shows an example of modulated supercurrent by gate voltage V_g in a S-SET. Supercurrent is turned on and off by V_g. In this figure, the observed maximum supercurrent is about 2 pA, which is much smaller than the Ambegaokar-Baratoff (AB) theoretical value, 3.2 nA. However, by adequate external-noise reduction and adjustment of junction parameters such as the junction tunnel resistance, it is possible to increase the maximum supercurrent to ≈ 10 nA which is just below the AB theoretical value and of the order of the supercurrent flowing in small superconducting ring sustaining one flux quantum.

One of the basic circuits is shown in Fig. 6. A S-SET (E-F and G) with large maximum supercurrent (≈ 10 nA) is inserted in a superconducting ring ABCD which sustains one flux quantum at B = 0. When the supercurrent in the S-SET is turned on and off by V_g as an input signal, the distribution of supercurrent changes due to the fluxoid quantization. The change in supercurrent at point D can be detected by a tunnel junction T as an output voltage signal. We can construct logic circuits by using this method. Besides, by using a similar technique, we can transfer single flux quantum. The experiment is now in progress.

Acknowledgments

This work has been partly supported by CREST (Core Research for Evolutional Science and Technology) Project of Japan Science and Technology Corporation (JST) and Grant-in-Aid for Scientific Research of the Ministry of Education, Science, Sports and Culture of Japan.

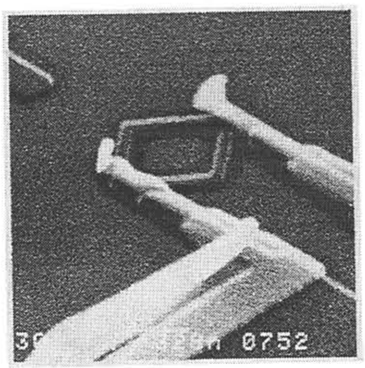

Fig. 1. A SEM picture of a small superconducting ring.

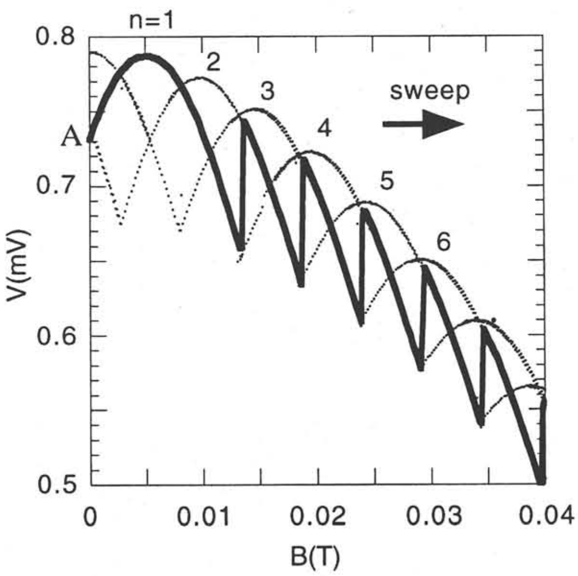

Fig. 2. Magnetic field dependence of voltage at I = 0.1nA.

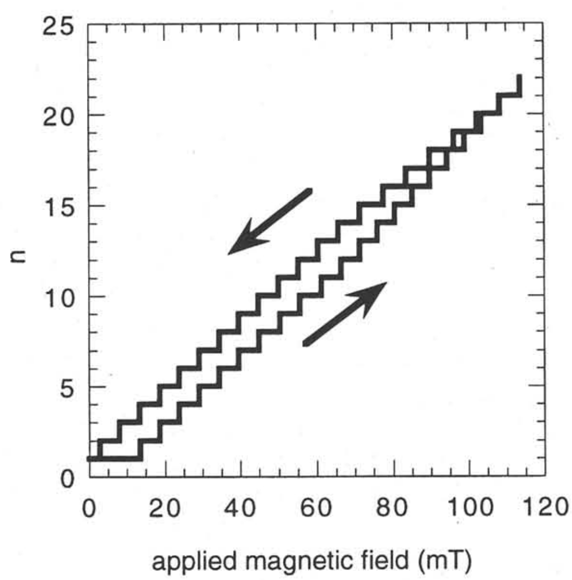

Fig. 3. Magnetic field dependence of fluxoid number n.

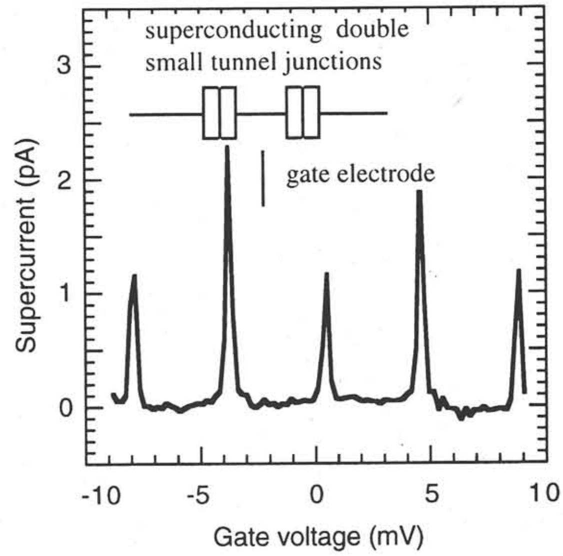

Fig. 4. Modulated supercurrent in S-SET. Inset is a schiematic view of S-SET.

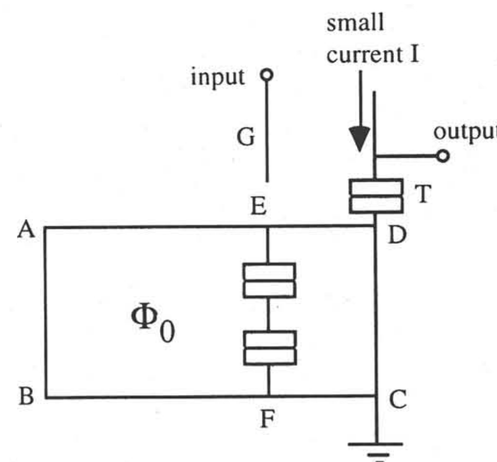

Fig. 5. Schiematic view of a circuit for a control of single flux quantum by voltage.