Quantum Fluctuations and Dissipative Phase Transition in One-Dimensional Josephson Junction Arrays

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Abstract

We studied superconductor-insulator (S-I) transition in one-dimensional (1D) arrays of small Josephson junctions in which each junction was shunted by ohmic resistor. The *I*-*V* characteristics changed from Coulomb-blockade type one to Josephson-like one for small shunt resistance R_{S}, even when the Josephson coupling energy E_{J} was much smaller than the charging energy $E_{\mathrm{C}}(\equiv e^2/C$ C:junction capacitance). The critical value of R_{S} was close to $R_{\mathrm{Q}}(\equiv 6.45\ \mathrm{k}\Omega)$, when $E_{\mathrm{J}}/E_{\mathrm{C}}$ was smaller than about unity. This agrees with the theoretical prediction for the dissipation-driven phase transition.

Key words: small Josephson junction array ; superconductor-insulator transition ; dissipation

1. Introduction

The Josephson junction arrays exhibit the quantum phase transition depending on well-controlled parameters. In these systems, the phase θ of the superconducting order parameter of each island can be regarded as the spin in the XY model. Such XY spins interact with neighboring ones and tend to align in order through the Josephson coupling. On the other hand, the charging effect makes the number N of Cooper pairs in order. Because of the uncertainty relationship $[\theta, N] = i$, the phase and the number of Cooper pairs cannot be in order at the same time. This competition leads to the S-I transition; the superconducting and the insulating states correspond to the phase-ordered and charge-ordered state, respectively. Moreover, dissipation introduced by an ohmic resistor shunting each junction suppresses the quantum-fluctuation of phases and drives the system into the superconducting state even when the Josephson coupling energy is much smaller than the charging energy. The magnitude of dissipation is proportional to $R_{\mathrm{Q}}/R_{\mathrm{S}}$. In 1D arrays of Josephson junctions, the Coulomb interaction between excess charges is stronger than in higher dimensional ones, and thus the insulating state is expected to occupy the wider region in the phase diagram.

For lithographically-fabricated 2D Josephson junction arrays many experimental studies have been reported on the S-I transition including the dissipative one [1–3]. In 1D arrays, however, there are few experimental studies in spite of many theoretical investigations [4–8]. Although the S-I transition caused by competition between the Josephson effect and the charging effect have been already observed [9], the quantitative comparison with theories is still lacking. Moreover, the S-I transition caused by dissipation have not been observed in 1D array.

In this study, we observed the dissipation-driven S-I transition in 1D arrays for the first time, and obtained the phase diagram in $E_{\mathrm{J}}/E_{\mathrm{C}}$-$R_{\mathrm{Q}}/R_{\mathrm{S}}$ plane.

2. Experiments

We fabricated two groups of 1D arrays. Each group had one unshunted arrays and three arrays with dif-

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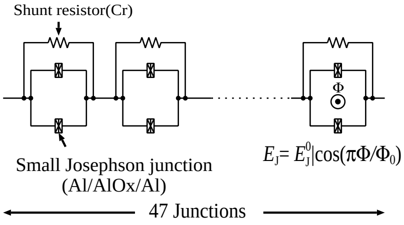

Fig. 1. Schematic drawing of the sample

ferent shunt resistances. The arrays in same group had nominally same junction parameters E_J and E_C. An array consisted of 46 superconducting islands of Al (see Fig. 1). Neighboring islands were connected with a Josephson junction (Al/AlO$_x$/Al) and a shunt resistor made of Cr. We made the Josephson junction with the DC-SQUID geometry to tune the effective Josephson coupling energy by applying small magnetic field.

Measuring the transport properties of the samples described above, we observed the following two types of behavior:

Type I The I-V characteristic shows the Coulomb gap, and the zero-bias resistance increases at lowest temperatures.

Type II The I-V characteristic shows the Josephson-like behavior, and the zero-bias resistance decreases at lowest temperatures.

The crossover between these two types was observed depending on two parameters E_J/E_C and R_Q/R_S as shown in Fig. 2. Regarding "type I" as the insulating state and "type II" as the superconducting state, we obtained the phase diagram at $T = 0$ K shown in Fig. 3. The critical value of R_Q/R_S was between 0.98 and 1.2 for E_J/E_C smaller than about unity. This agrees well with the theoretical prediction that $(R_Q/R_S)_{cr} = 1/d$ (d:dimensionality) [5]. The critical value of E_J/E_C without dissipation was 4.0. In 2D arrays, they were $(R_Q/R_S)_{cr} \approx 0.5$ and $(E_J/E_C)_{cr} \approx 0.6$ [3]. The experimental results support the intuitive idea that the quantum fluctuation of the phases are larger and insulating region is wider at lower dimension.

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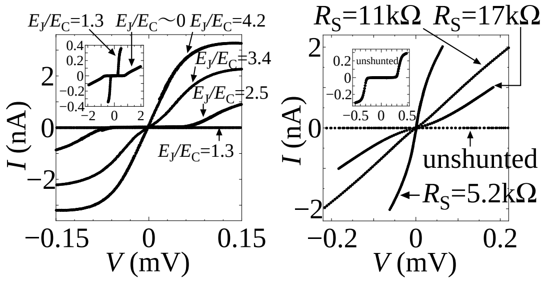

(a) unshunted
$T = 20$ mK

(b) $E_J/E_C = 1.1$
$T = 25$ mK

Fig. 2. I-V characteristics (a) for different E_J/E_C and (b) for different R_Q/R_S. The crossover between Coulomb-blockade type and Josephson-like type appears clearly in both cases.

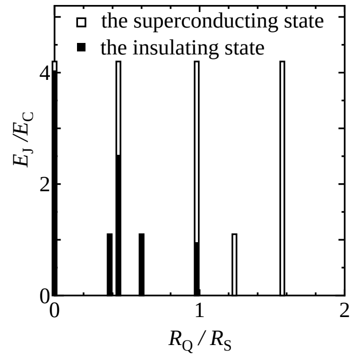

Fig. 3. The phase diagram in the $T = 0$ limit. Each bar represents the state of array at various values of E_J which is changed with the applied magnetic field; the white and black regions represent the superconducting and insulating states, respectively.

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