Superconductor-Insulator Transition in a Two-Dimensional Array of Resistively Shunted Small Josephson Junctions

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We have fabricated two-dimensional (2D) small-Josephson-junction arrays of which each Al-AlO_x-Al junction is shunted by a Cr resistor. The arrays with large junction resistance and large charging energy show a transition from insulating to superconducting behavior when the shunt resistance is lowered below a critical value, which is close to $2R_Q$ ($R_Q \equiv h/4e^2 = 6.45$ kΩ). The measured phase diagram is consistent with theories of quantum-fluctuation-driven and dissipation-driven phase transitions in the 2D Josephson-junction array with Ohmic shunt resistors.

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The superconductor-insulator (SI) transition in 2D small-Josephson-junction arrays has attracted considerable attention because it embodies interesting physics such as quantum phase transition and the dissipation effect on the quantum mechanics of macroscopic variables. At zero temperature, the phases of the superconducting order parameters on the islands are globally ordered because of the Josephson coupling E_J, and the array shows superconductivity, if the charging energy E_C associated with the junction capacitance is small. On the other hand, the large E_C leads to the Coulomb blockade of Cooper pair tunneling and makes the phases fluctuate quantum mechanically. When the ratio E_J/E_C decreases below a critical value, the phase order is destroyed by the quantum fluctuation, and the array turns into the insulator [1]. Dissipation, which is caused by Ohmic resistors shunting the junctions or quasiparticle tunneling through the junctions, is another important factor which decides the ground state of the array. It has been suggested [2,3] that strong dissipation suppresses the quantum fluctuation, and it drives a transition from insulator to superconductor, even if $E_J/E_C \ll 1$.

The SI transition depending on the ratio E_J/E_C has been observed in the 2D junction arrays fabricated using electron-beam lithography [4]. However, unambiguous experimental verifications of the dissipation-driven SI transition are still lacking. Although SI transitions observed in superconducting granular films [5] were attributed to the effect of dissipation [2], the origin of the dissipation is unclear because the subgap conductance should vanish at $T \rightarrow 0$ in the conventional understanding of superconductivity. Moreover, the films are strongly disordered with a large variation of the island size and the coupling between islands. Thus there have been some difficulties in explaining the results of the granular films by the theories of dissipation-driven phase transition. Rimberg *et al.* [6] found that the *IV* characteristics of a Josephson-junction array, which is capacitively coupled to a two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure, changed from insulatorlike to superconductorlike behavior as the resistance of 2DEG is decreased, and they interpreted the data as evidence for a dissipation-driven SI transition. However, the resistance of their "superconductorlike" array decreases as temperature falls to 50 mK and then it increases rapidly, which indicates that the array is rather "insulating" at $T \rightarrow 0$. Wagenblast *et al.* [7] pointed out that the resistance minimum is due to the capacitive coupling cutting off the dissipation at low frequencies, and that the dissipation-driven SI transition cannot occur in the system studied in Ref. [6].

In this Letter, we report the first clear observation of the dissipation-driven SI transition in a 2D small-Josephson-junction array of which each junction is shunted by an Ohmic resistor. We fabricated the samples using the electron-beam lithography and the shadow evaporation, following the method of Ref. [8]. The junction was Al-AlO_x-Al, which had an area of about 0.01 μm^2. The size of an H-shaped island was 10.0 μm × 2.8 μm, and the line width was 0.1 μm. The shunt resistors were made of Cr and were 1, 3, 6, or 8 μm long, 0.15 μm wide, and 5–8 nm thick. We inserted an Au layer between Al electrodes and a Cr resistor to attain a good electric contact between them. The metals were evaporated to the substrate successively from four different angles without breaking the vacuum during the process. We made four sets of samples, each of which consists of an unshunted array and three or four arrays with the different length of shunt resistors. We fabricated each set of arrays simultaneously and very close to each other (about 100 μm apart) on one substrate to make the junction parameters uniform. The uniformity is assured by our previous experiments [9] which show a maximum variation of ±5% in the junction tunnel resistance R_J for arrays on one substrate. We show the list of samples in Table I. The four sets are labeled as (A), (B), (C), and (D). In alphabetical order, the value of R_J decreases and the ratio E_J/E_C increases. Moreover, in this Letter, we will refer to a specific array by the set and the value of shunt resistance, e.g., (C)

$R_S = 5.4$ kΩ. All the arrays were 48 junctions long and 40 junctions wide. Narrower sides of the array were connected to end electrodes, from which current probes were extended. We fed current through these probes and measured a voltage between 40 junctions in the middle of the array. The samples were placed in the mixing chamber of a ^{3}He-^{4}He dilution refrigerator equipped with a superconducting magnet. We used battery-operated analog devices to measure the *IV* characteristics. For low-resistance samples we measured the zero-bias resistance by using two lock-in amplifiers.

We defined the junction tunnel resistance R_J as the resistance of the unshunted array at 4.2 K. The Josephson coupling energy E_J was estimated from the values of R_J and the superconducting energy gap Δ using the Ambegaokar-Baratoff formula $E_J = (R_Q/R_J)(\Delta/2)$, and the charging energy $E_C \equiv e^2/2C$ (C: the junction capacitance) from normal state *IV* characteristics of the unshunted arrays at the lowest temperature. We measured the self-capacitance C_0 of individual islands by applying voltage V_g between the ground and an unshunted array in the normal state. The *IV* characteristics of the array were periodic in V_g, and we estimated C_0 to be about 2 aF assuming that the period equals e/C_0.

The shunt resistance R_S was estimated by the equation $R_S = R_J R_{4.2\ \mathrm{K}}/(R_J - R_{4.2\ \mathrm{K}})$, where $R_{4.2\ \mathrm{K}}$ is the resistance of the shunted array at 4.2 K. R_S determined in this way were proportional to length l_S of the shunt resistor, giving resistivities $\rho = 1.6 \times 10^2\ \mu\Omega$ cm. To measure the temperature dependence of the Cr resistors alone, we fabricated on the substrate (A) an array of Al islands that were not connected by Josephson junctions but by 3 μm-long Cr resistors. As temperature decreases, the resistance of the array shows a stepwise increase by a factor of 1.3 at about 2.0 K, but below 1.9 K down to the lowest temperature it hardly depends on temperature with the maximum variation of ±5%. The temperature independence of a resistor having a length of 1 μm has also been confirmed [8]. These results rule out the possibility that the superconducting behavior of shunted junction arrays, which will be shown later, is caused by the superconducting proximity effect. This is consistent with the fact that the normal-metal coherence length $\xi_N = (\hbar D/2\pi k_B T)^{1/2}$ (D: the electron diffusion constant) of the Cr film is estimated to be 0.1 μm even at 10 mK [10] and is much smaller than the length of the Cr resistor. The temperature 2.0 K, where the resistance of the Cr-resistor array rises a little, coincides with the superconducting transition temperature of Al film, and the increase in the resistance disappears in a magnetic field larger than the critical field of Al film. Similar temperature dependence of zero-bias resistance R_0 at about 2.0 K appeared in all the shunted junction arrays. However, we did not find such resistance increase in a *single* Cr resistor which is also attached to films of Au and Al at both ends. Evidently the superconducting transition of Al films is responsible for the resistance rise, but at present we have no explanation for it.

TABLE I. Parameters for the 17 arrays. R_S: the shunt resistance. R_J: the junction tunnel resistance. $E_C(\equiv e^2/2C)$: the charging energy (C: the junction capacitance). E_J: the Josephson coupling energy.

	R_S (kΩ)	R_J (kΩ)	E_C/k_B (K)	E_J/k_B (K)	E_J/E_C
(A)	Unshunted	188	1.2	0.055	0.045
	17.5				
	11.9				
	1.3				
(B)	Unshunted	76.2	1.1	0.14	0.13
	17.7				
	5.7				
	1.4				
(C)	Unshunted	56.2	0.83	0.19	0.23
	15.3				
	12.2				
	5.4				
	1.2				
(D)	Unshunted	18.8	0.68	0.57	0.84
	7.5				
	3.6				
	0.8				

We note that the unshunted arrays showed very high subgap resistance at the lowest temperatures: 10^6–10^7 Ω for the sets (A), (B), (C), and 10^5–10^6 Ω for (D). Therefore in our samples the quasiparticle dissipation was negligible compared to the dissipation due to the shunt resistors.

Figure 1 shows the zero-bias resistance plotted as a function of temperature for four arrays in set (B). The arrays have nominally identical junction resistances $R_J = 76.2$ kΩ and identical ratios $E_J/E_C = 0.23$, but have different shunt resistances. We determined the zero-bias

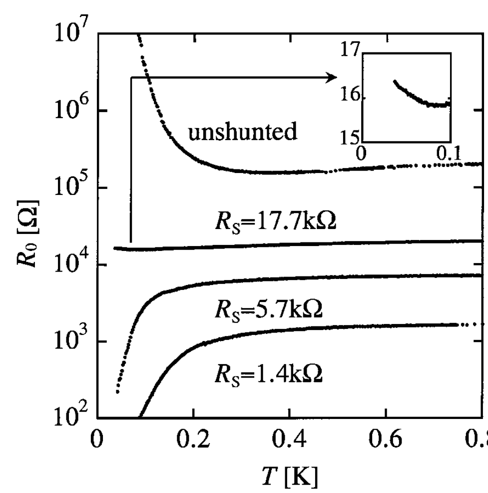

FIG. 1. Temperature dependence of zero-bias resistance for the arrays of set (B). The arrays have nominally the same junction tunnel resistance $R_J = 76.2$ kΩ and the same ratio $E_J/E_C = 0.13$.

resistance R_0 of the unshunted array by applying the least-squares fitting to the IV curves at $|V|<50\ \mu$V. R_0 of the other arrays was measured by the lock-in techniques with the excitation current 6×10^{-11} A for the arrays of $R_S = 5.7$ kΩ, 17.7 kΩ, and 1.9×10^{-10} A for $R_S = 1.4$ kΩ. The excitations were all in the linear parts of the IV curves so that the measured resistance can be regarded as a zero-bias one. In the figure the unshunted array clearly exhibits the insulating behavior with R_0 increasing rapidly as temperature decreases. The resistance of (B) $R_S = 17.7$ kΩ also increases with decreasing temperature at $T \leq 0.09$ K, which corresponds to the formation of the Coulomb gap. On the other hand, R_0 of the arrays (B) $R_S = 1.4$ and 5.7 kΩ falls monotonously with decreasing temperature.

The change of the characteristics depending on the value of R_S was also found in IV curves. The unshunted array of the set (B) shows the Coulomb gap clearly. The array (B) $R_S = 17.7$ kΩ also exhibits the Coulomb blockade as shown in Fig. 2(a) [11]. In the figure, we plot the differential resistance $R(\equiv dV/dI)$ as a function of current I. The differential resistance R decreases with decreasing current at high bias, but there is a clear increase in R in the vicinity of $I = 0$. This "W" shape of the RI curve means that the Coulomb gap is present in the supercurrentlike part of the IV curve. On the other hand, the RI curves of the arrays (B) $R_S = 5.7$ kΩ and $R_S = 1.4$ kΩ are in the shape of "V" (no resistance maximum at $I = 0$) as shown in Fig. 2(b); namely, the IV curves of the arrays have only a supercurrentlike structure and no Coulomb gap.

Thus in both R_0T and IV curves the arrays show a transition from insulating to superconducting behavior when the shunt resistance is lowered below a critical value, which is between 5.7 and 17.7 kΩ for the set (B). The arrays of (A) and (C) show the same SI transition as those of set (B) show, though the critical values of R_S differ. On the other hand, the arrays of the set (D), which have a relatively large value of $E_J/E_C = 0.84$, showed no dissipation-driven SI transition: even the unshunted array was superconducting. Deducing from the temperature dependence of the resistance and the IV characteristics, we obtained a phase diagram in the E_J/E_C–R_Q/R_S parameter space at zero temperature as shown in Fig. 3. We define the "superconductor" and the "insulator" at $T \to 0$ by the following two conditions: (1) $dR_0/dT < 0$ at the lowest temperature : insulator; $dR_0/dT > 0$ at the lowest temperature : superconductor. (2) RI curve is in the shape of "W" : insulator; RI curve is in the shape of "V" : superconductor. Both conditions gave the same result. In the figure, the superconducting and insulating arrays are plotted by open and filled circles, respectively. As described above, the shunt resistance R_S may be a little larger than that estimated at 4.2 K. In the phase diagram, we also show the values of R_S estimated at 1.9 K as the error bars. (The left ends of the error bars correspond to the values estimated at 1.9 K.)

There are several theories giving a $T = 0$ phase diagram of the 2D array [2,3]. To our knowledge, Fisher [3] treats the model most applicable to our arrays: (1) the dissipation is introduced by Ohmic shunts, and (2) the junction capacitance C is much larger than the island self-capacitance C_0. He used a perturbative renormalization group approach and obtained a phase diagram of a d-dimensional cubic array. His theory shows that the boundary between superconducting and insulating states lies at $R_Q/R_S = 1/d$ near the axis $E_J/E_C = 0$. Therefore, the critical value of R_Q/R_S is 0.5 for a 2D square array with a small E_J/E_C ratio, and this agrees well with the present experimental result. The measured phase diagram also shows that the critical value of E_J/E_C is between 0.23 and 0.84 for $R_Q/R_S = 0$. The SI transition in the limit $R_Q/R_S = 0$ (i.e., unshunted arrays) has been already investigated experimentally by Geerligs *et al.* [4]. The critical value $(E_J/E_C)_{\rm cr}$ obtained by them was between 0.55 and 0.67, which is consistent with our results. The $(E_J/E_C)_{\rm cr}$ predicted by the theories [1] vary from each other but are values somewhat smaller than 1.

The quantum-fluctuation-driven SI transition, i.e., the transition depending on the ratio E_J/E_C, stems essentially from the cooperation of the phases of individual

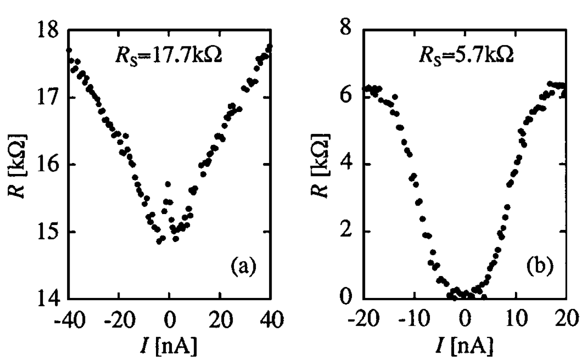

FIG. 2. Differential resistance $R(\equiv dV/dI)$ plotted as a function of current I for the arrays (B) $R_S = 17.7$ kΩ (a), and (B) $R_S = 5.7$ kΩ (b).

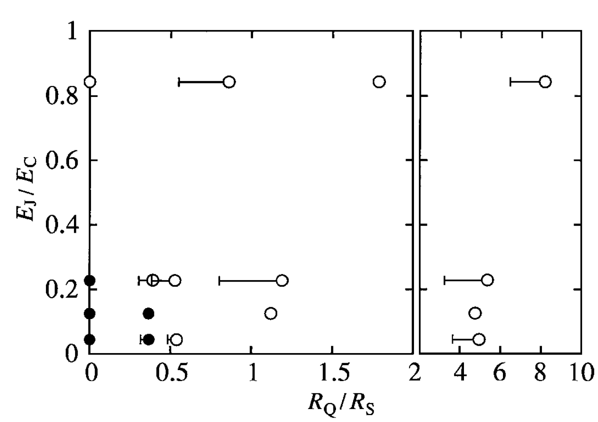

FIG. 3. Phase diagram of 2D small-Josephson-junction arrays of which each junction is shunted by an Ohmic resistor. The superconducting and insulating arrays are plotted by open and filled circles, respectively.

islands in the 2D array, and it is not expected to occur in a single shunted junction. Namely, the single junction should be insulating for $R_Q/R_S < 1$ and superconducting for $R_Q/R_S > 1$, irrespective of the ratio E_J/E_C [12]. In experiments on single shunted junctions, however, Penttilä *et al.* [13] observe the insulating behavior only for $R_Q/R_S < 1$ *and* small E_J/E_C; i.e., the measured phase diagram of the single junction is similar to that of the 2D array. They argue that the discrepancy from the theories is due to the inaccuracy of voltage measurements: the junction with $R_Q/R_S < 1$ and large E_J/E_C is insulating but the threshold voltage V_C for Coulomb blockade is too small to be observed experimentally. If the transport properties of the 2D array merely reflected those of single junctions, the 2D array should have a larger area of the insulating state in the phase diagram than the single junction has, because V_C of the array is larger and easier to detect than that of a single junction. Experimentally, however, the $(E_J/E_C)_{\mathrm{cr}}$ of the 2D array for $R_Q/R_S = 0$ is between 0.23 and 0.84, which is one order of magnitude smaller than the apparent critical value $(E_J/E_C)_{\mathrm{cr}} \approx 6$ for the single junction, in spite of almost the same junction parameters and minimum detectable voltage in both experiments. The phase transition in Fig. 3 is, therefore, a result of cooperative phenomena and the phase boundary is thought to be a "true" boundary.

In summary, 2D small-Josephson-junction arrays of which each junction is shunted by an Ohmic resistor showed an SI transition in both the R_0T and IV curves. The arrays, which have very high tunnel resistance and large charging energy, regain the superconducting behavior when the shunt resistance is lowered below a critical value, which is close to $2R_Q$. Theories of the 2D arrays of resistively shunted junctions explain well the obtained phase diagram in the E_J/E_C-R_Q/R_S parameter space. We think the observations are clear evidence for the dissipation-driven phase transition in the 2D Josephson-junction array.

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[10] We calculate the diffusion constant $D = [e^2 \rho N(\epsilon_{\mathrm{F}})]^{-1} = 0.79\ \mathrm{cm}^2\,\mathrm{s}^{-1}$, where $N(\epsilon_{\mathrm{F}})$ is the density of state at the Fermi energy and it is obtained from the Sommerfeld parameter $\gamma = 1.4\ \mathrm{mJ\,mol}^{-1}\,\mathrm{K}^{-2}$ for Cr [C. Kittel, *Introduction to Solid State Physics* (John Wiley & Sons, New York, 1986)].

[11] The differential resistance at $I = 0$ in Fig. 2(a) is slightly smaller than R_0 in Fig. 1. This is because R_0 in Fig. 1 is measured by lock-in techniques with the small excitation current 6×10^{-11} A, while Fig. 2(a) is obtained from the IV curve measured by dc methods and the interval in the current is fairly large (0.5–1 nA).

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