Dimensional crossover from 2D to 1D in small-Josephson-junction arrays

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Abstract

Dimensionality effect on the superconductor-insulator transition in small-Josephson-junction arrays has been studied experimentally. We have fabricated 2D arrays with different widths including a 1D array simultaneously on the same substrate and observed a crossover from superconducting to insulating behavior as the array width was reduced. The result indicates that the quantum fluctuations of the superconducting phases are enhanced by the dimensional reduction.

Key words: Josephson junction array; dimensional crossover; quantum phase transition

1. Introduction

It is well known that the dimensionality plays a significant role in phase transitions. Several theories have suggested that the nature of the quantum phase transitions in Josephson junction arrays depends on the dimensionality [1,2]. The phase transition, *i. e.*, superconductor to insulator (SI) transition, occurs owing to competition between the Josephson effect and the charging effect. Namely, the former tends to align the phases of superconducting order parameters of islands, leading to a superconducting ground state of the array. The latter causes quantum fluctuations of the phases and destroys the global phase ordering, leading to an insulating ground state. Lower dimensional arrays should have stronger quantum fluctuations and therefore stronger tendency to become insulating. The purpose of this study is to investigate such a dimensionality effect experimentally. To this end we have fabricated 2D arrays with different widths simultaneously on the same substrate.

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2. Results and Discussion

Three arrays which have different array widths ($W = 1, 2, 20$) and the same lengths ($L = 100$) were fabricated by electron-beam lithography. The junctions were made of Al and its oxide. Figure 1 shows the schematic view of arrays. The shapes of the islands were identical for all the arrays, although the islands of 1D arrays (and the edge islands of the W=2 and 20 ar-

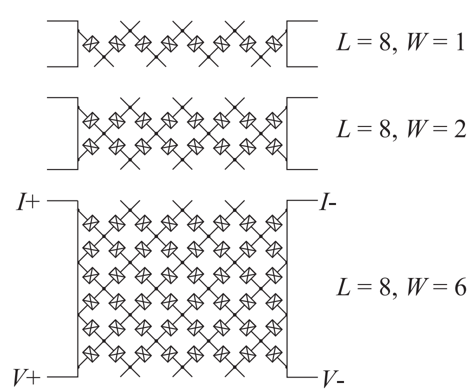

Fig. 1. Schematic layout of the arrays. For clarity, smaller arrays than those used in the actual measurement are shown.

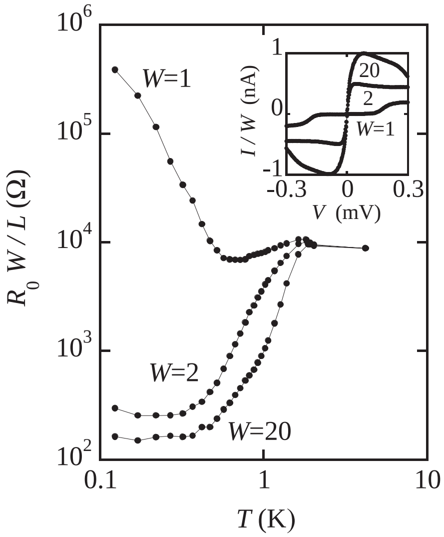

Fig. 2. Temperature dependence of the normalized zero-bias resistance R_0W/L. Inset: IV curves measured at 123 mK. The current is divided by the array width W.

rays) were connected to only two adjacent islands. The uniformity of the junction parameters was confirmed by a small scattering of resistances per junction RW/L (R: array resistance) at 4.2 K; 8.77 kΩ, 8.79 kΩ, and 8.75 kΩ for W=1, 2, and 20, respectively. From the junction resistance we estimated the Josephson coupling energy $E_J/k_B = 1.0$ K, using the Ambegaokar-Baratoff relation. The arrays were cooled in a dilution refrigerator equipped with RC and microwave filters at the low temperature (≈0.2 K) part. To estimate the charging energy, we measured IV curves at a magnetic field high enough to destroy the superconductivity of Al islands. The "normal-state" IV curves for the arrays all showed a Coulomb blockade voltage gap. From the offset voltage, we estimated the charging energy $E_C/k_B = 0.82$ K ($E_C \equiv e^2/2C$; C: the junction capacitance), so that $C = 1.1$ fF, $E_J/E_C = 1.2$. We also estimated the island self-capacitance $C_0 = 0.15$ fF by a numerical simulation.

Figure 2 shows the normalized zero-bias resistances R_0W/L (R_0: array zero-bias resistance) plotted as a function of temperature. The ambient magnetic field was canceled out by applying a compensating magnetic field. The superconducting transition temperature of Al islands was 2.0 K. The normalized resistances are almost the same at high temperatures, but as the temperature decreases the resistance of the 1D array increases while those of the $W = 2$ and 20 arrays decrease. The result indicates that the ground state of the array is insulating or superconducting depending on the dimensionality (1D or 2D). The inset to Fig. 2 shows the current-voltage characteristics at 123 mK. The IV curve of the 1D array shows a voltage gap due to Coulomb blockade, while those of the $W = 2, 20$ arrays show a Josephson-current-like structure.

Theoretically, the junction-capacitance model predicts that 2D arrays undergo the SI transition depending on the ratio E_J/E_C [3]. The critical value of E_J/E_C predicted by the model agrees with experimentally observed ones (≈0.6) [4,5]. On the other hand, the model predicts that 1D arrays are insulating irrespective of the ratio E_J/E_C [1,6]. (Theoretical models with self-capacitances C_0 considered predict that 1D arrays also show the transition [6,7].) Therefore, if E_J/E_C is larger than the critical value for 2D and C/C_0 is large enough, the 2D array should be superconducting and the 1D array should be insulating at zero temperature, which is consistent with our result.

According to an experiment performed by Penttilä *et al.*, *single* Josephson junctions are insulating at $E_J/E_C<6$ [8]. This indicates that in the parameter regime of our measurement a single junction is insulating but a 2D network of the junctions becomes superconducting with the fluctuation suppressed by cooperative phenomena.

3. Conclusions

We have fabricated a series of 2D arrays which have different array widths $W(\geq 1)$ but have nominally the same junction parameters. The temperature dependences of resistance and the IV curves show a crossover from superconducting to insulating behavior as the W is reduced. The results are explained qualitatively by enhancement of quantum fluctuations due to the dimensional reduction from 2D to 1D.

This work was supported in part by a Grant-in-Aid for Scientific Research from the Japan Ministry of Education, Science, Sports, and Culture. Y. T. would like to thank the Japan Society for the Promotion of Science for financial support.

References

[1] M. P. A. Fisher, Phys. Rev. B **36** (1987) 1917.

[2] S. Chakravarty *et al.*, Phys. Rev. B **37** (1988) 3283; A. Kampf and G. Schön, Phys. Rev. B **36** (1987) 3651.

[3] R. Fazio and G. Schön, Phys. Rev. B **43** (1991) 5307; C. Rojas and J. V. Jose, Phys. Rev. B **54** (1996) 12361.

[4] H. S. J. van der Zant *et al.*, Phys. Rev. B **54** (1996) 10081.

[5] Y. Takahide *et al.*, Phys. Rev. Lett. **85** (2000) 1974.

[6] M.-S. Choi *et al.*, Phys. Rev. B **57** (1998) R716.

[7] P.A. Bobbert *et al.*, Phys. Rev. B **45** (1992) 2294.

[8] J. S. Penttilä *et al.* Phys. Rev. Lett. **82** (1999) 1004.