Size effect on vortex states in superconducting mesoscopic aluminum disks

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Abstract

We report resistance measurements in superconducting Al disks whose sizes are much smaller than the superconducting coherence length of Al bulk. In the magnetic field, the disks show non-periodic resistance peaks depending on the sample size and topology. In circular and square disks with the size of 600 nm, there is no remarkable difference in the field intervals (ΔH) of the resistance peaks. However, significant difference in ΔH are observed between circular and square disks with the size of 500 nm. These results suggest that new vortex states depending on the sample topology appear when the size is sufficiently small.

Key words: mesoscopic superconductor; sample topology; vortex states;

1. Introduction

Recent experiments on mesoscopic Al structures with sizes comparable to the superconducting coherence length ξ_0 of Al bulk ($\xi_0\sim$ 1.6 μm) have revealed intriguing influence of the sample topology on the superconducting state. In disk structures, the configuration of the vortices inside the disks should depend strongly on the sample topology because the boundary condition of the superconducting order parameter determines the confinement geometry for the superconducting condensate [1–3].

In order to further study the effect of the confinement geometry, we fabricated Al disks with different topology and sizes, and performed the resistance measurements under the magnetic field. The sizes of our disks are much smaller than ξ_0. Therefore, the sample topology and size are expected to show significant effects on the superconducting state and the configuration of the vortices.

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2. Results

We fabricated two types of Al disks with the standard four-terminal configuration. One is circular disk with the diameter of 500 nm or 600 nm. The other is square disk with the size of 500×500 nm^2 or 600×600 nm^2. The wire widths of electrical leads are 60 nm and the deposition thickness of Al is about 30 nm. The resistance measurements were performed under the magnetic field perpendicular to the sample plane.

The insets of Fig. 1 show the resistance variations of the circular disks with the size of (a) 600 nm and (b) 500 nm. We can see that non-periodic resistance peaks are observed in both samples. The non-periodic peaks are also observed in the square disks of 600 nm and 500 nm. The main parts of Fig. 1 show the variations of the field intervals of the resistance peaks ($\Delta H'$) in all the samples. In the circular and the square disks with the size of 600 nm [Fig1. (a)], we note that $\Delta H'$ decreases monotonically with the increase of the peak number. Within the experimental error, there is no remarkable difference between them. In the disks with the size of 500 nm [Fig1. (b)], the circular disk shows a mono-

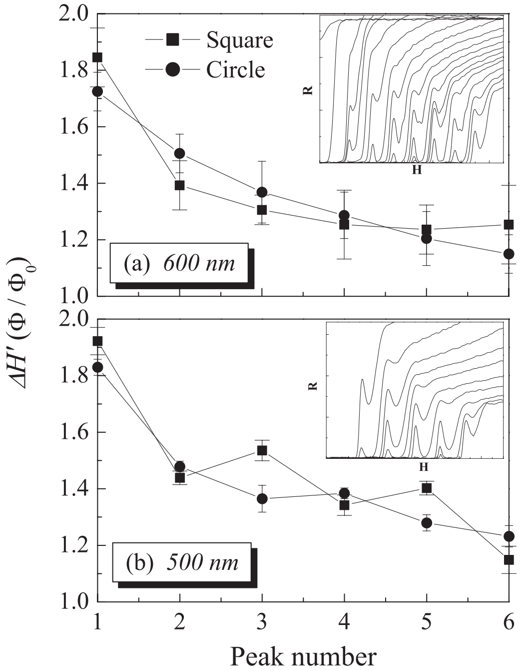

Fig. 1. Peak number versus the field intervals of the non-periodic resistance peaks ($\Delta H'$) in (a) 600 nm-disks, (b) 500 nm-disk. Insets : magnetic field dependence of the resistances in circular disks at temperatures of $0.2 \sim 1.2$ K.

tonic decrease of $\Delta H'$. On the other hand, the square disk seems to have significant oscillatory behavior in $\Delta H'$, especially enhancement of $\Delta H'$ for odd numbers. In further experiments, we measured the variations of $\Delta H'$ in disks larger than 600 nm and observed only a monotonic decrease in $\Delta H'$ for both circular and square disks. The results lead us to conclude that the difference of $\Delta H'$ between circular and square disks becomes prominent only when the disk size becomes sufficiently small.

3. Discussion

The quantized energy states of small superconducting disks are obtained by solving the linearized Ginzburg-Landau (LGL) equations with a proper boundary condition, where superconducting order parameter ψ_s is descried by the product of the radial ($f(r)$) and the angular ($e^{-iL\varphi}$) functions; $\psi_s = f(r)e^{-iL\varphi}$. At zero field, the $L = 0$ state is stable. As the field increases, states with larger orbital quantum numbers L are more stabilized [1]. The resistance peaks in the insets of Fig. 1 correspond to the transition fields from the L to $L + 1$ states. Buisson *et al*. solved the LGL equations with the boundary condition of a circular superconducting-insulator interface [4]. Although the magnetic field dependence of the total energy is complicated, it is predicted that $\Delta H'$ monotonically decreases with increasing field. On the other hand, Chibotaru *et al*. developed analytical gauge transformation and solved the LGL equation with the tetragonal boundary condition, i.e. a square structure [5]. They showed that additional vortex-antivortex pairs nucleate spontaneously so as to preserve the symmetry of the square structure. For instance, in the case of small L values ($3 \sim 5$), vortices can occupy one central and four diagonal positions. The central vortex can change its state from antivortex, zero vortex, and two vortices, keeping four diagonal vortices. In this sequence, $\Delta H'$ also monotonically decreases with increasing field.

In our results, the monotonic decrease in $\Delta H'$ was observed in the circular and the square disks of 600 nm, and in the circular disk of 500 nm. These results seem qualitatively consistent with the above theories. However, in the square disk of 500 nm, $\Delta H'$ shows the oscillatory behavior with the remarkable increases at the odd peak numbers. The results suggest that some new vortex states in small Al square disks appear, when the size of the square disk becomes sufficiently smaller than ξ_0. At the present, it is not clear how vortices occupy such small square disks. Further experimental and theoretical investigations are necessary.

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