Sample size dependence of excess resistance near critical field in mesoscopic superconducting Al disk

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Abstract. We report the size dependence of superconducting transition in mesoscopic Al disks with 1.0, 0.7, and 0.4 µm in diameter performed by resistance measurements under magnetic field. All the samples show excess resistance peaks near $H_{c2}$, which are 3 ~ 6 times larger than normal state resistance $R_n$, whereas there are no resistance peaks at $H = 0$. We find that the resistance peak rapidly increases and becomes the largest at the magnetic field just below the transition of vorticity $L : 0 \rightarrow 1$ with no relation to the sample size. The resistance peak, which shows the presence of large energy dissipation, would be caused by characteristic vortex dynamics confined in the small geometries.

1. Introduction
The advance in the microtechnology enables us to fabricate the submicron size of the sample geometry, which engaged us in detailed research of mesoscopic superconductivity. When the sample size become comparable to coherence length $\xi$ and London penetration depth $\lambda$, the characteristic oscillation of the superconducting transition temperature $T_c (H)$ is observed under magnetic field. The oscillation is caused by periodic instability of the superconducting state confined in small structures, where the vortex configuration, depending on the sample shape, plays a crucial role [1,2]. Near $T_c$, it has been reported that the electric resistance becomes much larger than the normal state resistance $R_n$ in the various geometries of the mesoscopic Al samples [3-7]. Although resistance peaks near $T_c$ in wire samples have been explained in terms of the phase slip centers [6] or S/N boundaries [7], mechanism of large resistance peaks observed in mesoscopic structures with thin leads under magnetic field has not been clarified yet [5].

In this work, we fabricated three different sizes of Al disks with 1.0, 0.7, and 0.4 µm in diameter, and measured the temperature dependence of resistance at various magnetic field in order to investigate the sample size effect on the superconducting $H - T$ phase diagram and the excess resistance peak near $H_{c2}$. We found that the possible relevance of vortex to the excess resistance peak, which is probably enhanced by the vortex dynamics around the transition between different vortex states.
2. Experiment

Samples were patterned on SiO$_2$ substrates by electron beam lithography (Hitachi S4200 equipped with Tokyo Technology Beam Draw System). Al films (30 nm thick) were deposited by thermal evaporation of high purity Al (99.999%) at room temperature followed by a lift-off process. Scanning electron microscope (SEM) measurements confirmed the presence of a smooth aluminum surface with no major cracks or holes. We prepared for three different sizes of disks, and their diameters are 1.0, 0.7, and 0.4 µm, respectively, with 0.1 µm width of the leads as illustrated in Fig. 1(a)-(c). The resistance measurements were performed using lock-in amplifiers (Stanford Research SR830) at the frequency of $\sim 10$ Hz at temperature down to 0.56 K under magnetic field up to 1000 Oe. All the electrical leads were shielded by low-pass filters (60 dB cutoff at 100 MHz) located near the samples.

3. Results and discussion

Figure 1(a)-(c) show the temperature dependence of resistance at various magnetic fields for three different sizes of Al disks with 1.0, 0.7, and 0.4 µm in diameter, respectively. Here, we applied the magnetic field perpendicular to the sample plane. At $H = 0$, sharp superconducting transitions are observed with decreasing temperature. In fields, however, we note that the large resistance peaks are evident and the superconducting transitions become significantly broad. Here, we define two characteristic temperatures, the onset of the large peak ($T_{\text{onset}}$) and the zero-resistance temperature ($T_{\text{zero}}$). It is too broad if the width of the superconducting transition is just ascribed to the inhomogeneity of $T_c$. The magnetic field versus temperature phase diagrams of three different disks are shown in Fig. 1(d)-(f). The $T_{\text{zero}}$ values show the marked size dependence, whereas $T_{\text{onset}}$ curves do not indicate the distinct difference in the three sizes. This result is consistent with our previous measurements: the onset of the large peak corresponds to $H_{c2}$ of the wires connecting to the disks [7]. As the disk size becomes larger, the zero-resistance field becomes smaller. The tendency can be easily explained by the difference of the area penetrated by the magnetic field [8], thus $T_{\text{zero}}$ should be directly related to the stability of the superconducting state in the disk parts of the samples. An important

![Figure 1](image)

**Figure 1.** Temperature dependence of resistance at various magnetic fields for three different sizes of Al disks. The diameters of the disks are (a) 1.0, (b) 0.7, and (c) 0.4 µm, respectively. Temperature versus magnetic field phase diagram of three Al disks with (d) 1.0, (e) 0.7, and (f) 0.4 µm in diameter, respectively. The solid and open symbols indicate $T_{\text{zero}}(H)$ and $T_{\text{onset}}(H)$, respectively.
Figure 2. Magnetic field dependence of resistance at various temperatures for three different sizes of Al disks with (a) 1.0, (b) 0.7, and (c) 0.4 μm in diameter, respectively. The dotted lines indicate the position of the small resistance peaks, where the vorticity $L$ transits to different vortex state.

feature is the oscillatory behavior in $T_{zero}$, whose period becomes shorter as the disk size becomes larger. Such oscillatory $T_c$ with field has been reported in various mesoscopic samples, and is well understood in terms of the transition between the different vortex state characterized by vorticity $L$ (number of the flux quanta penetrating the sample) [2]. At the transitions between the different $L$ states, $T_c$ is slightly lower than that at other fields because of the instability of the superconducting state. Starting from $L = 0$ at zero magnetic field, $L$ increases with one at every dip in $T_c$. The periods of the $T_c$ oscillations generally show complicated field dependence, depending on size, shape, and thickness of the samples. The period is longer than that corresponding to the magnetic flux density penetrating in the same area, $\Delta H = \phi_0 / S$, where $\phi_0$ and $S$ are the flux quantum and the total area of Al disk, respectively. In fact, the periods of our data are longer than the values $\Delta H = \phi_0 / S = 25.5, 52.0, 159.2$ Oe for the disks with 1.0, 0.7, and 0.4 μm in diameter, respectively.

The $T_c$ oscillation is clearly observed in the magnetic field dependence of the resistance at various temperatures for the same samples (Fig. 2). Below the value of magnetic field where the largest resistance peak appears, some small resistance peaks are observed. Interestingly, the positions of the resistance peaks are independent of temperature, depend only on the value of magnetic field as indicated by dotted lines. We should note that some small peaks are larger than $R_n$. The fact shows that the disk parts are in superconducting vortex states even in the field region where the resistance is larger than $R_n$. This is quite anomalous because the resistance cannot exceed $R_n$ in conventional flux flow dynamics [8].

Figure 3 shows the magnetic field dependence of $R_{peak}/R_n$ for three different sizes of Al disks. Here, $R_{peak}$ is the peak value of the resistance curves, indicated by dotted arrows in Fig. 1(a)-(c). It is noteworthy that the excess resistance peak appears and becomes robust under magnetic field. The maximum of $R_{peak}$ are 5.8, 5.3, and 4.2 times larger than $R_n$ for the disks with 1.0, 0.7, and 0.4 μm in diameter, respectively, under magnetic field. In the models of phase slip centers [6] and S/N boundaries [7], $R_{peak}$ is estimated to be just 1.3 times larger than $R_n$ at $H = 0$, which cannot probably explain significant large resistance peak under magnetic field. The values of $R_{peak}/R_n$ rapidly increase with field and become the largest at the magnetic fields just below the transitions for $L : 0 \rightarrow 1$ with no relation to the size of the disks. At the transition, two state ($L = 0$ and 1) are degenerated, which means the presence of large fluctuation. Such fluctuation would cause strong vortex dynamics inside the disks, which induces large energy dissipation. Again, in conventional theories, the flux flow resistance never exceeds $R_n$, where no boundary condition is imposed. Therefore, the results may suggest that a small numbers of vortices
Figure 3. Magnetic field dependence of $R_{\text{peak}}/R_n$ for three different sizes of Al disks with (a) 1.0, (b) 0.7, and (c) 0.4 µm in diameter, respectively. The lines indicate the transition of vorticity $L$ in Al disks obtained from Fig. 2.

Confined in small structure cause anomalously large energy dissipation at the boundaries when they come in and go out of the structure. Here, we note that $R_{\text{peak}}/R_n$ shows no significant peaks at the other transitions but smoothly decreases with field. The reason is not clear at present. Further experiments are required for the full understanding of the mechanism of the excess resistance peak.

4. Conclusions
In summary, we have investigated the sample size dependence of $T_c$ and the excess resistance peak near $H_{c2}$ in three different sizes of Al disks with 1.0, 0.7, and 0.4 µm in diameter, respectively, under magnetic field. It is observed that $R_{\text{peak}}/R_n$ becomes the largest at the magnetic field just below the transition of orbital quantum number $L : 0 \rightarrow 1$ with no relation to the size of Al disk. We believe that the disk parts are still in superconducting vortex states even above $T_{\text{zero}}(H)$, and the vortex dynamics is most enhanced around the transition.

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