Large energy dissipation due to vortex dynamics in mesoscopic Al disks

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(Received 13 January 2010; revised manuscript received 29 March 2010; published 3 May 2010)

We present systematic resistance measurements of mesoscopic Al disk samples with three different sizes and compare them with those of an Al-wire sample. When a magnetic field is applied perpendicular to the disks, a large excess resistance, which is approximately six times larger than the normal-state resistance (R_n), appears near the critical field of the Al leads connected to the disks. In the low-field region of the large excess resistance, successive resistant peaks are observed. These peaks are ascribed to the transitions of the vortex states in the disk. Remarkably, some of the resistance peaks are significantly larger than R_n, indicating that the Al disks are superconducting in the excess resistance state. Such behavior has never been observed in the case of a wire sample. These results suggest that the vortices in the mesoscopic disks cause anomalously large energy dissipation when they are driven by the sample current. The superconducting current leads connected to the disks also play a crucial role in the occurrence of the large excess resistance.

DOI: 10.1103/PhysRevB.81.174501 PACS number(s): 74.25.Dw, 73.23.−b, 74.78.Na

I. INTRODUCTION

A number of mesoscopic aluminum structures have been extensively studied to clarify the effects of the sample geometry on superconducting properties.[1] One of the intriguing size effects on superconductivity is the excess resistance: the electric resistance of mesoscopic Al wires, loops, and films anomalously exceeds the normal-state resistance (R_n) in the vicinity of the superconducting transition temperature T_c at $H=0$.[2–11] The magnetic field suppresses the excess resistance. The excess resistance has been explained by the Cooper-pair/quasiparticle charge imbalance[7] based on the nonequilibrium superconductivity near phase slip centers (PSCs) (Refs. 10 and 12) or static superconducting-normal (S-N) boundaries[11,13] created between voltage probes.

When PSCs are induced in Al samples, the nonequilibrium state relaxes to a charge-balanced state within the characteristic length Λ_Q, which is much larger than coherence length. While the electrochemical potential of the quasiparticles smoothly changes across a PSC on the scale of Λ_Q, that of the Cooper pairs is expected to drop rapidly at a PSC.[10] The distance between the superconducting voltage probes is much shorter than Λ_Q in the mesoscopic samples; this enables us to detect the excess resistance when PSCs appear between them. The charge imbalance can be induced by both rf irradiation and high dc in Al wires.[8–10] The PSCs nucleate at the weakest spots with a locally reduced critical current in the sample near T_c when the rf radiation or dc is increased. Consequently, the charge imbalance at PSCs causes the characteristic temperature dependence of the resistance and dV/dI curves.

On the other hand, the excess resistance has also been explained by the purely geometric effect of S-N boundaries due to the inevitable sample inhomogeneity.[11,13] At S-N boundaries, nonequilibrium quasiparticles are injected into the superconducting domain from a normal one. If the boundaries are significantly deformed between the voltage probes, the effect of the electric field penetration into the superconducting domain is enhanced, which causes the excess resistance. In Al wires, resistance anomalies are observed near T_c and the maximum value of the excess resistance is limited up to approximately 30% larger than R_n in the temperature dependence.

Recently, it has been reported that a significantly large excess resistance emerges in magnetic fields in a mesoscopic Al disk.[14] The largest magnitude of the excess resistance is approximately eight times as large as R_n under magnetic field. While there have been extensive experimental and theoretical studies on wire samples, there have been very few studies on the excess resistance in disk samples in fields, where vortex dynamics plays a crucial role. In this paper, we report the systematic resistance measurements of Al disks with different sizes and compare the data with those of an Al wire to investigate the mechanism of the excess resistance state in the disk samples. We present unambiguous evidence of anomalous large energy dissipation of the vortex dynamics in the disk samples and discuss the possible origin.

II. EXPERIMENTAL

The patterns of the samples were drawn on SiO_2 substrates by using electron-beam lithography and a resist (ZEP520A). After 30-nm-thick Al films were deposited by evaporation of high-purity Al (99.999%) in vacuum, lift-off processing was performed. Scanning electron microscope (SEM) measurements confirmed the presence of a smooth aluminum surface with no major cracks or holes, as shown in Fig. 1. We prepared three different sizes of disks with 1.0, 0.7, and 0.4 μm in diameter, and one wire with 0.4 μm in length. All the samples were measured using a standard four-terminal method with 0.1-μm-wide leads. The resistance measurements were performed using lock-in amplifiers (Stanford Research SR830) at a frequency of ~20 Hz with an ac of $I_{ac}=50$ nA, except for the measurements of I_{ac} dependence. A magnetic field was applied perpendicular to the sample plane up to 1000 Oe. All the electrical leads were

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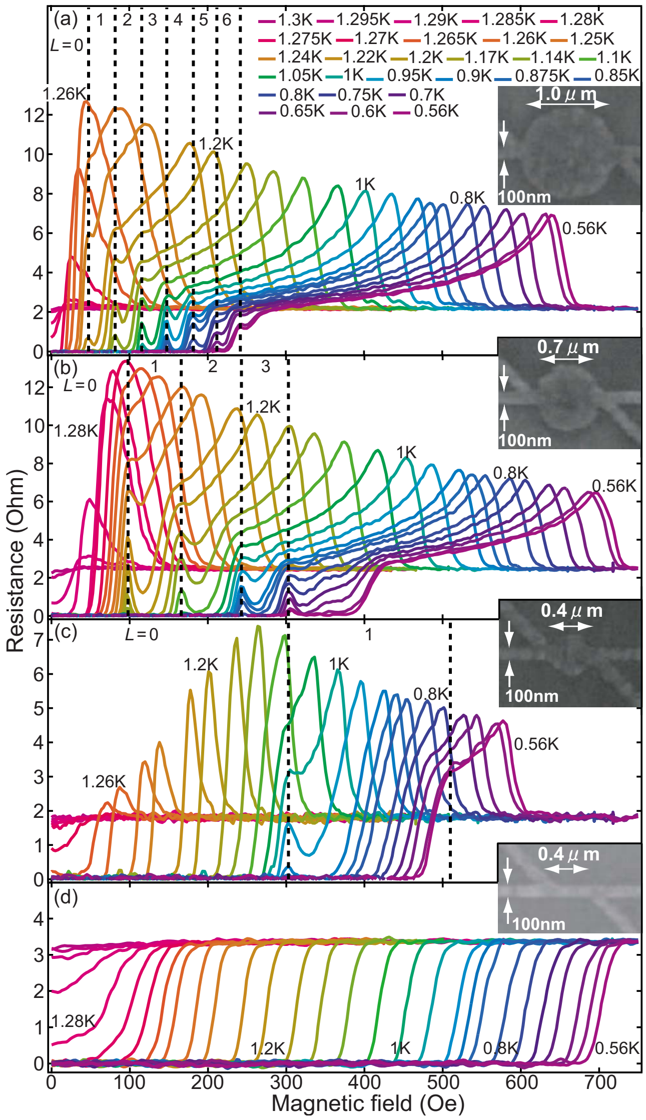

FIG. 1. (Color online) Magnetic field dependence of resistance at various temperatures for three sizes of Al disks with (a) 1.0, (b) 0.7, and (c) 0.4 μm in diameter, and (d) for an Al wire with 0.4 μm in length, respectively. The dashed lines indicate the position of the small resistance peaks, where the vorticity L transits as $L \rightarrow L+1$ ($L=0,1,2,\ldots$). The insets show the SEM images of the samples.

shielded by low-pass filters (60 dB cutoff at 100 MHz) located near the samples.

III. RESULTS

Figures 1(a)–1(c) show the magnetic field dependence of resistance at various temperatures for three sizes of Al disks with 1.0 μm, 0.7 μm, and 0.4 μm in diameter, respectively. These data are highly reproducible. At around $H=0$, there is no resistance anomaly. In field, however, the large excess resistance larger than R_n is evident. As the field increases, we note that the resistance exhibits successive small peaks in the low-field region of the large excess resistance. Such behavior is not observed in the Al wire, as shown in

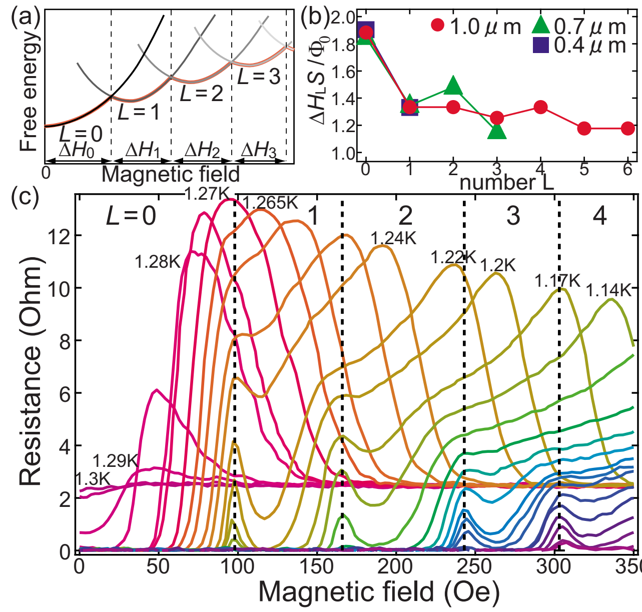

FIG. 2. (Color online) (a) Schematic plot of the free energy with vorticity L vs the magnetic field. Each curve corresponds to the free energy for each L. (b) Normalized field interval between the Lth and the $(L+1)$th peaks, $\Delta H_L S/\Phi_0$ as a function of L. (c) R vs H plot at various temperatures in a low-field region for the Al disk with 0.7 μm in diameter. Some of the successive resistance peaks are larger than R_n.

Fig. 1(d). These features are obviously related to the difference between the geometry/size of the disk and wire samples: several vortices exist in the Al disk while no vortex exists in the Al wire, as shown later. Although the excess resistance was reported to emerge at $H=0$ in some mesoscopic Al wires, it is not observed in the entire T-H region of our Al wire. The resistivity of our wire sample and the current density in the measurement are $\rho=2.6$ $\mu\Omega$ cm and $j=1.7\times10^3$ A/cm^2, respectively, which are comparable to those in previous works.[2,10,11]

For all the Al disk samples, the successive resistance peaks are observed at specific values of magnetic field and their positions are independent of temperature, as indicated by the dashed lines in Figs. 1(a)–1(c). The successive resistance peaks have been explained by the transition of the vortex state characterized by vorticity L (number of the vortices penetrating the sample). Figure 2(a) shows a schematic plot of the free energy vs the magnetic field obtained by the linearized Ginzburg-Landau (GL) equation, where each curve corresponds to the free energy for each L.[15,16] At the transition from the L to the $L+1$ state ($L=0,1,2,\ldots$), the lowest free-energy curve exhibits a cusp, as shown in Fig. 2(a). The decreased T_c at the transition appears as a resistance peak.[17] For the wire sample, the absence of small peak indicates that no vortex penetrates the wire because of the extremely small area between the voltage probes. The peak fields (dashed lines) and the field interval between the peaks apparently depend on the sample size: a smaller peak field and field interval are observed for a larger disk. In Fig. 2(b), $\Delta H_L S/\Phi_0$ is plotted as a function of L for the three Al disks, where ΔH_L is the field interval between the resistance peaks, S is the disk area, and Φ_0 is flux quantum. All the data exhibit a similar tendency: ΔH_L approaches unity with increasing L. This behavior is consistent with the theory.[16] Extensive theoretical and experimental investigations on various vortex configurations such as giant vortex states, multivortex states, and combined states have been studied in mesoscopic samples.[18–22] Because the four leads connected to the disk makes theoretical calculation of the vortex configurations complex, we cannot make any decisive conclusions on the vortex configuration from these results at present.

Figure 2(c) shows the magnetic field dependence of resistance at various temperatures for the Al disk with 0.7 μm in diameter, with an emphasis on the resistance above R_n in the low magnetic field region. It is remarkable that the resistance peak of the $L=0\rightarrow 1$ transition at $H\sim 100$ Oe is about six times larger than R_n at $T=1.265$ K. At the other transitions, e.g., $L=1\rightarrow 2$ and $L=2\rightarrow 3$, the peaks also exceed R_n. The observation of the resistance peaks clearly indicates that the Al disk is superconducting even for $R>R_n$. When the vortices are depinned in the sample, we may observe a finite resistance in the superconducting state. However, the flux-flow resistance never exceeds R_n for a conventional model in a bulk system.[23] Therefore, our observation suggests that the vortices driven by the sample current cause anomalously large energy dissipation in mesoscopic samples. This is consistent with the absence of hysteresis in the measurements. In the magnetization measurements, which is a typical static measurement, a large hysteresis has been reported in the M-H curve,[24,25] indicating that the vortices remain inside the disk: the vortices are pinned or confined in the Bean-Livingstone (BL) barrier.[26] Conductance measurements of an isolated Al disk with 0.75 μm in diameter by a multiple-small-tunnel-junction method also show hysteresis in field sweep, however, this is in the low-current limit ($I=0.1$ nA).[22] In our resistance measurements, the vortices are driven in the entire finite-resistance region because of the fairly large current, and therefore, no metastable states are achieved. Despite performing the measurements at low currents down to $I=20$ nA, we have found no appreciable hysteresis, indicating small pinning potential and a BL barrier in the Al disks.

Figure 3 shows the magnetic field dependence of T_{onset} and T_{zero} for the Al disks with 1.0, 0.7, and 0.4 μm in diameter, and T_c for the Al wire with 0.4 μm in length, as obtained from the resistance measurements as a function of temperature in Fig. 4(a). The two characteristic temperatures for the Al disks, the onset of the excess resistance temperature T_{onset}, and the zero-resistance temperature T_{zero} are defined in Fig. 4(a). The critical temperature T_c for the Al wire is determined at zero resistance. The data shown in Figs. 1 and 3 are consistent with each other. We note that $T_{zero}(H)$ exhibits remarkable sample-size dependence, however, $T_{onset}(H)$ has no significant dependence. The good agreement between $T_{onset}(H)$ and $T_c(H)$ in Fig. 3 shows that T_{onset} corresponds to T_c of the leads of the Al disks. In the framework of GL theory, the critical field of the thin films is given by $H=\sqrt{3}\Phi_0/\pi w\xi(T)$ for $w\ll\xi(T)$ when the magnetic field is applied parallel to the plane, where $\xi(T)$ is $\xi(T)=\xi_{GL}/\sqrt{1-T/T_c}$, ξ_{GL} is the GL coherence length, and w is the thickness of the film.[27] This formula is approximately applicable to the leads of the disk samples and wire sample because the leads and wire are much narrower than the coherence length $\xi(T)$ near T_c. In Fig. 3, the solid curve is calculated by the above formula with $w=0.1$ μm, $\xi_{GL}=0.13$ μm, and $T_c=1.28$ K. The coherence length ξ_{GL} is given by $\xi_{GL}=0.86(\xi_0 l)^{0.5}$, where ξ_0 and l are the BCS coherence length and mean free path, respectively.[27] l is obtained from the normal-state resistivity of the wire using $\rho l=4\times 10^{-12}$ Ω cm^2 for aluminum.[28] On the other hand, T_{zero}

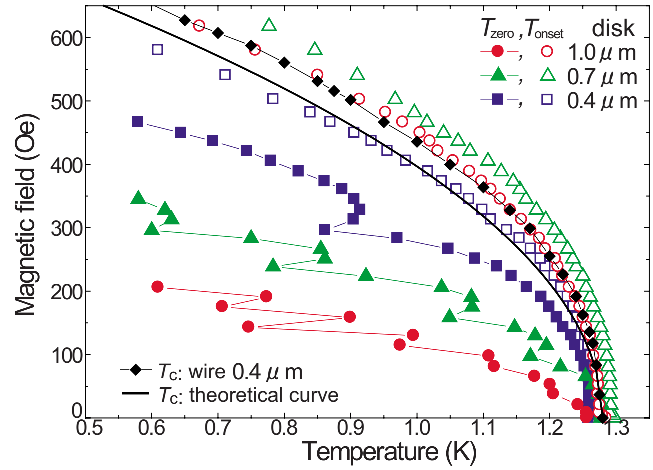

FIG. 3. (Color online) Magnetic field dependence of T_{onset} (open symbols) and T_{zero} (solid symbols) for the Al disks with 1.0 (circles), 0.7 (triangles), and 0.4 μm (squares) in diameter, and T_c for the Al wire with 0.4 μm (solid diamonds) in length. The solid curve is calculated by the formula $H=\sqrt{3}\Phi_0/\pi w\xi(T)$ with $w=0.1$ μm, $\xi_{GL}=0.13$ μm, and $T_c=1.28$ K.

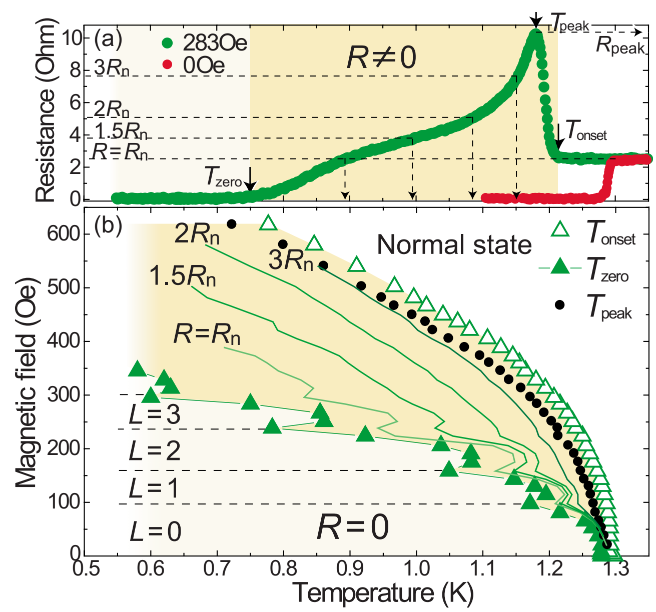

FIG. 4. (Color online) (a) Temperature dependence of resistance at $H=0$ and 283 Oe for the Al disk with 0.7 μm in diameter. T_{onset}, T_{zero}, and T_{peak} are defined at $H\neq 0$, as indicated by the arrows. (b) Resistance contour plots for $R=R_n$, $1.5\times R_n$, $2\times R_n$, and $3\times R_n$ along with T_{peak}, T_{onset}, and T_{zero}. The transitions of the vorticity L are also indicated by dotted lines.

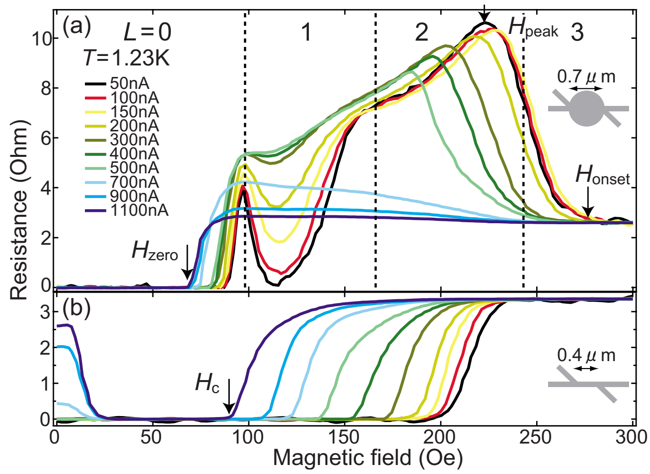

FIG. 5. (Color online) Magnetic field dependence of the resistance with various ac at $T=1.23$ K for (a) the disk with 0.7 μm in diameter and (b) the Al wire with 0.4 μm in length.

is substantially smaller than T_c of the Al wires. As the disk size increases, T_{zero} decreases. Additionally, oscillatory T_{zero} indicates that T_{zero} is associated with the disk part.

Figure 4(a) shows the temperature dependence of the resistance at $H=0$ and 283 Oe for the Al disk with 0.7 μm in diameter. It should be noted that the excess resistance is not observed at $H=0$. The application of magnetic field induces the excess resistance in the mesoscopic Al disks. At $H=283$ Oe, the large excess resistance is clearly observed immediately below T_{onset}, and it is approximately 4.6 times larger than R_n. Below T_{peak}, the resistance gradually decreases, but it remains large ($R>R_n$) in the wide temperature region from T_{onset} to $T\sim 0.9$ K. The data provide a marked contrast to the fact that the excess resistance in the mesoscopic Al wire was observed only in the vicinity of T_c.[2,7,10,11] In Fig. 4(b), we show the resistance contour plot for $R=R_n$, $1.5\times R_n$, $2\times R_n$, and $3\times R_n$ along with T_{peak}, T_{onset}, and T_{zero}. The dip parts (dotted lines) of the resistance contour plots where the vorticity transitions occur are evident up to $H=300$ Oe. We can slightly see the transition at approximately $H=100$ Oe, even for the $3\times R_n$ curve, close to T_{peak}. Again, these results show that the Al disk is superconducting up to $T\sim T_{peak}$. The oscillation of the resistance contour plot is smeared out at higher T and H. This is because thermal fluctuation is larger at higher T, and the oscillation amplitude of the free energy in field is reduced at high H.[21,25] Therefore, although the vorticity transitions are not visible in the higher T and H region, the Al disk might be superconducting in a wide T region below T_{peak}.

Figures 5(a) and 5(b) show the magnetic field dependence of the resistance with various ac I_{ac} at $T=1.23$ K for the disk with 0.7 μm in diameter and the Al wire with 0.4 μm in length, respectively. For the wire sample, the resistive transition simply shifts to a low-field region with increasing current. Again, there is no vortex in the wire. For $I>500$ nA, we note that a finite resistance less than R_n appears at around $H=0$. This probably corresponds to the reported resistance anomalies, which have been ascribed to PSC or S-N boundary effects.[2,7,10,11] For the disk sample, however, a few characteristic features are evident. (a) The values of H_{onset}, H_{peak}, and H_c decrease gradually with increasing I_{ac}, while H_{zero} shifts to a low field slowly. (b) The resistance value at H_{peak} is strongly suppressed above $I_{ac}=150$ nA. No excess resistance is evident at $I_{ac}=1100$ nA. (c) The vorticity transition at $H\sim 100$ Oe is visible up to $I_{ac}=500$ nA, but invisible above $I_{ac}=500$ nA.

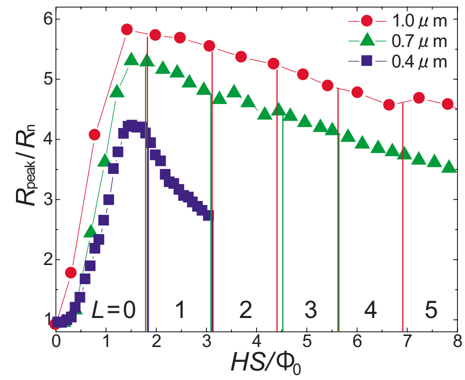

FIG. 6. (Color online) R_{peak}/R_n vs HS/Φ_0 for the three sizes of the Al disks. The vorticity transition lines are indicated by solid lines for all samples.

These features are also observed for the other disk samples. All the results cannot be explained by the Joule heating effect because the data at high currents are not consistent with those at higher temperatures shown in Fig. 2(c). At a fixed field, it is likely that the superconductivity of the narrower current leads (not voltage leads) is first broken with increasing current. Therefore, the results (a) and (b) show the crucial role of the superconducting current leads for the onset of the large excess resistance. Because the boundary condition between the current leads and disk part differs due to the characteristic geometry, there exists some mismatch of the order parameter at the boundaries between them. The driven vortices in the confinement geometry with such inhomogeneous order parameters might cause large energy dissipation by unknown mechanisms.

Figure 6 shows R_{peak}/R_n vs HS/Φ_0 for the three sizes of the Al disks. Here, R_{peak} is obtained from the maximum value of the excess resistance at each magnetic field, as shown in Fig. 4(a). The vortex transition lines for all the samples are determined from the data shown in Fig. 1. We note that all the disk samples exhibit similar behavior. At $H=0$, no excess resistance is observed, namely, $R_{peak}/R_n=1$. As the magnetic field increases, however, R_{peak}/R_n rapidly increases and it has a maximum at around the $L=0\rightarrow 1$ transition where the first vortex penetrates the Al disk. After attaining the maximum value, R_{peak}/R_n decreases gradually, but it remains over unity in the entire temperature and field region. The excess resistance is observed when the vortices are present in the disk. The data at the low fields corresponds to the data at high temperatures. Therefore, the R_{peak}/R_n maxima at $L=0\rightarrow 1$ suggests that thermal fluctuation enhances the energy dissipation.

An interesting feature is that the larger disk possesses a larger R_{peak}/R_n in the entire HS/Φ_0 region. This presents a marked contrast to the excess resistance reported for the wire samples: the shorter distance voltage probes cause the larger excess resistance.[2,7,10,11] We have not measured the larger disk samples than 1 μm in diameter yet, however, it is expected that such excess resistance diminishes in the large limit.

IV. DISCUSSIONS

Our experimental data have shown two necessary conditions for the excess resistance larger than R_n: presence of the vortices in the disk and superconducting current leads connected to the disk part. These features cannot simply be explained by the PSC or S-N boundary effect without the contribution of vortices, as has been discussed for Al wires.[2,10,11] The theoretical calculation on charge imbalance due to them in mixed state may be required. Here, we discuss the other possible origins of the excess resistance in the disks.

As we have shown, the observation of the finite resistance implies that some energy dissipation occurs in the superconducting disk. Because the energy dissipation does not occur as far as the vortices remain inside the disk, the excess resistance is attributed to the dynamics of the vortices in the superconducting Al disk. The energy dissipation of the moving vortices in bulk systems has been explained in terms of the Bardeen-Stephen model.[23] In this model, the vortex is assumed to be the normal-state core within the coherence length for simplification. The electric field caused by the moving vortex is proportional to the velocity of the vortices and the number of vortices. Therefore, the energy dissipation increases with current and magnetic field. A few other models have been proposed on the microscopic mechanism of energy dissipation by moving vortices.[27] However, such models, which are applicable to bulk superconductors, cannot explain a flux-flow resistance larger than the normal-state resistance R_n. Our experimental results clearly require a new mechanism for the energy dissipation due to the vortex dynamics.

In the above theoretical models, a few points are not treated: (1) vortex-vortex interaction, (2) superconducting fluctuation effect, and (3) size effect. The large excess resistance is observed even in the $L=1$ state, as shown in Figs. 1(a)–1(c), and therefore, vortex-vortex interaction is not the main origin. Next, it would be worthwhile to discuss the fluctuation effect associated with the vortex motion. Because the free energies of the $L=n$ and $n+1$ states are degenerate at the transition fields,[15,16] as shown by the dotted lines in Fig. 2(a), the vortices should be strongly thermally and/or quantum mechanically fluctuated at the transition fields. This fluctuation, which could be associated with the fluctuation of the vortex positions, may enhance the energy dissipation if the fluctuation is sufficiently rapid. However, the fluctuation effect does not explain why the excess resistance larger than R_n appears in such a wide field region, as shown in Figs. 1(a)–1(c). The fluctuation of the vortex motion is not the main mechanism either. The most likely mechanism of the excess resistance would be the size effect in the confinement geometry. The finite resistance implies that the vortices frequently go into and come out of the disk part. For instance, when the vortices are located well inside the disk, there independently exist both shielding current at the edge of the disk and superconducting current around the vortices, which is flowing in the opposite direction. Because of the confinement geometry where both the penetration depth and coherence length are comparable to the disk size, the current and magnetic field distributions should change steeply in the disk, depending on the vortex arrangement.[25] When the vortices go in or come out from the disk over the pinning centers or the BL surface barrier,[26] the distributions of both the shielding current at the edge and the superconducting current around the vortices are strongly deformed, especially at the edges. Such deformation may cause anomalously large energy dissipation. The presence of the superconducting leads makes additional inhomogeneous order-parameter distributions in the sample, which is another important factor for the excess resistance.

At present, the origin of the large energy dissipation of the vortex dynamics in the confinement geometry remains unclarified. Further theoretical and experimental studies are required to obtain a complete understanding of this phenomenon.

V. CONCLUSIONS

In addition to the successive small peaks due to the vortex phase transitions, a large excess resistance above R_n is observed in the superconducting vortex state for the mesoscopic Al disk samples, whereas it is not observed in the Al wire sample. The excess resistance of the Al disk cannot simply be explained by PSCs or S-N boundaries, as has been discussed in the case of Al wires.[2,10,11] The experimental results indicate that the excess resistance is ascribed to the strong energy dissipation due to the vortex dynamics in the confinement geometry. It is suggested that the inhomogeneous distributions of the shielding current at the edge and the superconducting current around the vortices are required for the occurrence of the excess resistance. The superconducting current leads connected to the disk part are another important factor for the excess resistance. The mechanism of the excess resistance remains to be clarified.

ACKNOWLEDGMENTS

We would like to thank Y. Takahide for the fruitful discussions. This work was partially supported by Grant-in-Aid for Young Scientists B (Grant No. 21740269) from the Japan Society for the Promotion of Science (JSPS) and Grant-in-Aid for Scientific Research on Innovative Areas, Grant No. 20110004.

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