Dynamic transition and metastability in the nonlinear *I*-*V* regime in a Corbino disk superconductor

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In zero field below the superconducting transition T_c, the linear resistivity disappears and, instead, the nonlinear current-voltage characteristics appear. In a picture of vortex dynamics, the nonlinear dissipation is described by the motion of vortices and antivortices, whereas in actual systems, heating effects are important at temperatures near T_c. Here, we study the thick amorphous Mo_xSi_{1-x} films with the Corbino disk contacts, in which the vortices (and antivortices) are confined and rotated around the center of the sample, and "heat sources" are nonuniformly distributed in the radial direction. We have observed unusual large voltage pulses that oscillate almost periodically under the constant radial current in the nonlinear regime just below T_c. The results indicate the existence of the two metastable states, low- and high-resistive states, and the dynamic transition between them. We suggest that the vortex dynamics and thermal properties are important to understand the phenomena.

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I. INTRODUCTION

In the vicinity of the superconductor-to-normal transition, a rapid conversion from the superconducting to the normal resistive state can occur irreversibly. A well-known example is a quench phenomenon of a superconducting magnet, which is caused when the equilibrium inside the superconductor is disturbed by the motion of field (B)-induced vortices and the large heat (voltage V) exceeding the cooling power is generated locally. For small superconductors, such as superconducting films studied in this work, where the heat dissipated within the sample is much smaller than the cooling power, we can observe not only the irreversible jump in V (Refs. 1 and 2) but also the reversible change in V (i.e., large V fluctuations). Such phenomena have been observed numerically[3–5] as well as experimentally in the nonlinear current-voltage (I-V) regime in the presence of applied field B.[6]

In recent years, we have studied the dynamic properties of vortices thermally created and driven in the presence of the dc current I in the Meissner phase ($B=0$) of thick [three-dimensional (3D)] and thin [two-dimensional (2D)] amorphous films. For the thin (2D) films,[7] the transport properties are described by the well-known Berezinskii-Kosterlitz-Thouless (BKT) theory.[8–10] For the thick (3D) films we study in this paper, the nonlinear dissipation is observed below the zero-resistivity ($\rho=0$) transition temperature T_c, which is caused by thermally activated nucleation and subsequent growth of vortex loops.[11] Each grown loop is eventually dissociated into two free vortices with opposite vorticities in the presence of I and they move to the opposite directions and produce voltage V until they disappear at the sample edges, which is similar to the 2D case. This is schematically illustrated in Fig. 1(a). We have shown previously[2] that the transport properties (I-V characteristics) in the Meissner phase of 3D superconductors are described semiqualitatively by the vortex-loop model.[11,12] We have found that largest broadband V noise induced by I appears at $B=0$, irrespective of dimensionality, whose origin has been mainly attributed to the large number fluctuations δn of thermally created free vortices and antivortices in the presence of I.[1,13–15]

Using a thick amorphous Mo_xSi_{1-x} film with the Corbino disk (CD) geometry, we have recently found unusual large voltage pulses $V(t)$ that oscillate almost periodically under the constant radial current density J,[16] indicating the existence of the metastable states. The observed $V(t)$ is similar to the two-level *random* telegraph noise reported earlier, but the remarkable difference is that $V(t)$ observed in our system is periodic rather than random. From the viewpoint of vortex dynamics, the vortices confined in CD move in concentric circles by feeling a nonuniform Lorentz force $f_L(\propto J \propto 1/r)$ inversely proportional to a radius r of rotation in the presence of J.[17,18] In $B=0$ dissociated, free vortices with opposite vorticity are driven to the opposite directions and one vortex can annihilate only by "colliding" with another vortex with opposite vorticities [see Fig. 1(b)]. Accordingly, one can expect enhanced δn in CD than in the conventional strip-shaped samples. On the other hand, we also note that in CD, largest heat is generated around the center of the sample and heat sources are nonuniformly distributed in the sample. Thermal properties (characteristic times of thermal diffusion) are considered to vary in the radial direction. Thus, we suggest that the particular vortex dynamics and thermal properties in CD may play an important role in the phenomena. In this paper, we present the detailed data and analyses of the

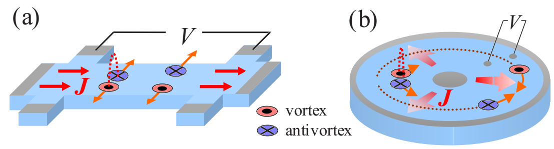

FIG. 1. (Color online) Schematic illustration of the vortex flow by the applied current. (a) In an ordinary strip-shaped sample, the current density J and the Lorentz force f_L acting on vortices are uniform. (b) In CD, both J and f_L are inversely proportional to the radius r of rotating vortices around the center of the sample. "⊙" and "x," respectively, denote the vortex and antivortex, which are thermally created and driven in the presence of J.

time-dependent voltage $V(t)$ taken systematically as functions of I, B, and probe position r at temperature just below T_c and discuss the possible origin responsible for the unusual $V(t)$ oscillation.

II. EXPERIMENT

The samples for which we present data in this paper are thick (100 nm) a-Mo_xSi_{1-x} films (films 1 and 2) with $x \approx 0.6$. They were prepared by coevaporation of pure Mo (99.99%) and Si (99.999%) onto the glass substrate held at room temperature in vacuum better than 10^{-8} Torr.[1,13,19–21] In order to improve the homogeneity of the film,[22] the substrate was rotated at $\sim(1-2)\times10^2$ rpm during deposition with an evaporation rate of $\sim$1 nm/min. The structure of our films was confirmed to be highly amorphous by means of transmission electron microscopy. The superconducting transition (ρ=0) temperature T_c and upper critical field at T =2 K are 3.33 K and 3.9 T and are 3.30 K and 4.0 T for films 1 and 2, respectively. The superconducting coherence length is typically 20 nm, which is smaller than the film thickness (100 nm).

The arrangement of the silver electrical contacts evaporated on the a-Mo_xSi_{1-x} films 1 and 2 is shown in the insets of Figs. 2(c) and 3(e), respectively. When measuring the CD, the current flows between the contact $+C$ of the center and that $-C$ of the perimeter of the disk, which produces radial current density J that decays as $1/r$. For the measurements in the striplike geometry, contacts $+S$ and $-S$ were used. For both contact geometries, we used the same voltage contacts, e.g., $+P$ and $-P$ for film 1. Similar contact arrangement was used originally by Paltiel *et al.* to study comparatively the vortex states in the mixed state for the CD and striplike geometries on the same sample.[18] For film 2, three voltage contacts (P_1–P_3) were evaporated at 0.8 mm intervals along a radius, which serve as two voltage probes (V_{12} and V_{23}) with different r (r_{12} and r_{23}).[17] The inner diameter d of CD for both films is d=5.5 mm.

The linear dc resistivity ρ and the time-dependent voltage $V(t)$ induced by the dc current I were measured using a four-terminal method. $V(t)$ enhanced with the preamplifier was recorded using a fast-Fourier transform spectrum analyzer (Ono Sokki CF-5220) in the "V-t mode" with a time resolution of 39 or 390 μs.[16,21] We monitored the temperature $T(t)$ of the thermometer (Ru-O chip resistor) during the $V(t)$ measurements of the sample. The thermometer and the sample were mounted on the same cold plate, and all of them were directly immersed in liquid ^{4}He to ensure good thermal contact. Stability of the temperature was as small as $\sim$1 mK, which was maintained by controlling the vapor pressure of ^{4}He electrically. We did not find clear correlation between $V(t)$ and $T(t)$ within our experimental resolutions, as shown later. The magnetic field B was applied perpendicular to the plane of the films. For the measurements at B=0, we applied a small perpendicular field B ($\sim10^{-4}$ T) to cancel the ambient magnetic field including the Earth's field.

III. RESULTS AND DISCUSSION

Plotted in Fig. 2(a) with filled black circles are I-V characteristics for film 1 with the CD geometry measured in B =0 at T=3.23 K that is slightly lower than T_c(=3.33 K). The filled triangles denote the voltage lower than 10^{-8} V (experimental resolutions). As I exceeds a certain critical value I_c $\approx$10 mA, the detectable voltage ($V>10^{-8}$ V) appears. However, V is not stationary but takes time-dependent values

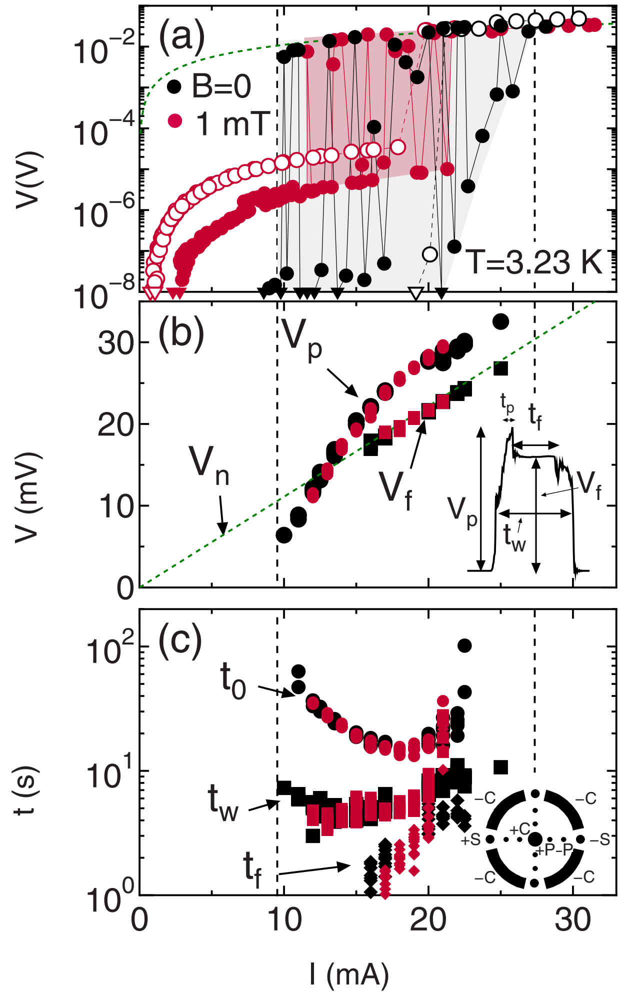

FIG. 2. (Color online) (a) Current-voltage (I-V) characteristics for film 1 with the CD contact geometry measured at 3.23 K slightly below T_c (=3.33 K) in B=0 (filled black circles) and 1 mT (filled red circles). Filled triangles denote the voltage lower than 10^{-8} V. In B=0, once the detectable voltage appears at $I>I_c$ ($\approx$10 mA), V takes time-dependent values which span over the broad range, as indicated with a gray zone. The corresponding data for the striplike geometry are shown with open symbols, where the unstationary voltage is not visible. A green dotted curve represents the normal-state voltage V_n. (b) The height V_f (filled squares) of the flat region and the peak value V_p (filled circles) of the voltage pulses in B=0 (black symbols) and 1 mT (red symbols) as a function of I. A green dotted line represents $V_n(I)$. Note that at I >14 mA, V_p exceeds V_n. The inset illustrates the definition of the characteristic heights and widths of the voltage pulse. (c) The current dependence of the period t_0 (circles) and width t_w (squares) of the voltage pulse, together with the width t_f (diamonds) of the flat region, in B=0 (black symbols) and 1 mT (red symbols). The inset schematically illustrates the arrangement of the electrical contacts for film 1. Vertical dashed lines in each figure define the I region where the voltage oscillation is observed at B=0.

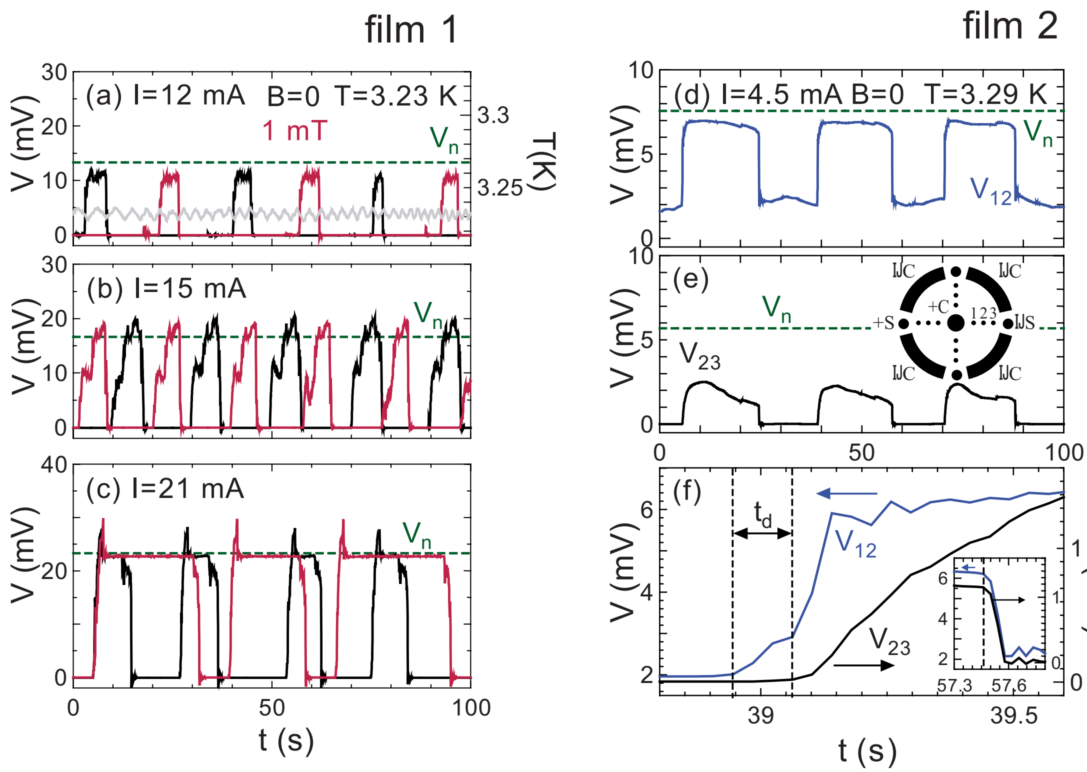

FIG. 3. (Color online) The time evolution of the voltage $V(t)$ for film 1 measured at 3.23 K in $B=0$ (black) and 1 mT (red) in the presence of (a) $I=12$ mA, (b) 15 mA, and (c) 21 mA. A gray line in (a) represents the temperature $T(t)$ (reading) of the resistor thermometer. The voltage oscillation is also observed for film 2 at the (d) inner (V_{12}) and (e) outer (V_{23}) voltage probes in the presence of $I=4.5$ mA in $B=0$ at 3.29 K, which is just below $T_c=3.30$ K. The horizontal (green) dotted lines in (a)–(e) mark the normal-state voltage V_n. The inset of (e) schematically illustrates the arrangement of the electrical contacts for film 2. (f) The rise in the voltage pulses, V_{12} and V_{23}, is enlarged and shown: $V_{23}(t)$ is slightly delayed compared to $V_{12}(t)$. By contrast, the fall of the voltage pulses V_{12} and V_{23} occurs simultaneously, as depicted in the inset.

which span over the broad range, as indicated with a gray zone. A green dotted curve represents the location of the normal-state voltage V_n, which is proportional to I. In the case of the striplike geometry, on the other hand, V is always stationary, exhibiting a steep rise at $I\approx 20$ mA (shown with open black circles).

In order to explore the origin giving rise to the unstationary voltage in CD, we have measured the time-dependent voltage[16,21] $V(t)$ at 3.23 K in the presence of constant I. Figures 3(a)–3(c) display $V(t)$ (solid black lines) for film 1 taken at $I=12$, 15, and 21 mA, respectively. It is commonly observed that unusual large voltage pulses appear almost periodically on the base line of $V\approx 0$. We display the I dependence of the period t_0 (black circles) and the width (full width at half maximum [see the inset of Fig. 2(b)]) t_w (black squares) of the voltage pulse in Fig. 2(c). Over the whole current range ($I=10$–25 mA) where the unusual voltage oscillation is observed, t_w is weakly dependent on I, while t_0 changes more strongly and nonmonotonically against I: With increasing I, t_0 exhibits a steep decrease, taking a minimum ($t_0\sim 15$ s) at around $I=16$–17 mA, and then increases. As I approaches either 25 or 10 mA, t_0 grows progressively ($>10^2$ s) and eventually exceeds the time window (160 s) available in the present measurements. Such a nonmonotonic dependence of t_0 on I would not be expected if the temperature fluctuations within the sample were the dominant cause of the unusual $V(t)$ oscillation. It is important to note that both t_0 and t_w are much longer than the characteristic time for free vortices to rotate (half) in the circles, which is roughly estimated to be of order 0.1 ms at the position of the voltage contact. Within the picture of vortex dynamics, this means that the phenomenon that we have observed here does not originate from individual vortex motion but from collective motion of many vortices which leads to large δn of rotating vortices over the long time duration.

It is also noted in Figs. 3(a)–3(c) that the height of the voltage pulses takes generally large values comparable to V_n, which is indicated with a horizontal (green) dotted line. Even though the basic shape of the individual voltage pulses is nearly rectangular, the top region of the voltage pulse is not completely flat but rather rough, containing small peaks and/or dips. To quantify the shape of the voltage pulse, we heuristically define the height and width of the "flat" region as V_f and t_f, respectively, and the width of the small peak as t_p, as illustrated in the inset of Fig. 2(b). The I dependence of V_f (filled squares) and the peak value V_p (filled circles) of the voltage pulse is shown in Fig. 2(b) and that of t_f (black diamonds) is plotted in Fig. 2(c).

The data points of $V_f(I)$ fall onto a straight line of $V_n(I)$ shown with a green dotted line, indicating that the flat region of the voltage pulse appears remarkably only when its magnitude grows up to V_n. Seeing in more detail, for small currents (I=10–12 mA), the pulse height is as high as 50%–90% of V_n, where no flat region is visible, while for I larger than 15 mA, there appears small peak(s) or cusplike structure that *exceeds* V_n in addition to the flat region that reaches V_n. Seemingly, the result at $I>15$ mA is rather surprising, because one cannot usually expect the voltage larger than V_n in any superconductor. We note here that V_n (or ρ_n) is a decreasing function of T and its variation is as small as 3% over the T range studied ($T<77$ K). This means that unexpected large heating within the sample that could not be detected with our thermometry cannot explain the anomalously large V_p/V_n=1.1–1.3 observed at $I \approx 15$–20 mA. As I exceeds ≈20 mA and approaches I_d(≈27 mA), both the values of V_p/V_n and t_p decrease, suggesting that the anomalous voltage ($V>V_n$) tends to vanish as the system approaches the normal state ($I \rightarrow I_d$). The possible origin may be sought in the large number fluctuations of vortices and antivortices, while we have currently no theoretical justification or experimental evidence for the picture: It is not easy to accept the vortex dynamics (existence of vortices) in the highly dissipative state near V_n, where no vortex should be present in the equilibrium. Furthermore, there is no appropriate experimental technique to visualize such fast-moving vortices as studied here.

We next turn to the effects of a small applied field. The application of 1 mT shifts the I-V curves for the CD and striplike geometries to the low-I direction, as shown with filled and open red circles in Fig. 2(a), respectively. This is due to the penetration of many flux lines into the film. Similarly to the case of zero field, the time-dependent voltage is observed for the CD geometry. Despite the remarkable difference between the I-V curves in B=0 and 1 mT, the current region over which the unstationary voltage appears is close to each other; it decreases slightly from 10–25 mA (a gray zone) to 12–21 mA (a red zone) by applying 1 mT. We representatively show $V(t)$ in B=0 (black lines) and 1 mT (red lines) measured at I=12 and 15 mA, respectively, in Figs. 3(a) and 3(b). At each I(=12–20 mA), except at high I(>20 mA) [Fig. 3(c)], we observe the essentially same voltage oscillation $V(t)$ in 1 mT as observed in B=0. Figures 2(b) and 2(c) depict, respectively, the I dependence of the characteristic voltages, $V_p(I)$ and $V_f(I)$, and the characteristic times, $t_0(I)$, $t_w(I)$, and $t_f(I)$, extracted from $V(t)$ in B=1 mT (red symbols) as well as in B=0 (black symbols). It is evident that the shape of $V(t)$, as a function of I, is insensitive to whether the field-induced vortices are present or not. Within the picture of vortex dynamics, in B=0, dissipation is due mainly to thermally created vortices and antivortices in the presence of I, while in 1 mT, it originates from both field-induced vortices and thermally created free vortices. The implication of the result obtained here is that the dissipation mechanism originating from thermally created vortices in the presence of I, which is determined by T and I, is not seriously affected by the field-induced vortices (1 mT).

Now, let us focus on the spatial (r) dependence of the vortex dynamics. Figures 4(a) and 4(b) display the J-V characteristics of film 2 measured at the inner (r_{12}) and outer (r_{23}) voltage probes, respectively, in B=0. At either probe,

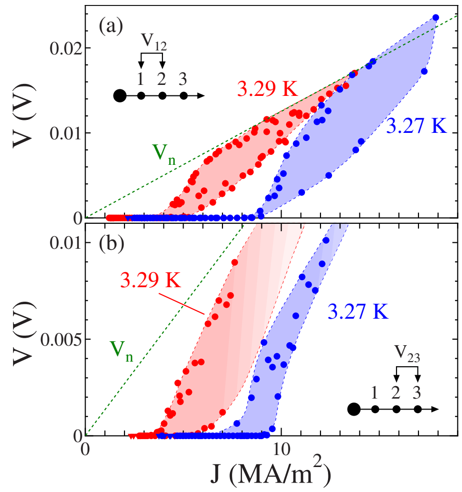

FIG. 4. (Color online) J-V characteristics of film 2 measured at the (a) inner (V_{12}) and (b) outer (V_{23}) voltage probes in B=0. At either probe, the unstationary voltage is observed just below T_c (=3.30 K), which is indicated with red (3.29 K) and blue (3.27 K) zones. At each temperature, the current region where the unstationary voltage appears is nearly independent of the probe position. A green dotted line represents $V_n(J)$. Location of voltage contacts is schematically illustrated in the inset.

the unstationary voltage similar to that observed for film 1 is observed in nearly the same T regime slightly below T_c(=3.30 K), which is indicated with red (3.29 K) and blue (3.27 K) zones. It is noted that at each T, the current region where the unstationary voltage appears is nearly independent of the probe position. In Figs. 3(d) and 3(e), we show the voltage oscillations $V_{12}(t)$ and $V_{23}(t)$ for film 2 observed at the inner (r_{12}) and outer (r_{23}) voltage probes, respectively, at fixed I=4.5 mA (in B=0 at T=3.29 K). The voltage pulses at r_{12} and r_{23} are synchronized with each other. Seeing more closely, we find that the rise in the individual $V(t)$ pulses at the outer radius r_{23} is slightly delayed compared to that at the inner radius r_{12}, as shown in the main panel of Fig. 3(f). The delay time t_d is typically ≈0.1 s, which is smaller than the characteristic times (t_0, t_w, $t_f \approx 1$–100 s) of the $V(t)$ oscillation, but much larger than the period (~0.1 ms) for individual vortices to rotate (half) on a circle with the radius r_{12} or r_{23}.

Within the scenario of vortex dynamics, the results presented here are consistent with the picture that the increase in number of depaired vortices at the inner portion may trigger off unbinding of vortex-antivortex pairs at the outer portion.[24] Since both the number and velocity of free vortices (antivortices) rotating in the inner portion are larger than those in the outer portion (because $J \propto f_L \propto 1/r$), the depaired vortices at the inner portion predominantly induce unbinding of vortex-antivortex pairs at the outer portion. This picture, of course, does not apply to the annihilation process of vortices and antivortices. Actually, the fall of the voltage pulses $V(t)$ measured at r_{12} and r_{23} is found to occur simultaneously within our experimental time resolutions of ≈40 ms [see the inset of Fig. 3(f)]. Alternatively, the observed delay of the rise in $V(t)$ at r_{23} with respect to that at r_{12} may be interpreted in terms of heat that diffuses from the center to the perimeter of CD. In the present system, the thermal properties are rather complicated because it is composed of multistates, i.e., Meissner, mixed, and normal states, having different thermal-diffusion characteristic times in addition to possible insufficient thermal coupling of the sample to the helium bath, as discussed later.

Certainly, the phenomena presented in this paper are unusual but experimentally reproducible and systematic. We have observed essentially the same phenomena in three different samples at temperatures slightly below T_c. We consider that these phenomena are general, which can be observed not only in a-Mo_xSi_{1-x} films but also in other superconductors.[23] On the other hand, there is no available theory to account for the observed oscillation of $V(t)$ comprehensively. To explain it, Hayashi and Ebisawa have developed a theory describing vortex nucleation and annihilation in CD, taking account of the vortex-vortex interaction effects.[25] They have noted the two "stationary" voltage (resistivity) states in our data and shown that, as the current is increased above a certain critical value, the vortex density increases significantly. They have suggested that the density fluctuations derived in their calculation may be a key to understand the large $V(t)$ fluctuations observed above a certain threshold current, e.g., 10 mA (Fig. 2). However, the theory has not yet explained why $V(t)$ itself oscillates, as well as why $V(t)$ depends on I, B, and r in the way as found in this work.

From an experimental point of view, it is important to note that in the time duration where the large $V(t)$ pulses appear, relatively large power, e.g., ~ 0.1 mW [Figs. 3(a)–3(c)], is dissipated within the sample, although we cannot detect it explicitly as an increase in temperature T of the thermometer, e.g., see a gray line in Fig. 3(a), which shows $T(t)$ of the resistor thermometer taken simultaneously with $V(t)$ of the sample. Strictly speaking, this experimental fact does not immediately imply the absence of correlations between $V(t)$ and the temperature within the sample, because the thermal coupling of the sample with the helium bath can be strongly degraded, considering the possible boiling of helium around the sample. In that case, the sample temperature grows very fast and can stay at high temperature for a long time before the sample couples back to the thermal bath. We note, however, that it seems difficult to explain the oscillation of $V(t)$ or the nonmonotonic current dependence of the characteristic times shown here based on the heating effects alone.

In the superconducting (or the low-resistance) state, the dissipation is caused by the vortex motion. The dissipation, as well as the voltage due to the vortex motion, decreases abruptly after the pair annihilation of many vortices takes place. Therefore, to fully understand the mechanism responsible for the $V(t)$ oscillation, we may need a theory taking account of the effects of dissipation (heating) on vortex dynamics. In CD, the density of dissipation is mainly located near the center of the sample where the current density J is maximum. In the sample plane, the induced heat diffuses along the radius. This suggests that a nucleation (or a depinning) of the vortices, if it exists, may take place through a mixed mechanism including both thermal and current density sources, although we cannot explain why the temperature variation within the sample could give rise to large voltages exceeding the normal-state values as well as the voltage oscillations. In this picture, the characteristic time for the heat to flow across the sample may play an important role in the metastable phenomena.

Finally, it may be also important to note that the unusual $V(t)$ oscillation is observed only in a limited T regime just below T_c.[26] This fact makes it difficult to conclude definitely that the CD geometry is indispensable for observing the phenomenon, because we cannot entirely exclude the possibility that, if we performed measurements at particular T (and B) immediately below T_c with improved T resolutions (stability), the similar phenomenon might be visible in CD with the striplike geometry or even in the ordinary strip-shaped samples. Insensitiveness of the wave form of the $V(t)$ oscillation for a given I to weak applied field mentioned earlier may also suggest the possibility that the phenomenon might originate from a more common mechanism other than the vortex dynamics. Recently, in an effort to explore a mechanism giving rise to the unusual $V(t)$ oscillation, the time evolution of the phase of the order parameter has been calculated numerically at fixed I using the strip-shaped superconductors with a periodic boundary condition.[27] The simulation is quite general, independent of details of the vortex dynamics or thermal fluctuations. The preliminary results suggest that some sort of voltage oscillation appears at certain I.

To summarize, we present the detailed measurements and analyses of unusual large voltage pulses that oscillate almost periodically under the constant current in the nonlinear regime just below T_c for the thick amorphous Mo_xSi_{1-x} films with the CD contact geometry. The results indicate the existence of the two metastable states, low- and high-resistive states, and the dynamic transition between them, whose origin has not yet been well specified. We propose that large number fluctuations of vortices and antivortices may be a possible origin responsible for the phenomena. We note, however, that different origins, such as heating effects or a mixed mechanism including both vortex dynamics and thermal properties, may play an important role in the phenomena. We believe that our results will stimulate the detailed research into the metastable resistive states just below T_c and/or the vortex-antivortex-type fluctuations in BKT physics. Furthermore, they will provide useful information on the stability of the superconducting states in the vicinity of T_c, which is important for the broad application of superconductivity.[28]

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[23] The reason why we use the a-Mo_xSi_{1-x} films in this work is that for this system, we have intensively studied the vortex dynamics driven by the dc current in $B=0$ [S. Okuma and M. Kamada, J. Phys. Soc. Jpn. **73**, 2807 (2004)] and in low fields near $B=0$ [S. Okuma and M. Kamada, Phys. Rev. B **70**, 014509 (2004)], as well as in high fields. Other superconductors with higher T_c, such as high-T_c cuprates and MgB_2, in which thermal fluctuations are stronger and the transport properties in $B\approx 0$ are expected to be better described by the vortex-loop-excitation mechanism, are promising to observe the phenomena reported here more clearly.

[24] Here, we assume that the radial component of the velocity is nonzero. This assumption is not unreasonable, if we take account of the facts that the trajectory of rotating vortices is not perfectly circular due to the possible inhomogeneity in the distribution of the current density and that the interaction between vortices rotating on circles with different r yields the radial component of the force [M. Hayashi and H. Ebisawa, J. Phys. Chem. Solids **66**, 1380 (2005)].

[25] M. Hayashi and H. Ebisawa, J. Phys. Chem. Solids **66**, 1380 (2005).

[26] Even at $T=3.23$ K (just below T_c), at which all the data in Fig. 1 are taken, the penetration depth λ is not divergingly large; it is estimated to be $\sim 3\lambda(0)$, where $\lambda(0)$ is λ at $T=0$.

[27] X. Hu (private communication).

[28] This is important, e.g., for development of cryogenic particle (photon) detectors based on T_c-edge sensor microcalorimeters and, in more general, for understanding of a quench mechanism of a superconducting magnet whose physical mechanism has not yet been fully clarified.