Order-disorder transition of vortex matter in a-Mo_xGe_{1-x} films probed by noise

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We measure voltage noise spectra $S_V(f)$ generated by current-driven vortices at various fields B including the peak-effect regime for amorphous Mo_xGe_{1-x} films with Corbino-disk and striplike contact geometries. Field dependences of the critical current I_c and $S_V(f)$ are nearly independent of contact geometries, indicating that edge effects are not important on static or dynamic vortex properties. This is in contrast to the result reported for $NbSe_2$ crystals with much larger thickness. $S_V(f)$ at low frequency f exhibits a sharp peak just below the peak field B_p of I_c, where the characteristic time of vortex motion increases significantly. The results suggest the existence of the order-disorder transition and vortex instabilities due to coexisting vortex phases at around B_p.

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In the mixed state of conventional (low-T_c) superconductors, vortex states near the peak-effect (PE) regime, where the critical (depinning) current I_c shows a peak with magnetic field B or temperature T, have attracted considerable interest for many years.[1–11] While the PE was considered to originate from softening of vortex lattice just prior to the second critical field and random pinning due to quenched disorder, it has become clear that it marks the phase transition of vortex matter from weakly pinned ordered phase (OP) to strongly pinned disordered phase (DP), as described below.

It has been demonstrated by comparative studies using Fe-doped 2H-$NbSe_2$ single crystals with Corbino-disk (CD) and striplike contact geometries that the sample edges play a crucial role in equilibrium (dc voltage) and dynamic (voltage noise) properties of vortices:[8] With increasing B for CD, where vortices circulate around the center of the sample without crossing the sample edges, $I_c(B)$ exhibits a sharp rise at a certain field (B_p) while for the striplike geometry the peak in $I_c(B)$ is smeared. Furthermore, large voltage noise S_V associated with flux flow is observed around B_p for the striplike geometry while S_V is significantly suppressed for CD. These results are explained in terms of edge contamination (EC) effects, i.e., the injection of the disordered vortices through the sample edges and subsequent annealing into the OP. The coexistence of the DP with OP just below B_p results in an increase in I_c and instabilities of the vortex motion.[8] Both EC and the sharp vortex phase transition [order-disorder transition (ODT)] at B_p found in $NbSe_2$ crystals are believed to be universal characters of conventional type-II superconductors with weak pinning. However, it has not yet been verified experimentally to what extent these phenomena are generalized to other superconductors, including superconducting films.

Here, we study the dynamic properties of vortices driven by dc current I for amorphous (a-)Mo_xGe_{1-x} films with CD and striplike geometries. We measure voltage noise spectra $S_V(f)$ in various B corresponding to the vortex solid phase. Judging from the PE of $I_c(B)$ and mode-locking resonance, the equilibrium solid state is considered to be a weakly disordered vortex lattice.[10,11] We find that the field dependences of I_c and $S_V(f)$ are nearly independent of contact geometries, indicating that the edge effects are not important on static or dynamic vortex transport as opposed to the results of $NbSe_2$ crystals.[8] The difference may be attributed to much different sample thickness between the films and crystals. On the other hand, voltage noise at low frequencies (f=10 Hz) exhibits a sharp peak just below B_p, where the characteristic time of vortex motion increases significantly. The results indicate the existence of the sharp phase transition of vortex solid, most likely the ODT, and the metastable vortex states near it, as reported in $NbSe_2$ crystals.[8] The results also show that EC is not the sole mechanism responsible for the peculiar vortex dynamics (large flow noise) near the ODT.

Two a-Mo_xGe_{1-x} films (films 1 and 2) with thickness d =330 nm were prepared independently by rf sputtering on a Si substrate held at room temperature.[10,11] The mean-field transition temperature T_{c0} defined by a 95% criterion and the zero-resistivity (ρ=0) temperature T_c for both films are 6.3 and 6.2 K, respectively. Both the CD and striplike contacts are evaporated on the same surface of each film. The arrangement of the silver electrical contacts is shown schematically in the insets of Fig. 1. 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 [inset of Fig. 1(b)]. For the measurements in the striplike geometry, contacts +S and −S were used [inset of Fig. 1(a)]. For both geometries, we used the same voltage contacts: +V and −V. The inner radius of CD is 2.3 and 0.8 mm for films 1 and 2, respectively. The similar contact arrangement was used originally by Paltiel and co-workers[8] to study comparatively the vortex states for CD and striplike geometries on the same sample. In measuring $S_V(f)$ over a broad f range (1 Hz–40 kHz), the voltage enhanced with a preamplifier was analyzed with a fast-Fourier transform spectrum analyzer. We obtained the excess noise spectra $S_V(f)$ by subtracting the background contribution, which was measured with I=0.[12] The films were directly immersed into liquid ^{4}He and the field B was applied perpendicular to the

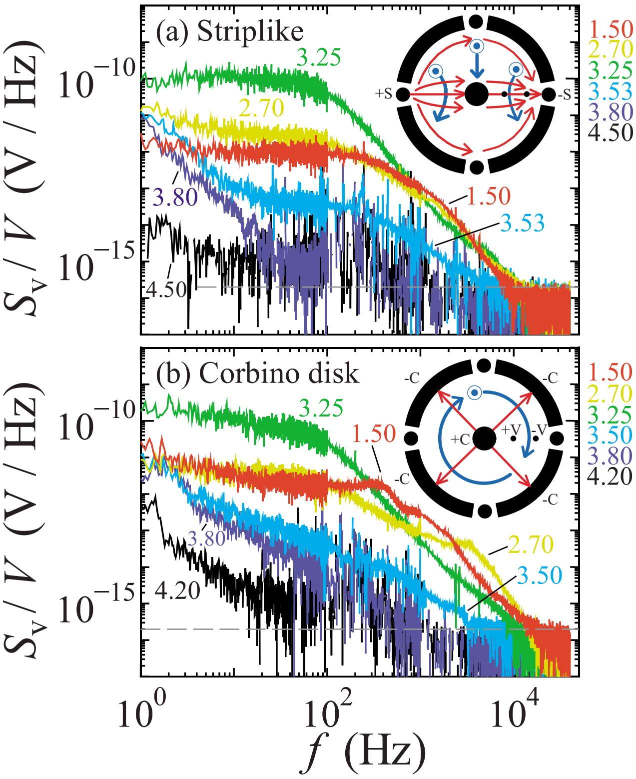

FIG. 1. (Color online) Noise spectra $S_V(f)/V$ of film 1 for (a) striplike and (b) CD geometries measured for 0.5 mV at 4.1 K in various fields, which are listed on the right-hand side. A horizontal dashed line in each figure represents a background level. Insets: Schematic illustration of the arrangement of electrical contacts and vortex flow ("⊙") by the applied current.

plane of the film. All the data were taken in zero-field-cool mode.

Let us first show the results of film 1. From the measurements of I-V characteristics at $T=4.1$ K in various fields ($B=0.5-4.5$ T), we define a critical current I_c as a threshold current at which the vortices start to move, using a 10^{-7} V criterion.[11] In Fig. 2(a) we plot the B dependence of I_c at 4.1 K for CD (full circles) and striplike (open circles) contact geometries. For either geometry the peak of I_c is clearly visible at 3.3 T($\equiv B_p$) before I_c vanishes at a field of 3.72 T. Here, we plot I_c normalized by the peak value of I_c at B_p to compare the shape of $I_c(B)$ between the two contact geometries in the PE regime. It is clearly seen that the shape of the $I_c(B)/I_c(B_p)$ curves is similar to each other, indicating that the edge effects are not important on equilibrium (static) transport properties. It is also noted that the sharp rise in $I_c(B)$ at B_p, as reported in $NbSe_2$ crystals for the CD geometry,[8] is not observed in our a-Mo_xGe_{1-x} film for either geometry. Seemingly, this result suggests the absence of the sharp phase transition in the solid phase.

To clarify this point, we measure $S_V(f)$ generated by the current-driven vortices (i.e., at I larger than I_c) for both contact geometries as a function of B. Since $S_V(f)$ is a function of I as well as B, we first examine the I dependence of S_V/V (S_V divided by V). With increasing I, detectable noise S_V/V appears just above the onset of V. With further increasing I, S_V/V grows rapidly and eventually becomes almost I inde-

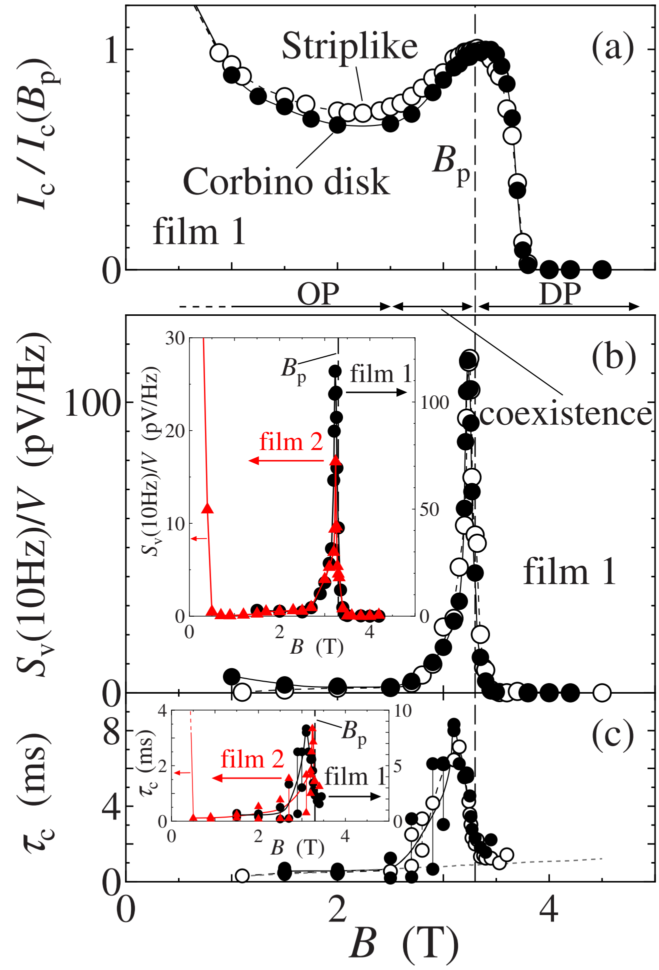

FIG. 2. (Color online) (a) I_c normalized by $I_c(B_p)$ vs B at 4.1 K for film 1 with CD (full circles) and striplike (open circles) geometries. (b) S_V/V at 10 Hz vs B for film 1 with CD (full circles) and striplike (open circles) geometries. Inset: S_V/V at 10 Hz vs B for films 1 (circles) and 2 (triangles) with CD geometry. (c) τ_c vs B for film 1 with CD (full circles) and striplike (open circles) geometries. A dotted line indicates the characteristic time expected from the time-of-flight picture. Inset: τ_c vs B for films 1 (circles) and 2 (triangles) with CD geometry. The location of B_p is indicated with vertical dashed lines and other lines are guides for the eye.

pendent or weakly dependent on I in the flux-flow regime. In the discussion that follows, we focus on S_V/V measured in the flow state.[13] Shown in the main panels of Figs. 1(a) and 1(b) are selected data of noise spectra $S_V(f)/V$ of film 1 with the striplike and CD geometries, respectively, measured for $V=0.5$ mV at 4.1 K in various fields ($B \geq 1.5$ T). A horizontal dashed line in each figure represents a background level. As detailed below, the field dependences of the spectra for both contact geometries are similar to each other, implying that the sample edges do not play an important role in dynamic as well as static properties of vortices. This result is contrasted with what has been reported for $NbSe_2$ crystals.[8]

With increasing B, $S_V(f)/V$ changes in the following ways: (i) In low fields below the PE regime ($B<2.3$ T), the spectral shape for both contact geometries is of Lorentzian type with nearly a f-independent (white) portion below a cutoff frequency f_c ($\approx 10^2-10^3$ Hz) while a slight increase in $S_V(f)/V$ is visible at lowest f (~ 1 Hz). For the CD geometry the Lorentzian shape is slightly degraded by the appearance of small humps, whose origin has not been specified. (ii) In the lower part of the PE regime (2.3 T$<B<B_p$), the magnitude of $S_V(f)/V$ at low f increases significantly with field: e.g., $S_V(f)/V$ in 3.25 T ($\approx B_p$) is about 10^{-10} V/Hz, which is much larger than that ($10^{-12}-10^{-11}$ V/Hz) in 2.5–2.7 T. (iii) In the higher part of the PE regime ($B_p<B<3.7$ T), the Lorentzian-type spectrum is no longer visible or f_c decreases below the f window of our S_V measurement and the magnitude of $S_V(f)/V$ at low f falls down to very small levels [$S_V(10\text{ Hz})/V \approx 10^{-13}$ V/Hz].

In order to see the change in the magnitude of low-f noise more clearly, we plot $S_V(f)/V$ at $f=10$ Hz for both contact geometries against B in Fig. 2(b). For either geometry, a narrow peak with a sharp rise followed by an almost vertical drop of $S_V(10\text{ Hz})/V$ is seen at around B_p, indicating that a structural transformation of vortex solid, most likely the ODT from the weakly disordered lattice to disordered amorphouslike phase, occurs at $\sim B_p$. We observe essentially the same B dependence of $S_V(10\text{ Hz})/V$ (for $V=0.5$ mV) for film 2, as shown in the inset of Fig. 2(b). Here, we plot the values of $S_V(10\text{ Hz})/V$ for film 2 with a slightly enlarged scale (left-hand axis) to compare the shape of peaks between films 1 (circles) and 2 (triangles) for CD configuration. The similarity of the peak shape between the two films implies that the phenomenon observed here is reproducible between samples and independent of the sample size at least on length scales of ~ 0.1 mm (spacing between voltage contacts for film 2).

As mentioned above, the increase in low-f noise in the PE regime is also observed in the $NbSe_2$ single crystals with the striplike geometry, while in the CD geometry the magnitude of noise is remarkably suppressed. From these results, origin of noise in $NbSe_2$ has been reasonably attributed to the metastable DP injected through the sample edges and subsequently annealed into the OP in the bulk.[8] The insensitiveness of $S_V(f)/V$ vs B, as well as I_c vs B to the contact geometries observed in our film, clearly indicates that the origin of voltage noise is not due to the disordered vortices coming through the sample edges. The absence of EC in our a-Mo_xGe_{1-x} film may be attributed to much smaller sample thickness ($d=0.33$ μm) than in the $NbSe_2$ crystals ($d=40$ μm). In the $NbSe_2$ crystals where d is much larger than the penetration depth λ, vortex lines enter the sample by forming two vortex segments in the opposite sharp corners of the sample edge, which reconnect in the bulk. This results in the formation of a disordered, entangled phase in the sample interior.[14,15] Such an effective "mechanical entangler" of the vortex lines is supposed to be absent in thin films ($d<\lambda$), where vortices enter the sample as rigid straight lines.

Nevertheless, we consider that vortex instabilities resulting from the coexistence of OP and DP, as found in $NbSe_2$ crystals,[8] are also present in our film below B_p. Here, the DP intermixed with the OP is metastable and more strongly pinned than the OP, i.e., the DP is characterized by the larger critical current. When a moderately strong current is applied, the DP survives annealing over the relevant experimental time scales. The coexistence of OP and DP in fields below B_p is not unreasonable, considering a supercooled metastable DP in the OP[7–9,16] and/or possible slight inhomogeneities of a-Mo_xGe_{1-x} films. The metastability mentioned here may explain the absence of the sharp peak in $I_c(B)$ in our a-Mo_xGe_{1-x} films.

The vortex motion in the coexisting vortex states should be unstable and accompanied by large velocity fluctuations, which lead to pronounced voltage noise.[8] In such states a cutoff (corner) frequency f_c in the spectrum $S_V(f)$ does not reflect a simple time-of-flight dynamics but is dominated by random motion of the metastable DP in the OP. This feature is actually seen in Fig. 2(c), where the inverse of f_c extracted from $S_V(f)$ for CD (full circles) and striplike (open circles) configurations is plotted against B. Here, we use the formula $S_V(f) \propto 1/[1+(\pi f/f_c)^p]$ with $p\approx 2-3$ to extract f_c. The results are again nearly independent of the contact configuration. In the vortex solid phase except for the lower part of the PE regime, the characteristic time $\tau_c(\equiv f_c^{-1})$ of vortex dynamics is almost consistent with the time-of-flight picture with a certain characteristic length $l_c\approx 0.3$ mm, as indicated with a dotted line.[17] On the other hand, in fields slightly lower than B_p, $S_V(f)/V$ is not well reproduced by the above formula with a single value of τ_c but requires two characteristic times, both of which exhibit an increase associated with the increase in low-f noise. We observe essentially the same result for film 2, as shown in the inset of Fig. 2(c), where we plot the values of τ_c for films 2 and 1 in the CD configuration with triangles and circles, respectively.

For film 2 with CD configuration we have measured S_V down to low enough fields (=0.3 T), and found pronounced rises of $S_V(10\text{ Hz})/V$ and τ_c in B slightly below 0.5 T, as shown with triangles in the insets of Figs. 2(b) and 2(c), respectively. The observed steep rises in $S_V(10\text{ Hz})/V$ and τ_c reflect a change in spectral shape from a Lorentzian type [with a slight increase in $S_V(f)$ at lower $f(<10\text{ Hz})$] to a $1/f$ type within a narrow B range (0.3–0.5 T). This abrupt change in the spectra indicates the existence of another phase transition in the solid phase. This low-field transition that occurs with decreasing B is suggestive of the OP-DP transition and the reentrant behavior of the equilibrium DP, as reported in Fe-doped $NbSe_2$ crystals.[3,8] In contrast to the high-field transition at $\sim B_p$, whose location is determined by the static voltage (I_c) measurements, the low-field transition is detected only by dynamic voltage (S_V) measurements in the flux-flow regime. At low B as well as at low T, however, I_c takes large values, and hence, large I is needed to measure S_V in the flux-flow state. This might lead to innegligible joule heating, making the precise determination of the low-field phase boundary difficult. In this paper, we therefore focus only on the high-field transition around B_p.

To summarize, we measure voltage noise spectra $S_V(f)$ induced by current-driven vortices for a-Mo_xGe_{1-x} films with CD and striplike geometries. Field dependences of I_c and $S_V(f)$ are nearly independent of contact geometries, indicating that the EC effects are not important on static or dynamic vortex properties as opposed to crystals of $NbSe_2$. The difference may be attributed to different sample thickness. S_V at low f exhibits a sharp peak just below B_p, where the characteristic time of vortex motion increases significantly. The results suggest the existence of the structural transition (ODT) from the weakly disordered vortex lattice to disordered amorphouslike phase around B_p and metastable vortex states near it, as reported in $NbSe_2$. The present results also suggest that EC is not the sole mechanism responsible for the coexisting vortex phases and large flow noise near the ODT.

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