Order-disorder transition and flow noise for vortices in amorphous films

Okuma S\(^1\), Suzuki Y\(^1\), Kashiro K\(^1\) and Kokubo N\(^2\)

\(^1\) Research Center for Low Temperature Physics, Tokyo Institute of Technology, Tokyo, Japan
\(^2\) Center for Research and Advancement in Higher Education, Kyushu University, Fukuoka, Japan

E-mail: sokuma@o.cc.titech.ac.jp

Abstract. In order to examine the universality of edge contamination (EC) and an order-disorder transition (ODT) for vortex matter reported in NbSe\(_2\) single crystals, we measure voltage noise spectra \(S_V(f)\) induced by current-driven vortices for amorphous Mo\(_x\)Ge\(_{1-x}\) films with Corbino-disk and striplike geometries. Field dependences of the critical current \(I_c\) and \(S_V(f)\) are nearly independent of contact geometries, indicating that the EC effects are not important on static or dynamic vortex properties in our films. This result is in contrast to what has been reported in NbSe\(_2\) crystals. At 4.1 K, \(S_V\) at low frequency \(f\) exhibits a sharp peak just below the peak field \(B_p\) of \(I_c\), suggesting the existence of ODT and metastable vortex states at around \(B_p\). At 5.5 K near the superconducting transition \(T_c\)(=6.2 K), however, clear evidence for ODT is not visible.

1. Introduction

It is commonly accepted through comparative studies using Fe-doped 2H-NbSe\(_2\) single crystals with Corbino-disk (CD) and striplike contact geometries that the sample edges play an important role in equilibrium and dynamic properties of vortices [1]. This is based on the following findings: With increasing field \(B\), the critical (depinning) current \(I_c(B)\) exhibits a sharp rise at a certain field \((B_p)\) for CD while the peak in \(I_c(B)\) is smeared for the striplike geometry. Associated with flux flow, large voltage noise \(S_V\) is observed around \(B_p\) for the striplike geometry while \(S_V\) is significantly suppressed for the peak field \((B_p)\) for CD while the peak in \(I_c(B)\) is smeared for the striplike geometry. The injection of the disordered vortices through the sample edges and subsequent annealing into the OP. The DP coexists with OP just below \(B_p\), resulting in an increase in \(I_c\) and instabilities of vortex motion [1]. It is important to examine whether EC and ODT found in NbSe\(_2\) crystals are generalized to other superconductors, including superconducting films.

In this work we study the dynamic properties of vortices driven by dc current \(I\) for amorphous \((\alpha\)-Mo\(_x\)Ge\(_{1-x}\) films with CD and striplike geometries. We measure voltage noise spectra \(S_V(f)\) in various \(B\) including the peak-effect (PE) regime [2-8], where \(I_c\) shows a peak with \(B\). Judging from the PE behavior of \(I_c(B)\) and mode-locking resonance, the equilibrium solid state is considered to be a weakly disordered vortex lattice [7, 8]. Preliminary results related to present work have been published elsewhere [9].

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2. Experimental details
We prepared two α-Mo$_2$Ge$_{1-x}$ films (films 1 and 2) with thickness $d = 330$ nm independently by rf sputtering on a Si substrate held at room temperature [7, 8]. The mean-field transition temperature $T_{c0}$ and the zero-resistivity ($\rho = 0$) temperature $T_c$ for both films are 6.3 and 6.2 K, respectively. The arrangement of the electrical contacts is shown schematically in the insets of figure 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 figure 1(b)]. For the measurements in the striplike geometry, contacts +S and -S were used [inset of figure 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. We measure $S_V(f)$ over a broad frequency range (1 Hz-40 kHz) by using a fast-Fourier transform spectrum analyzer and obtained the excess noise spectra $S_V(f)$ by subtracting the background contribution, which was measured with $I=0$ [10]. All the data were taken in zero-field-cool mode.

3. Results and discussion
We measure $I-V$ characteristics for film 1 at $T = 4.1$ K in different $B (= 0.5-4.5$ T). A critical current $I_c$ is defined as a threshold current at which the vortices start to move, using a $10^{-7}$ $V$ criterion [8]. Figure 2(a) shows the $B$ dependence of $I_c$ with CD (full circles) and striplike (open circles) contact geometries, where $I_c$ is normalized by the peak value of $I_c$ at $B_p$. 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. 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 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 [1], is not observed for either geometry.

Thus, we measure $S_V(f)$ generated by current-driven vortices. With increasing $I$, detectable noise $S_V/V$ appears just above the onset of $V$. With further increasing $I (> I_c)$, $S_V/V$ grows rapidly and, after showing a small peak, it eventually becomes almost $I$ independent or weakly dependent on $I$ in the flux-flow regime. The typical data (for film 2 with CD geometry) taken at $4.1$ K in $3.0$ T is shown with open circles in the inset of figure 2(a). In this work, we focus on voltage noise in the flow state and, therefore, we mainly present $S_V/V$ measured at $V = 0.5$ mV. The main panels of figures 1(a) and (b) illustrate noise spectra $S_V(f)/V$ of film 1 with the striplike and CD geometries, respectively, at $4.1$ K in various fields ($B \geq 1.5$ T). A horizontal dashed line in each figure represents a background level. The field dependences of the spectra for both contact geometries are similar to each other, indicating that the sample edges do not play an important role in dynamic as well as static properties of vortices.

In figure 2(b) we plot the field dependence of $S_V(f)/V$ at $f = 10$ Hz for both contact geometries. For either geometry, a narrow peak with a sharp rise followed by an almost vertical drop of $S_V(10$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 around $B_p$. We observe essentially the same $B$ dependence of $S_V(10$Hz)/$V$ (at $V = 0.5$ mV) for film 2, as shown in the inset of figure 2(b). 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 $\sim 0.1$ mm.

We have also taken some data (for film 2) at lower voltage $V = 0.1$ mV, around which $I-V$ characteristics show nonlinearity and $S_V(10$Hz)/$V$ vs $I$ takes a small peak [see the inset of figure 2(a)]. Plotting $S_V(10$Hz)/$V$ at 0.1 mV against $B$, we again find the similar peak behavior of $S_V/V$ just below $B_p$ irrespective of contact geometries, as shown in the inset of figure 2(b) with full (CD) and open (striplike) squares. The peak width is somewhat broader and the peak field ($\approx 3$ T) is slightly suppressed compared to those measured at 0.5 mV. The similar feature was
From these results, origin of noise in NbSe$_2$ single crystals with striplike geometry while in the CD geometry the magnitude of noise is remarkably suppressed. Significant difference in current-induced noise for striplike and CD geometries stays essentially unchanged at reduced $V$ (=$0.1$ mV).

The increase in low-$f$ noise just below $B_p$ 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 [1]. Our results mentioned above clearly indicate that the origin of voltage noise is not due to the disordered vortices coming through the sample edges. We propose that the absence of EC in our a-Mo$_2$Ge$_{1-x}$ film may be due to much smaller sample thickness ($d$=0.33 $\mu$m) than in the NbSe$_2$ crystals ($d$=40 $\mu$m). In the NbSe$_2$ crystals where $d$ is much larger than the penetration depth $\lambda$, 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 [11, 12]. By contrast, in the case of thin films ($d < \lambda$), vortices enter the sample as rigid straight lines.

We consider, however, that vortex instabilities resulting from the coexistence of OP and DP,
as revealed in NbSe$_2$ crystals [1], 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. 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 [1, 5, 6, 13] and/or possible slight inhomogeneities of $a$-Mo$_x$Ge$_{1-x}$ films. The metastability mentioned here may also account for the absence of the sharp peak in $I_c(B)$ in our $a$-Mo$_x$Ge$_{1-x}$ films.

For film 2 with CD configuration we have extended measurements of $S_V$ at $V = 0.5$ mV down to low fields ($= 0.3$ T) and found pronounced rises of $S_V$(10Hz)/$V$ in $B$ slightly lower than 0.5 T, as shown with triangles in the inset of figure 2(b). This abrupt change in noise suggests 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 [1]. In order to determine the vortex phase diagram in the $B - T$ plane, we have conducted further measurements of $S_V$ vs $B$ at higher temperature $T = 5.5$ K near $T_c (= 6.2$ K). At 5.5 K, the solid phase is smaller and a peak in $I_c(B)$ is less pronounced than at 4.1 K. Preliminary data show that, although a broad peak in $S_V$(100Hz)/$V$ (at $V = 0.5$ mV) occurs in the “PE” regime, another low-$B$ peak is not visible down to the lowest $B(= 0.05$ T) measured. This result implies that at 5.5 K a single OP is not present in the solid phase or is significantly suppressed. This behavior is qualitatively in agreement with the phase diagram of NbSe$_2$ near $T_c$ [1, 14].

To summarize, we present comparative measurements of voltage noise spectra $S_V(f)$ induced by current-driven vortices for $a$-Mo$_x$Ge$_{1-x}$ films with CD and striplike geometries. We find that $B$ dependences of $I_c$ and $S_V(f)$ are nearly independent of contact geometries, indicating that EC effects are not important on static or dynamic vortex properties. This result is in contrast to what has been reported in NbSe$_2$ crystals. The difference may be attributed to different sample thickness. We observe a sharp peak in $S_V(B)$ (at low $f$) suggestive of ODT just below $B_p$ at 4.1 K while clear evidence for ODT is not visible at higher $T(= 5.5$ K) near $T_c(= 6.2$ K).

Acknowledgments
We thank M. Konczykowski for useful discussions. This work was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and by the CTC program under JSPS.

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