Vortex dynamics in amorphous Mo_xSi_{1-x} films detected by voltage noise

S. Okuma and N. Kokubo
Research Center for Very Low Temperature System, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152-8551, Japan

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We have measured the current-induced voltage noise S_V for both the thick and thin films of amorphous Mo_xSi_{1-x} with strong pinning, over a broad frequency range, to study the effects of both the current I and magnetic field B on the vortex dynamics. The results show that the vortex dynamics probed by S_V strikingly depends on the static vortex states. Irrespective of the film thickness, noise is largest at $B\sim 0$, while small vortex shot noise is observed at high B in the vortex-liquid phase. The origin of large noise at $B\sim 0$ is due mainly to density fluctuations of the thermally excited and subsequently grown vortex loops and dissociated vortex-antivortex pairs for three dimensions (3D) and 2D, respectively, in the presence of an applied current. In the three-dimensional vortex-solid phase, the $1/f^{\beta}(\beta<0.6)$-like noise spectra resulting from a plastic-flow motion of vortices are observed at low I over the *broad* field region, which is attributed to high concentration of pinning centers. With increasing I in the nonlinear regime, both the amplitude and spectral exponent β of S_V decrease and eventually approach the values in the vortex-liquid phase.

I. INTRODUCTION

The vortex dynamics in type-II superconductors has been actively studied over recent years. Of particular interest is the current-driven dynamical phase transition between the plastically deformed phase and a moving crystal for vortex lines.[1–9] Experimental evidence for the dynamical transition has been suggested by neutron-diffraction studies[4] as well as transport measurements[1] including voltage noise[2] in the layered superconductor 2H-$NbSe_2$, and by the current-voltage (I-V) characteristics in two-dimensional (2D) films of amorphous $Mo_{77}Ge_{23}$ (Ref. 6). To date, the systems used for the studies of the vortex dynamics are relatively clean samples with a moderate strength of pinning,[1–6,10–14] where the melting transition is first order and the ''peak effect'' associated with reduction in the shear modulus c_{66} on approach to melting is usually found at a characteristic field B_p, just prior to melting. On the other hand, the vortex dynamics in disordered (but uniform) superconductors with higher pinning strength has been much less studied and this is the subject of this paper.

In this work we have made the systematic measurements of the current-induced voltage noise S_V in both the thin (2D) and thick (3D) films of amorphous (a-)Mo_xSi_{1-x} at a fixed temperature below the superconducting transition temperature T_c. Since our films are highly uniform at least down to the thickness of 4 nm (Refs. 15, 16), the complicated voltage noise arising from inhomogeneities of the films, such as grain boundaries,[17–20] is ignored. Although this system looks essentially similar to the a-$Mo_{77}Ge_{23}$ system[6] mentioned above, neither the signature of the first-order transition nor the peak effect in the critical current I_c is observed at any temperature down to 0.05 K. In addition, the linear-response (flux-flow) resistance is not visible up to the highest current studied. These results strongly suggest that the pinning strength, probably a concentration of pinning centers, in our films is substantially higher than that in clean 2H-$NbSe_2$ and a-$Mo_{77}Ge_{23}$.

In a recent paper,[21] we have reported the preliminary results of the voltage noise measurements on the thick a-Mo_xSi_{1-x} system. We have demonstrated that S_V at high frequencies ($f\sim 10$ Hz–100 kHz) is dominated by the flux motion. In the present paper, we focus only on the high-frequency noise and will show that the vortex dynamics probed by S_V strikingly depends on the static ($I=0$) vortex states. The results are summarized as follows: Irrespective of the film thickness, noise is largest at $B\sim 0$ while small vortex shot noise is observed at high B in the vortex-liquid phase. In the 3D vortex-solid phase, the spectral shape is expressed as $S_V\sim 1/f^{\beta}$ ($\beta<0.6$) and S_V at fixed f shows a peak as a function of I (or V). This type of noise is only visible in the 3D vortex-solid phase and hence, it is attributed to a plastic-flow motion of the vortex solids (islands) in the presence of the random pinning potential. While the similar dynamics has been suggested in clean 2H-$NbSe_2$ (Ref. 2) and in thin (2D) films of a-$Mo_{77}Ge_{23}$ (Ref. 6), we note that the present result is different from the previous results in the following respects: (1) A plastic-flow state is visible only in the thick (3D) film but not in the thin (2D) film; (2) The plastic flow occurs over the *broad* field region in the 3D solid phase; (3) With increasing current in the plastic-flow state, both the amplitude and exponent β of S_V decrease and eventually approach the values in the vortex-liquid phase.

II. EXPERIMENTAL

A. Samples

We prepared two Mo_xSi_{1-x} films by coevaporation of pure Si and Mo in the pressure better than 10^{-8} Torr. One was the thick film ($x=55$ at. %) with $t=100$ nm in thickness, $l=1.6$ mm in length, and $w=0.3$ mm in width, and the other was the thin film ($x=77$ at. %) with $t=6$ nm, $l=1.0$ mm and $w=0.37$ mm. The structure of the films was confirmed to be amorphous by means of transmission electron microscopy consistent with the previous results.[15,16,22]

The edge of the films was trimmed by a sharp stylus to avoid ambiguity in thickness and x. These films were directly immersed into liquid ^{4}He to achieve good thermal contact. The resistance R and current-voltage (I-V) characteristics were measured by standard four-terminal dc and low-frequency lock-in methods. The magnetic field B was directed perpendicularly to the film surface. For measurements at $B=0$, we applied a small perpendicular field ($\sim 9\times 10^{-5}$ T) to cancel the ambient field.[15,16]

B. Voltage noise S_V measurements

All the data of the voltage noise spectral density $S_V(f)$, presented in this paper, was measured at a fixed temperature $T=1.8$ K below the λ point; the sample was directly immersed in the superfluid of ^{4}He. To avoid unexpected noise generated by a cable oscillation, the wire leads were rigidly attached to the support pipes of the cryostat. To minimize the external noise, the dc transport current I was supplied by a battery-operated current source and the field was produced by a superconducting magnet in the persistent-current mode.

Since we focused on the relatively low impedance region near the superconducting transition, we selected an ultralow-noise preamplifier (NF SA-400F3 or SA-200F3) with very small input-*voltage* noise rather than small *current* noise. The voltage noise S_V enhanced with the preamplifier was analyzed with an Ono Sokki CF-5220 fast-Fourier-transform spectrum analyzer. In order to measure S_V over the wide frequency range without making complicated calibration, we employed no matching transformer. Meanwhile, we checked that the gain (40 dB) of the preamplifier was frequency independent by injecting a known white-noise generated by the random-noise generator (NF WG-721A). The (excess) noise spectrum was obtained by subtracting the background contribution such as the thermal (Johnson) noise, which was measured with $I=0$. We also took account of the contribution from the current noise generated by the preamplifier. This noise was estimated from the two-terminal resistance of the sample and subtracted from the measured noise. Thus, we were able to measure $S_V(f)$ over a broad frequency range spanning six decades ($f=0.1$ Hz–100 kHz) with the sensitivity as high as $\sim 10^{-20}$ V^2/Hz.

III. RESULTS AND DISCUSSION

A. I-R characteristics

Both of the films have the superconducting transition temperatures T_c's of approximately 2.4–2.5 K and critical fields B_c's of $\sim$6 T. Thus, the superconducting coherence length ξ is estimated to be $\sim$18 nm, which is smaller than the thickness (100 nm) of the thick film but larger than that (6 nm) of the thin film. Figure 1 depicts the current-resistance (I-R) characteristics of the thick film at $T=1.79$ K in various fields ($B=0-3$ T). At $B\geqq 0.7$ T the low current parts of the isomagnetic curves exhibit positive curvature and Ohmic resistance remains at $I\rightarrow 0$, while those below 0.3 T display negative curvature, suggesting that the transition between the vortex-liquid and vortex-solid phases takes place at $B\sim 0.5$ T. We suppose from this data, as well as the previous studies for the similar a-Mo_3Si films,[23] that the melting transition is (nearly) second order rather than first order. From

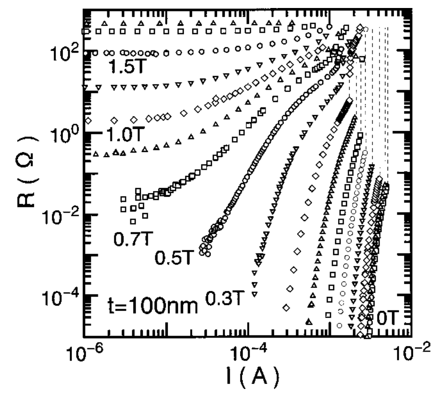

FIG. 1. Current-resistance (I-R) curves of the thick (100 nm) film at $T=1.79$ K in different magnetic fields: $B=0$, 0.3, 1, 3, 10, 30, and 60 mT, 0.1, 0.15, 0.3, 0.5, 0.7, 0.85, 1.0, 1.2, 1.5, 2, and 3 T (from right to left).

the slope of the critical I-R data, the dynamical critical exponent z for the second-order transition is obtained to be $z\sim 8$, in agreement with the value for the thick indium films.[24–26] In the case of the thin (2D) film, we have not found any sign suggesting the presence of the first-order nor second-order transition at $T=1.8$ K. Quite recently, we have performed transport measurements at very low temperatures ($\sim$0.05 K) and obtained the data supporting the notion that the field-driven transition from the vortex-glass to Bose-glass phase takes place at $T=0$.[15]

It is also seen from Fig. 1 that the I-R curve at $B\geqq 1$ mT shifts to the left with increasing B while it is independent of the field strength at $B\leqq 0.3$ mT. This result suggests that penetration of the flux lines occurs between 0.3 and 1 mT and hence, the lower critical field B_{c1} is roughly estimated to be $B_{c1}=0.3$–1 mT at $T=1.79$ K.

The I-V characteristics at high currents are rather different from those of the clean films. We are not able to observe clearly the flux-flow regime where the voltage should be proportional to the current. Instead, we have found that the voltage exhibits a steep jump at a characteristic current I^* that is dependent on B. The similar jump in the I-V characteristics has been reported in 2H-$NbSe_2$ (Ref. 4) and interpreted as suggesting the ordering of the moving vortex lattice. In the present case, however, I^* is found to increase with decreasing temperature, which is not consistent with the theories for the current-driven dynamical transition.[7,9] We, therefore, seek another possible explanation. According to the 3D vortex-loop theory,[27] the similar structure in the I-V characteristics is expected at high currents due to the change in the dissipation process of vortex loops from the thermally activated (weak nonlinear) to nonactivated (strong nonlinear) process. The present I-R data at low fields are explained within the framework of this theory. The result is presented elsewhere.[28]

B. Shot noise in high fields (the vortex-liquid phase)

Useful information about fluctuations of flux flow is obtained from measurements of the voltage noise spectral density S_V. First, we consider S_V in high fields (the vortex-liquid phase). As an example of the noise spectrum $S_V(f)$ in the liquid phase, we show $S_V(f)$ of the thick film measured

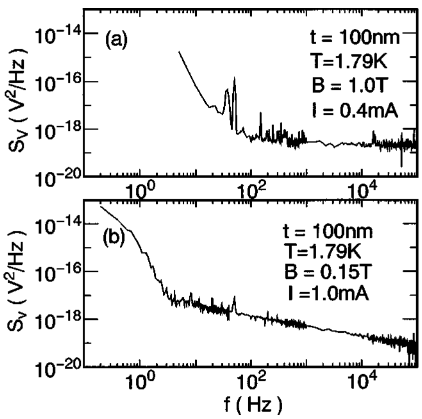

FIG. 2. Frequency dependence of the excess noise spectral density S_V for the thick film measured at (a) $T=1.79$ K, $B=1.0$ T, and $I=0.4$ mA and (b) $T=1.79$ K, $B=0.15$ T, and $I=1.0$ mA.

at $B=1.0$ T and $I=0.4$ mA in Fig. 2(a). Below a few tens Hz a rapid increase in $S_V(f)$ is observed with decreasing f, which is considered to be a flicker noise,[21] while at $f > 100$ Hz the spectral form is nearly white. Qualitatively similar noise spectra are obtained in other currents higher than 0.2 mA.

Figure 3 displays the voltage dependence of S_V measured at $f=900$ Hz for various fields. Almost a linear dependence of $S_V(900\,\text{Hz})$ on V, $S_V(900\,\text{Hz}) \sim V^\alpha$ ($\alpha=0.9\pm0.1$), is observed for $B=1.0$ T (shown with a thick straight line). Although the spectral shape is not of a complete Lorentzian form and the corner frequency ($\sim$ MHz) is not visible in our frequency range, the observed frequency and voltage dependences of S_V in 1.0 T look consistent with the modified shot-noise model[29] for a vortex assuming a shorter vortex mean free path $l_V \sim 1$ μm than the sample width $w=0.3$ mm. This short mean free path l_V is not unreasonable considering that our films contain many pinning centers. These features are essentially similar to what have been observed in the 2D liquid phase ($B \geqq 0.1$ T). As illustrated in Fig. 3, the S_V-V data of the thin film in the liquid phase ($B=0.1$ [●] and 0.3 T [▲]) also collapse onto a straight line that is nearly identical to the line for the thick film. This result indicates that within the model discussed here the value of l_V for the thin film is very close to that for the thick film.

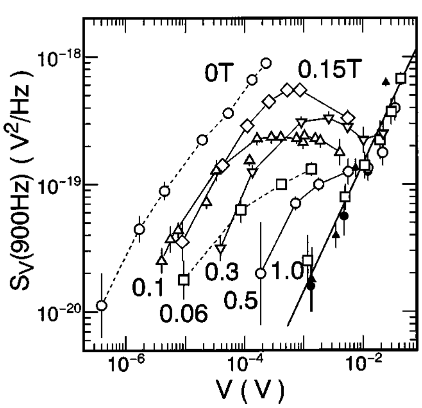

FIG. 3. $S_V(900\,\text{Hz})$ vs V at $T=1.79$ K for the thick film in different fields B: ○, 0 T; □, 0.06 T; △, 0.1 T; ◇, 0.15 T; ▽, 0.3 T; ○, 0.5 T; □, 1 T. Each symbol corresponds to the field shown in Fig. 1. Also shown are $S_V(900\,\text{Hz})$-V data for the thin (6 nm) film at $T=1.80$ K in $B=0.1$ (●) and 0.3 T (▲). The slope of the thick straight line is unity.

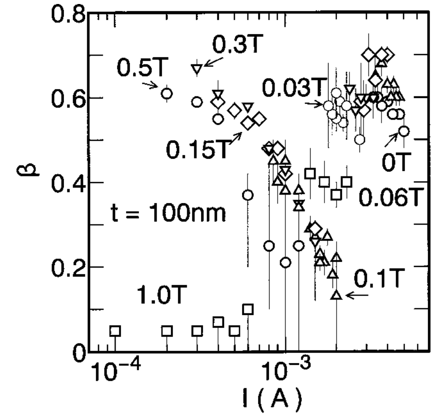

FIG. 4. β vs I for the thick film at $T=1.79$ K in various fields $B=0-1.0$ T, where β is an exponent of a power law ($1/f^\beta$) fitted to the frequency spectrum in the range $f=10$ Hz–100 kHz. Each symbol corresponds to B shown in Figs. 1 and 3. The large error bars that are visible at $B=0.5$ T imply that β is dependent on the frequency.

The discussion mentioned above is based on the assumption that the observed shot noise arises from the independent motion of individual vortices in the vortex liquid driven by the current. Similar arguments have been made in explaining the voltage noise in the vortex liquid phase of clean, untwinned Y-Ba-Cu-O crystals.[13] We note, however, that controversy still exists about the nature of the shot noise in the vortex liquid. It is not fully proved whether the motion of the individual vortices, which remain highly correlated in the vortex liquid, indeed yields the simple shot noise. We assume here that the correlation between vortices in the liquid does not drastically alter the shot-noise behavior. Quite different mechanisms may be responsible for this noise. If the vortex liquid contains some sort of defect whose motion is uncorrelated with each other, it can be the source of the shot noise.

C. $1/f^\beta$ noise in the 3D plastic-flow regime

Next, we focus on the voltage noise S_V in the 3D vortex-solid phase ($B=0.1-0.3$ T). The frequency dependence of $S_V(f)$ at $B=0.15$ T and $I=1$ mA is representatively shown in Fig. 2(b). It is expressed as $S_V \sim 1/f^\beta$ with a single value of $\beta(=0.4)$ over the broad frequency range (5 Hz–100 kHz). Such a spectral form is commonly observed in other fields ($B=0.1$ and 0.3 T) in the vortex-solid phase, which is markedly different from $S_V(f)$ in the vortex-liquid phase ($B=1.0$ T). With increasing I, β decreases from about 0.6 to less than 0.3 and eventually, it appears to approach zero (i.e., S_V approaches white) near $I \sim 3$ mA as shown in Fig. 4. As mentioned above (Fig. 1), the dc voltage V exhibits a steep jump at $I^* \sim 2$ mA which is slightly lower than 3 mA. It is also noted in Fig. 4 that the β-I data measured at $B=0.1-0.3$ T collapse onto nearly a single line, which is distinguishable from the data near zero field ($B=0-0.03$ T) and in the liquid phase ($B=1.0$ T). The large error bars that are visible at $B=0.5$ T imply that β is dependent on the frequency in the range $f=10$ Hz–100 kHz.

The current (voltage) dependence of S_V(900 Hz) in $B = 0.1–0.3$ T is nonmonotonic. As I is increased, S_V appears near the onset of the dc voltage and shows a peak at a certain current that is dependent on B. More importantly, the voltage dependence of S_V becomes weaker than the linear dependence as shown in Fig. 3. The height of the peak in the S_V-V curves takes on the largest value at the intermediate field $B \sim 0.15$ T in the solid phase. As the liquid phase is approached ($B \rightarrow \sim 0.5$ T), the peak becomes less pronounced and eventually disappears. We note that except at high current (voltage) regions, $S_V(V)$ in the solid phase is remarkably larger than that (shown with the thick straight line) in the liquid phase.

Simultaneous changes in the β-I and S_V-V relations around the melting field ($B \sim 0.5$ T) strongly suggest that the physical origin of the voltage noise in the solid phase is different from that in the liquid phase. Marley *et al.*[2] have measured the similar current dependence of S_V [peak in $S_V(I)$] in the vortex-solid (lattice) phase of 2H-$NbSe_2$ and claimed that the peak in S_V arises from the plastic flow of vortices. According to their arguments, the voltage noise appears as a result of transitions among the various metastable moving-vortex states of a plastically deformed flux-line lattice. We consider that the qualitatively similar picture also applies to the present case: i.e., S_V measured at low currents in $B = 0.1–0.3$ T (the solid phase) originates from the vortex motion dominated by the random pinning potential. The decrease in S_V with increasing I has been often interpreted as signaling the coherent vortex motion at high I, because there is no metastability in the coherent vortex motion. However, this argument looks inconclusive because the noise may be small for incoherent flow.

Furthermore, it is difficult to claim strongly the coherence of flux motion from the decrease in β (Ref. 2). This is because β can be small for incoherent flow, while, as far as we know, there is no definite model that explains the noise spectrum or the spectral exponent β in the plastic flow region and in the transition (crossover) region from plastic flow to elastic flow. The $1/f^{\beta}$-type spectral shape such as shown in Fig. 2(b) is probably related to the spread of velocities of the moving vortex islands.[30] This velocity spreading is due to different depinning energies associated with different kinds of pinning. At present, however, it is not possible to make a quantitative explanation for the spectral shape. We are not certain whether the $1/f^{\beta}$ spectrum which persists over the four decades of the frequency is indeed explained by a summation over many Lorentzians assuming a suitable distribution of relaxation times, i.e.,

$$S_V(\omega) \sim \int \tau g(\tau) d\tau / [1 + (\omega\tau)^2], \tag{1}$$

where τ is the characteristic time and $g(\tau)$ is a distribution function for τ. Experimentally, the result obtained here can unambiguously rule out the possibility that one might see only a limited region of the Lorentzian spectrum.[2] Although this problem requires further theoretical investigations, this idea is valid in interpreting S_V at high currents qualitatively.

With increasing current I, the vortex velocity increases and the pinning effect becomes progressively weak. This leads to uniform vortex motion and disappearance of the long-time correlation that yields low-frequency noise. Accordingly, both S_V (more precisely, S_V/V) and β show a decrease at high I, as actually seen in Figs. 3 and 4, respectively. We propose that at high currents, in addition to the reduced effect of pinning, the depletion in the size of the moving vortex islands [the velocity correlation length L_V (Ref. 2)] may occur as a result of splitting of large islands into smaller ones.[30] The data shown in Fig. 3 where $S_V(V)$ in $B = 0.1–0.5$ T approaches that in $B = 1.0$ T (the liquid phase) with increasing V (or I) may indicate that the size of the moving vortex islands (or L_V) actually reaches a lower limit, intervortex spacing a_0, for the vortex liquid. This result is contrary to the picture of the current-driven dynamical phase transition, where L_V should remain substantially larger than a_0. The decrease in the average bundle size with increasing I has also been reported in the quasilinear I-V regime of InPb alloy samples from the direct flux-detection measurements using a superconducting quantum interference device magnetometer.[30] It has been suggested that the bundle size of the flux lines is determined by the force balance between the pinning force and driving forces for the flux lines. The latter forces include the Lorentz force due to the transport current and the repulsive force between the flux lines, both of which increase as the bundle size builds up. Thus, as the current increases, the bundles with smaller sizes can start to move over the pinning potential barrier and contribute to the flow. As already noted in the previous section, the discussion presented here is based on the assumption that the shot noise in the liquid phase originates from the motion of individual vortices. We naively interpret the data in $B = 0.1–0.5$ T around largest currents in terms of the vortex shot-noise model with a bundle size of $n = 1$, because the spectral exponent β is close to zero and S_V (the available data for $B = 0.3$ and 0.5 T) shows a trend to increase and fall on the straight line for $B = 1$ T (the liquid phase). If the origin of the shot noise is different from what has been assumed here, we cannot conclude from the present data whether the moving vortex solid becomes disordered or ordered at high I.

It is interesting to investigate what fraction of vortices are moving at the largest currents and what the vortex motion becomes at much larger I. The fraction of moving vortices cannot be estimated until we know what the flux-flow resistance is. As mentioned above, however, we are not able to observe fully (pin-free) flux-flow regimes and hence, we can neither estimate the fraction of moving vortices from the present data nor measure S_V for much higher currents where pinning effects are negligible. To perform these investigations, we have to prepare films with even lower concentration of pinning centers, though we do not currently know the way to control the pinning strength in the present amorphous Mo_xSi_{1-x} system.

D. S_V near zero field

We consider S_V near the zero field $B = 0–30$ mT. The noise spectrum of the thick film exhibits a $1/f^{\beta}$($\beta \sim 0.6$)-like frequency dependence, which is similar to the spectrum observed at low I in the solid phase. With increasing I, β stays almost unchanged or decreases slightly as shown in Fig. 4, while S_V increases monotonically up to the maximum I (or V) for S_V to be measured. (In Fig. 3 S_V-V data for $B = 1$, 3, 10, and 30 mT are not plotted for clarity.) Insensitivity of the current dependence of β [the spectrum form $S_V(f)$] to the field strength as well as the similarity of the voltage dependence of S_V in these fields ($B=0-30$ mT) seems to suggest that the mechanism responsible for the voltage noise in a small field ($B=1-30$ mT) is essentially similar to that in the Meissner phase ($B=0$). However, we note that S_V at fixed V is largest in $B=0$ and decreases abruptly by applying a small field ($B=1-60$ mT). Such a remarkable feature is commonly observed in the thin film, as will be seen in more detail later.

Obviously, it is difficult to explain such large S_V at $B \sim 0$ in the framework of the simple shot-noise model for independent vortex motion,[29] because the spectral shape is far from white and the characteristic size n of the magnetic bundles contributing vortex shot noise is estimated to be much larger than unity ($n \sim 10^2$). It is natural to consider that the origin of large S_V at $B \sim 0$ is due to thermally activated and subsequently grown vortex loops and the dissociated vortex-antivortex pairs for 3D and 2D, respectively, in the presence of an applied current. The existence of these ($B=0$) vortices has been predicted by the 3D vortex-loop[27] and 2D vortex-unbinding[31] theories and indeed confirmed by experiments, such as I-V characteristics, for both dimensions.[16,28,32] Although these theories make no specific predictions about the voltage noise, they can qualitatively account for the present results. The basic idea is that large noise at $B \sim 0$ results from large vortex-density fluctuations,[33] such as associated with nucleation, growth of vortex loops, unbinding of vortex-antivortex pairs, and pair annihilation.

To support the above interpretation in the 2D case, we have made additional measurements of the voltage noise, $S_{V1}(I_1, V_1, B_1, T_1)$ and $S_{V2}(I_2, V_2, B_2, T_2)$, for the thin film at the same I and V but different B and T; i.e., $I_1 = I_2$, $V_1 = V_2$, $B_1 = 0$, $B_2 = 0.1$ mT, and $T_{KT} > T_1 > T_2$, where T_{KT} is the Kosterlitz-Thouless (KT) transition temperature. The results show that S_{V1} generated (only) by the dissociated vortex-antivortex pairs is indeed larger than S_{V2} generated by both the dissociated pairs and field-induced vortices. In order to explore the nature of the voltage noise at $B \sim 0$ for both dimensions, further measurements including the temperature dependence of S_V are in progress.

E. Field dependence of S_V

The changes in the physical origin of S_V as a function of the field B can be seen more impressively by plotting $S_V(900\,\mathrm{Hz})$ at fixed voltage V against B (=0–1.0 T). In the simple model of the flux-flow noise, the constant V implies that the number of moving vortices across the sample per unit time is constant. Thus, the change in S_V directly reflects the change in the ratio of the fluctuating component to the flux-flow voltage. In Fig. 5 we plot $S_V(900\,\mathrm{Hz})$ of the thick film measured at $V = 2 \times 10^{-4}$ V, where most data for different B are available and the interesting peak in the S_V-V curves is observed for $B = 0.1-0.3$ T. As the field B is increased from $B=0$, $S_V(900\,\mathrm{Hz})$ first decreases abruptly; it then starts to increase at $B \sim 0.06$ T and shows a broad maximum at $B \sim 0.15$ T. After showing a maximum, $S_V(900\,\mathrm{Hz})$ again exhibits a gradual decrease and in the liquid phase

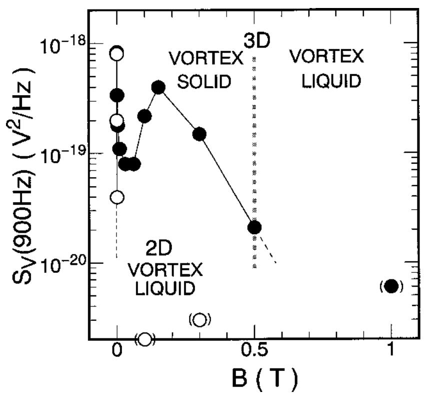

FIG. 5. Field dependence of $S_V(900\,\mathrm{Hz})$ for the thick film (solid circles) at $T = 1.79$ K and $V = 0.2$ mV and for the thin film (open circles) at $T = 1.80$ K and $V = 0.1$ mV. The background level is approximately $10^{-20}\,\mathrm{V}^2/\mathrm{Hz}$. For the thick film, the vortex-solid-to-vortex-liquid transition occurs at $B \sim 0.5$ T.

($B \gtrsim 0.5$ T), it falls below the background level $\sim 10^{-20}\,\mathrm{V}^2/\mathrm{Hz}$. In the case of the thin film, the field dependence of $S_V(900\,\mathrm{Hz})$ is rather different. By applying a small field of up to $B \sim 1$ mT, S_V decreases abruptly below the background level without showing a peak. These results indicate that the dimensionality of the system plays a crucial role in the voltage noise. The difference of the dimensionality implies the different static ($I=0$) vortex states. According to the vortex-glass theory,[27,34–36] the vortex-solid (glass) state is present in 3D at finite T but not in 2D except at $T=0$. Consequently, the peak in the S_V-V or S_V-B curves observed in the thick film is naturally ascribed to the particular current-dependent dynamical states of the vortex solid.

Recent numerical studies of a 2D vortex system, which have successfully explained the I-V data for thin a-$Mo_{77}Ge_{33}$ films,[6] have proposed a picture describing the plastically deformed regime.[37] In this regime the vortex flow is composed of unpinned individual vortices in the flux-flow state and pinned vortex islands with local hexatic order. The latter contributes to the flow through intermittent motion. With increasing I, the size of the pinned vortex islands shrinks and at sufficiently large I, the system heals back to the relatively ordered regime. We consider that this picture may partly account for the present result in the 3D plastic-flow regime.

It is also noted in Fig. 5 that for the thick film large noise is present over the broad field range in the solid phase, which is contrasted with the result for clean 2H-$NbSe_2$ where noise is localized in a narrow range of B just below B_p (Ref. 2). This difference is attributed to the different pinning strengths between these systems. In our system the concentration of pinning is high enough for the highly disordered plastic flow to be observed even at fields far below the melting field. Also, the high-sensitivity measurements of S_V has made its detection possible. Quite recently, it has been suggested numerically[38] that the softness of the vortex lattice, which corresponds to the field strength in the experiment, is an impact factor determining the vortex behavior at high driving currents. Though it remains unclear whether this simulation can be applicable to the present system with much disorder, the predicted behavior of S_V, such as a field dependence of maximum noise power S_{max}, looks similar to the present result.

On the experimental side, the use of the second spectral technique will be helpful, because it can provide further information about the vortex dynamics. The second spectrum allows us to distinguish between complicated kinetics involving many linked processes with different rates, and simpler superpositions of single-rate processes with a distribution of rates.[39] We expect that the origin of the shot noise will be clarified from the measurement of the non-Gaussian higher moments of the noise. We are now conducting experiments including the second spectrum (higher moments) measurements.

To summarize, we have measured the current-induced voltage noise S_V in disordered films of amorphous Mo_xSi_{1-x} over a broad frequency range. The results show that the vortex dynamics probed by S_V strikingly depends on the static vortex states. (1) Irrespective of the film thickness, the largest noise is observed at $B=0$, whereas it decreases abruptly by applying a small field. The origin of the large noise is due mainly to density fluctuations of the thermally excited and subsequently grown vortex loops and dissociated vortex-antivortex pairs for 3D and 2D, respectively, in the presence of an applied current. (2) In the vortex-liquid phase, small shot noise is observed for both films. (3) In the 3D vortex-solid phase, the $1/f^{\beta}(\beta<0.6)$-like noise spectra originating from a plastic-flow motion of vortices are observed at low currents I over the broad field region, which is attributed to high concentration of pinning centers. With increasing I in the nonlinear regime, both the amplitude and exponent β of S_V decrease and eventually approach the values in the vortex-liquid phase. (4) The plastic-flow state is not visible in the thin (2D) film. This is consistent with the view of the 2D vortex-glass theory that the vortex solid is not present at any finite temperature.

Quite recently, F. Nori has kindly informed us of the applicability of his simulations to the disordered systems. He has also pointed out that the similar jump in the I-V curves is visible in simulations.[40]

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