Vortex dynamics and possible vortex states just below the vortex-glass phase

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We have measured current-induced voltage noise S_V of thick amorphous Mo_xSi_{1-x} films in various fields H from zero to high fields near the vortex-glass (VG) transition H_g. Irrespective of temperature T, S_V is highest in the Meissner phase ($H<H_{c1}$). With applying H that exceeds H_{c1}, S_V decreases abruptly and falls to the background level. With further increasing H, S_V then starts to rise at characteristic field $H_{Lg}^0(\ll H_g)$ and the broad peak resulting from a plastic-flow motion of VG occurs before H_g is approached. Combined with the S_V data for the Corbino disk, we suggest that the edge-contamination effects reported in the clean $NbSe_2$ single crystals are not important in our disordered films. Within the T range studied, $H_{Lg}^0(T)$ shows an increase on cooling, which is different from the T-independent disorder-driven transition. We interpret the field regime $H_{c1}(T)<H(T)<H_{Lg}^0(T)$ as the vortex state different from the VG phase.

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I. INTRODUCTION

The vortex state or vortex phase diagram in the low-field (H) regime near the Meissner phase ($H<H_{c1}$) of the type-II superconductors has not yet been fully clarified. Theoretically, the physics of the individual vortex line is realized in the low-field part of the field-temperature (H-T) phase diagram and thus it is important to study this field region.[1] In clean superconductors the ordered vortex lattice (or Bragg glass) can melt not only with increasing T (thermal fluctuations) at fixed H, but also with decreasing H (vanishing shear modulus) at fixed T, leading to a reentrant behavior of the melting line. Thus, the (reentrant) *dilute vortex-liquid phase* has been predicted to exist at low H between the Meissner phase and vortex-lattice (or Bragg-glass) phase.[1–4]

In the meantime, the solid-solid transition driven by disorder and related phenomena in the vortex system have attracted wide attention.[3,5,6] Most experimental studies have been performed using the clean single-crystal superconductors,[7–18] in which the pronounced peak effect (PE)[19,20] in the critical current I_c is observed below the upper critical field H_{c2}. It has been also reported in some systems that large excess noise S_V induced by current (I) appears in the very narrow regime near the PE,[21,22] whose origin has been attributed to plastic-flow motion of I-driven vortex lattice. According to the recent studies for the $NbSe_2$ single crystals,[10–12] however, the excess noise does not result from any previously known flux-flow noise mechanism, but rather is due to a conceptionally different phenomenon of random creation and annihilation of a metastable phase. This has been explained in terms of the edge-contamination effects in clean superconductors.

While a number of studies have been performed using clean superconductors, very little has been studied about the vortex state in dirty superconductors which exhibit the vortex-glass transition (VGT).[23–29] In particular, the vortex state in the low-H regime,[7,15,16,30] as well as the low-T/high-H regime, remains still unrevealed, which is the subject of this paper. In the uniformly disordered superconductors which we focus on in the present paper the complicated edge-contamination mechanism is much less effective (or negligible)[12] and, hence, the dynamic as well as the static vortex state is expected to be much simpler. On the other hand, it is not easy to study experimentally the vortex states at low H, because there is no suitable measurement in studying the region, where direct current (dc) resistivity ρ in the limit $I=0$ is zero. In this paper we will show that the measurement of I-induced voltage noise S_V is useful to study the vortex states at low H

In our previous work using thick (100 nm) a-Mo_xSi_{1-x} films we have found that noise is largest at $H\approx 0$, while only very small noise appears at high H in the vortex-liquid phase. The origin of large noise at $H\approx 0$ is due mainly to density fluctuations of the thermally excited and subsequently grown vortex loops in the presence of an applied current.[2,31] In the vortex-solid phase, the $1/f$-type noise spectra $S_V(f)$ are observed over the broad field region, which result from a plastic-flow motion of vortex solid driven by current.[32] On the basis of alternating current (ac) complex resistivity, we have recently determined the equilibrium vortex phase diagram for the thick$a$-Mo_xSi_{1-x} film system over the broad T (>0.04 K) and H regime except for the low-H regime near H_{c1}.[25–27]

In this paper we perform simultaneous measurements of the linear ac complex resistivity, current-voltage ($I-V$) characteristics, and I-induced voltage noise S_V[32,33] of a thick (100 nm) a-Mo_xSi_{1-x} film at different T down to $T=0.38T_c$, where T_c is the zero-resistivity temperature at $H=0$, in various fields H from zero to high fields near H_{c2}. We have commonly observed irrespective of T that noise is largest in the Meissner phase, consistent with the previous result for the similar thick film.[32] When H exceeds H_{c1}, S_V/V decreases steeply and falls down to the background level at certain characteristic field H^0, that is dependent on T. With further increasing H, S_V/V then starts to rise at another characteristic field $H_{Lg}^0(\ll H_g)$, that is again T dependent down to the lowest T measured, and the broad peak occurs before the VGT (H_g) is approached. We have also studied another 100-nm-thick a-Mo_xSi_{1-x} film with the Corbino-disk (CD) and strip-like contact geometries. In CD the vortices circulate in the sample without crossing the edges. Combined with the S_V data for the film, we suggest that the edge-contamination effects reported in the clean $NbSe_2$ single crystals are not important in our disordered films. We interpret the field regime $H_{c1}(T) < H(T) < H^0_{Lg}(T)$ as the vortex state different from the VG phase. Preliminarily data relating to the present results have been presented elsewhere.[28,29]

II. EXPERIMENT

We prepared a 100-nm-thick a-Mo_xSi_{1-x} film with $x = 55$ at.% by coevaporation of pure Mo and Si in vacuum better than 10^{-8} Torr. Details of the preparation and characterization of the film were presented elsewhere.[34,35] The magnetic field was applied perpendicular to the plane of the film using a superconducting magnet in a persistent-current mode. For the measurements at $H=0$ we applied a small perpendicular field H (~ 0.1 Oe) to cancel the ambient field including the earth field.[34] Also, the "zero-field" measurement was performed using a double-wall μ-metal shielded dewer. The $I-V$ characteristics, frequency (f)-dependent linear ac complex resistivity ($f = 75$ kHz–3 MHz),[23–25] and the excess voltage noise spectral density $S_V(f)$ ($f = 1$ Hz–100 kHz)[32,33] were measured by the four-terminal method. The voltage noise enhanced with a preamplifier was analyzed with a fast-Fourier transform spectrum analyzer. We obtained the excess noise spectrum by subtracting the background contribution, which was measured with $I=0$. The film was directly immersed in liquid ^{4}He or ^{3}He.[33]

III. RESULTS AND DISCUSSION

The mean-field transition temperature T_{c0} and zero-ρ temperature T_c at $H=0$ are 2.93 and 2.85 K, respectively. Here, we define T_{c0} as a temperature at which ρ decreases to 95% of the normal-state resistivity at 4.2 K, ρ_n(4.2 K).[26,27] The width of the transition curve, as defined as $\Delta T = T_{c0} - T_c$, is 0.08 K. In $H=10$ Oe, ΔT(=0.12 K) is larger than that in zero field. With increasing H, $\Delta T(H)$ increases, while in $H > 1$ kOe, $\Delta T(H)$ stays almost unchanged or increases very slowly. In order to examine the equilibrium vortex phase diagram, we have measured the linear ac complex resistivity, from which location as well as the existence of VGT has been clearly determined.[2,23–25] Based on the ac data[36] taken in different H, we illustrate in Fig. 1 the $H_g(T)$ line. Also shown in the figure is the $H_{c2}(T)$ line, which is determined using a criterion that ρ decreases to 95% of ρ_n(4.2 K). This is the same criterion as used previously.[26,27] As described later, the lower critical field H_{c1}(<0.3 Oe) and the lower characteristic field for the VG phase, H^0_{Lg}(<300 Oe), are so small that they are not shown in this figure.

In Fig. 2(a) we plot the H dependence of the "critical current I_c" for the onset of V at various T over the broad range ($T = 1.10$–2.76 K), where I_c is defined using a criterion that $V(I_c) = 10^{-8}$ V. At 2.15 K,[28] for example, I_c, as well as $I-V$ characteristics, stays almost unchanged up to about 0.3 Oe. With further increasing H, I_c shows a sudden drop (i.e., $H_{c1} \sim 0.3$ Oe) and decreases monotonically up to the

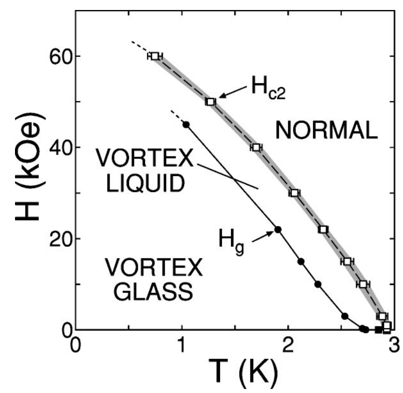

FIG. 1. H-T phase diagram of the 100-nm-thick a-Mo_xSi_{1-x} film with $T_c = 2.85$ K. Full circles and open squares denote $H_g(T)$ and $H_{c2}(T)$, respectively. A full square corresponds to $\rho(T_c) = 0$ in $H = 0$. The full and dashed lines are guides for the eye. H_{c1}(<0.3 Oe) and H^0_{Lg}(<300 Oe) are too small to be shown here.

highest field $H = 10$ kOe measured, where I_c becomes very small ($\approx 5 \times 10^{-4}$ A). We do not observe the PE in $I_c(H)$, which is widely observed in single-crystal superconductors with much less disorder[11–13,37] where the $\rho=0$ vortex-solid state is the ordered vortex lattice or Bragg glass. Absence of PE in our system is reasonable considering that $\rho=0$ vortex-solid state is the disordered VG. The degradation of PE with introducing disorder has been reported in $NbSe_2$ crystals.[38]

Voltage noise S_V is detectable only when substantial V appears at $I > I_c$. In Figs. 3(a) and 3(b) we display the noise spectra $S_V(f)/V$ [$S_V(f)$ divided by V][39] at 2.15 K in different H in the low-I($>I_c$) region, where S_V/V is insensitive to I. In the Meissner phase ($H=0$ and 0.22 Oe) large broadband noise with $1/f$-like form is observed at currents where the $I-V$ characteristics show strong nonlinearity. The $1/f$-type noise is commonly observed over the broad H range from 0 to about 10 kOe, whereas in $H \sim 10$ Oe [Fig. 3(a)] and $H \geqslant 15$ kOe ($\approx H_g$) [Fig. 3(b)], $S_V(f)$ is nearly f independent (white like) and its magnitude falls down (close) to the background level. Since the background level of our S_V measurement is around 10^{-20} V^2/Hz,[32] that of S_V/V depends on V (or I). The horizontal dotted lines in Figs. 3(a) and 3(b) mark the background level of S_V/V for the I (or V) used in measuring S_V at each field. We also notice that in $H \geqslant 100$ Oe many fine spikes appear in the noise spectra at $f = 50n$ and $60n$ Hz ($n = 1, 2, 3, \ldots$). They are most likely originating from external line noise [28] and, hence, eliminated from the spectra in Fig. 3(b) for clarity.

Next, let us discuss the H dependence of noise at different T. In Fig. 2(b) we plot S_V/V (at 90 Hz) measured in the low-I regime where S_V/V is insensitive to I. We have commonly observed irrespective of T (except for 2.76 K, where we have only two data points) that S_V/V is highest in the Meissner phase. When the flux lines start to penetrate the film at $H > H_{c1}$, S_V/V decreases abruptly and falls to the background level at certain characteristic field H^0, that is dependent on T (e.g., $H^0 \sim 100$, 10, and 1 Oe at 1.79, 2.15, and 2.70 K, respectively). As H is increased, S_V/V then starts to rise at another characteristic field H^0_{Lg}($\ll H_g$), that is again T dependent (e.g., $H^0_{Lg} \sim 110$, 30, and 4.5 Oe at 1.79, 2.15, and

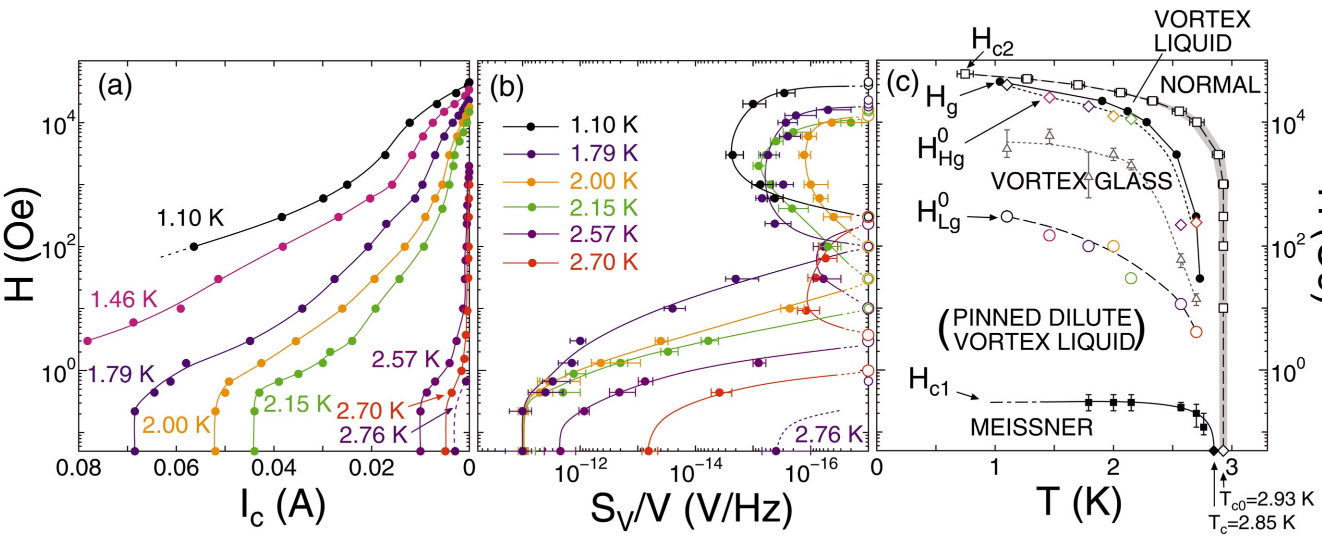

FIG. 2. (Color) (a) I_c and (b) S_V/V (at $f=90$ Hz) at low $I(>I_c)$ vs H for different T. In (b) the data points at 1.46 K are not shown for clarity. Open circles denote the points where S_V/V falls down to the background level. (c) Vortex phase diagram: $H_{c1}(T)$ (full squares), $H^0_{Lg}(T)$ (open circles), $H_p(T)$ (open triangles), $H^0_{Hg}(T)$ (open diamonds), $H_g(T)$ (full circles), and $H_{c2}(T)$ (open squares). All the lines are guides for the eye.

2.70 K, respectively), and the broad peak occurs before the VGT field (e.g., $H_g\sim 25$, 14, and 0.3 kOe at 1.79, 2.15, and 2.70 K, respectively) is approached. For ultrathin (6 nm) films of a-Mo_xSi_{1-x}, in which the VG is not formed at any nonzero T, such a peak has not been observable.[32]

The peak in noise with varying H has been also reported in clean single-crystal superconductors, such as 2H-$NbSe_2$.[21] However, the peak is limited in a narrow field regime just prior to melting. The result has been interpreted in terms of plastic-flow (or defective) motion [37] of vortex lattice. Recently, Paltiel *et al.* have performed the comparative study of excess noise generation in the CD and strip-like contact geometries for an Fe-doped $NbSe_2$ single crystal which exhibits a reentrant disorder-driven transition.[12] The results show that (only) in a strip-like configuration large excess noise is observed on the Bragg-glass side of the disorder-driven transition both along the high-field (H^H_{DT}) and low-field (H^L_{DT}) (reentrant) transition lines. Thus, the origin of voltage noise has been reasonably attributed to random generation of a metastable disordered vortex phase at the sample edges and its subsequent dynamic annealing in the bulk.

The transport properties and vortex states revealed in the $NbSe_2$ crystal are much different from those in our a-Mo_xSi_{1-x} films. In the (strip-like) $NbSe_2$ crystal,[10–12] (i) in addition to PE in $I_c(H)$, a distinct intermediate field region ($H^L_{\mathrm{DT}}<H<H^H_{\mathrm{DT}}$), which corresponds to the "ordered phase," is observed, where $I_c(H)$ shows a discontinuous drop; (ii) $S_V(H)$ exhibits two peaks at fields close to the disorder-driven transitions, H^L_{DT} and H^H_{DT}, for moderate I; and (iii) I dependence of S_V changes remarkably depending on whether H is close to the transition or in the central region of the ordered phase. In contrast, in our a-Mo_xSi_{1-x} films, (i) with increasing H (or T), I–V curves shift monotonically to the low-I direction and neither the PE in I_c nor the anomalous intermediate field region is observed at any T studied [Fig.

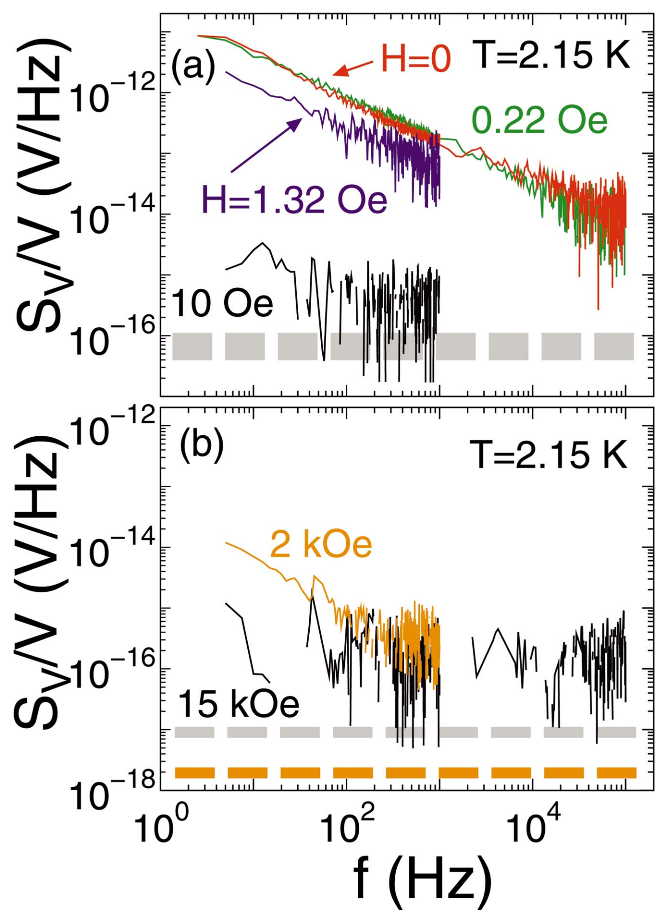

FIG. 3. (Color) Noise spectra $S_V(f)/V$ in the low-$I(>I_c)$ region at $T=2.15$ K in fields of (a) 0, 0.22, 1.32, and 10 Oe, (b) 2, and 15 kOe. A horizontal dotted line marks the background level of S_V/V. Note that the background level for 2 kOe (orange) is lower than that for 15 kOe (gray).

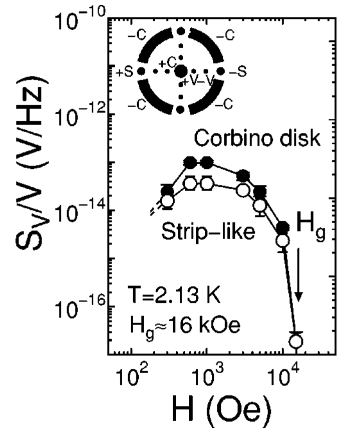

FIG. 4. H dependence of S_V/V (at $f=90$ Hz) of another 100-nm-thick a-Mo_xSi_{1-x} film ($T_c=3.00$ K) measured at low $I(>I_c)$ for the CD (full circles) and strip-like (open circles) geometries in the VG phase at 2.13 K. Inset: Arrangement of the electrical contacts. For CD, current flows between the contact $+C$ of the center and that $-C$ of the perimeter of the disk, while for the strip-like geometry, contacts $+S$ and $-S$ were used. For both contact geometries, the same voltage contacts $+V$ and $-V$ were used. The inner diameter of CD is 9.6 mm and the distance between the centers of the voltage contacts is 0.8 mm.

2(a)]; (ii) S_V exhibits a very broad peak over H covering the VG phase and no sharp peaks are visible near the high-H or low-H region of the VG phase [Fig. 2(b)]; and (iii) a significant change in $S_V(I)$ is not found in the H range studied.

The remarkable difference between the results of the two low-T_c type-II superconductors is attributed to the fact that our a-Mo_xSi_{1-x} film is much more disordered, containing much more pinning centers, than the $NbSe_2$ single crystal. In the (strip-like) $NbSe_2$ crystal the edge-contamination effects due to the injection of the disordered vortices through the sample edges play a significant role in the transport properties and vortex states.[10–13] By contrast, in our a-Mo_xSi_{1-x} films there is no ordered vortex states and the VG phase is the thermodynamically stable "disordered" phase. Therefore, the edge-contamination mechanism is not considered as a main source of voltage noise.

To further check this contention, we have performed experiments in the CD geometry for another 100-nm-thick film with $T_c=3.00$ K. The electrical contacts, which allow us to make a comparative study of noise in the CD and strip-like geometries,[12] are illustrated in the inset of Fig. 4. In the main panel of Fig. 4 we show the H dependence of S_V/V (at $f=90$ Hz) measured at low $I(>I_c)$ for the CD (full circles) and strip-like (open circles) geometries in the VG phase ($H_g \approx 16$ kOe) at 2.13 K. We find the similar S_V/V vs H curves for both geometries, supporting our earlier-mentioned view.

The broad peak in noise similar to that observed in the VG phase of our a-Mo_xSi_{1-x} system has been reported in computer simulations of I-driven vortices.[40] According to Ref. 40, plastic-flow motion of vortices generates large noise. With changing the vortex-vortex interaction A_v, which roughly reflects the field strength, voltage noise takes a broad peak at the intermediate strength of A_v. We thus interpret the broad peak in S_V/V observed commonly at $T=1.10-2.70$ K [Fig. 2(b)] as originating from plastic-flow motion of VG.[32]

Origin of I-induced voltage noise in low fields ($0 \leq H < H^0$) is quite different from that in higher fields (VG phase). We have proposed that large noise in the Meissner phase ($0 \leq H < H_{c1}$) is due mainly to large vortex-density fluctuations associated with nucleation and growth of vortex loops in three dimensions (3D).[31,32] Using the notion, the abrupt drop and subsequent monotonic decrease in S_V/V in fields just above H_{c1} [Fig. 2(b)] is naturally explained as follows. Neglecting the edge-contamination effect, free vortices originating from external field do not primarily contribute to the vortex-density fluctuations, as compared with free vortices created thermally at $H=0$ in the presence of I.[2] In the 3D Meissner phase ($0 \leq H < H_{c1}$) noise is generated only by the thermally nucleated and grown vortex loops, while in the mixed state ($H_{c1} < H < H^0$) noise is generated both by the field-induced vortices and the thermally grown loops in the presence of I. Thus, the relative strength of noise normalized by voltage, S_V/V, in the Meissner phase is larger than that in $H > H_{c1}$. The qualitatively same field dependence of S_V/V is obtained in the low-H regime of ultrathin [two-dimensional (2D)] films where largest noise appears again at $H(\approx H_{c1})=0$. This result has been explained by the essentially similar picture to that used for 3D mentioned earlier: In 2D voltage noise is due to large vortex-density fluctuations associated with 2D unbinding of vortex-antivortex pairs and pair annihilation.[32]

Based on all the data obtained in this work, we construct the log H vs T vortex phase diagram in Fig. 2(c), where we plot the four characteristic fields, $H_{c1}(T)$, $H^0_{Lg}(T)$, $H_g(T)$, and $H_{c2}(T)$. As already mentioned, $H_{c1}(T)$ and $H_g(T)$ (shown with the full lines) are well determined from the dc $I-V$ characteristics and the ac complex resistivity, respectively. Both represent the true phase transitions. In contrast, $H^0_{Lg}(T)$ and $H_{c2}(T)$ (shown with the dashed lines) are less precisely determined from the measurements of S_V and dc resistivity, respectively. $H^0_{Lg}(T)$ as well as $H_{c2}(T)$ is considered to be a crossover rather than a phase transition (see later). Also plotted in Fig. 2(c) are $H_p(T)$ and $H^0_{Hg}(T)$ (shown with the dotted lines), which are defined as fields at which S_V/V (at $f=90$ Hz) takes a peak and falls close to the background level, respectively, with increasing H in the VG phase. The $H_p(T)$ line marks the location where plastic-flow motion is most remarkable in the H-T plane. Upon cooling, $H_p(T)$ increases correlatively with $H_g(T)$.

We note that the $H^0_{Hg}(T)$ line nearly coincides with the $H_g(T)$ line. This fact, together with the finding that the spectral shape changes from $1/f$ to white like as one enters the liquid phase from the VG phase, supports the view that S_V indeed probes the plastic-flow state of VG driven by current. This fact also implies that another (lower) characteristic field H^0_{Lg} below which the spectral shape changes from $1/f$ to white like, as well as S_V falls to the background level, signals the disappearance of plastic flow and therefore the disappearance of VG order at $H < H^0_{Lg}$. This is physically reasonable:[2] At low fields just above the Meissner phase an average distance between vortices, a_0, is very large. From the experimental value of $H_{c1} \sim 0.3$ Oe (except near T_c), we estimate $a_0 \sim 10$ μm, that is of the same order of magnitude as or larger than the penetration depth ($\sim 1\ \mu$m).[41] Therefore, in the low-field regime ($H_{c1}<H<H^0_{Lg}$) the vortex-vortex interaction is not strong enough to establish VG order or to generate plastic-flow noise in the presence of I.

From the present data alone, it is difficult to definitely specify the vortex state below the $H^0_{Lg}(T)$ line. What we can tell from our data is that the dynamical ($I>I_c$) vortex state in the low-field regime, $H_{c1}(T)<H<H^0_{Lg}(T)$, is different from that (i.e., the plastic-flow state) in the high-field (VG) regime, $H^0_{Lg}(T)<H<H_g(T)$. One may suggest that the equilibrium ($I=0$) vortex state existing just below the $H^0_{Lg}(T)$ line may be a relatively ordered vortex phase (Bragg glass) and that absence of current-induced voltage noise in this regime may imply occurrence of the moving-lattice state instead of the plastic-flow state.[42–51] We note, however, that the temperature dependence of $H^0_{Lg}(T)$ persists down to the lowest $T(=0.38T_c)$ measured [Fig. 2(c)], although it may saturate at lower T, and the VG phase exists just above the $H^0_{Lg}(T)$ line. This does not look consistent with the picture of the disorder-driven Bragg-glass-to-VG transition, that is insensitive to T.[6,52]

The existence of the reentrant liquid phase below the low-field branch of the melting line has been suggested in several theories.[1–4] Most theories have dealt with the clean type-II superconductors, such as high-T_c oxide superconductors, neglecting the pinning effects, which certainly play a crucial role in our system. We particularly notice the theory of Blatter and co-workers,[1] who have examined the phase diagram taking account of the effects of thermal fluctuations and quenched disorder (pinning). We find that the phenomenological phase diagram presented by them (Fig. 6 of Ref. 1) is qualitatively similar to the phase diagram [Fig. 2(c)] obtained in this study. The theory predicts that, in addition to the usual vortex-liquid phase just above the VG phase, that is composed of pinned (viscous) liquid and unpinned liquid, a novel (*pinned*) *dilute vortex-liquid phase* is present between the Meissner phase and the VG phase. The two melting lines are shown to exist along the high-field and (reentrant) low-field transition lines of the VG phase.[1]

As mentioned earlier, in our system the $H^0_{Lg}(T)$ line shown in Fig. 2(c) is most likely a crossover rather than a phase transition, since no anomaly is visible at $H^0_{Lg}(T)$ in the dc ($I-V$) measurements. Nevertheless, we consider that the picture of the "pinned dilute liquid" is in itself reasonable, adequately describing the low-H vortex state just above the Meissner phase $[H_{c1}(T)<H<H^0_{Lg}(T)]$. In order to demonstrate the applicability of the theory to the present system more convincingly, it is necessary to observe the peak in the "low-field melting line", $H^0_{Lg}(T)$, which is expected to occur at lower $T(<1$ K), and the disappearance of the "dilute-liquid phase" [i.e., $H^0_{Lg}(T)\rightarrow H_{c1}(0)$] in the limit $T\rightarrow 0$. On the experimental side, however, it is not easy to extend our measurements to the lower T/H regime, because the $I-V$ curves shift to higher I and heating effects become more serious.

Finally, we compare quantitatively the extent of the regime $H_{c1}<H<H^0_{Lg}$ obtained in this study with that of the reentrant "disordered phase" reported in the $NbSe_2$ crystal[11] and with that of the reentrant liquid phase just below the vortex-lattice phase predicted by the theory for clean superconductors.[2] We find that in our system the value of $H^0_{Lg}(T)$ at $T=0.75T_{c0}$, for example, is 40 Oe, where $H_{c2}/H^0_{Lg}=710$ and $H^0_{Lg}/H_{c1}=130$. This H^0_{Lg} value is much smaller than the low-H order-disorder transition $H^L_{\rm DT}(T)=1000$ Oe at $T=0.75T_{c0}$ in the $NbSe_2$ crystal, where $H_{c2}/H^L_{\rm DT}=10$, but much larger than the theoretical value of the low-H melting line, that is predicted to be of order H_{c1}. Thus, we confirm quantitatively as well as qualitatively that the field region $H_{c1}<H<H^0_{Lg}$ obtained in this study is indeed a regime, which is entirely different from the reentrant phases reported so far in clean type-II superconductors.

To summarize, we have measured I-induced voltage noise S_V of thick a-Mo_xSi_{1-x} films at various H and T. Irrespective of T, S_V/V is highest in the Meissner phase. As H exceeds H_{c1}, S_V/V decreases abruptly and falls to the background level. With further increasing H, S_V/V then rises at characteristic field H^0_{Lg}, which increases upon cooling, and the broad peak occurs before H_g is approached. The S_V data for CD suggest that the edge effects are not important in our disordered films. We interpret the field regime $H_{c1}(T)<H(T)<H^0_{Lg}(T)$ as the novel vortex state different from the VG phase.

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