Anomalous Vortex Motion in the Quantum-Liquid Phase of Amorphous Mo_xSi_{1-x} Films

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We measure, in real time (t), the fluctuating component of the flux-flow voltage $V(t)$, $\delta V(t) \equiv V(t) - V_0$, about the average V_0 in the vortex-liquid phase of amorphous Mo_xSi_{1-x} films. For the thick film, $\delta V(t)$ originating from the vortex motion is clearly visible in the quantum-liquid phase, where the distribution of $\delta V(t)$ is asymmetric, indicative of large velocity and/or number fluctuations of driven vortices. For the thin film the similar anomalous vortex motion is observed in nearly the same (reduced-)temperature regime. These results suggest that vortex dynamics in the low-temperature liquid phase of thick and thin films is dominated by common physical mechanisms, presumably related to quantum effects.

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The vortex phase diagram in the mixed state of type-II superconductors has attracted intense theoretical and experimental attention. Numerous experiments have revealed a variety of phases and phase transitions, which depend crucially on the dimensionality and disorder of the superconductors. It has been well established that a vortex-liquid phase exists just below the upper critical field B_{c2} for three-dimensional (3D) and 2D superconductors. In the liquid phase the vortex motion causes nonzero dc resistivity ρ (or voltage V) in the presence of an arbitrarily small applied current I. On the other hand, when the vortex (flux) lines form a solid and I is small enough to pin the solid, ρ is truly zero. At high temperatures T properties of vortex lines are dominated by thermal fluctuations, while at sufficiently low T they are subject to quantum fluctuations. Quantum fluctuations are able to melt the vortex solid into the quantum vortex liquid (QVL) at $T = 0$. The existence of the QVL phase at low T has been reported in various type-II superconductors with weak pinning, which include high-T_c cuprates [1], organic superconductors [2,3], MgB_2 [4], and amorphous films [5–8].

For thick (100 nm) amorphous (a-)Mo_xSi_{1-x} films with moderately strong pinning we have recently obtained evidence for the QVL phase as well as the vortex-glass (VG) transition for 3D at low T on the basis of dc (ρ) and ac complex resistivities [9]. Upon cooling in fixed fields B which correspond to the QVL phase at $T \to 0$, curvature in $\log\rho$ vs $1/T$ curves changes from downward to upward at certain temperature T_Q, indicative of crossover from temperature dominated to quantum driven fluctuations in the liquid phase. Moreover, the relative width of the QVL phase has been shown to increase along the B and T axes nearly proportional to the normal-state resistivity ρ_n [10]. This is in accord with the view that the QVL phase is caused by strong quantum fluctuations [5,11], which are enhanced with increasing ρ_n, and consistent with earlier work on 2D films [6].

We have also studied very thin (4 or 6 nm) films of a-Mo_xSi_{1-x}, which exhibit the $T = 0$ field-driven superconductor-insulator (VG) transition in 2D [12]. For the thin films it is difficult to determine the $B - T$ phase diagram, because the 2D VG transition occurs only at $T = 0$ [13]. Furthermore, in our thin films T_Q is not well determined from $\rho(T)$ [9], which makes it difficult to detect the onset of quantum-fluctuation effects by using usual static transport measurements.

While a great deal of effort has been directed at clarifying the equilibrium vortex states, comparatively less attention has been devoted to the *dynamic* properties of vortices. As far as we know, there is no paper reporting experimentally, as well as theoretically, the vortex dynamics in the low-T and high-B regime of the phase diagram, where quantum fluctuations play an important role. The purpose of this paper is to study, in real time, the change in vortex dynamics associated with the change in vortex states from the thermal to quantum liquid by measuring the fluctuating [time- (t-)dependent] component of the flux-flow voltage, $\delta V(t)$, about the average voltage V_0. We have known from recent studies that the measurements of voltage fluctuations or noise generated by driven vortices are very useful in probing the change in vortex states that cannot be detected by usual static transport measurements [14].

The results are summarized as follows. For the thick film the contribution of $\delta V(t)$ from the flux-flow motion is clearly visible in the QVL phase [and in the crossover regime between the thermal-vortex-liquid (TVL) and QVL phases], where the distribution of $\delta V(t)$, $P(\delta V)$, is asymmetric having a tail along the direction of the vortex motion. This means that the vortex motion in the QVL phase is not stationary but accompanied by large velocity and/or number fluctuations of moving vortices. For the thin film, on cooling, the similar unusual behavior of $\delta V(t)$ suggestive of the anomalous vortex motion appears at nearly the same reduced temperature $T/T_{c0} \sim 0.1$ as that for the thick film, where T_{c0} is the mean-field transition temperature. These results suggest that vortex dynamics in the low-T liquid phase of thick and thin films is dominated by common physical mechanisms, presumably related to quantum-fluctuation effects. Preliminary data on this work has been reported elsewhere [15].

The a-Mo_xSi_{1-x} films for which we present data in this Letter are the most resistive film 5 ($x = 47$ at. %) among the five thick (100 nm) films studied in Ref. [10] and a thin (6 nm) film ($x = 65$ at. %). They were prepared by coevaporation of pure Mo and Si [12]. The structure of the film was confirmed to be highly amorphous by means of transmission electron microscopy. The T_{c0} and ρ_n just above T_{c0} are, respectively, 1.13 K and 7.2 $\mu\Omega$ m for the thick film and 1.96 K and 4.0 $\mu\Omega$ m for the thin film. 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 with a time resolution of 39 or 390 μs. The magnetic field B was applied perpendicular to the plane of the film using a superconducting magnet in a persistent-current mode.

In Fig. 1(a) we illustrate the low-T and high-B part of the vortex phase diagram for the thick film, that was obtained in our recent work [Fig. 4(b) in Ref. [10]]. Here, the VG transition field $B_g(T)$ (full circles) is determined from the ac complex resistivity, while the upper critical field $B_{c2}(T)$ (gray squares) is defined as a field at which ρ decreases to 95% of ρ_n [9,10,16]. Upon cooling in the field region $B_g(0) < B < B_{c2}(0)$, which corresponds to the $T = 0$ QVL phase, curvature in the logρ vs $1/T$ plots changes from downward to upward below the certain temperature T_Q (~0.1 K), suggestive of the normal phase at $T = 0$, which is most likely metallic [10]. The location of T_Q is indicated with full diamonds in Fig. 1(a). We have also noticed that with decreasing T (increasing B), the dynamic exponent z of the VG transition extracted from the phase of ac resistivity exhibits a peculiar increase from the theoretical values of $z \sim 5$–7 to ~9 at low T (~0.2 K), that is slightly higher than T_Q, as shown in the inset of Fig. 1(a). These features are commonly observed for the 100-nm-thick films with different ρ_n, signaling a crossover from temperature dominated to quantum driven fluctuations [9].

Let us concentrate on $\delta V(t) [\equiv V(t) - V_0]$ measured at various (B, T) points in the liquid phase, which are indicated with open circles in Fig. 1(a). Here, we select the combination of T and B which yields nearly the same linear resistivity ρ_f (i.e., $\rho_f/\rho_n = V_0/V_n = 0.45 \pm 0.03$ at $I \rightarrow 0$, where V_n is the normal-state voltage) in the liquid phase. In the absence of I (i.e., $V_0 = 0$), the origin of $\delta V(t)$ is due to external noise, including (50 Hz) line noise. We do not observe any significant difference between the ($I = 0$) background data in the TVL and QVL phases. In the TVL phase, for all the I studied, the amplitude of $\delta V(t)$ is as small as 4–5 μV and its distribution $P(\delta V)$ is nearly symmetric, as expected usually. The inset (top) of Fig. 1(b) shows $\delta V(t)$ and $P(\delta V)$ taken at $I = 4.0$ μA [$V_0 = 387$ μV ($<V_n$)] in the TVL phase [at 0.15 K ($>T_Q$) in 3.12 T] close to the QVL phase. As far as measurements are performed in the TVL phase, we cannot detect substantial $\delta V(t)$ originating from the vortex motion within our experimental resolutions.

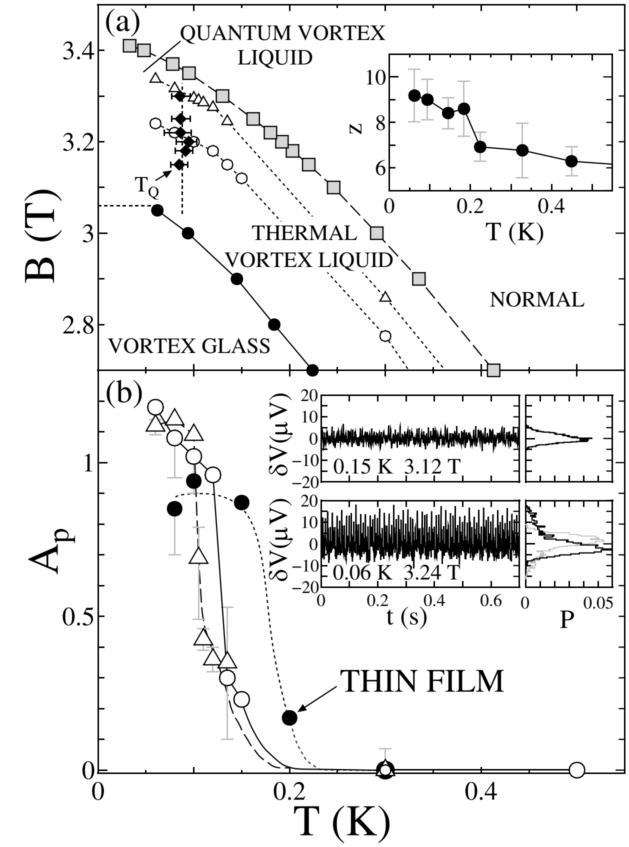

FIG. 1. (a) The $B - T$ phase diagram at low T in high B for the thick film. Full circles, gray squares, and full diamonds represent $B_g(T)$, $B_{c2}(T)$, and $T_Q(B)$, respectively. Open circles and triangles indicate (B, T) yielding $V_0/V_n = 0.45 \pm 0.03$ and 0.86 ± 0.03 at $I \rightarrow 0$, respectively, where $V(t)$ is measured. A horizontal dotted line marks the upper bound of the VG phase and the other lines are guides for the eye. Inset: z vs T. (b) The T dependence of the peak value of the skewness (A_p) of the voltage-noise (-fluctuation) distribution $P(\delta V)$; open circles and triangles denote $A_p(T)$ for $V_0/V_n \approx 0.45$ and ≈ 0.86, respectively. For comparison, $A_p(T)$ of the *thin* film for $V_0/V_n \approx 0.47$ is also shown with full circles. Inset: (Top) $\delta V(t)$ and $P(\delta V)$ (at $I = 4.0$ μA) at 0.15 K in 3.12 T; (Bottom) $\delta V(t)$ and $P(\delta V)$ at $I = 2.0$ μA (solid black lines), together with $P(\delta V)$ at $I = -2.0$ μA (a gray line), at 0.06 K in 3.24 T.

In the QVL phase, on the other hand, the contribution of $\delta V(t)$ from the vortex motion is clearly visible. The amplitude of $\delta V(t)$ for nonzero V_0 ($<V_n$) is remarkably larger than that for $I = 0$ ($V_0 = 0$). Furthermore, the shape of $P(\delta V)$ is highly asymmetric having a tail which extends to the direction of the vortex motion [$\delta V(t) > 0$]. We have verified by changing the polarity of I that the shape of $P(\delta V)$ is determined by the direction of the vortex motion. The data of $\delta V(t)$ and $P(\delta V)$ measured at $I = 2.0$ μA [$V_0 = 193$ μV ($<V_n$)] (solid black lines), together with $P(\delta V)$ at $I = -2.0$ μA (a gray line), in the central region

of the QVL phase [at 0.06 K ($<T_Q$) in 3.24 T] are typically illustrated in the inset (bottom) of Fig. 1(b). In the presence of larger I(e.g., 40 μA) where the film is nearly in the normal state, both $\delta V(t)$ and $P(\delta V)$ are almost identical to the background data. We have also found by measuring $\delta V(t)$ at fixed T and different B in the QVL phase that the anomalous $\delta V(t)$ with the asymmetric $P(\delta V)$ is much less remarkable near B_{c2} or B_g. All of these results support the view that the physical origin of large $\delta V(t)$ with asymmetric $P(\delta V)$ is due to the anomalous vortex motion in the liquid phase.

In order to quantify the degree of the asymmetry A of the distribution $P(\delta V)$, we calculate the skewness of the data, which is defined as $A = \frac{1}{N}\sum_i^N(\frac{V(t_i)-V_0}{\sigma})^3$, where V_0 is the mean, σ is the standard deviation, and N is the number of data points. The skewness for a normal distribution is zero, while positive values indicate that the right (positive) tail is heavier than the left tail. Figures 2(a) and 2(b) display the I dependences of V/I (full circles) and A (open circles) in the TVL phase (at 0.15 K in 3.12 T) near the QVL phase and in the QVL phase (at 0.06 K in 3.24 T), respectively. Also plotted in Fig. 2(a) with gray squares is $A(I)$ in the higher-T regime of the TVL phase (at 0.30 K in 2.78 T), where $A(I) = 0$ for any I studied. In the vicinity of the QVL phase (at 0.15 K in 3.12 T), $A(I) \approx 0$ at low I, while it takes a small broad peak at higher I above which nonlinear $V(I)$ occurs. In the QVL phase (at 0.06 K in 3.24 T), the anomaly in A is much more pronounced: With increasing I, $A(I)$ starts to rise at very small I, almost simultaneously with the onset of V, and exhibits a very large peak. We note that A is very large even in the linear regime.

We extract representatively the peak value of the skewness, A_p, from the A vs I data. In the main panel of Fig. 1(b) we plot the T dependence of A_p with open circles, which are measured at different (T, B) points (open circles)

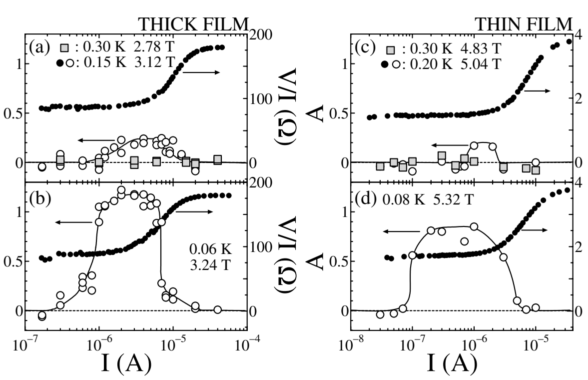

FIG. 2. (a) V/I vs I (full circles) and A vs I (open circles) for the thick film measured at 0.15 K in 3.12 T and (b) at 0.06 K in 3.24 T, and (c) those for the thin film measured at 0.20 K in 5.04 T and (d) at 0.08 K in 5.32 T. Gray squares in (a) and (c) represent $A(I)$ at 0.30 K in 2.78 T and at 0.30 K in 4.83 T, respectively. Solid lines are guides for the eye.

in the liquid phase located on a lower dotted curve in Fig. 1(a). It is clearly seen that, upon cooling, $A_p(T)$ exhibits an abrupt rise at around 0.12–0.13 K, which is close to or slightly higher than $T_Q \sim 0.1$ K. Upon further cooling, A_p increases gradually. The amplitude of voltage fluctuations normalized by V_0, $|\delta V|/V_0$, which is estimated from a base length of $P(\delta V)$ divided by $2V_0$, also shows an increase at low T in the QVL phase. We have observed similar A_p vs T [open triangles in Fig. 1(b)] and $|\delta V|/V_0$ vs T for another combination of (B, T) in the liquid phase [open triangles in Fig. 1(a)] yielding higher V_0/V_n ($= 0.86 \pm 0.03$) at $I \to 0$.

The anomalies at $T \sim 0.1$–0.2 K are commonly observed by three different transport measurements of dc ρ, ac resistivity, and $\delta V(t)$, as depicted in the main panel and inset of Fig. 1(a), and in the main panel of Fig. 1(b), respectively. This fact strongly supports the view that the crossover from the TVL to QVL phase occurs near T_Q, around which the vortex dynamics changes significantly. Figure 1(b) impressively shows that, on cooling, the anomalous flux-flow motion with large asymmetric voltage fluctuations appears in the crossover regime between the TVL and QVL phases; it grows significantly as one enters (approaches) the QVL phase and seems to survive at $T \to 0$.

We consider the possible vortex dynamics. Since the measured voltage V ($<V_n$) is proportional to the velocity v and number n of moving vortices, in the particular $B - T$ regime where A_p takes substantially large values, the vortex motion is not stationary but accompanied by large velocity fluctuations δv and/or number fluctuations δn. Within the classical theory [17], these fluctuations originate from plastic-flowlike vortex dynamics or the random (pinning-)depinning processes dominated by temperature in the presence of a constant I. This picture is acceptable even in the liquid phase studied here, since in the low-T regime, the effective pinning strength for flux lines is generally so strong that many vortices remain pinned even in the intermediate I we used in this experiment. The present results suggest that once some pinned vortices are depinned in the QVL phase, they may join the flux-flow with velocities even larger than those in the TVL phase and/or induce depinning of other pinned vortices near them more remarkably than in the TVL phase, which in turn generate large voltage pulses along the direction of the vortex motion, as seen in the inset (bottom) of Fig. 1(b). We emphasize that the picture proposed here does not explain the proximity of the temperature below which A_p rises (the onset of the anomalous vortex motion) to T_Q (the onset of the QVL phase). To explain this fact, we need a theory taking account of quantum-fluctuation effects on vortex dynamics.

We next present the results of a thin (2D) film. In our previous studies we have demonstrated that our thin a-Mo_xSi_{1-x} films exhibit a field-driven superconductor-insulator transition at certain critical field B_c in the limit $T \to 0$ [12]. For most of our thin films, as well as for the thin film used in this study ($B_c \approx 6.3$ T), $\rho(T)$ in fixed fields B (>0) below B_c follows the Arrhenius-type T dependence down to the lowest T (~ 0.05 K) measured [12]. Thus, the crossover from thermal to quantum liquid is not seen from $\rho(T)$, which is different from the result for the thick films. Furthermore, in 2D the VG phase exists only at $T = 0$ and, therefore, only the vortex state in the mixed state at $T > 0$ is the vortex liquid [13].

To compare with the results for the thick film, we measure $\delta V(t)$ at different (B, T) points which yield nearly the same ρ_f/ρ_n ($= V_0/V_n = 0.47 \pm 0.02$ at $I \to 0$) as that for the thick film in the liquid phase. Figs. 2(c) and 2(d) illustrate the I dependences of V/I (full circles) and A (open circles) at 0.20 K in 5.04 T and at 0.08 K in 5.32 T, respectively. In Fig. 2(c), $A(I)$ at 0.30 K in 4.83 T is also plotted (gray squares). Similarly to the case of the thick film, we observe a large peak in $A(I)$ in the linear regime suggestive of the anomalous vortex motion (only) at lower T (<0.2 K). In the main panel of Fig. 1(b) we display the T dependence of A_p with full circles, together with that for the thick film (open symbols). A pronounced rise in $A_p(T)$ is again visible in the low-T regime. As a whole, the T dependence of A_p for the thin film looks similar to that for the thick film. Plotting A_p against the reduced temperature T/T_{c0}, we find that the characteristic temperature below which A_p rises is close to that ($T/T_{c0} \sim 0.1$) for the thick film. This result suggests that the quantum-fluctuation effects for our thin film, which cannot be detected by dc $\rho(T)$, may appear at approximately the same T/T_{c0} (~ 0.1) as that for the thick film. The similarity found between the $A_p(T)$ curves for the thick and thin films, despite the difference in the equilibrium vortex phase diagram between them [9], suggests that vortex dynamics in the low-T liquid phase, probed by $\delta V(t)$, is dominated by common physical mechanisms, presumably related to quantum-fluctuation effects.

Finally, we propose that the real-time measurement of $V(t)$ presented in this Letter should be employed widely in various type-II superconductors to detect both static and dynamic properties of vortex matter. For example, it is interesting to perform this measurement (i) for overdoped as well as underdoped $Bi_2Sr_2CaCu_2O_8$ in which an extremely large QVL phase is observed below the $T = 0$ field that closes the pseudogap ($\approx B_{c2}$) [1], (ii) for the quasi-2D organic superconductors in which a novel quantum vortex slush state with a short-range order of vortices is proposed [2], and (iii) for amorphous thin (2D) films with weak pinning in which the T-independent or weakly T-dependent resistance indicative of the metallic 2D QVL phase at $T \to 0$ is reported [6,7,18].

In summary, we measure the fluctuating component of the flux-flow voltage, $\delta V(t)$, for a-Mo_xSi_{1-x} films. For the thick film, $\delta V(t)$ originating from the vortex motion is clearly visible in the quantum-liquid phase, where the distribution of $\delta V(t)$ is asymmetric having a tail along the direction of the vortex motion. This means that the vortex motion in the QVL phase is accompanied by large velocity and/or number fluctuations. For the thin film the similar unusual $\delta V(t)$ is observed at nearly the same $T/T_{c0} \sim 0.1$ as that for the thick film, suggesting that vortex dynamics in the low-T liquid phase of thick and thin films is dominated by common physical mechanisms, presumably related to quantum-fluctuation effects.

[1] T. Shibauchi *et al.*, Phys. Rev. B **67**, 064514 (2003).
[2] T. Sasaki *et al.*, Phys. Rev. B **57**, 10889 (1998); **66**, 224513 (2002).
[3] M. M. Mola, S. Hill, J. S. Brooks, and J. S. Qualls, Phys. Rev. Lett. **86**, 2130 (2001).
[4] H. H. Wen *et al.*, Phys. Rev. B **64**, 134505 (2001).
[5] G. Blatter *et al.*, Phys. Rev. B **50**, 13013 (1994).
[6] J. A. Chervenak and J. M. Valles, Jr., Phys. Rev. B **54**, R15649 (1996); **61**, R9245 (2000).
[7] D. Ephron, A. Yazdani, A. Kapitulnik, and M. R. Beasley, Phys. Rev. Lett. **76**, 1529 (1996).
[8] N. Marković *et al.*, Phys. Rev. Lett. **81**, 701 (1998).
[9] S. Okuma, Y. Imamoto, and M. Morita, Phys. Rev. Lett. **86**, 3136 (2001); S. Okuma, M. Morita, and Y. Imamoto, Phys. Rev. B **66**, 104506 (2002).
[10] S. Okuma, S. Togo, and M. Morita, Phys. Rev. Lett. **91**, 067001 (2003).
[11] R. Ikeda, Int. J. Mod. Phys. B **10**, 601 (1996).
[12] S. Okuma, S. Shinozaki, and M. Morita, Phys. Rev. B **63**, 54523 (2001).
[13] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991).
[14] S. Okuma and M. Kamada, Phys. Rev. B **70**, 014509 (2004).
[15] S. Okuma, M. Kamada, and M. Kobayashi, Physica C (Amsterdam) **412-414**, 539 (2004).
[16] Physically, $B_{c2}(T)$ is not a true phase transition and an absolute value of B_{c2} cannot be determined precisely from the transport data. In the B range studied (2.7–3.5 T) the width of the resistive transition ΔB defined from the 5–95% criterion $[0.05 < \rho(B)/\rho_n < 0.95]$ is typically as small as 0.2 T ($\Delta B/B_{c2} \approx 6\%$). The B_{c2} value obtained from the 95% criterion is slightly larger (by $\approx$1.5%) than that determined with the flux-flow theory, $\rho/\rho_n \approx 1 - a(1 - B/B_{c2})$, where a is a T-dependent constant.
[17] C. J. Olson, C. Reichhardt, and F. Nori, Phys. Rev. Lett. **81**, 3757 (1998); S. Field, J. Witt, F. Nori, and X. Ling, *ibid.* **74**, 1206 (1995).
[18] P. H. Kes, M. H. Theunissen, and B. Becker, Physica C (Amsterdam) **282-287**, 331 (1997).