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Unusual vortex dynamics in the quantum-liquid phase of a-Mo_xSi_{1-x} films

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Abstract. We find the unusual vortex dynamics in the low-temperature liquid phase of amorphous Mo_xSi_{1-x} films by measuring the fluctuating component of the flux-flow voltage $\delta V(t)$ about the average voltage. For the thick film, in which the quantum-vortex-liquid (QVL) phase has been well-determined in the field–temperature plane, $\delta V(t)$ originating from the vortex motion is clearly visible in the QVL phase, where the distribution of $\delta V(t)$ is anomalously asymmetric, implying large velocity and/or number fluctuations of driven vortices. For the thin film, in which the QVL phase has not been determined from the static transport measurements, similar unusual vortex motion is observed in nearly the same reduced-temperature regime. We suggest that vortex dynamics in the low-temperature liquid phase of thick and thin films is dominated by common physical mechanisms related to quantum-fluctuation effects.

Keywords. Flux flow; quantum liquid; fluctuations; superconductor–insulator transition.

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1. Introduction

The existence of a vortex liquid just below the upper critical field B_{c2} has been well-established through a variety of experiments for three-dimensional (3D) and two-dimensional (2D) superconductors. The properties of vortex lines at high temperatures T are dominated by thermal fluctuations, while they are subject to quantum fluctuations at sufficiently low temperatures. If quantum fluctuations are strong enough, a quantum-vortex-liquid (QVL) state is expected to appear [1–6]. The QVL phase has been actually reported for several low-T_c superconductors, such as thin (2D) [7–11] and thick (3D) [1] films of amorphous superconductors, the quasi-2D organic superconductors [12], and high-T_c cuprates [13]. As far as we know, however, dynamic properties of vortices in the QVL phase have not yet been studied experimentally or theoretically.

For disordered 2D superconductors in particular, the issue of QVL phase is closely related to the field-driven superconductor–insulator (SI) transition. The SI transition [8–11,14–20] is one of the most important subjects in condensed matter physics, which has been studied actively for more than two decades. In disordered superconductor, with random point pinning, a vortex-solid state is a vortex glass (VG) [20,21] rather than an ordered vortex lattice. According to the VG theory for 2D [19], the field-driven SI transition corresponds to the VG transition from the VG to Bose-glass (insulating QVL) phase at $T = 0$, although direct experimental evidence has not been obtained yet.

In the meantime, several groups have reported the existence of a *metallic* QVL phase at $T = 0$ through the experiments using different amorphous thin (2D) films [7–10]. The $T = 0$ metallic phase has been proposed based on the T-independent or weakly T-dependent resistance $R(>0)$ lower than the normal-state resistance $R_{\rm n}$ at $T \to 0$ in fields B below the (putative) field-driven SI transition at $B_{\rm c}$. Whether the $T = 0$ metallic phase is present or not in thin films is very important, because it challenges the traditional picture of the 2D field-driven SI transition. Some theories predict that the metallic phase in 2D is a Bose-metal phase in which Cooper pairs lack phase coherence [22,23], while there is a theory which precludes the possibility of an intermediate metallic vortex phase at $T = 0$ [24].

In recent years, we have intensively studied the thick and thin films of amorphous (a-)Mo_xSi_{1-x} with moderately strong pinning. For thick films, convincing evidence for the QVL phase, as well as the 3D VG transition, has been obtained at low T [25]. We have found that, upon cooling in fixed fields B which corresponds to the QVL phase at $T \to 0$, the curvature in $\log \rho$ vs. $1/T$ curves (where ρ is the DC linear resistivity) changes from downward to upward at certain temperature $T_{\rm Q}$, indicative of the cross-over from temperature-dominated to quantum-driven fluctuations in the liquid phase [26]. In our *thin* a-Mo_xSi_{1-x} films, by contrast, we have observed the behavior indicating the $T = 0$ field-driven SI (2D VG) transition [17]. That is, the linear resistance $R(T)$ in fixed fields $B(>0)$ below $B_{\rm c}$ follows the Arrhenius-type temperature dependence down to the lowest T ($\sim$0.05 K) measured [17] and evidence for the metallic QVL phase at $T = 0$ is not visible. Thus in our 2D films, it is difficult to detect the onset of quantum fluctuation effects on cooling by usual static transport measurements.

In this report we present the measurement of the time(t)-dependent component of the flux-flow voltage, $\delta V(t)$, about the average voltage V_0 for both thick and thin a-Mo_xSi_{1-x} films. We show that this real-time fluctuation measurement is very useful to probe sensitively the change in vortex dynamics associated with the change in vortex states from the thermal to quantum liquid. In the low-T liquid phase of the thin film, as well as in the QVL phase of the thick film, we observe $\delta V(t)$ originating from the vortex motion, where the probability distribution of $\delta V(t)$, $P(\delta V)$, is anomalously asymmetric, suggesting large velocity and/or number fluctuations of driven vortices. We also find that the unusual vortex motion in the thick and thin films occurs in nearly the same reduced-temperature ($T/T_{\rm c0}$) regime (where $T_{\rm c0}$ is the mean-field transition temperature). This finding suggests that vortex dynamics in the low-T liquid phase of thick and thin films is dominated by common physical mechanisms related to quantum effects. Thus, we obtain a clue to determine the QVL regime in the B–T plane for our thin (2D) films, which cannot be performed by the usual static transport measurements. The preliminary [27] and detailed data [28,29] concerning the present paper have been published elsewhere.

2. Experimental

We have studied a thick (100 nm) a-Mo_xSi_{1-x} film with $x = 47$ at% and a thin (6 nm) a-Mo_xSi_{1-x} film with $x = 65$ at%, which were prepared by coevaporation of pure Mo and Si in vacuum better than 10^{-8} Torr [17]. The structure of the films was confirmed to be highly amorphous by means of transmission electron microscopy. T_{c0} and the normal-state resistivity 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 (Ono Sokki CF-5220) with a time resolution of 39 or 390 μs. All the data presented in this paper were taken in our ^{3}He-^{4}He dilution refrigerator. The magnetic field B was applied perpendicular to the plane of the film using a superconducting magnet in a persistent-current mode.

3. Results and discussion

First, we present the results for the thick film. Figure 1a illustrates the Arrhenius plots of $\rho(T)$ in different B [26]. Upon cooling in the field region $B_g(0) < B < B_{c2}(0)$, which corresponds to the $T = 0$ QVL phase (see the next paragraph), curvature in the $\log\rho$ vs. $1/T$ plots changes from downward to upward below a certain temperature T_Q, suggesting normal (or metallic) phase at $T = 0$. Here, B_g is the VG transition field, which is determined unambiguously from the frequency-dependent AC complex resistivity, and the upper critical field B_{c2} is defined as a field at which DC $\rho(T)$ decreases to 95% of ρ_n [25,30]. The location of T_Q is indicated with open diamonds, which is defined as a temperature at which $\mathrm{d}^2\log\rho/\mathrm{d}x^2 = 0$, where $x \equiv 1/T$. We have confirmed that a deviation of the data points of $\rho(T)$ from the functional form expected by the VG theory [21] occurs at around T_Q [26]. The change in curvature of $\log\rho(T)$ around T_Q, in addition to a peculiar increase in the dynamic exponent of the VG transition at temperature slightly above T_Q, on cooling, is commonly observed for the 100-nm-thick films with different ρ_n [25,26,28,30]. These features are interpreted as signaling a cross-over from temperature-dominated to quantum-driven fluctuations.

The vortex phase diagram at low-T and high-B regime is enlarged and shown in figure 2. The cross-over temperatures T_Q for different B are plotted with filled diamonds. A horizontal dotted line marks the upper bound of the VG phase. We can see that the $B_g(T)$ (solid circles) line extrapolates to a field lower than $B_{c2}(0)$, indicating the existence of QVL phase at $T = 0$ [30]. Open circles and triangles denote (B, T) yielding $V_0/V_n = 0.45 \pm 0.03$ and 0.86 ± 0.03 at $I \to 0$, respectively, where $V(t)$ is measured. Here, $V_n(\equiv IR_n)$ is the voltage in the normal state.

Let us focus on the fluctuating component of the (flux-flow) voltage, $\delta V(t)$, about the average voltage V_0, which is defined as $\delta V(t) \equiv V(t) - V_0$. Figures 3a and 3c depict $\delta V(t)$ measured at $T = 0.15$ K ($>T_Q$) in $B = 3.12$ T (in the thermal liquid phase) and at 0.06 K ($<T_Q$) in 3.24 T (in the QVL phase), respectively, in the *absence* of applied current. These data represent the background contribution due

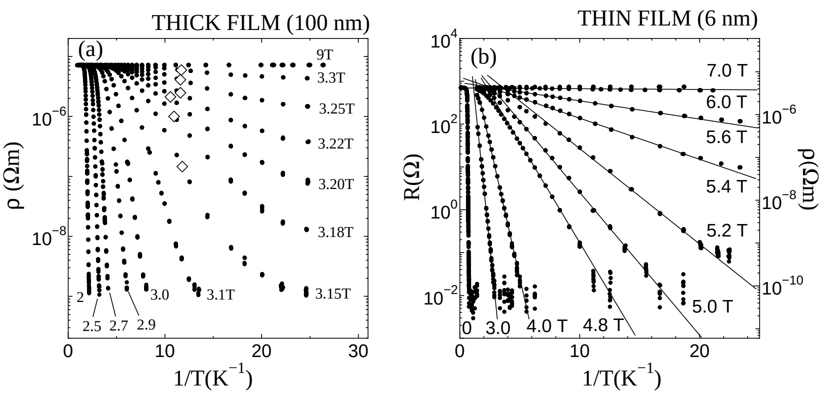

Figure 1. Arrhenius plots of $\rho(T)$ in different B for (**a**) thick and (**b**) thin films. The open diamonds in (a) indicate the location of T_{Q} at which the sign of curvature changes. The straight lines in (b) represent the linear fit of the data to the activated functional form.

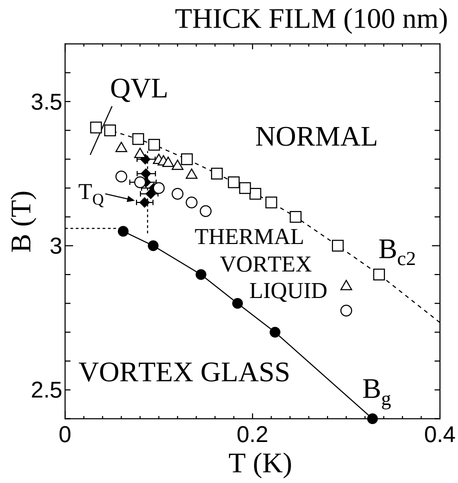

Figure 2. The enlarged view of the B–T phase diagram at low T and high B for the thick film. Filled circles, open squares, and filled diamonds represent $B_{\mathrm{g}}(T)$, $B_{\mathrm{c2}}(T)$, and $T_{\mathrm{Q}}(B)$, respectively. Open circles and triangles indicate (B, T) yielding $V_0/V_{\mathrm{n}} = 0.45 \pm 0.03$ and 0.86 ± 0.03 at $I \to 0$, respectively. A horizontal dotted line marks the upper bound of the VG phase. Other lines are guides for the eye.

to external noise. The amplitude of $\delta V(t)$ in figures 3a and 3c is as small as 5 μV and its distribution $P(\delta V)$ is symmetric, as expected usually. In the TVL phase, for all the I studied, both $\delta V(t)$ and $P(\delta V)$ are similar to the background data: The amplitude of $\delta V(t)$ is as small as 4–7 μV and its distribution $P(\delta V)$ is nearly symmetric (see figure 3b). As far as the measurements performed in the

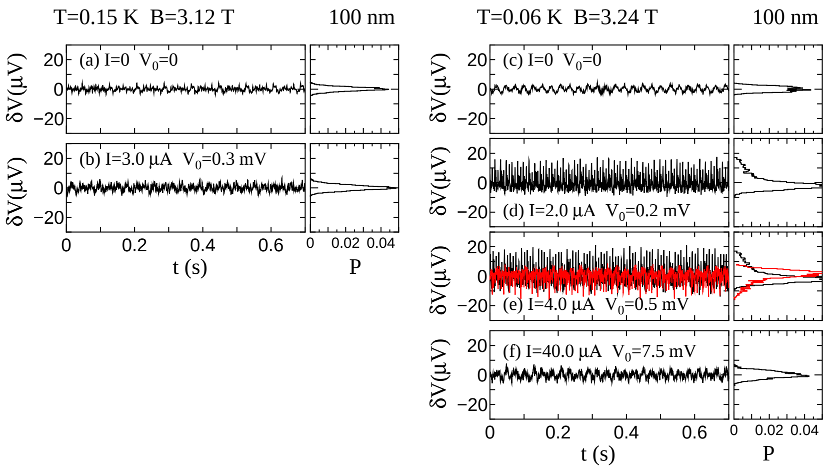

Figure 3. $\delta V(t)$ (left) and $P(\delta V)$ (right) for the thick film measured at $T = 0.15$ K in $B = 3.12$ T for $I =$ (**a**) 0 and (**b**) 3.0 μA, and at 0.06 K in 3.24 T for $I =$ (**c**) 0, (**d**) 2.0, (**e**) 4.0, -4.0 (red lines), and (**f**) 40.0 μA.

TVL phase are concerned, we cannot detect substantial $\delta V(t)$ originating from the vortex motion within our experimental resolutions.

In the QVL phase, by contrast, the contribution of $\delta V(t)$ from the flux motion is clearly visible. Figures 3d and 3e display $P(\delta V)$, as well as $\delta V(t)$, measured at 0.06 K in 3.24 T (in the QVL phase) in the presence of I =2.0 μA (V_0 =0.2 mV) and $I = 4.0$ μA ($V_0 = 0.5$ mV), respectively. The amplitude of $\delta V(t)$ measured at $V_0 > 0$ is remarkably higher than that at $I = 0$ ($V_0 = 0$) (figures 3a and 3c) and the shape of $P(\delta V)$ is highly asymmetric having a tail which extends to the direction of flux motion [$\delta V(t) > 0$]. As shown in figure 3e, we have confirmed by changing the polarity of I (red lines) that the shape of $P(\delta V)$ is determined by the direction of flux motion. In this particular T, B, and I regime, where $P(\delta V)$ exhibits the unusual asymmetry, large broad-band noise of a Lorentzian type is observed. In the presence of larger I (e.g., 40.0 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, as shown in figure 3f. All 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.

Next, we turn to the results for the thin film. As described in the 'Introduction', our thin a-Mo_xSi_{1-x} films exhibit a field-driven SI transition at certain critical field B_c in the limit $T \to 0$ [17]. The value of B_c for the present film is about 6.3 T. For most of our thin films as well as the one used in this study, $R(T)$ in fixed fields $B(>0)$ below B_c follows the Arrhenius-type temperature dependence down to the lowest measured T ($\sim$0.05 K) [17], as shown in figure 1b. Thus, the cross-over from thermal to quantum liquid is not seen from $R(T)$, which is different from the result for the thick films. Furthermore, in 2D, the VG phase is considered to exist only at $T = 0$ and, hence, only the vortex state in the mixed state at $T > 0$ is the vortex liquid [21]. Accordingly, it is rather difficult to determine experimentally the vortex phase diagram in 2D.

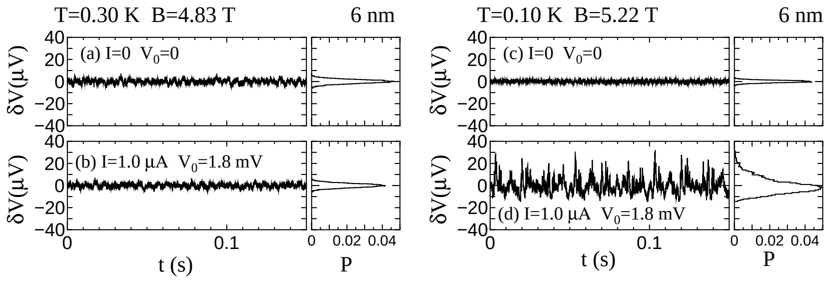

Figure 4. $\delta V(t)$ (left) and $P(\delta V)$ (right) for the thin film measured at $T = 0.30$ K in $B = 4.83$ T for $I =$ (**a**) 0 and (**b**) 1.0 μA, and at 0.10 K in 5.22 T for $I =$ (**c**) 0 and (**d**) 1.0 μA.

In figure 4, we show the data of $\delta V(t)$ and $P(\delta V)$ taken at $T = 0.30$ K in $B = 4.83$ T in the presence of (a) $I = 0$ and (b) 1.0 μA [$V_0 = 1.8$ mV($<V_{\rm n}$)], and at 0.10 K in 5.22 T in the presence of (c) $I = 0$ and (d) 1.0 μA [$V_0 = 1.8$ mV($<V_{\rm n}$)]. At 0.30 K, for all the I studied, both the data of $\delta V(t)$ and $P(\delta V)$ are almost identical to the $I = 0$ background data shown in figures 4a and 4c; the amplitude of $\delta V(t)$ is as small as 4–6 μV and its distribution $P(\delta V)$ is nearly symmetric (see figure 4b). However, as the temperature decreases down to 0.10 K, the contribution of $\delta V(t)$ from the vortex motion becomes noticeable and also, the shape of $P(\delta V)$ becomes highly asymmetric having a tail which extends to the direction of vortex motion [$\delta V(t) > 0$]. In figure 4d, we representatively show the results measured at 0.10 K in 5.22 T in the presence of $I = 1.0$ μA [$V_0 =$1.8 mV($<V_{\rm n}$)]. Thus we find that the anomalous vortex motion appears not only in the QVL phase of the thick film but also in the low-T liquid phase of the thin film.

To quantify the degree of asymmetry A of the probability distribution $P(\delta V)$, we calculate the skewness of the data. The skewness for a normal distribution is zero, while positive values of the skewness indicate that the right (positive) tail is heavier than the left tail. In the low-T liquid phase of both the thick and thin films, the I dependence of A, as well as that of V/I, are similar to each other. With increase in I, $A(I)$ rises even in the low-I linear (ohmic) regime prior to the nonlinear $V(I)$ regime and exhibits a large broad peak; with further increase in I, $A(I)$ shows a decrease and finally tends to zero at high I, where $V(I)/I$ approaches the normal-state value $R_{\rm n}$.

In figure 5, we plot the T dependence of the peak value of the skewness, $A_{\rm p}$, extracted from the $A(I)$ curves for both the thick and thin films. As mentioned earlier, for the thick film these data were measured at different (T, B) points yielding $V_0/V_{\rm n} = 0.45 \pm 0.03$ and $V_0/V_n = 0.86 \pm 0.03$ at $I \to 0$, which are plotted with open circles and triangles, respectively (see also figure 2). For either combination of (B, T), upon cooling, $A_{\rm p}(T)$ exhibits an abrupt rise at around 0.10–0.13 K, which is close to or slightly higher than $T_{\rm Q} \sim 0.1$ K. Upon further cooling, $A_{\rm p}$ increases gradually or stays nearly constant. The amplitude of voltage fluctuation 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. In the case of thin film, we also observe an abrupt rise of $A_{\rm p}(T)$ at $T \sim 0.2$ K (see filled circles in figure 5), which was measured at (B, T) points yielding $V_0/V_{\rm n} = 0.47 \pm 0.02$ at $I \to 0$. This

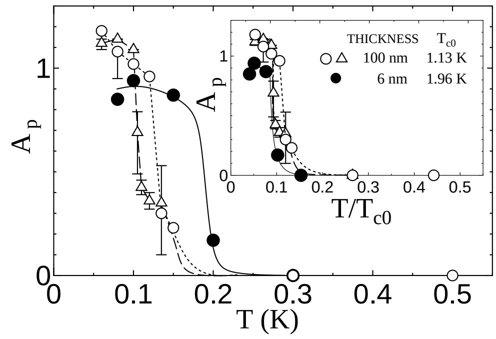

Figure 5. The peak value of the skewness (A_p) of the voltage fluctuation distribution $P(\delta V)$ vs. T: Open circles and triangles represent $A_p(T)$ of the thick film measured for $V_0/V_n \approx 0.45$ and ≈ 0.86, respectively; filled circles denote $A_p(T)$ of the thin film measured for $V_0/V_n \approx 0.47$. Inset: The same data of A_p as shown in the main panel are plotted against the reduced temperature T/T_{c0}, where $T_{c0} = 1.13$ and 1.96 K for the thick and thin films, respectively. All the lines are guides for the eye.

temperature ($\sim$0.2 K) is higher than that ($T \sim 0.10$–0.13 K) for the thin film. However, by plotting A_p against T/T_{c0}, as shown in the inset of figure 5, we notice that all the data for the thin and thick films collapse onto nearly a single curve. This result suggests that the quantum fluctuation effects for both thick and thin films may appear at approximately the same T/T_{c0} ($\sim$0.1). Based on these results, we propose that the vortex dynamics in the low-T liquid phase of thin and thick films is dominated by common physical mechanisms related to quantum fluctuation effects.

From the present data alone, it appears difficult to tell the specific picture of the vortex motion at low T. What we can say at present is that, in the particular B–T regime where A_p takes substantially large values, the vortex motion is not stationary but is accompanied by large velocity and/or number fluctuations. Within the simple picture, these fluctuations may originate from plastic-flow-like vortex dynamics or random (pinning-)depinning processes dominated by temperature in the presence of I [31–38]. Also, as a possible scenario, it has been suggested quite recently [39] that the asymmetric fluctuations observed in our experiment seem to be due to vortex avalanches, which have been shown to occur by computer simulations at extremely low T ($T = 0$) in systems containing pinning centers [40,41]. We note, however, that the proximity of the temperature, below which A_p rises to T_Q, below which quantum fluctuations are dominant, cannot be explained in any existing theory. To explain this remarkable finding, we need a theory which takes into account the quantum fluctuation effects on vortex dynamics.

On the experimental side, in order to demonstrate convincingly the above-mentioned notion that the vortex motion at low temperatures is dominated by common mechanisms related to quantum effects, further studies, for example, using the samples with higher T_{c0} (such as high-T_c cuprates [13], MgB_2, or organic superconductors [12]) are necessary. Since the strength of the quantum fluctuations is determined by T/T_{c0}, for these 'high-T_c' materials the quantum fluctuation effects are expected to appear at much higher temperature than 0.1–0.2 K observed in the present a-Mo_xSi_{1-x} films.

To summarize, we report on the unusual vortex dynamics observed in the low-T liquid phase of amorphous Mo_xSi_{1-x} films based on the measurements of the fluctuating component of the flux-flow voltage $\delta V(t)$. For the thick film, $\delta V(t)$ originating from the vortex motion is clearly visible in the QVL phase, where the distribution of $\delta V(t)$ is anomalously asymmetric, implying large velocity and/or number fluctuations of driven vortices. For the thin film, similar unusual vortex motion is observed in nearly the same reduced-temperature regime. We suggest that vortex dynamics in the low-T liquid phase of thick and thin films is dominated by common physical mechanisms related to quantum fluctuation effects.

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