Vortex States at Low Temperature and Disorder in Thick a-Mo_xSi_{1-x} Films

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Abstract

We measure the dc and ac complex resistivities for two thick a-Mo_xSi_{1-x} films with different disorder (normal-state resistivity ρ_n). For both films, we can precisely determine the vortex-glass-transition line $B_g(T)$, which persists down to low enough temperatures T up to high fields B near $B_{c2}(0)$, where $B_{c2}(0)$ is an upper critical field at $T = 0$. The finite quantum-vortex-liquid (QVL) phase at $T = 0$ is clearly observed in the region $B_g(0) < B < B_{c2}(0)$. The width of the $T = 0$ QVL phase is wider for a more resistive film, indicating that disorder plays an important role in the appearance of QVL through the enhancement of quantum fluctuations. Also, we determine the crossover temperature between the thermal and quantum liquid regime in the $B - T$ phase diagram.

Key words: vortex glass; quantum fluctuations; quantum liquid; disorder

Based on the ac complex resistivity for thick amorphous (a-)Mo_xSi_{1-x} films, we have recently demonstrated the existence of the vortex-glass transition (VGT) [1] down to low temperatures T ~$0.04T_{c0}$ up to high fields B ~$0.9B_{c2}(0)$, where T_{c0} and $B_{c2}(0)$ are the mean-field transition temperature and upper critical field at $T = 0$, respectively [2–4]. We have also found the quantum-vortex-liquid (QVL) phase at $T = 0$ in the region $B_g(0) < B < B_{c2}(0)$. It has been generally believed that an increase in disorder in the system makes the QVL phase [5] more favorable through the enhancement of quantum fluctuations. However, their effects on the VGT [6] have not yet been fully clarified. In this work we determine the QVL regime in the $B - T$ plane and discuss the effects of disorder. The data related to present work has been reported elsewhere [4].

Two 100-nm-thick films of a-Mo_xSi_{1-x} with different x were prepared independently. One is film 1 with T_{c0}=2.4 K and $B_{c2}(0)$= 5.64 T [2] and the other is more resistive film 2 with T_{c0}=1.6 K and $B_{c2}(0)$=4.05 T [4]. The dc and ac resistivities were measured using four-terminal methods. The ac data, the amplitude ρ_{ac} and phase ϕ of the ac resistivity, were measured in a linear regime as a function of T and frequency f employing the precision LCR meter. Details of measurements were published previously [2,7,8]. The field was applied perpendicular to the plane of the film.

Qualitatively, dc and ac resistivities as a function of T and B are independent of films. Most remarkable feature is the frequency dependence of ρ_{ac} and ϕ, which shows the behavior indicating the critical slowing down of the vortex dynamics near the second-order transition. The VGT temperature T_g is clearly determined from the ϕ vs T curves at different f which merge to the same value lower than 90° at T_g [1,2,7,8].

In Fig. 1 we representatively show the Arrhenius plots of the dc resistivity $\rho(T)$ in various B for film 2. We can roughly confirm that $\rho(T)$ follows the power-law functional form predicted by the VG theory in B lower than a certain characteristic field B_0($\approx$ 3.7 T). In B just above B_0, however, the logarithm of $\rho(T)$ decreases with upward curvature below about 0.1 K and the finite T-independent ρ (the so-called "flat

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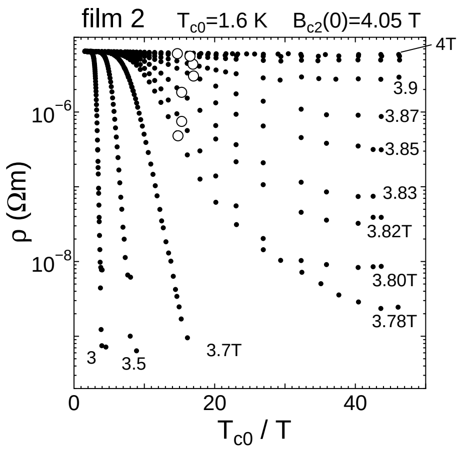

Fig. 1. Arrhenius plots of $\rho(T)$ in different B for film 2.

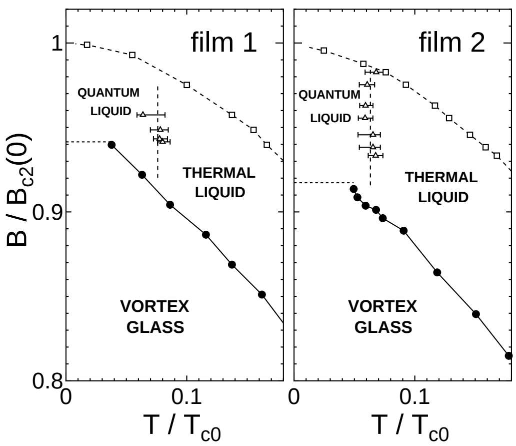

Fig. 2. $B-T$ phase diagrams for film 1 (left) and film 2 (right). The full and dashed lines are guides for the eye.

tail") seems to remain at lowest temperatures [2]. If the flat tail exists at $T \to 0$, B_0 is identified with the critical field of the superconductor-metal transition at $T = 0$. For both films, the upper bound of the VG phase, $B_g(0)$, determined from the ac resistivity coincides with B_0 determined from the dc resistivity. Open circles represent the temperature T^* at which the slope in the Arrhenius plots for $B > B_0$ takes a maximum; curvature is positive below T^*.

In Fig. 2 we present the $B-T$ phase diagrams at low T for films 1 and 2. Here, B and T-axes are normalized by $B_{c2}(0)$ and T_{c0} for each film, respectively. The upper critical field $B_{c2}(T)$ (open squares) is estimated from the resistive transition using a 95% criterion. The full circles represent T_g for different B determined from the phase ϕ of the ac resistivity. A dotted line marks the upper bound of the VG phase, $B_g(0)$. A QVL regime is clearly visible in the region $B_g(0) < B < B_{c2}(0)$. We also plot $T^*(B)$ with the open triangles. The $T^*(B)$ line is interpreted as a crossover line between the high-T thermal and low-T quantum liquid regime.

The phase diagrams for films 1 and 2 are qualitatively similar to each other, while the relative width of the QVL region, as defined by $\Delta B_{QVL} = 1 - B_g(0)/B_{c2}(0)$, is different. The ratio of ΔB_{QVL} for film 2 to that for film 1 is about 1.4. According to the theory [9], the width of the QVL phase at $T = 0$ is determined by the strength of quantum fluctuations, which is proportional to ρ_n. We note that the ratio of the strength of quantum fluctuations (ρ_n) for film 2 to that for film 1 is also about 1.4. This result is consistent with the notion that the origin of QVL is due to quantum fluctuations, which are enhanced with increasing disorder.

In contrast, the (reduced) crossover temperature, $T^*(B)/T_{c0}$, which separates the thermal-liquid regime from the quantum-liquid one, is nearly independent of disorder (ρ_n) or slightly lower for film 2 with higher disorder. This result is different from our expectation that the QVL regime should become large along the direction of T-axis as well as B-axis, with increasing disorder. Part of the reason may be due to different pinning strength between films 1 and 2, since they were prepared independently. Disorder in the films assists the appearance of the quantum liquid state through strong quantum fluctuations, while it can also enhance the vortex-glass state through strong pinning [6]. To clarify this issue, we are now conducting experiments using a series of a-Mo_xSi_{1-x} films with varying x (ρ_n) but fixed film thickness. These films are prepared simultaneously and hence, except for the difference in Mo concentration x, the microscopic or mesoscopic morphology of films responsible for pinning is expected to be similar to each other.

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