Dynamic melting of driven vortices at low temperature in $\alpha$-Mo$_x$Ge$_{1-x}$ films

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Abstract. Using a mode-locking technique, we have detected dynamic ordering of driven vortex matter in amorphous Mo$_x$Ge$_{1-x}$ films at different temperatures $T$ down to 0.8 K, which is well below the superconducting transition ($\approx 6$ K). As the field exceeds a certain critical field $B_{c,dyn}$ at fixed $T$, moving vortices no longer exhibit dynamic ordering. At high $T$, this dynamic-melting field $B_{c,dyn}(T)$ nearly coincides with a characteristic field $B_c(T)$ where the linear resistivity vanishes while at low $T$, $B_{c,dyn}(T)$ is significantly suppressed compared to $B_c(T)$.

1. Introduction

Based on the measurements of dc and ac resistivities for thick amorphous ($\alpha$-)Mo$_x$Si$_{1-x}$ films with moderately strong pinning, we have previously determined the vortex phase diagram including the quantum-vortex-liquid (QVL) phase at low temperature $T$ [1, 2]. The QVL phase originates from quantum-driven melting of vortex solid. Experimentally, this can be seen in superconductors with strong quantum fluctuations, such as amorphous films with large resistivity or layered superconductors, by increasing magnetic field $B$ in the solid phase [3-10].

In general, the pinning strength may significantly affect the equilibrium as well as dynamic vortex properties at low $T$. Thus, to clarify possible effects of pinning, we have recently studied thick $\alpha$-Mo$_x$Ge$_{1-x}$ films, whose superconducting properties and degree of disorder (normal-state resistivity $\rho_n$) are similar to those for the $\alpha$-Mo$_x$Si$_{1-x}$ films while the pinning strength is much weaker. In fact, the peak effect (PE) for the critical (depinning) current $I_c$, which is not observed in $\alpha$-Mo$_x$Si$_{1-x}$ films at any $T$ [11], is clearly visible in the $\alpha$-Mo$_x$Ge$_{1-x}$ films. We find that the QVL phase similar to that in $\alpha$-Mo$_x$Si$_{1-x}$ films is present in $\alpha$-Mo$_x$Ge$_{1-x}$ films [12]. We thus conclude that the existence of the QVL phase at low $T$ is a common characteristic to the highly disordered amorphous films and that the difference in the pinning strength between the two amorphous systems does not significantly affect the static vortex state or the phase diagram.

Then, an interesting question arises as to how the vortex state, in particular, the (quantum) melting transition changes in the limit of small pinning.

In the meantime, we have studied dynamic ordering of driven vortex matter in the same $\alpha$-Mo$_x$Ge$_{1-x}$ film system at relatively high $T$, using a mode-locking (ML) technique [13, 14]. When an object (vortex matter in the present study) moves in a periodic potential in the presence of combined dc and ac forces, step-like structure analogous to Shapiro steps found in Josephson...
junctons appears in the current-voltage ($I-V$) characteristics [15-22]. The steps appear, when the internal frequency of the system locks to the external frequency $f_{\text{ext}}$ of the ac drive. This phenomenon is called the ML resonance. For driven vortices, ML has been observed not only in superconductors with periodic pinning [19, 20] but also in those with random pinning [17, 21, 22], such as amorphous films studied here, where a periodicity can be induced dynamically as a result of the coherent motion [23, 24] of a vortex lattice.

Over the broad fields $B$ in the solid phase including the PE regime, we observe step-like structures indicative of ML in the $I-V$ curves in the presence of superimposed ac drive $I_{rf}$. However, as $B$ exceeds a certain critical field $B_{c,\text{dyn}}$, at fixed $T$, moving vortices no longer exhibit dynamic ordering. This field $B_{c,\text{dyn}}$ is called dynamic melting. At high $T$ ($=2$ and $4$ K), $B_{c,\text{dyn}}$ nearly coincides with a characteristic field $B_c$ where dc resistivity $\rho$ and $I_c$ fall below experimental resolutions. Here, $B_c$ is conventionally regarded as a static “melting” field, which is determined from an ordinary transport measurements in the presence of pinning. At low enough $T$ ($=0.8$ K), we also observe ML steps. However, $B_{c,\text{dyn}}(T)$ is clearly smaller than $B_c(T)$. We suggest that at $0.8$ K, quantum effects may play a crucial role in the vortex dynamics and/or the intrinsic melting field ($B_{c,\text{dyn}}$) in the absence of pinning is reduced compared to the static “melting” field $B_c$ in the presence of pinning.

2. Experimental

We prepared the two 330 nm-thick $\alpha$-Mo$_x$Ge$_{1-x}$ films with nearly the same superconducting properties by rf sputtering [13]. The one film was directly immersed into liquid $^3$He and measured above $1$ K and the other film was attached to the cold plate of our $^3$He-$^4$He dilution refrigerator and measured below $1$ K. The mean-field transition temperatures $T_{c0}$ defined by a 95 % criterion [1], i.e., the linear resistivity $\rho$ decreases to 95 % of $\rho_n$, are $5.9$ and $6.1$ K and the zero-resistivity temperatures $T_c$ are $5.8$ and $6.0$ K for the two films, respectively. $\rho$ and $I-V$ characteristics were measured using a four-terminal method. In measuring the ML resonance, the ac (rf) current $I_{rf}$ with frequency $f_{\text{ext}}$ of $10$ MHz was applied through an rf transformer. The field $B$ was applied perpendicular to the plane of the film.

3. Results and discussion

We measure $I-V$ characteristics at $T=4.0$ and $0.80$ K in different $B$. The critical current $I_c$ is defined as a threshold current at which the vortices start to move. We extract $I_c$ from the $I-V$ curves using a $10^{-7}$ V criterion [14, 25]. As plotted in figures 1(a) and (b), respectively, at $4$ and $0.8$ K, $I_c(B)$ takes a peak at around $3.5$ and $9.6$ T ($=B_p(T)$) before $I_c(B)$ vanishes at $B_c(T) = 4.1$ and $11.5$ T. Quite recently, we have found from the measurements of flux-flow noise that the peak field $B_p(T)$ marks the order-disorder transition from the weakly disordered vortex lattice to the highly disordered amorphouslike phase [25].

In figures 2(a)-(c)(left) we display the $I(V)$ curves measured at $4$ K in $4.3$, $4.1$, and $3.3$ T, respectively, with superimposed ($10$ MHz) rf currents of different amplitudes ($I_{rf} = 0.04-0.66$ mA). The data taken in the absence of $I_{rf}$ are indicated with black dots and lines. In $3.3$ and $4.1$ T, for $I_{rf} > 0$ the step-like behavior indicative of the ML resonance is observed up to the third or fourth steps while for $I_{rf} = 0$ such steps are not visible. The location as well as the existence of the steps can be more clearly seen by plotting the differential conductance $dI/dV$ against $V$, as shown in the right panels of figures 2(b) and (c). Assuming a triangular vortex array moving in the direction parallel to one side of the triangle(s), we can calculate a value of the fundamental voltage step for given $B$, whose location is indicated with the lowest horizontal dashed line in each figure. Also shown with horizontal dashed lines is the location of the higher-order ML steps. In $3.3$ T, the experimental data well coincides with the calculation. Thus, the step-like structures in the $I(V)$ curves indeed correspond to ML of driven vortex lattice.
due to the vortex motion may not be completely ignored at high
been observed at higher
close to
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The ML steps persist up to 4.1 T(= Bc), although the discrepancy between the data and calculation is remarkable at higher ML steps. In 4.3 T, which corresponds to the equilibrium liquid phase, ML is no longer visible, as shown in figure 2(a). This means that at 4 K, the dynamic melting occurs at a field very close to or slightly higher than Bc (=4.1 T). We have also performed similar measurements at 2 K. Preliminary data show that Bc,dyn is again close to Bc. These results are consistent with the recently reported data at relatively high T near Tc [13].

At low temperature T = 0.8 K, which corresponds to T/Td0 =0.13, we again observe the ML steps in 7.0 and 9.0 T, as shown in figures 2(f) and (e), respectively, where we use Irf ranging from 0.07 to 0.27 mA. The ML signals look somewhat degraded compared to those at 4 K, whose origin has not been specified yet. As the field increases up to 10.0 T, all evidence for ML steps; n =1, 2, 3,... from the bottom. Other lines are guides for the eye.

Now, we consider the possible heating effects within the sample. At 0.8 K local heating effects due to the vortex motion may not be completely ignored at high V(I), e.g., when V(I) exceeds the second ML step. We have confirmed from the T-dependent resistivity with different I in 13 T (i.e., in the normal state) that heating effects are negligible at least up to around the first ML
Let us discuss the possible interpretation of data at 0.8 K. In the particular field region $B_{c,dyn} < B < B_c$, which corresponds to the equilibrium vortex solid phase, the driven vortex matter does not form a mode-locked moving lattice but dynamically melts into a moving liquid. This phenomenon occurs only at very low $T(\approx 0.13T_c)$. In addition, the $T$ dependence of $B_{c,dyn}$ is much weaker than $B_c(T)$ in this low-$T$ region, which is inferred from the significant suppression of $B_{c,dyn}$ compared to $B_c$ at 0.8 K. We propose from these results that quantum effects may play an important role in the vortex dynamics at 0.8 K, preventing the driven vortex solid from being dynamically ordered.

Alternatively, we may interpret the present results as follows: $B_{c,dyn}(T)$ reflects the intrinsic melting in the absence of pinning. At low $T$, this true melting field is significantly suppressed compared to the static “melting” field $B_c(T)$ in the presence of pinning. Within this interpretation, the true quantum melting in the limit $T \to 0$ occurs at a field close to the order-disorder transition $B_p(0)$, instead of $B_c(0)$.

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