Lattice orientation of driven vortex matter in amorphous superconducting films

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Abstract. We present measurements of the mode-locking resonance in the high-field region prior to the dynamic melting field, where driven vortex lattices melt into a moving liquid, in an amorphous MoₓGe₁₋ₓ film. Under increasing field, a switching of the lattice orientation from a perpendicular to parallel orientation is observed at the characteristic field $B_{ori}$. We find a trend for the perpendicular orientation to change to the parallel orientation with increasing the lattice velocity in fields just prior to $B_{ori}$, while $B_{ori}$ is not sensitive to the velocity within the range studied. We suggest that the dynamic pinning force moving vortices feel is important for the lattice orientation and is significantly reduced around $B_{ori}$ as a precursor of dynamic melting.

1. Introduction

Vortices in type-II superconductors form a triangular lattice by vortex-vortex interactions and its dynamics is readily controlled by a Lorentz force due to an applied current. For isotropic superconductors with random point pinning, such as amorphous films studied here, the lattice orientation with respect to the flow direction is either parallel or perpendicular, while it is not trivial which orientation the driven vortex lattice favors. A theory showed that at large velocities the motion of vortices driven over the random pinning potential is parallel to their nearest-neighbor direction (i.e., parallel orientation) [1], as schematically illustrated in the top inset of Fig. 1(b). However, recent mode-locking (ML) experiments on amorphous films conducted both at high and low temperatures $T$ have shown evidence for the perpendicular orientation [bottom inset of Fig. 1(b)] over the broad fields $B$ [2, 3]. As the field approaches the dynamic melting field $B_{c,dyn}$, where driven lattices melt into a moving liquid, the moving lattice rotates from the perpendicular to parallel orientation at a $T$-dependent characteristic field $B_{ori}$. The results suggest that the lattice orientation is closely related to lattice softening due to thermal or quantum fluctuations, while its mechanism has not been fully understood [3].

In general, the lattice orientation would be dependent on the velocity of driven vortices; namely, dc and ac components of the velocity at ML, which can be controlled by changing the frequency and amplitude of the ac drive, respectively. Previous work has focused on the data measured at moderate velocities, while in this work we present detailed measurements of the ML resonance around $B_{ori}$ including the data measured at larger velocities. We find a trend for the perpendicular lattice orientation to change to the parallel orientation with increasing the dc and/or ac velocities in fields just prior to $B_{ori}$. The result is consistent with the recent simulation.
that the lattice orientation is parallel in the absence of pinning but perpendicular in the presence of pinning [4]. We also find that $B_{\text{ori}}$ extracted from the main signal of the ML resonance is not sensitive to the dc velocity within the range studied, indicating that the dynamic pinning force is significantly reduced around $B_{\text{ori}}$ prior to dynamic melting. The detailed data and discussion concerning present work have been published elsewhere [3].

2. Experimental
The amorphous $\text{Mo}_x\text{Ge}_{1-x}$ film with thickness of 330 nm was fabricated by rf sputtering onto a silicon substrate mounted on a water cooled rotating copper stage [5]. The mean-field transition temperatures $T_c$ defined by a 95 % criterion of the normal-state resistivity and the zero-resistivity temperatures $T_c$ are 6.1 and 6.0 K, respectively. In measuring the ML resonance, the ac current $I_{\text{rf}}$ with frequency $f_{\text{ext}}$ of 10 and 70 MHz was applied through an rf transformer superimposed with the dc current $I$ [6, 7]. By increasing the frequency $f_{\text{ext}}$ and amplitude of $I_{\text{rf}}$, we are able to increase the dc and ac components of the velocity of driven vortex matter at ML, respectively. The film was attached to the cold plate of our $^3\text{He}-^4\text{He}$ dilution refrigerator. The field was applied perpendicular to the plane of the film.

3. Results and discussion
From the $I-V$ characteristics, we define the depinning current $I_c$ as a threshold current at which the vortices start to move, where a $10^{-7}$ V criterion is used [7, 8]. The peak in the $I_c(B)$ curve indicative of the peak effect [9, 10, 11] is visible over the whole temperature region ($T = 0.08-5.0$ K) studied. The representative data at 1 K is shown in Fig. 1(a). In our previous work it has been shown [8] that the peak field $B_p$ in $I_c(B)$ marks an order-disorder transition [12, 13, 14] from the ordered vortex lattice (OP) ($B < B_p$) to amorphous-like disordered phase (DP) ($B_p < B < B_c$). $B_c$ at which $I_c$ falls to zero reflects a static “melting” field. We have revealed recently that the dynamic melting field $B_{c,\text{dyn}}$ is close to the static melting field $B_c$ at high temperature ($T > 2$ K), but it is significantly suppressed from $B_c$ at low $T$ (<2 K) due to strong quantum fluctuation effects [6].

![Figure 1](image-url)
The peaks in $dI/dV$ vs $V$ curves, namely, ML steps are visible over the broad fields from the lowest field measured, 1.5 T, up to 9.3 T. In Figs. 2(a)-2(c) we show $dI/dV$ vs $V$ taken for 7.0, 7.5, and 8.3 T, respectively, at 1.0 K with superimposed 10-MHz $I_{rf}$ of different amplitudes, which are shown in each figure. Here, the amplitude of $I_{rf}$ covers the region where the width of the ML current step in the $I - V$ curves or the amplitude of the ML peak in the $dI/dV$ vs $V$ curves as a function of $I_{rf}$ takes a first peak, around which the ML resonance is most clearly observed. Assuming a triangular vortex array moving in the direction perpendicular to one side of the triangles, as schematically shown in the bottom inset of Fig. 1(b), one can calculate a value of the voltage for a given $B$ satisfying the subharmonic resonant condition of $p/q = 1/2$; i.e., $V_{1/2}^{\text{para}} = l(p/q) f_{\text{ext}} 2a_\perp B = l f_{\text{ext}} (\sqrt{3}\Phi_0 B/2)^{1/2}$, where $l$ is the distance between the voltage contacts, $2a_\perp$ is the lattice period in the direction of vortex motion, and $\Phi_0$ is the flux quantum [15]. For 7.0 T the first ML peak voltage $V_{\text{peak}}$ marked with an arrow well coincides with the calculation for $V_{1/2}^{\text{para}}$ indicated with a vertical solid line. The inset shows the insensitiveness of $V_{\text{peak}}$ to $I_{rf}$ in the $I_{rf}$ range studied, where a horizontal solid line indicates the location of $V_{1/2}^{\text{para}}$. Qualitatively the same behavior is observed in other fields down to 1.5 T [3].

As $B$ increases slightly from 7.0 to 7.5 T, however, the ML peak becomes broad and $I_{rf}$ dependent, as seen in Fig. 2(b). With increasing $I_{rf}$, the ML peak voltage $V_{\text{peak}}$ increases from a value around $V_{1/2}^{\text{para}}$ indicated with a vertical solid line to a value approximately 15% larger than $V_{1/2}^{\text{para}}$ indicated with a vertical dashed line. The dependence of $V_{\text{peak}}$ on $I_{rf}$ is more clearly seen in the inset, where $V_{\text{peak}}$ exhibits a jump from $\approx V_{1/2}^{\text{para}}$ (a horizontal solid line) to $\approx 1.15 V_{1/2}^{\text{para}}$ (a horizontal dashed line). As the field increases further ($B = 8.9$ T), $V_{\text{peak}}$ takes a value close to $1.15 V_{1/2}^{\text{para}}$ for most of $I_{rf}$ measured, as illustrated in the main panel and inset of Fig. 2(c). This resonant voltage, as indicated with dashed lines, is consistent with the condition for the parallel lattice orientation [see the top inset of Fig. 1(b)], which is given by $V_{1/1}^{\text{para}} = (2/\sqrt{3}) V_{1/2}^{\text{para}}$. On
approaching $B_p(=9.34 \, T)$, $V_{\text{peak}}$ drops abruptly below $V_{\text{perp}}^{1/2}$ and at 9.4 T all evidence for ML disappears, indicative of dynamic quantum melting of the driven lattice [6].

Thus, the ML data in the low-field region ($B = 1.5 - 7 \, T$) are explained by a triangular vortex array moving with the perpendicular orientation, whereas those in higher fields ($B = 8 - 9 \, T$) indicate the parallel orientation. In the crossover region ($B_{\text{ori}} = 7-8 \, T$) around which the switching of the lattice orientation occurs, the triangular arrays with either orientation may exist depending on the amplitude of $I_f$.

When the frequency of $I_f$ is increased from $f_{\text{ext}} = 10$ to 70 MHz, which leads to the increase in the dc component of the lattice velocity at ML by seven times, the $dI/dV$ vs $V$ curves exhibit peculiar double peaks at around $V_{\text{perp}}^{1/2}$ and $V_{\text{para}}^{1/2}$. Since the dc voltage $V$ is proportional to the dc velocity, this result may imply the dc-velocity-induced rotation of the vortex lattice from the perpendicular to parallel orientation. Such a behavior could not be observed for 10 MHz. This is probably because the separation between the dc velocities at $V_{\text{perp}}^{1/2}$ and $V_{\text{para}}^{1/2}$ for 10 MHz is much smaller compared to that for 70 MHz.

In order to see how the lattice orientation changes with $B$, in Fig. 1(b) we plot the $B$ dependencies of $V_{\text{peak}}/f_{\text{ext}}$ at 1 K for $f_{\text{ext}} = 10$ and 70 MHz with circles and triangles, respectively. In the particular field region where the two peaks with different amplitudes are observed in the $dI/dV$ vs $V$ curves, we plot the positions of the main and secondary peaks with solid and open symbols, respectively. Over the broad fields the data points for 10 MHz fall onto a solid curve $V_{\text{perp}}^{1/2}(B)/f_{\text{ext}}$ corresponding to the perpendicular lattice orientation, while for high $B$, $V_{\text{peak}}(B)/f_{\text{ext}}$ satisfies with the parallel resonant condition given by $V_{\text{para}}^{1/2}(B)/f_{\text{ext}} = (2/\sqrt{3})V_{\text{perp}}^{1/2}(B)/f_{\text{ext}}$, as indicated with a dashed curve. Although we do not have enough data for $f_{\text{ext}} = 70 \, MHz$ at present, the location of $B_{\text{ori}}$ extracted from the main signal of the ML resonance nearly coincides with that for 10 MHz.

It has been shown numerically using the time-dependent Ginzburg-Landau theory that in thin superconductors with random point pinning, as studied in this work, the lattice orientation of driven vortex matter is parallel in the absence of pinning but perpendicular in the presence of pinning [4]. This is consistent with the velocity-induced rotation of the lattice orientation observed in this work. We may also interpret the insensitiveness of $B_{\text{ori}}$ to the dc velocity in the range studied as well as the appearance of the parallel orientation in fields exceeding $B_{\text{ori}}$ in terms of significantly decreased dynamic pinning forces prior to dynamic melting.

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