Dynamic ordering and lattice orientation of driven vortex matter

S Okuma¹, D Shimamoto¹ and N Kokubo²

¹ Department of Physics and Research Center for Low Temperature Physics, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152-8551, Japan
² Center for Research and Advancement in Higher Education, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
E-mail: sokuma@o.cc.titech.ac.jp

Abstract.

We report on the dynamic ordering and lattice orientation of fast driven vortex matter for an amorphous MoₓGe₁₋ₓ film based on the measurements of the mode-locking resonance. With increasing the velocity, a rotation of the lattice orientation from a perpendicular to parallel orientation takes place, indicative of a dynamic transition. In the middle of the transition region the lattice orientation is neither parallel nor perpendicular, where a characteristic time for the vortex to travel one lattice spacing is \( \tau_{th} \approx 9 \) ns, which is close to the value obtained at smaller dc velocity. We suggest that \( \tau_{th} \) reflects a quasiparticle recombination time.

1. Introduction

In last several decades much attention has been devoted to the motion of the Abrikosov lattice driven by an applied current [1-5]. In a uniform vortex system composed of triangular arrays the lattice orientation with respect to the flow direction is either parallel or perpendicular to one side of the triangles, while it is not trivial which orientation the driven vortex lattice favors. The motion of vortex lattice in the presence of weak pinning is predicted to be parallel to its closed-packed direction (i.e., a parallel orientation) [2]. This simply is a consequence of the fact that to minimize energy dissipation, the moving vortex is preferably attracted to the site where the preceding nearest-neighbor vortex was present. To realize this situation, however, the velocity of the moving lattice must be large enough that the following vortex is attracted to the site before the superconductivity at the site is recovered. This recovery time could be related to a quasiparticle recombination time \( \tau_{qp} \) [6-8].

In recent years we have performed a mode-locking (ML) experiment [1, 9-12] for amorphous films [13, 14] at moderate velocities, which enables us to detect dynamic ordering of driven vortex matter. From the resonant voltage, we can immediately know the period of the lattice along the flow direction. We have obtained firm evidence for a perpendicular orientation over a broad field\((B)\) range, while the parallel orientation is visible in a high-filed region prior to the melting field, where the dynamic pinning force is weak [14]. These results are consistent with the simulation that dynamic pinning effects could induce the perpendicular orientation [3, 5]. Thus, if the velocity is increased in the perpendicular orientation, switching of the lattice orientation dominated by \( \tau_{qp} \) would be visible. We have indeed observed the velocity-induced rotation of lattice orientation from the perpendicular to parallel orientation, indicative of a dynamic
transition [15]. Notably, at the threshold of the rotation, a characteristic time \( \tau (\equiv \tau_{th}) \) for the vortex to travel one lattice spacing \( a_0 \) turns out to be nearly independent of \( a_0 \), suggesting that \( \tau_{th} \) is a key quantity yielding the parallel orientation.

Here, we present the detailed measurements of the ML resonance taken at the maximum frequency \( f_{ext} = 70 \text{ MHz} \) of ac current \( I_{rf} \) available in our experiment. Since \( f_{ext} \) is proportional to the dc velocity \( v_{dc} \) of driven vortex lattice at ML, we can discuss here the results (e.g., \( \tau_{th} \)) at the maximum \( v_{dc} \), which are compared with those at 50 MHz obtained recently [15]. Peculiar double resonance peaks in the \( dI/dV \) vs \( I \) curves are observed in an intermediate \( I_{rf} \) region, indicative of the \( v_{dc} \)-induced switching of the lattice orientation, where \( I \) and \( V \) are dc current and voltage, respectively. Such a double-peak structure makes it difficult to determine \( \tau_{th} \) precisely, which is in contrast to the case of 50 MHz, where there is only a single resonance peak and hence \( \tau_{th} \) is simply determined from the \( I_{rf} \) evolution of the peak position. In this work we attempt to estimate \( \tau_{th} \) at 70 MHz by measuring ML at small intervals of \( I_{rf} \).

2. Experimental

We prepared a 330-nm-thick amorphous \((a-x)\text{Mo}_x\text{Ge}_{1-x}\) film by rf sputtering onto a silicon substrate mounted on a water cooled rotating copper stage [14]. The transition temperature \( T_c \) at which the resistivity falls to zero is 6.0 K. The resistivity and \( I-V \) characteristics were measured using a standard four-terminal method. For the \( I-V \) measurements the current was swept in the upward direction and for the ML measurements the ac current \( I_{rf} \) with a frequency of \( f_{ext} = 70 \text{ MHz} \) was superimposed with the dc current. At the ML resonance the velocity of the driven lattice is composed of dc (\( v_{dc} \)) and ac (\( v_{ac} \)) components and the magnitude of \( v_{dc} \) and \( v_{ac} \) can be controlled independently by changing \( f_{ext} \) and \( I_{rf} \), respectively. The film was attached to the cold plate of our dilution refrigerator and the field was applied perpendicular to the plane of the film.

3. Results and discussion

All the data presented in this paper were taken at 2.2 K and 7.0 T. In Fig. 1(a) we plot the differential conductance \( dI/dV \) vs \( V \) measured with superimposed 70-MHz \( I_{rf} \) of different amplitudes, which are shown in the figure. The small peak structure is visible in each \( dI/dV \) vs \( V \) curve, as indicated with arrow(s). These peaks correspond to the ML resonance, indicative of the \( dI/dV \) vs \( V \) curve exhibits double peaks, the main and secondary peaks are indicated with circles and triangles, respectively, and a solid curve is drawn taking account of relative height of the two peaks.

The data for 70 MHz presented here as well as that for 50 MHz (not shown here) [15] implies that triangular arrays with either orientation may exist depending on the amplitude of \( I_{rf} \). Since \( I_{rf} \) is nearly proportional to the ac component of the velocity, this result is attributed to
Figure 1. (Color online) (a) $dI/dV$ vs $V$ in 7.0 T at 2.2 K measured with superimposed 70-MHz $I_{rf}$ with amplitudes shown in the figure. Arrows mark the peak position. Vertical solid and dashed lines indicate the location of the ML peak expected for the perpendicular and parallel orientations, respectively. Curves are vertically shifted for clarity. The insets of (a) show schematic diagrams of vortex lattices moving with the perpendicular (left) and parallel (right) orientations, where the flow directions are indicated with arrows. (b) $V_{peak}$ vs $I_{rf}$ extracted from the plots in (a). The circles and triangles denote the main and secondary $V_{peak}$, respectively. Horizontal solid and dashed lines indicate $V_{peak}$ expected for the perpendicular and parallel orientations, respectively. In the transition region ($I_{rf}$ =1.2-1.6 mA) a curve is drawn taking account of the relative height of the two ML peaks. (c) $x_{th}$ per cycle measured for $f_{ext}$ =70 MHz in 7.0 T at 2.2 K. Horizontal and vertical lines mark $a_0$ and $\tau_{th}$, respectively.

increased $|v_{ac}|$ superimposed with $v_{dc}$. As mentioned earlier, for 50 MHz the threshold value $I_{rf}(=I_{rf,th})$ of the lattice rotation from the perpendicular to parallel orientation was clearly determined from the $V_{peak}$ vs $I_{rf}$ plot [15], while for 70 MHz the double-peak structure made it difficult to determine $I_{rf,th}$ from the same analysis. To overcome it, in this work we measure the ML resonance at 70 MHz with smaller $I_{rf}$ intervals, as shown in Fig. 1(a), and as a result we are able to determine $I_{rf,th}$ (≈1.5 mA) as a point at which the two peaks merge into a single peak $V_{peak} \approx (V_{perp}^{1/2} + V_{para}^{1/2})/2$. At this point, the lattice orientation is found to be neither parallel nor perpendicular.

Knowing the value of $I_{rf,th}$, we obtain the threshold value of $v_{ac}(=v_{ac,th})$ and thus the total velocity $v_{th}(t) = v_{dc} + v_{ac,th}\sin(2\pi f_{ext}t)$. By integrating $v_{th}(t)$ with respect to time $t$, we can calculate straightforwardly the time evolution of the vortex position $x_{th}(t)$ at the threshold. In Fig. 1(c), $x_{th}(t)$ per cycle (0 $\leq t \leq$ 14 ns) is shown with a solid curve. A horizontal line marks the location of the lattice spacing $a_0(B) = 18.5$ nm for $B = 7.0$ T. The vortex lattice travels a distance of $a_0$ in almost the former half cycle (0 $\leq t \leq$ 8.7 ns). At the threshold of the lattice
rotation, the characteristic time $\tau$ for the vortex to travel a lattice spacing $a_0$, $\tau(=\tau_{th})$, turns out to be $\tau_{th} \approx 8.7$ ns, as indicated with a vertical line.

Let us discuss the physical meaning of $\tau_{th}$. As outlined in the introduction, the moving vortex is preferably attracted to the site where the preceding nearest-neighbor vortex was present. When the vortex velocity is small and $\tau$ is much larger than the quasiparticle life time $\tau_{qp}$, the following vortex does not remember the presence of the preceding one and the direction-dependent attractive interaction between the vortices [4] becomes ineffective. Thus, $\tau_{qp}$ is not much smaller than $\tau_{th}$. On the other hand, when the vortices move so fast that $\tau$ is close to or smaller than $\tau_{qp}$, the flow channel would be unstable, accompanied by the voltage jump in the $I - V$ characteristics [6, 16]. Therefore, $\tau_{qp}$ is smaller than $\tau_{th}$. Based on the argument, we estimate the value of $\tau_{qp}$ to be $\approx 0.1 \times \tau_{th}$, which yields $\tau_{qp} \approx 0.9$ ns. This value is in agreement with $\tau_{qp} \approx 0.9$ ns obtained for 50 MHz [15]. From the earlier tunneling experiment for low $T_c$ superconductors [7] and recent $I - V$ measurements clarifying the vortex instability for similar $a$-Mo$_x$Ge$_{1-x}$ films [16], the values of $\tau_{qp} = 0.1 - 1$ ns have been reported at temperature comparable to that studied in our experiment. All these results including the present data for 70 MHz are in favor of the view that $\tau_{th}$ obtained from the ML experiment reflects $\tau_{qp}$ [15]. Our results also show that $\tau_{qp}$ could play a crucial role in the vortex dynamics (i.e., lattice orientation) on a macroscopic scale and dominate the dynamic transition.

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