Orientation of a Moving Vortex Lattice in an Amorphous Mo$_{1-x}$Ge$_x$ Superconducting Film

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Abstract. The orientation of a vortex lattice in the flux-flow state of an amorphous Mo$_{1-x}$Ge$_x$ superconducting film is studied by mode-lock experiments. The formation of a hexagonal moving lattice is observed for a wide range of vortex velocity up to ~20 m/s, which is about 1/10 of the critical velocity (~ 200 m/s) at which the flux-flow instability occurs. The orientation of the hexagonal lattice is observed to be either parallel or perpendicular to the flow direction, and a reorientation occurs at a characteristic velocity (~ 1 m/s), separating the perpendicular orientation for low velocity from the parallel orientation for high velocity.

1. Introduction

The lattice formation of field induced vortices in the mixed state of type II superconductors is one of the most studied issues in superconductors. In addition to a triangular lattice, a variety of lattice structures including square and (oblique) rectangles have been observed in many of (anisotropic) crystalline superconductors.[1, 2, 3] Despite of these studies, there is still fundamental question as to what kind of the vortex structure appears when the vortices are driven by a transport current. Theoretical studies have proposed unique lattice structures of the moving vortices [4, 5]: As vortex velocity increases the moving hexagonal lattice exhibits a reorientation with respect to the flow direction in the flux-flow state. Further increasing vortex velocity, the moving hexagonal lattice changes structurally into moving chains (rows) near the critical velocity for the flux-flow instability. These are, however, not experimentally tested so far due to the lack of experimental techniques to detect the moving vortex structure for high velocity.

When the vortices form a lattice in the moving state, the moving lattice accompanies periodic velocity modulation characterized by a washboard frequency $f_{int}(=v/a)$, where $v$ is the average vortex velocity and $a$ is the vortex spacing along the flow direction. This motion can be synchronously detected when an ac current $I_{ac}$ with a frequency $f$ is applied on top to the transport (dc) current. When $f_{int}$ and $f$ are harmonically related, the dynamic resonance occurs as multiple current steps in current-voltage ($I-V$) characteristics. This is called mode-lock (ML) resonance which has been studied mostly in charge-density waves so far [6]. The advantage of this technique to apply in driven vortices in superconductors is that one can find...
not only the vortex spacing $a$ in the moving vortex structure [7, 8] but also the orientation of the moving lattice with respect to the flow direction.[9, 10] Employing an improved ML technique for detecting the resonance at high frequencies up to 1 GHz, in this study we report the moving structure of driven vortices observed in an amorphous MoGe film.

2. Experimental
The ML resonance technique is based on the dynamic resonance for a moving lattice driven by the combined ac and dc transport current. We made a simple high frequency ML setup consisting of a rf generator (Agilent Technology 4420B), a dc current source (Keithley Instruments Inc. 220), a dc voltmeter (Agilent Technology 34420A) and a home-made coaxial inset for a cryostat with a 15 T superconducting magnet (Oxford Instruments). $I_{ac}$ from the generator is superimposed on top of the dc current $I$ from the dc current source by a bias-Tee (Mini-circuit). The sample space is filled with liquid $^4$He in order to minimize heating in the sample(s).

The amorphous MoGe film was sputtered on a silicon substrate on a water cooled, rotating copper stage. The thickness of the film is 0.26 $\mu$m. We patterned the film into narrow bridges with different width of 200 $\mu$m and 100 $\mu$m by lift-off technique. Both bridges have 1.55 mm length $l$ between voltage contacts. The superconducting transition temperature $T_c$ is 7.0 K. The slope $S$ of the second magnetic field $H_{c2}$ against temperature $T$ near $T_c$ is 2.6 T/K, the normal state resistivity $\rho_n$ is 1.51 $\mu\Omega m$.

3. Results and Discussions
Because of a weak pinning property of the amorphous film, the flux-flow behavior characterized by a linear $I-V$ curve appears for a wide range of vortex velocity. The application of $I_{ac}$ changes the $I-V$ curve in shape. Shown in Fig. (a) is a series of $I-V$ curves taken by superimposing 100 MHz $I_{ac}$ with different amplitudes in $\mu_0 H = 7.3$ T. A step like feature indicative of the ML resonance is visible at $\approx 16$mV, although it is smeared. The ML resonance voltage condition is given as

$$V_{p/q} = \frac{p}{q} f l B a$$

(1)

where $p$ and $q$ are integers. Assuming a regular hexagonal lattice, we find that the observed step is the fundamental resonance ($p = q = 1$) with the periodic spacing equal to the vortex lattice spacing, i.e., $a = a_\Delta = \sqrt{(2/\sqrt{3})\Phi_0/B}$. This implies the parallel orientation of the moving lattice where one of closed packed directions of the moving lattice is aligned with the flow direction as illustrated in Fig. (b).

Eq. (1) implies that the ML resonance voltage should be proportional to frequency (or vortex velocity $v = f a$). In order to test this, we measure the ML resonance in different frequencies. The results are summarized in Fig. (d). For a wide range of frequency (2 MHz $\leq f \leq 1$ GHz) we observe the linear dependence of the resonance voltage on frequency. The slope of the relation satisfies the condition of $a = a_\Delta$ observed above. Thus, we conclude that for all the frequencies, the moving vortices form the hexagonal lattice with the parallel orientation.

A different behavior is observed at a low magnetic field ($\mu_0 H = 4.1$ T). As shown in Fig. (e) the slope $V/f B$ for higher frequencies is larger than that for lower frequencies and there is a crossover around 50 MHz. The solid and dotted lines correspond to the vortex lattice spacing $a_\Delta$ and the vortex row spacing $a_\perp = a_\Delta (\sqrt{3}/2)$, respectively, estimated from the magnitude of the applied magnetic field. Comparisons show that on increasing frequency the periodic spacing $a$ changes from $a_\perp$ to $a_\Delta$ at $\approx 50$ MHz. The coincidence of $a = a_\perp$ implies the perpendicular orientation of the moving lattice as depicted in Fig. (c). Thus, the crossover marks a reorientation of the moving lattice from the perpendicular orientation for the low frequencies to the parallel orientation for the high frequencies.
Figure 1. (a) Mode-lock resonance feature at 3.5 K and 7.3 T observed in the 100 μm bridge. $I-V$ curves taken with superimposed 100 MHz ac currents with different amplitudes are plotted. Representations of vortex lattices with parallel and perpendicular orientations with respect to the flow direction are shown in (b) and (c), respectively. The lattice parameters of the lattice spacing $a_\triangle$ and the row spacing $a_\perp$ are indicated. (d) Plot of the ML resonance voltage vs. frequency taken at 3.5 K and 7.3 T. (e) Plot of $V/fB$ vs. $f$ measured at 4.1 T and 4.0 K observed in the 200 μm bridge. Solid and dotted lines represent the lattice spacing $a_\triangle$ and the row spacing $a_\perp$ of a hexagonal vortex lattice, respectively.

A structural transition from the moving hexagonal lattice to the moving chains has been predicted near the critical velocity for the flux-flow instability.[5] This phenomenon should accompany anomaly in the resonance voltage, however, it does not appear in our results. A possible reason is that the vortex velocity is not high enough to observe the structural transition in the moving vortices. A rough estimate for the critical velocity $v_c$ for our amorphous MoGe film gives $v_c \sim 200$ m/s,[11] which is 10 times higher than the maximum velocity $v_{max}(= f_{max} a_0)$ we reached ($v_{max} \sim 20$ m/s). Thus, to detect we need further to improve the ML resonance technique for even higher frequencies.

4. Conclusions
We have investigated the structure of driven vortices in the amorphous MoGe film by using the high frequency ML experimental setup ($f \leq 1$ GHz). We find that the moving vortices form the hexagonal lattice for the wide range of frequency (velocity), and they exhibit the reorientation from the perpendicular to the parallel orientations as frequency (velocity) increases.
The maximum velocity measured in the present experimental setup is \( \sim 20 \text{ m/s} \), which is \( \sim 1/10 \) of the critical velocity for the flux flow instability.

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