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Lattice orientations of driven vortex matter in amorphous MoGe films

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ABSTRACT

We have investigated the lattice orientation of driven vortex matter in amorphous MoGe films. Mode locking experiments in the flux flow state reveal that in addition to the theoretically predicted lattice orientation parallel to the flow direction also the perpendicular orientation occurs. Mapping out the orientations in a phase diagram, the perpendicular orientation is found to dominate the phase diagram covering a wide field and temperature range. Scanning tunneling microscopy images of the vortex lattice frozen from the flux flow state confirm the switching between parallel and perpendicular orientations in the phase diagram. The effect is possibly caused by the influence of the sample edge.

1. Introduction

Driven vortex matter in type II superconductors is known as an example and ideal experimental system for investigating non-equilibrium collective transport properties of periodic media driven over pinning environments. Tuning the interaction between vortices by magnetic field, one can investigate various dynamic states with different temporal, positional and orientational order, ranging from a pinning dominated, disordered (plastic) flow state characterized by many degrees of freedom in motion, to an interaction dominated, flow state where vortices flow together and they may be crystallized into a moving lattice [1–5]. The motion of a driven vortex lattice (VL) has limited degrees of freedom, including the lattice rotation with respect to the flow direction. This issue was first discussed in an elastic theory by Schmid and Hauger: From their argument of the minimum power dissipation of a VL driven over the pinning environment, they suggested that at large velocities the orientation of the driven VL is aligned to the flow direction [6]. More sophisticated theoretical and numerical simulation studies have supported the parallel orientation of the driven VL and proposed novel, coherent lattice flow states at large velocity [3–5]. However, experimental investigations for the lattice orientation have been limited to small velocities [7–10] and so far no study has been reported in the high velocity regime.

Recently, we have shown that the mode locking (ML) experiment is a powerful technique to detect the transport properties of driven VL in the flow regime [11–13]. ML is a dynamic resonance between a superimposed ac drive and collective velocity modulation excited in a driven VL at an internal frequency given by $f_{int} = qv/a$ with the average velocity v and the periodic vortex spacing a along the flow direction. This dynamic synchronization occurs at characteristic velocities given by $v_{p/q} = (p/q)fa$ where p and q are integers. This implies that the resonant condition is sensitive to the periodic spacing along the flow direction and this may vary with the orientation of the driven VL. As shown in Fig. 1a when the lattice orientation, characterized by the orientation of the closed packed rows, is aligned to the flow direction, a is equal to the lattice spacing $a_\triangle$ of VL. It is also possible to have other orientations. For instance, if the orientation is perpendicular to the flow direction, as shown in Fig. 1b, the periodic spacing is given by the row spacing $a_\perp$ of VL. Thus, the resonant conditions may allow us to determine the orientations of driven VL.

In this study we investigate the orientations of driven VL in the flux-flow (FF) state of weak pinning, amorphous MoGe films. These films are structurally amorphous and do not have crystallographic symmetry which may influence the orientations of driven VL. From a quantitative analysis of the ML resonant conditions, we will show that two characteristic flow configurations occur with parallel and perpendicular orientations with respect to the flow direction. The scanning tunnel microscope (STM) measurements made after quenching the VL from its flow state, will support the conclusions of the ML experiments about these orientations of the driven VL. A preliminary report of this work has been given in [14].

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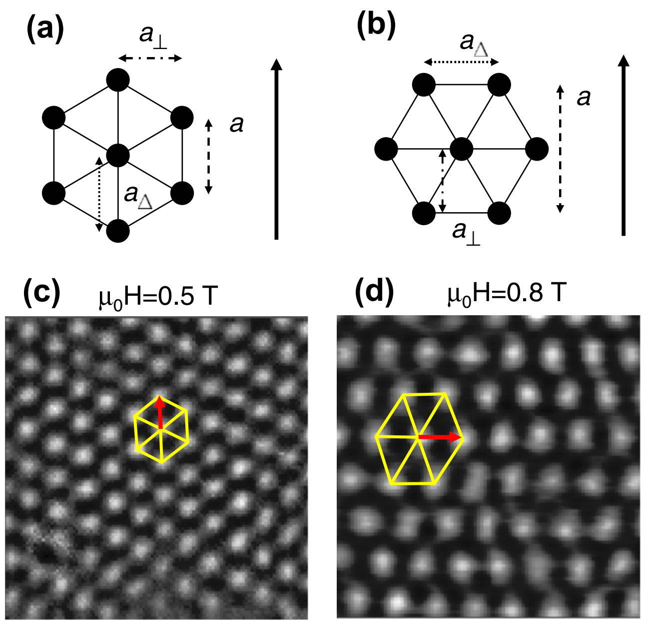

Fig. 1. Schematic illustrations of VL with parallel (a) and perpendicular orientations (b) with respect to flow directions (thick arrows). The lattice spacing $a_{\triangle}$ and the row spacing $a_{\perp}$ are indicated. STM images of the VL taken at 0.5 T (c) and 0.8 T (d) after quenching from the flux flow state with flow in the same direction as in the panels (a) and (b). Image sizes are 600 nm × 600 nm and 350 nm × 350 nm for (c) and (d), respectively. A direction of a closed packed row is indicated by an red arrow in each image. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

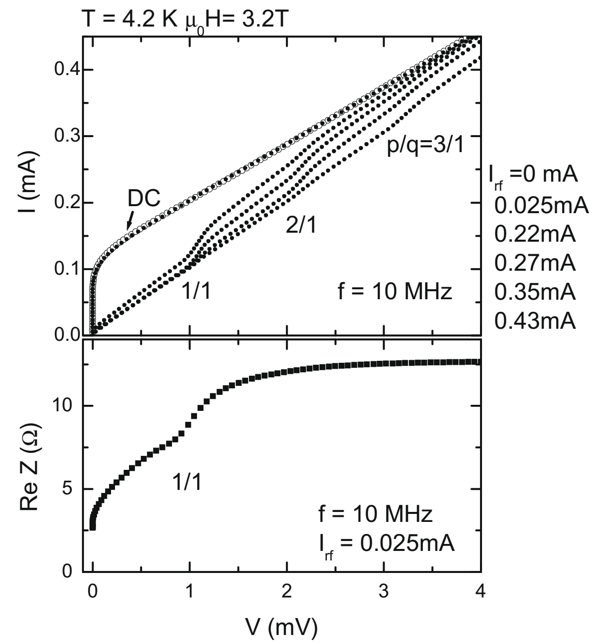

Fig. 2. A bunch of I–V curves measured with superimposing 10 MHz I_{rf} with various amplitudes (the upper panel) and a real part of rf impedance ReZ (the lower panel) measured by $I_{rf} = 0.025$ mA. The ML conditions of p/q are denoted. For clarity, a I–V curve without I_{rf} indicated by DC is plotted by open symbols.

2. Experimental

Amorphous ($\alpha-$)$Mo_{1-x}Ge_x$ films with $x \approx 0.22$ were sputtered on silicon substrates on a water cooled, rotating copper stage. Films used for the ML experiments were patterned by lift-off technique in a bar shaped geometry. The width and thickness of the samples are 0.3 mm and 0.33 μm, respectively. The superconducting transition temperature T_c is 6.1 K and the slope of the second critical field H_{c2} with temperature near T_c is 2.6 T/K. For the STM measurement, we prepared another α-MoGe film with 64 nm thickness covered by a gold film of 4 nm thickness [15]. This film has T_c of 5.7 K. In the ML experiment, we employed four-terminal pair method as described in Ref. [13]. This setup allows us to perform both dc and rf impedance measurements of the ML resonance. All the measurements were performed after cooling the samples in zero magnetic field.

3. Results and discussions

The upper panel of Fig. 2 shows the resonant features for the dc ML measurement taken at 3.2 T and 4.2 K. The current–voltage (I–V) curve without rf-current I_{rf} applied, is indicated by DC. It exhibits clear FF behavior well above the critical current I_c of 0.066 mA, as determined by a voltage criterion of 1 μV. Superimposing a 10 MHz large amplitude $I_{rf}(> I_c)$ we observe the ML features in the I–V curves as current steps at equidistant voltages. The first step appears around 1 mV and corresponds to the fundamental ML resonance for $p/q = 1/1$. The steps appearing at higher voltages are harmonics with $p > 1$ and $q = 1$. Regarding the shape of the I–V curves, we find that upon applying a large I_{rf} the FF branch shifts to larger voltages, thus demonstrating the influence of I_{rf} or "rf shaking" on the vortex dynamics by effectively reducing the pinning potential. For the rf-impedance experiments, where the complex rf-voltage in direct response to I_{rf} was measured, the resonance is detectable by superimposing a small I_{rf}. The lower panel shows a typical resonant feature appearing in the real part of the rf impedance ReZ measured at $I_{rf} = 0.025$ mA, which is much smaller than I_c. As observed, a jump like anomaly appears clearly in ReZ at the dc voltage where the fundamental ML resonance occurs in the I–V curves measured with large I_{rf}. The I–V curve measured with the small I_{rf} is also plotted in the upper panel. Because of the small I_{rf}, no resonant feature is visible in the curve. Moreover, this coincides well with the I–V curve indicated by DC, implying the negligible influence of rf shaking on vortices. These features indicate that the rf impedance technique is more sensitive to the ML resonance than the dc method and is better for studying a steady flow of driven vortices. Therefore we focus in the following on the results obtained from rf impedance experiments.

Next, we turn to the magnetic field dependence of the ML resonance. In order to show the resonant feature clearly, we differentiate the $ReZ-V$ curves measured at different fields and plot them together in Fig. 3a. For clarity, the curves are shifted vertically. The magnetic field is denoted in the figure. One can clearly see the resonance feature as a peak in $dReZ/dV$ plotted against V. Marking the position of the resonant peak, we find that the peak voltage shifts to higher voltages on increasing field except for the data at the highest magnetic field.

Plotting the resonant voltage against magnetic field in Fig. 3c, we find that it shows non-trivial behavior with field. After showing a monotonic increase with field, the resonant voltage seems to exhibit a small plateau around 0.8 T (defined as the lower characteristic field H_L) and then it increases monotonically again up to a field of 3 T (defined as the higher characteristic field H_H) where a rapid increase occurs. After the rapid increase, the resonant voltage turns to show a slow increase in a narrow field interval, followed by rapid reduction at high fields. In the frequency range of our experiments, i.e. between 10 and 30 MHz, the described behavior does not depend on frequency (velocity), and thus not on FF velocity. In the high fields where the reduction of the resonant