Field dependent orientation of driven vortex lattice in amorphous MoGe films

N. Kokubo¹, B. Shinzaki², and P. H. Kes³
¹ Center for Research and Advancement in Higher Education, Kyushu University, 4-2-1, Ropponmatsu, Chuoh-ku, Fukuoka, Fukuoka 810-8560, Japan.
² Department of Physics, Kyushu University, 4-2-1, Ropponmatsu, Chuoh-ku, Fukuoka, Fukuoka 810-8560, Japan
³ Kamerlingh Onnnes Laboratory, Leiden University, 2300 RA Leiden, The Netherlands
E-mail: kokubo@rche.kyushu-u.ac.jp

Abstract. We have investigated orientations of a driven vortex lattice in amorphous MoGe films by means of mode locking (ML) techniques. The ML resonance is sensitive to the periodic, vortex spacing along the flow direction and this may allow us to determine the orientations of the driven vortex lattice. We find that the resonant voltage $V_{ML}$ exhibits a jump like, rapid increase around the peak field $H_p$ of the critical current, on top of a smooth increase with field $H$ as $V_{ML} \propto \sqrt{H}$. This result can be interpreted as a lattice rotation between parallel and perpendicular orientations occurring around $H_p$.

1. Introduction
An issue of angular orientations of a driven vortex lattice in type II superconductors has focused recent interests [1-4]. A theoretical consideration suggested that a principal axis of the vortex lattice may be aligned parallel to the averaged flow direction, in order to minimize the power dissipation of the lattice motion over the pinning environments [4]. This parallel orientation of the lattice flow was observed experimentally in a scanning tunneling microscope (STM) study on NbSe₂ crystals [2]. However, a recent study on MgB₂ crystals has measured transient signals due to the vortex motion under a STM tip and shown that results do not agree with the parallel orientation [3]. This suggests the presence of different orientation of the driven vortex lattice.

Recently, we have shown that mode locking (ML) resonance is a powerful technique for investigating flow properties of the driven vortex lattice [5-11]. The ML resonance occurs when ac (rf) drive with frequency $f$ superimposed on top of dc drive is synchronized harmonically to a collective velocity modulation exited over the driven vortex lattice at an internal frequency given by $f_{int} = qv/a$ with an integer $q$, the average velocity $v$ and the periodic vortex spacing $a$ along the flow direction. This appears as multiple steps in force-velocity characteristics at resonant condition, given by

$$v_{p/q} = \frac{p}{q} fa$$

with another integer $p$. The resonant condition depends sensitively on the periodic spacing of the vortex lattice along the flow direction and it may allow us to determine orientations of the driven lattice with respect to the flow direction. In this study, we present ML results of the driven vortex lattice in weak pinning, amorphous MoGe films.
2. Experimental
Amorphous MoGe films were sputtered on silicon substrates on water cooled, rotating copper stage. We patterned films into a Hall-bar shape by lift-off technique. The thickness of the films is 0.33 $\mu$m. The superconducting transition temperature $T_c$ is 6.1 K.

We performed the ML experiments by using a precision impedance analyzer with proper shielding and calibrations [10]. The samples were immersed in liquid $^4$He of 4.2 K to avoid heating. We observed clear peak behavior of the critical current at 3.1 T ($=H_p$) just below the second critical field.

3. Results and Discussions
Figure 1(a) shows a bunch of voltage($V$)-current($I$) curves measured at 3.3 T just above $H_p$ with superimposing 10 MHz rf current of various amplitudes. We observed clear current steps appearing at equidistant voltages denoted by $p/q=1/1$ and $2/1$.

Next, we turn to the magnetic field dependence of the ML features. In Fig. 1(b) differential conductance $dI/dV$ vs $V$ taken at different magnetic fields is given. The ML features appear as peaks in $dI/dV$ curves. As marked in the figure, the peak position shifts to higher voltages on increasing magnetic field. At high fields ($\sim$ 3.5 T), the ML peak becomes broad and disappears just before $H_{c2}$. As discussed in previous studies, the disappearance of ML resonance marks the dynamic melting transition of the driven vortex lattice at a given velocity [6, 8, 10].

In Fig. 1(c) we plot the peak voltage measured at 20 MHz against magnetic field. On increasing magnetic field, the resonant voltage increases monotonically up to a field of 3 T (close to $H_p$), above which a jump like, rapid increase of the resonant voltage occurs. After the jump, the resonant voltage increases again monotonically with field.

Let us compare this behavior to the resonant conditions for the lattice orientation. When the orientation of the driven vortex lattice is parallel to the flow direction, the periodicity along the flow direction is given by the lattice spacing of the vortex lattice. Namely, for a perfect hexagonal lattice, $a = a_\Delta = \sqrt{2\Phi_0/\sqrt{3}B}$ with the flux quantum $\Phi_0$ and the vortex density $B$. Substituting this to Eq. (1), we obtain the fundamental resonant voltage for the parallel orientation as

$$V_{1/1,\parallel} = v_{1/1,\parallel}Bl = fa_\Delta Bl = fl\sqrt{\frac{2}{\sqrt{3}}\Phi_0 B}$$

As represented by the solid curve in Fig. 1(c), $V_{1/1,\parallel}$ increases with field as $\sqrt{H}$. Adjusting $l$ as a fitting parameter, we find a quantitative agreement with ML results above 3 T when $l = 1.3$ mm, consistent with the sample length. The results below 3 T show similar square root dependence on magnetic field, however, they are smaller by a factor of 0.86. Applying other resonant conditions, we find the best agreement when the perpendicular orientation ($a = 2a_\perp$) and the subharmonic ML resonance with $p/q=1/2$ are assumed. As represented by a dotted curve, this resonant condition is given by

$$V_{1/2,\perp} = v_{1/2,\perp}Bl = \frac{1}{2}f2a_\perp Bl = fl\sqrt{\frac{\sqrt{3}}{2}\Phi_0 B}$$

with $a_\perp(=a_\Delta \sqrt{3}/2)$ being the row spacing of the vortex lattice.

These findings suggest that the orientation of the driven vortex lattice changes with magnetic field. Namely, on increasing magnetic field, the driven vortex lattice rotates from the perpendicular to the parallel orientations around $H_p$. The appearance of the perpendicular orientation would be related to the surface effect, implying that the orientation remains parallel to the sample edge under certain favorable circumstances.
Figure 1. (a) A series of voltage-current curves measured with superimposing 10 MHz rf current with various amplitudes (amplitude 0.025, 0.13, 0.16 and 0.20 mA from top to bottom ) at 3.3 T and 4.2 K. The ML conditions of $p/q$ are denoted with arrows. (b) A series of differential conductance $dI/dV$ vs voltage $V$ measured with superimposing a 20 MHz rf current at different magnetic fields from 1.3 T (top) to 3.7 T (bottom) in 4.2 K. For clarity, the conductance curves are vertically shifted. (c) Magnetic field dependence of the ML voltage measured at 20 MHz in 4.2 K. A solid curve represents the fundamental ML condition for the parallel lattice orientation, while a broken curve for the subharmonic of $p/q = 1/2$ with the perpendicular orientation.

4. Conclusions

We presented the ML results of the driven vortex lattice in the amorphous MoGe films. Employing the resonant conditions for the lattice orientation, we suggest the presence of two orientations of the driven lattice flow; one is the parallel orientation where one of principal axes of the vortex lattice aligns parallel to the flow direction and the other is the perpendicular orientation characterized by one of the principal axes perpendicular to the flow direction. The anomaly observed in field dependence of the resonant voltage would mark the lattice rotation between the parallel and the perpendicular orientations.
Acknowledgments
N. K thanks T. Nishizaki and E. Pasca for useful comments. This work was supported partly by the grant in Aid for Scientific research from MEXT (the Ministry of Education, Culture, Sports, Science and Technology), Japan and by the CTC program under JSPS (Japan Society for the Promotion of Science).

References
[1] Hess H F, Robinson R B and Waszczak J V 1990 Phys. Rev. Lett. 64 2711
[2] Troyanovski A M, Aarts J and Kes P H 1999 Nature 399 665
[3] Kohen A, Cren T, Proslier Th, Noat Y, Sacks W, Roditchev D, Giubileo F, Bobba F, Cucolo A M, Zhigadlo N, Kazakov S M and Karpinski J 2005 Appl. Phys. Lett. 86 212503
[4] Schmid A and Hauger W 1973 J. Low. Temp. Phys. 11 667
[5] Kokubo N, Besseling R, Vinokur V M and Kes P H 2002 Phys. Rev. Lett. 88 147004
[6] Besseling R, Kokubo N and Kes P H 2003 Phys. Rev. Lett. 91 177002
[7] Kokubo N, Besseling R and Kes P H 2004 Phys. Rev. B 69 064504
[8] Kokubo N, Kadowaki K and Takita K 2005 Phys. Rev. Lett. 95 177005
[9] Kokubo N, Besseling R, Sorop T G and Kes P H 2006 Phys. Rev. B 73 224514
[10] Kokubo N, Asada T, Kadowaki K, Takita K, Sorop T G and Kes P H 2007 Phys. Rev. B 75 184512
[11] Okuma S, Inoue J and Kokubo N 2007 Phys. Rev. B 76 172503