Absence of mode-locking resonance for driven vortices in a thin amorphous Mo$_x$Ge$_{1-x}$ film

H. Sato and S. Okuma
Department of Physics and Research Center for Low Temperature Physics, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152-8551, Japan
E-mail: sokuma@o.cc.titech.ac.jp

Abstract. We present measurements of the mode-locking (ML) resonance for the thin amorphous Mo$_x$Ge$_{1-x}$ film with weak pinning. In contrast to the thick film, where the clear ML resonance indicative of driven vortex lattices is observed over a wide temperature $T$ and field $B$ range, any sign of ML is not detected for the thin film down to below 1 K. The results suggest that the vortex lattice for the thin film may be unstable against small pinning. We construct the vortex phase diagram in the $B-T$ plane, which consists of disordered solid phase and large liquid phase.

1. Introduction
The vortex phase diagram in type-II superconductors has been studied in a variety of three-dimensional (3D) superconductors. When the samples contain moderately strong pinning, the long range order of vortex positions are destroyed and a continuous transition from a vortex glass (VG) to liquid phase takes place under increasing field $B$ or temperature $T$ [1]. For low-$T_c$ superconductors with small fluctuations the VG phase occupies a large area of the $B-T$ plane [2]. However, as the thickness of the sample is reduced, the phase diagram changes drastically. According to the 2D VG theory [1], the vortex liquid phase is enhanced significantly [3-5] and the VG phase survives only at $T=0$. Thus the VG-liquid transition is a quantum phase transition that occurs at zero temperature ($T=0$) driven by $B$. Experimentally, this phenomenon has long been studied in relation to the field-driven superconductor-insulator transition in 2D [4-12].

Here, we consider the weak-pinning case. For the thick samples the vortex solid state is a little complicated due to the emergence of the peak effect (PE) [13]. With increasing $B$, the depinning current $J_c$ exhibits a peak just prior to the melting field $B_c$ and the peak field $B_p$ marks the structural transition from the vortex lattice to amorphouslike glass state. This transition has been actually observed in NbSe$_2$ single crystals [14] and amorphous ($a$-)Mo$_x$Ge$_{1-x}$ films [15]. For the 2D superconductors with no pinning the melting line $B_m(T)$ of the vortex lattice is predicted to be nearly independent of field at low $B$ [16]. However, to the best of our knowledge, the sharp melting transition as well as PE has not yet been observed in real thin superconducting films [17]. This fact suggests that the vortex lattice for thin films may be unstable against small pinning and/or the first-order melting transition may be observable only in limited $B-T$ regions, such as, low-$T$ and high-$B$ regions.

Based on an idea that the effects of pinning could be much reduced by simply driving the vortices, we have recently conducted a mode-locking (ML) experiment, which enables us to detect
the coherent motion of driven vortices, for weak-pinning \(a\)-Mo\(_x\)Ge\(_{1-x}\) films with thicknesses of 10 and 350 nm. The clear ML resonance indicative of driven vortex lattices was observed over a wide \(T\) and \(B\) range for the thick film, whereas it was not visible down to the lowest temperature (1.8 K) measured for the thin film [19]. In order to prove or disprove the possibility of the moving lattice state in the thin film, in this work we extend the measurements to even lower temperatures (0.65 K) and higher fields (2.0 T).

2. Experimental

We prepared the \(a\)-Mo\(_x\)Ge\(_{1-x}\) films with thicknesses of 330 and 10 nm by rf sputtering on a silicon substrate mounted on a water cooled rotating copper stage. The resistivities \(\rho\) in the normal state (at 10 K) are \(\rho_n = 1.80\) and 1.98 \(\mu\)2m for the thick and thin films, respectively. The mean-field transition \([\rho(T_{c0}) = 0.95\rho_n]\) and zero-resistivity temperatures \([\rho(T_c) = 10^{-3}\rho_n]\) are \(T_{c0} = 6.1\) K and \(T_c = 6.0\) K, and \(T_{c0} = 3.8\) K and \(T_c = 3.3\) K for the thick and thin films, respectively. The superconducting coherence length \(\xi\) estimated from the upper critical field \(B_{c2}\) at \(T = 0\) is around 14-21 nm, which is close to or slightly larger (or sufficiently smaller) than the thickness of the thin (or thick) film. Thus, for the thin (or thick) film the dimensionality with respect to \(\xi\) is two (or three). The lower \(T_c\) and wider transition width, \((T_{c0} - T_c)/T_{c0}\), for the thin film than for the thick film are due mainly to the reduced dimensionality. In measuring the ML resonance, ac currents \(I_{ac}\) with a frequency \(f_{ext}\) of 10 MHz were applied through an rf transformer. The films were 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

For the thick film we observe the peak in the \(J_c(B)\) curve at a field \(B_p\) prior to the melting field \(B_c\), indicative of PE [13]. As mentioned above, the peak field \(B_p\) in \(J_c(B)\) marks the order-disorder transition (ODT) from the ordered (or weakly disordered) vortex-lattice phase (OP) to disordered (amorphouslike) VG phase (DP) [14, 15]. In contrast, for the thin film the peak in \(J_c(B)\) is not observed down to the lowest temperature (0.5 K) measured, suggesting the absence of ODT. The pinning force per unit volume \(F_p\), as estimated from \(F_p = BJ_c\) [13], at low \(B/B_c\) for the thin film is several times larger than that for the thick film when compared at approximately the same reduced temperature \(T/T_c\). These results suggest that for the thin film the vortex solid phase is composed of only the VG phase (DP), as observed earlier in thick and thin \(a\)-Mo\(_x\)Si\(_{1-x}\) films with stronger pinning [2].

In Fig. 1 we illustrate the vortex phase diagram in the \(B\) – \(T\) plane for the thick (right; black symbols) and thin (left; red symbols) films. All the data for the thick film [18] and the data points at \(T > 1.8\) K for the thin film [19] are obtained from our previous work. The static melting field \(B_c(T)\) indicated with solid circles and upper critical field \(B_{c2}(T)\) indicated with open squares are determined from the resistivity, \(\rho(B_c) = 10^{-3}\rho_n\) and \(\rho(B_{c2}) = 0.95\rho_n\), respectively. For the thick film the PE field \(B_p(T)\) indicated with triangles marks the ODT. Compared with the thick film, the \(B_c(T)\) line for the thin film is much suppressed from the \(B_{c2}(T)\) line and the liquid phase is enhanced particularly in the high temperature region. The large liquid phase persists down to \(T \rightarrow 0\), which is attributed to strong fluctuation effects in 2D as well as the high resistivity of the amorphous films. This nonvanishing liquid phase at low \(T\) is identified with a quantum-vortex-liquid (QVL) phase. For the thick film the suppression of \(B_c(0)\) and enhancement of the QVL phase are observed only when the pinning strength is significantly weakened by driving the vortices [18]. Although the pinning strength for the thin film is found to be stronger than for the thick film, as mentioned above, \(B_c(0)\) for the thin film is much more suppressed. This is in contrast to the general belief that the pinning effect pushes up the \(B_c(T)\) line. This fact again reflects the strong fluctuation effects in 2D, which dominate over the pinning effects.
To obtain information on the existence of the vortex-lattice phase in the thin film, we perform the measurements of the ML resonance. First, we note that observation of the ML resonance does not immediately imply the existence of the static vortex-lattice phase (OP), because ML could occur even in the static DP [18]. If the ML resonance is not observed, on the contrary, we may conclude that the static vortex-lattice phase (OP) is most likely absent. In Figs. 2(a) and 2(b) we show the $V$ dependencies of the differential conductance $dI/dV$ superimposed with 10-MHz $I_{rf}$ with different amplitudes (0.5-0.7 mA) at 0.82 K in 5.0 T (OP) and at 0.65 K in 2.0 T (vortex-solid phase) for the thick and thin films, respectively. Since in this work the ML measurements have been performed at lower $T$ (<1 K) than in previous work ($T$ = 3.0 and 1.8 K), heating effects due to the vortex motion is more serious for larger $V$ (or $I$), resulting in an increase in the local temperature within the samples. To decrease the heating effects while maintaining the clear ML signal, we have employed $I_{rf}$ with $f_{ext}$ = 10 MHz, which is lower than 35 and 50 MHz used in previous work [19]. This is because the voltage $V$ at ML is proportional to $f_{ext}$ and hence the smaller $f_{ext}$ leads to smaller dissipation. Nevertheless, at the maximum voltages $V$ ≈ 2 and 1.6 mV shown in Figs. 2(a) and 2(b), temperatures in the samples are increased by 0.02 K from the values (0.82 and 0.65 K) at $V$ ≈ 1 mV for the thick and thin films, respectively. We consider, however, that such local heating will not significantly alter the discussion regarding the presence or absence of ML.

It is seen from Fig. 2(a) that the clear ML peak indicative of driven lattice is detected for the thick film. Assuming a triangular vortex array moving in the direction perpendicular to one side of the triangles (i.e., perpendicular orientation), we can calculate a value of the voltage ($V_{perp}^{p/q}$) for a given $B$ satisfying the subharmonic resonant condition of $p/q = 1/2$; i.e., $V_{1/2}^{perp} = l(p/q)f_{ext}a_\perp B = l_{ext}(\sqrt{3\Phi_0}B/2)^{1/2}$, where $l$ is the distance between the voltage contacts, $a_\perp$ is the lattice period in the direction of vortex motion, and $\Phi_0$ is the flux quantum [18]. The location of $V_{1/2}^{perp}$ is indicated with vertical dashed lines in Fig. 2(a) and 2(b). For the thick film the driven vortex matter turns out to be the triangular vortex array with perpendicular lattice orientation, while for the thin film evidence for the ML resonance cannot be found at any $I_{rf}$ measured. In Fig. 2(b) only the two curves with different $I_{rf}$ are shown for clarity. We have also performed the ML measurements for the thin film at different $B$ and $T$, which are indicated with crosses in Fig. 1; however, the ML resonance is not observed at any point.

The absence of ML for the thin film may be attributed to the fact that for the thin-film (2D) superconductors the elasticity of driven lattices is significantly reduced and the vortex lattice is unstable against small pinning as well as thermal/quantum fluctuations. This would account for
the absence of the sharp melting transition reported so far in various thin superconducting films. Furthermore, we do not find any sign of the vertical melting line \( B_c(T) \), which is predicted to lie at finite \( T \) and in low \( B \) for the pinning-free thin films [16, 17]. We consider that to observe these phenomena, further experiments using thin films with smaller pining strengths are needed. It is also of interest to study thinner films (e.g., 3-5 nm thick films) from the viewpoint of the superconductor-insulator transition in 2D. It is known that ultrathin (4 nm) \( a\)-Mo\(_x\)Ge\(_{1-x}\) films exhibit the \( B \)-driven two-step \((T = 0)\) transitions from the superconductor to metal phase at low \( B \) and from the metal to insulator phase at high \( B \) [7], while the nature of these phases is not well clarified in view of vortex states.

This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

References

[1] Fisher D S, Fisher M P A and Huse D A 1991 Phys. Rev. B 43 130
[2] Okuma S, Imamoto Y and Morita M 2001 Phys. Rev. Lett. 86 3136
[3] Paalanen M A, Hebard A F and Ruel R R 1992 Phys. Rev. Lett. 69 1604
[4] Chervenak J A and Valles J M Jr. 1996 Phys. Rev. B 54 R15649
[5] Okuma S, Terashima T and Kokubo N 1998 Phys. Rev. B 58 2816
[6] Okuma S, Shinozaki S and Morita M 2001 Phys. Rev. B 63 054523
[7] Mason N and Kapitulnik A 2001 Phys. Rev. B 64 060504(R)
[8] Gantmakher V F et al. 1998 JETP Lett. 68 363: Gantmakher V F 2010 Usp. Fiz. Nauk 180 3
[9] Marković N, Christiansen C and Goldman A M 1998 Phys. Rev. Lett. 81 5217
[10] Sambandamurthy G, Engel L W, Johansson A and Shahar D 2004 Phys. Rev. Lett. 92 107005
[11] Baturina T I, Strunk C, Balandov M R and Satta A 2007 Phys. Rev. Lett. 98 127003
[12] Marrache-Kikuchi C A et al. 2008 Phys. Rev. B 78 144520
[13] Kes P H and Tsuei C C 1983 Phys. Rev. B 28 5126
[14] Paltiel Y et al. 2002 Phys. Rev. B 66 060503
[15] Okuma S, Kashiro K, Suzuki Y and Kokubo N 2008 Phys. Rev. B 77 212505
[16] Fisher D S 1980 Phys. Rev. B 22 1190
[17] Saiki T and Ikeda R 2011 Phys. Rev. B 83 174501
[18] Okuma S et al. 2011 Phys. Rev. B 83 064520; 2009 Phys. Rev. B 80 132503
[19] Sato H and Okuma S 2011 J. Phys.: Conf. Ser. 302 012028