Mode-locking resonance for driven vortex matter in thick and thin superconducting films

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 report on measurements of the mode-locking (ML) resonance for the thick and thin films of amorphous Mo\textsubscript{x}Ge\textsubscript{1-x} with weak pinning. The clear ML resonance indicative of driven vortex lattices is observed for the thick film, while it is not visible for the thin film. The results suggest that for the thin film the elasticity of driven lattices may be significantly reduced and the lattices may be unstable against small pinning.

1. Introduction

Vortex states in type-II superconductors are largely dependent on the dimensionality (thickness) of superconductors. When the samples contain moderately strong pinning, a continuous transition from the vortex glass to liquid takes place [1]. For thick films the vortex-glass phase occupies a large area of the field-temperature (\(B - T\)) plane [2], while for thin films only the liquid phase exists at any nonzero \(T\) in the mixed states [1, 3, 4]. In the case of weak-pinning samples we focus on in this work, the vortex solid state for the thick samples is somewhat complicated. Under increasing the field, the critical current \(J_c\) exhibits a peak just prior to the melting field \(B_c\). This is called a peak effect (PE)\[5, 6\] and the peak field marks the sharp structural transition from the vortex lattice to amorphouslike glass state. This is actually observed in NbSe\textsubscript{2} single crystals [7] and amorphous (a-)Mo\textsubscript{2}Ge\textsubscript{1-x} films [8]. For thin films with no pinning the melting line of vortex lattice is predicted to be nearly independent of field at low \(B\) [9]. However, to the best of our knowledge, the sharp melting transition as well as PE has not yet been observed in real thin films [10]. These results suggest that the vortex lattice for the thin films may be unstable against small pinning.

The effects of pinning would be much reduced by simply driving the vortices. Here, we conduct a mode-locking (ML) experiment [11, 12, 13, 14], which enables us to detect the coherent motion of driven vortices, for a-Mo\textsubscript{2}Ge\textsubscript{1-x} films with thicknesses of 10 and 350 nm. For the thin film both the transition temperature \(T_c\) in zero field and the static “melting” field \(B_c\) are smaller than those for the thick film, while the difference between the upper critical field \(B_{c2}(T)\) and \(B_c(T)\) is significantly larger, indicative of the enhanced liquid phase due to the reduced dimensionality [1, 15]. Neither the PE for \(J_c(B)\) nor the ML resonance observed for the thick film is visible for the thin film. The results suggest that for the thin film the elasticity of driven lattice may be much reduced, which would account for the “absence” of the sharp melting transition of vortex lattice for the thin films.

International Symposium "Nanoscience and Quantum Physics 2011" IOP Publishing
Journal of Physics: Conference Series 302 (2011) 012028 doi:10.1088/1742-6596/302/1/012028
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2. Experimental

The $a$-Mo$_x$Ge$_{1-x}$ films with thicknesses of 350 and 10 nm were prepared by rf sputtering on a substrate mounted on a water cooled rotating copper stage. The thickness of the films was controlled by changing the sputtering time. The resistivities in the normal state (at 10 K) are $\rho_n = 1.63$ and 1.98 $\mu\Omega$m 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 $T_{c0} = 5.8$ K and $T_c = 5.6$ K, and $T_{c0} = 3.8$ K and $T_c = 3.3$ K for the thick and thin films, respectively. The relative widths of the resistive transition, as defined as $(T_{c0} - T_c)/T_{c0}$, are 0.04 and 0.12 for the thick and thin films, respectively. The superconducting coherence length estimated from $B_{c2}$ at $T = 0$ is around 15-20 nm, which is close to or slightly larger (sufficiently smaller) than the thickness of the thin (thick) film. Thus, for the thin (thick) film the dimensionality with respect to $\xi$ is two (three). Both the lower $T_c$ ($T_{c0}$) and wider transition width for the thin film than for the thick film are due mainly to the reduced dimensionality. In measuring the ML resonance, ac currents $I_{rf}$ with frequencies $f_{ext}$ of 35 and 50 MHz were applied through an rf transformer for the thick and thin films, respectively [14, 16]. The films were directly immersed in the liquid $^4$He and the field (up to 6.5 T) was applied perpendicular to the plane of the film.

3. Results and discussion

From the current-voltage ($I-V$) characteristics, we define the critical (depinning) current density $J_c$ as a threshold current at which the vortices start to move, where a $10^{-7}$ V criterion is used [8, 14]. In Fig. 1 we plot the field dependence of $J_c$ at 3.0 K for the thick film (black solid circles) and at 1.8 K for the thin film (red solid circles). Here, we selected the temperatures $T$ which give rise to the same reduced temperature $T/T_c = 0.54$ for both films. To compare the shape of $J_c(B)$ between the two films, the field is normalized by $B_{c2}(T)$ of each film. For the thick film we observe the peak behavior in the $J_c(B)$ curve indicative of PE [5, 6, 17]. The peak is more pronounced at lower temperatures, which is seen from the typical data at 2.3 K shown in the inset. 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) vortex-glass phase (DP) [7, 8].

In the case of the thin film, by contrast, the peak in $J_c(B)$ is not visible at any temperature measured, suggesting the absence of ODT. Furthermore, the value of $J_c$, which reflects the pinning strength, is comparable to or slightly larger than that for the thick film. These results imply that for the thin film the vortex solid phase is composed of only the vortex-glass phase.

![Figure 1](image-url) (Color online) The critical current density $J_c$ vs reduced field $B/B_c$ at 3.0 K for the thick (350 nm) film (black solid circles) and at 1.8 K for the thin (10 nm) film (red solid circles). Inset: $J_c$ vs $B/B_c$ at 2.3 K for the thick film. All the lines are guides for the eye.
Figure 2. (Color online) $B_{c}$ vs $T$ (solid circles) and $B_{c2}$ vs $T$ (open squares) for the thick (black symbols) and thin (red symbols) films. $B_{p}$ vs $T$ (triangles) for the thick film. All the lines are guides for the eye.

(DP), as observed earlier in thick and thin $a$-Mo$_2$Si$_{1-x}$ films with stronger pinning.

Figure 2 displays the vortex phase diagram in the $B$–$T$ plane for the thick (black symbols) and thin (red symbols) films, where we plot the static melting line $B_{c}(T)$ (solid circles) and upper-critical-field line $B_{c2}(T)$ (open squares) determined from $\rho(B_{c}) = 10^{-3}\rho_{n}$ and $\rho(B_{c2}) = 0.95\rho_{n}$, respectively. We also show $B_{p}(T)$ (triangles) indicative of ODT for the thick film. One can clearly see that, as compared with the thick film, the $B_{c}(T)$ line for the thin film is significantly suppressed from the $B_{c2}(T)$ line, resulting in the enhanced liquid phase in a low-field region. The larger liquid phase for the thin film than for the thick film is attributed to stronger fluctuation effects for two dimensions.

In order to explore the possibility of the vortex-lattice phase in the thin film, we perform the measurements of the ML resonance. Figures 3(a) and 3(b) show the $V$ dependencies of the differential conductance $dI/dV$ superimposed with $I_{rf}$ with different amplitudes at 3.0 K in 2.0 T (OP) and at 1.8 K in 0.1 T (vortex-solid phase) for the thick and thin films, respectively. 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., the perpendicular orientation), we can calculate a value of the voltage $(V_{p/q}^{\text{perp}})$ for a given $B$ satisfying the subharmonic resonant condition of $p/q = 1/2$; i.e., $V_{p/q}^{\text{perp}} = l(p/q)f_{\text{ext}}a_{\perp}B = l_{\text{ext}}(\sqrt{3}/2)\Phi_{0}B/2)^{1/2}$, 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 $V_{p/q}^{\text{perp}}$ is indicated with vertical dashed lines in Fig. 3(a) and 3(b). The results in Fig. 3(a) show that for the thick film the driven vortex matter is the triangular vortex array with perpendicular lattice orientation, consistent with previous work on the similar thick films.

For the thin film, however, evidence for the ML resonance cannot be found for any $I_{rf}$ measured. To reduce the dynamic pinning force, $I_{rf}$ with $f_{\text{ext}} = 50$ MHz higher than $f_{\text{ext}} = 35$ MHz for the thick film is superimposed. We also perform the measurements of ML in 0.5 T, which corresponds to the high-$B$ part of the solid phase; however, the results stay unchanged. In our previous work using the thick films we have revealed that at relatively high $T$ ($>0.4T_{c0}$), as studied in this work, the moving-lattice states are observed over the broad fields in the equilibrium DP as well as OP, while the moving-liquid state is visible only in the equilibrium liquid phase ($B_{c} < B < B_{c2}$). In other words, even if the equilibrium solid phase is the disordered vortex-glass phase (DP), it can be dynamically ordered when it is driven at high velocity. Based on these facts, we may interpret the absence of ML for the thin film as that
for the thin film the elasticity of driven lattice may be significantly reduced and the vortex lattice may be unstable against small pinning as well as thermal/quantum fluctuations. This may account for the “absence” of the sharp melting transition reported so far in various thin superconducting films.

**Acknowledgments**

We thank D. Shimamoto for his technical assistance. This work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

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