Observation of Kosterlitz-Thouless-Type Melting of the Disordered Vortex Lattice in Thin Films of *a*-MoGe

Ali Yazdani, W. R. White, M. R. Hahn, M. Gabay,[a] M. R. Beasley, and A. Kapitulnik

Department of Applied Physics, Stanford University, Stanford, California 94305

(Received 7 October 1992)

Measurements of the ac penetration depth of *a*-MoGe films in the presence of a perpendicular magnetic field reveal an anomaly in the ac response of the vortex lattice at a characteristic temperature below the $H_{c2}(T)$ line. The field and frequency dependence of this anomaly is found to be consistent with a Kosterlitz-Thouless-type melting of the two-dimensional vortex lattice. Moreover, we observe a crossover in the frequency dependence which suggests that the vortex lattice remains disordered on long length scales below the melting temperature.

PACS numbers: 74.60.Ec, 74.60.Ge

The question of the existence of a finite-temperature phase transition within the vortex state of type-II superconductors has received considerable attention since the discovery of the high-T_c superconductors. One possible phase transition in these superconductors, as well as conventional superconductors with reduced dimensions, is the dislocation-mediated Kosterlitz-Thouless (KT) [1] melting transition in the two-dimensional vortex lattice (VL). In conventional superconductors, the possibility of this phase transition was first suggested by Huberman and Doniach [2] and by Fisher [3]. At the transition, the solid vortex lattice phase which contains thermally created bound pairs of dislocations, melts as these pairs dissociate at large distances to create free dislocations. However, as Larkin [4] showed long ago, in the solid phase, any amount of disorder will disturb the lattice on long length scales, hence limiting positional correlations to a length scale R_c. The consideration of disorder raises two important questions: (1) Can the disordered VL "melt locally" as each correlated volume (vortex bundle) melts internally via a KT-type transition with increasing temperature? (2) Do these correlated volumes freeze into a glasslike state at a lower temperature [5]?

To date, there are two reports of experiments that have been interpreted as evidence for KT-type melting of the VL. The vibrating-reed experiments of Gammel, Hebard, and Bishop [6] on amorphous composite In/InO_x films showed a large dissipation peak at around the predicted melting temperature. However, recently Brandt [7] has argued that these experimental results are likely related to a size-dependent electromagnetic crossover rather than the melting of the VL. The other case is the resistivity and *I-V* measurements of Berghuis, van der Slot, and Kes [8] on films of *a*-NbGe. These experiments were interpreted as a crossover of a pinned VL with a finite critical current at low fields to a melted vortex fluid with flux flow resistance at high fields. The crossover was found to occur close to the expected phase boundary.

In this Letter, we present evidence for the existence of a melting transition on short length scales in the disordered VL by studying the behavior of the ac penetration depth of amorphous $Mo_{77}Ge_{23}$ thin films in the presence of a perpendicular magnetic field. Specifically, we interpret observed abrupt changes in the ac penetration depth as evidence for melting of the two-dimensional VL. We will discuss our measurements within the context of recent calculations [9] of vortex response in ac fields to show that a sudden change in the VL's elastic parameters is required to explain the data. The observed anomaly measured at various frequencies behaves consistently with a KT transition observed at finite frequency. Using the KT dynamical theory [10,11], we extrapolate the transition temperature to zero frequency and find good agreement with the predicted melting temperature. Equally important, we observe a crossover in the frequency dependence at low frequencies that is suggestive of the lack of order in the system on long length scales, in accordance with the Larkin-Ovchinnikov (LO) theory [12].

The MoGe samples studied were grown by multitarget magnetron sputtering on sapphire substrates. From zero-field measurements, we have found the bulk penetration depth to be well described by the BCS dirty limit with the zero-temperature value of 7000 Å. The Ginzburg-Landau coherence length in these films is about 55 Å, which makes them extreme type-II superconductors. The measured critical currents range from 10^4 to 10^2 A/cm^2, depending on the thickness. Hence, the strength of pinning ranges from moderate to weak. We have studied samples with thickness ranging from 500 to 5000 Å with $T_c \approx 7$ K. The characteristic bending length for vortices due to thermal fluctuations [13] ($l_z \approx 8$ μm) and due to the pinning potential [12] ($l_c \approx 6$ μm) in these films is much larger than the thickness for all samples studied here; hence the vortex lattice in these samples is indeed two dimensional.

The main experimental technique utilized is a two-coil mutual inductance measurement used by several groups in investigating the properties of superconducting films [14]. The experimental configuration consists of a drive coil and an astatically wound pickup coil placed concentrically on the same side of the film. Both coils are small compared to the lateral extent of the film so as to avoid finite-size effects. The drive coil induces an emf in the film which in turn produces shielding currents that are detected by the pickup coil. Using linear response theory, we can calculate the complex sheet conductance of the film from the measured in-phase and out-of-phase components of the induced currents. The gradiometer configuration of the pickup coil ensures rejection of any background noise as well as the emf induced by the drive coil. We use standard lock-in detection of the induced current signal and can easily verify the linearity of the response as well as study the effects of the measurement frequency. In a thin film ($d < \lambda$), the complex sheet conductance G is related to the generalized bulk complex ac penetration depth λ_{ac}: $\omega G = d/i\mu_0\lambda_{ac}^2$. A recent calculation of the ac vortex response by Coffey and Clem [9] shows that λ_{ac} for a superconductor in a magnetic field B is related to the flux-flow diffusion length, δ_f, intrinsic bulk penetration depth, $\lambda = \lambda(T,H)$, and the Campbell penetration depth, λ_C, in the following way:

$$\lambda_{ac}^2 = \lambda^2 + 1/(\lambda_C^{-2} + 2i\delta_f^{-2}) . \tag{1}$$

The Campbell length and the diffusion length are defined in terms of the Labush parameter α_L, which characterizes the restoring force of the vortex system in the presence of the pinning potential and the vortex viscous drag coefficient η (see references in Ref. [9]):

$$\lambda_C^2 = B\phi_0/\mu_0\alpha_L, \quad \delta_f^2 = 2B\phi_0/\mu_0\eta\omega . \tag{2}$$

In the presence of a large enough field, the kinetic response of the superconducting electrons [the λ^2 term in Eq. (1)] can be neglected since most of the response is due to the vortices. In this case, the imaginary part of the sheet conductance, ωG_I, is a direct measure of α_L. The exact functional form of α_L depends on the VL's elastic constants as well as the pinning potential. The real part of the sheet conductance, ωG_R, is related to η and to the dissipation caused by the motion of vortices. The above equations ignore the effect of thermal activation of the vortices over the pinning potential. An attempt to include the thermal activation is discussed in Ref. [9].

In Fig. 1, we show the typical behavior of the ωG_I and $\omega G_R \times 10$ measured at 10 kHz for a 3000 Å film at 10 kOe. Also shown is the ac $R_\square$ calculated from G along with the dc $R_\square$ measured on the same sample using the standard four-probe resistivity measurement. The imaginary part of the conductance ωG_I shows a sharp drop near the temperature at which there is a distinct peak (width $\approx$ 35 mK) in ωG_R. At temperatures of the peak or the drop, $R_\square$ appears to be activated with a large activation energy, if plotted as an Arrhenius plot. The excellent agreement between the two methods of measuring $R_\square$ confirms the ability of our technique to measure sheet conductance. This agreement further demonstrates that the position of the observed dissipation peak is not determined by a size-dependent electromagnetic crossover as

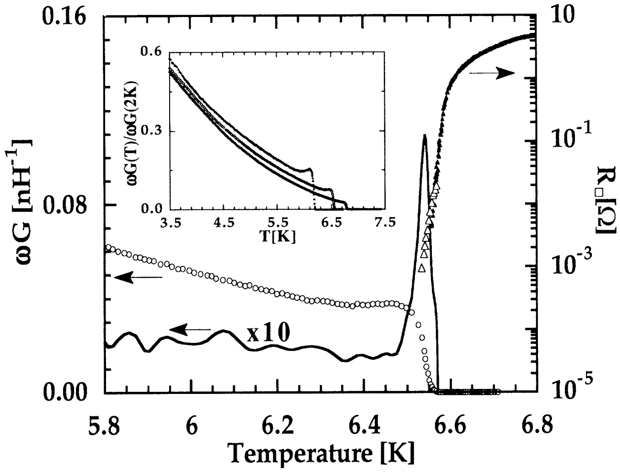

FIG. 1. Typical behavior of ωG_I (open circles) and $\omega G_R \times 10$ (solid line). The open triangles are the ac $R_\square$ and the solid triangles are the dc $R_\square$ for the same film (3000 Å, $H = 10$ kOe). Inset: ωG_I for 5, 10, and 18 kOe scaled to their values at 2 K.

has been argued to be the case in other ac experiments [7]. In the inset of Fig. 1, ωG_I's for several fields have been scaled to illustrate that the sudden drop in ωG_I becomes *sharper as the field is increased.* Given the direct relation between α_L and ωG_I, the sudden drop in ωG_I implies an anomaly in α_L at the temperature of the drop.

It is this *sudden drop in the restoring force* of the VL which we take as evidence for the melting transition of the VL. The presence of an activated region in $R_\square$ at temperatures above the drop argues strongly against the possibility that the observed dissipation peak is associated with thermal depinning of vortices or that thermal depinning could have occurred at a lower temperature. For thin films, the most relevant elastic constant that determines α_L is the shear modulus c_{66}, which in two dimensions is expected to have an abrupt universal drop at the KT melting temperature [2,3]. Experimentally, however, the drop in ωG_I and hence in α_L becomes harder to observe at lower fields (few hundred oersteds) probably due to a larger contribution to ωG_I from the kinetic inductance of the superconducting electrons. The peak in ωG_R is observed at all fields, however, and can be taken as the location of the drop in ωG_I due to their close connection described above. We also stress that the peak at lower fields can *only* represent KT melting if its field *and* frequency dependence follows that of the KT melting theory.

The KT phase boundary can be calculated using the universal jump [2,3] condition for c_{66}:

$$A_{c_{66}} a_0^2 d/k_B T_m(H) = 4\pi , \tag{3}$$

where T_m is the melting (KT) temperature, a_0 is the VL spacing, d is the film thickness, and A is a factor ≤ 1 reflecting the renormalization of c_{66} by nonlinear lattice vibrations [3]. In Fig. 2, we show the position of the peak in ωG_R measured at 10 kHz for two different films for fields up to 18 kOe. Also shown is the calculated phase boundary $T_m(H)$ for each sample using known material parameters, $A=1$, and Brandt's expression for c_{66} [15]. The sharp dropoff seen in both the data and theory in Fig. 2 corresponds to the expected field-independent melting temperature at the intermediate vortex densities. As the field is raised closer to $H_{c2}(T)$, the melting line recedes to lower temperatures. Although the transition observed at finite frequency occurs slightly above the $T_m(H)$ line as expected, the overall agreement in the shape of the phase boundary is impressive. Similar behavior has been seen in all the films studied. We will comment on the deviation at low fields below. It is worth pointing out here that the overall shape of the phase diagram in Fig. 2 bears a remarkable similarity to the irreversibility line observed in some single crystals of YBaCuO [16].

A dynamical theory [10] of the KT phase transition has been developed for the case of 2D superfluid transition and successfully fitted to the experimental results [11] on thin ^{4}He films. Measurements at a finite frequency ω probe the system on length scales $r_\omega \approx \sqrt{aD/\omega}$, where D is the diffusion constant of a dislocation in the VL and a is numerical constant (≈ 10) specific to the motion of dislocations in the triangular VL. Under such conditions, the melting is observed at a temperature $T_\omega > T_m$, when the average separation between unbound dislocations becomes of order r_ω. This average distance is determined by the correlation length $\xi_+(T)$, and an expression for the frequency dependence can be obtained by equating this length to r_ω. In making the calculation, we have used the expression for $\xi_+(T)$ derived for the case of KT melting in a triangular lattice [17,18], so our frequency-dependence fit depends on nonuniversal parameters b, $T_m(H)$, and aD:

$$\frac{T_\omega}{T_m} = 1 + \left(\frac{b}{\ln\sqrt{aD/\omega}}\right)^{2.71} . \qquad (4)$$

The frequency dependence has been measured at several fields, and they all have the characteristic behavior shown in Fig. 3. As shown for this 1200 Å film at 5 kOe, the higher frequency region can be fitted with the dynamical theory (solid line in Fig. 3) using $b=0.6$ and $aD/a_0^2 \approx 10^{10}$ Hz. This frequency is consistent with a simple estimate of the harmonic vibrations of the vortices in a lattice. It is also interesting to note that this diffusion frequency for a dislocation [18] in the VL is nearly the same as the vortex diffusion frequency in the liquid phase estimated from the measured resistance. Explicitly, the T_m's obtained from these fits are in excellent agreement with the predicted melting temperature at each field; the deviations are less than 1% (<60 mK) in the actual temperatures. However, as seen in Fig. 3, the frequency dependence starts to deviate from the theory at lower frequencies, i.e., at longer length scale. More specifically, for each field, we can identify a crossover frequency which corresponds to a length scale, R_ω, above which the dynamical KT theory breaks down. This length can be estimated using the expression for r_ω above, and the diffusion constant obtained in the fit with the

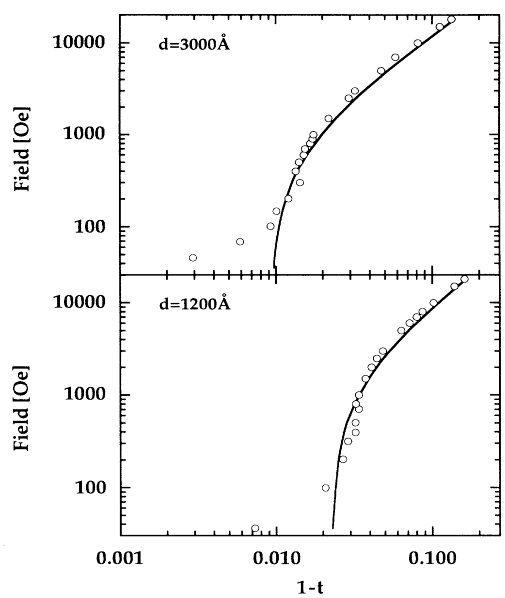

FIG. 2. Position of the peak or drop (see text) in the H-T plane measured at 10 kHz. The solid lines are the KT melting line ($\omega=0$) calculated from Eq. (3) for the two-dimensional VL.

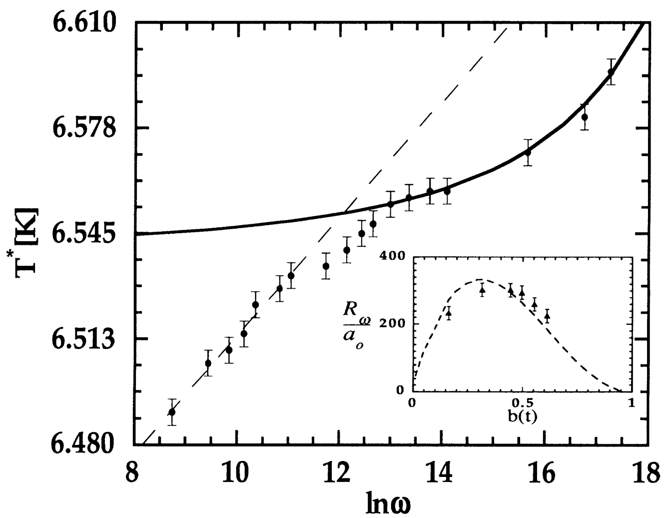

FIG. 3. Typical frequency dependence of the peak temperature. Solid line is a fit by the dynamical theory [Eq. (4)] and the dashed line is a fit by an activated model. Inset: The crossover length vs reduced field. The dashed line is $c_{66}(b)$ in arbitrary units.

dynamical theory. A natural explanation for this crossover is that the disorder cuts off the divergence of the correlation length $\xi_+(T)$ at larger length scales, preventing the system from reaching the KT fixed point. In fact, the dependence of R_ω on the magnetic field shown in the inset of Fig. 3 is consistent with the predicted behavior for R_c by the LO theory [dashed line is $c_{66}(b)$ in arbitrary units, $b=H/H_{c2}(T)$]. Estimates of R_c obtained from the critical current measurements on similar samples [19] based on LO theory [12] are about an order of magnitude smaller than the typical R_ω. While this discrepancy may reflect the inaccuracy of the criteria used in estimating the value of R_c, it may also be a consequence of the method of probing the correlated volumes in each experiment. Similarly, a crossover occurs at low fields in the phase diagram measured at finite frequency (see Fig. 2). At these fields, R_c can be much smaller than the r_ω; hence the peak no longer corresponds to $T_m(H)$. However, the *critical behavior* observed at high frequencies seems to provide clear evidence for a dislocation-unbinding melting transition on length scales comparable to R_ω, i.e., the "local melting" of the disordered VL.

Observations of the vortex system on length scales larger than R_c should probe the activated behavior of the "vortex bundles" in the presence of the pinning potential. In this case, the experiment is probing these bundles and the peak is observed when the relaxation time for these bundles is equal to the measurement time. In fact, the low-frequency behavior easily fits (see Fig. 3) the form $U_0/T_\omega=-\ln(\omega/\omega_0)$, which is characteristic of an activated process with activation energy U_0 and attempt frequency ω_0. Typical parameters, $U_0\approx 2000$ K and $\omega_0\approx 10^{12}$ Hz, are reasonable for such a process in these films [20]. More measurements at lower frequencies are required to further investigate this long-length-scale regime.

The emerging physical picture from these results is that dislocation unbinding dominates the response of the disordered two-dimensional VL on short length scales, i.e., a local melting occurs for $l<R_c$. Therefore probing the VL on short length scales exhibits the critical behavior of the KT transition for the pure system. However, in a real system with disorder, T_{KT} is an unstable fixed point and a crossover from the KT critical behavior is observed when the system is probed on long enough length scales ($l>R_c$). The expected fixed point of the disordered two-dimensional VL is the so-called vortex-glass transition at $T=0$, at which the "vortex bundles" freeze into a spin-glass-like phase. While our experimental results are unaffected by this transition, the idea that vortex creep dominates the response of a disordered two-dimensional VL on long length scales at $T>0$ is consistent with our observations [5].

We thank Seb Doniach, Daniel Fisher, and David Nelson for helpful conversations and suggestions. This work was supported by the Air Force Office of Scientific Research.

[a]Permanent address: Laboratoire de Physique des Solides, Universite Paris-Sud, 91405 Orsay, France.

[1] J. M. Kosterlitz and D. J. Thouless, J. Phys. C **6**, 1181 (1973).
[2] B. A. Huberman and S. Doniach, Phys. Rev. Lett. **43**, 950 (1979).
[3] D. S. Fisher, Phys. Rev. B **22**, 3519 (1980).
[4] A. I. Larkin, Zh. Eksp. Teor. Fiz. **58**, 1466 (1970) [Sov. Phys. JETP **31**, 784 (1970)].
[5] D. S. Fisher, M. P. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991).
[6] P. L. Gammel, A. F. Hebard, and D. J. Bishop, Phys. Rev. Lett. **60**, 144 (1988).
[7] E. H. Brandt, Phys. Rev. Lett. **68**, 3769 (1992).
[8] P. Berghuis, A. L. F. van der Slot, and P. H. Kes, Phys. Rev. Lett. **65**, 2583 (1990).
[9] M. W. Coffey and J. R. Clem, Phys. Rev. Lett. **67**, 386 (1991); E. H. Brandt, Phys. Rev. Lett. **67**, 2219 (1991).
[10] V. Amebegaokar *et al.*, Phys. Rev. B **21**, 1806 (1980).
[11] D. J. Bishop and J. D. Reppy, Phys. Rev. B **22**, 5171 (1980).
[12] A. I. Larkin and Yu. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).
[13] D. R. Nelson, Phys. Rev. Lett. **60**, 1973 (1988).
[14] See B. Jeaneret *et al.*, Appl. Phys. Lett. **55**, 2336 (1989), and references within.
[15] E. H. Brandt, Phys. Status Solidi B **77**, 551 (1976).
[16] L. Krusin-Elbaum *et al.*, Phys. Rev. Lett. **67**, 3156 (1991).
[17] A. P. Young, Phys. Rev. B **19**, 1855 (1979); B. I. Halperin and D. R. Nelson, Phys. Rev. B **19**, 2457 (1979).
[18] For a more detailed analysis of the dynamics of two-dimensional melting, see A. Zippelius, B. I. Halperin, and D. R. Nelson, Phys. Rev. B **22**, 2514 (1980).
[19] S. Yoshizumi, W. L. Carter, and T. H. Geballe, J. Non-Cryst. Solids **61 & 62**, 584 (1984).
[20] W. R. White, A. Kapitulnik, and M. R. Beasley (to be published).