# Vortex Dynamics in Two-Dimensional Amorphous $Mo_{77}Ge_{23}$ Films

M. C. Hellerqvist, D. Ephron, W. R. White,* M. R. Beasley, and A. Kapitulnik
*Department of Applied Physics, Stanford University, Stanford, California 94305*
(Received 29 August 1995)

We have investigated the effects of an applied current on the vortex dynamics in thin films of amorphous superconducting $Mo_{77}Ge_{23}$. At high currents, we see evidence of an ordering of the moving vortices in the flux flow regime. At lower currents and at very low temperatures, we see evidence of plastic and filamentary flow. We compare our data to recent theories of ordering and phase transitions in the moving vortex lattice. [S0031-9007(96)00252-9]

PACS numbers: 74.25.Dw, 74.60.Ge, 74.60.Jg, 74.76.–w

Much attention has focused lately on the issue of current induced ordering of vortices in superconductors. Recent experimental [1–7], theoretical [8,9], and computer simulation [8,10,11] work has put forth a scenario in which a pinned vortex configuration responds to an applied current by flowing plastically at first, and then becoming more ordered, possibly forming a lattice, at higher applied currents. On the experimental side, recent work on 2H-$NbSe_2$ [1,2,4–7] indicates that, in a given range of temperature and field, increasing the applied current causes the system to undergo a crossover from a state dominated by plastic deformations to a state dominated by elastic deformations of the vortex lattice. The possibility of a current induced increase in the spatial order of the vortex state has also been invoked to explain experimental results in superconducting/insulating multilayers of $Mo_{79}Ge_{21}$/Ge [3]. The nature of this current induced ordering and its dependence on dimensionality are, however, still in question. In a recent theoretical work [8], Koshelev and Vinokur proposed that a true phase transition from a plastically flowing state to a moving defect-free crystal occurs at high currents in two-dimensional systems. A recent analysis of driven charge density waves finds that, in that system, a moving solid phase is stable in three dimensions but not in two [9]. In general, simulations show that the defect density in the plastically flowing vortex configuration drops sharply as the ordering occurs [8,10,11].

In this paper, we present an investigation of the vortex dynamics in two-dimensional thin films of amorphous $Mo_{77}Ge_{23}$. We have observed strong evidence of an increase in the lattice correlations of the moving vortices at high currents. At very low temperatures, we find that the onset of vortex motion occurs very abruptly as the current is increased, and that the initial motion exhibits characteristics of plastic flow. While this type of dynamics has been seen in the three-dimensional 2H-$NbSe_2$ system [1,2,4–7], we note that our $Mo_{77}Ge_{23}$ samples are considerably more disordered than 2H-$NbSe_2$, and that our work is the first to present results in a strictly two-dimensional system. Moreover, we are able to make direct comparisons between our data and the predictions of Koshelev and Vinokur [8], and we find that the current vs temperature line characterizing the ordering in our data agrees in form with that predicted in Ref. [8].

The experiments were performed on thin films grown by multitarget sputtering as described elsewhere [12]. Amorphous $Mo_{77}Ge_{23}$ is a strongly type II superconductor, with bulk penetration depth $\lambda(0) = 7700$ Å and Ginzburg-Landau coherence length $\xi(0) = 55$ Å ($\kappa \approx 140$). The films are well within the two-dimensional regime (60 Å thick), and have $T_c$'s of approximately 5.5 K. The pinning in these films is moderate; the measured critical current densities are $J_c \sim 10^4$ A/cm$^2$, which is less than 1% of the depairing critical current for this material. The films were wet etched into four-point electrical measurement patterns (sample area being measured is 0.5 mm wide, 2.8 mm long), and standard low-frequency lock-in techniques were used to measure the differential resistance $\partial V/\partial I$ as a function of an applied current in a perpendicular magnetic field. The magnetic fields were all well below $H_{c2}$ [$H_{c2}(0) \sim 11$ T].

Figure 1 shows a set of $\partial V/\partial I$ vs $I$ curves and the corresponding $V$ vs $I$ curves for an applied field of 0.5 kOe. The $\partial V/\partial I$ vs $I$ curves were measured with the sample immersed in liquid helium to minimize heating effects, which are absent. The $V$ vs $I$ curves were obtained by integration of the $\partial V/\partial I$ vs $I$ curves (and confirmed

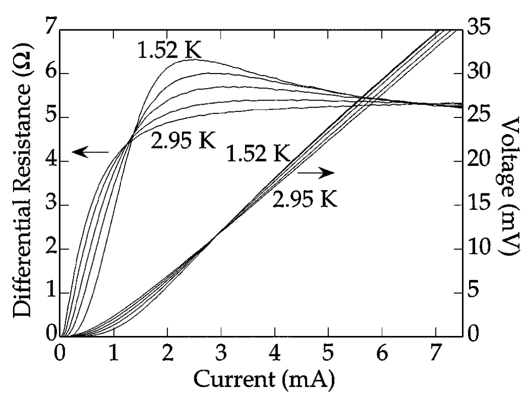


FIG. 1. Differential resistance and voltage vs current at 1.52, 1.92, 2.29, 2.63, and 2.95 K in an 0.5 kOe perpendicular applied field.

 

by occasional direct measurement of $V$ vs $I$). For each isotherm shown in Fig. 1, the curve measured after an initial field cooling of the sample is identical to the curves measured after a cycling of the current. Two interesting features of these data that we will discuss in detail below are the pronounced peak in the $\partial V/\partial I$ vs $I$ curves that arises at low temperatures and the rather sharp crossing points in both the $\partial V/\partial I$ vs $I$ and $V$ vs $I$ sets of curves.

First let us consider the peak in the differential resistance. As seen in Fig. 1, there is no peak in the high temperature curves. The highest temperature $\partial V/\partial I$ vs $I$ curve shown rises monotonically with increasing $I$ and asymptotically approaches the flux flow value. (The value of the zero temperature flux flow resistance calculated from the Bardeen-Stephen theory with known material parameters is 5.5 $\Omega$.) The corresponding $V$ vs $I$ curve also exhibits a smooth monotonic rise and asymptotic approach to its linear flux flow behavior. Curves measured at higher temperatures (not shown) are qualitatively similar. All of this corresponds to the classical flux flow picture.

The behavior of the low temperature curves is different. In the lowest temperature curves shown, we see that a kink in the $V$ vs $I$ curve signifies a range of current over which the differential resistance exceeds the flux flow value, as shown by the peak in the $\partial V/\partial I$ vs $I$ curves. These features arise below a field-dependent temperature and become more pronounced in curves measured at lower temperatures.

The idea that an applied current can cause vortices to order in the presence of pinning is a simple expression of the fact that an applied current tilts the disorder potential, thereby reducing the effective pinning strength. Much work to date [1–3,6,8,10,11] suggests that a peak in the differential resistance indicates such an ordering of the vortices. The peak arises since $\partial V/\partial I$ at first increases as a current is applied and the vortices depin and flow defectively, and then drops as the vortices order and the dynamic friction they experience decreases. The ordering can be seen explicitly in the computer simulations [8,10,11] in which a peak in $\partial V/\partial I$ is associated with a drop in the defect density of the moving vortex configuration. Although some simulations indicate that the defect density drops sharply to a vanishingly small value, it seems plausible that for moderate to strong pinning not all defects disappear. The peak then indicates some increase in the order of the system of vortices, but not necessarily a crossover to a fully ordered state. The fact that $\partial V/\partial I$ levels off at high currents does suggest that the defect density is no longer changing in that high current regime.

If we characterize the occurrence of ordering, for each temperature, by the current corresponding to the peak in the differential resistance, then we can plot an $I_{\mathrm{peak}}$ vs $T$ curve that defines a rough boundary between the more and less ordered regimes. This $I_{\mathrm{peak}}$ vs $T$ curve, shown as the upper curve in Fig. 2, qualitatively resembles the phase boundary curve separating a plastically flowing vortex system from

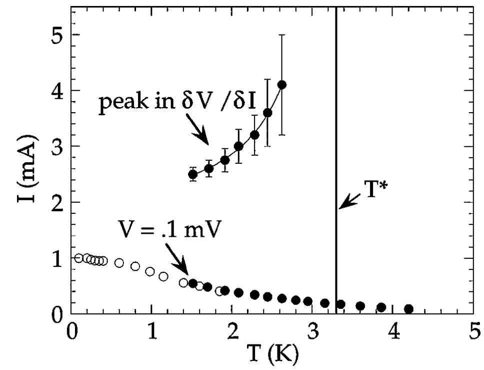


FIG. 2. Diagram showing the temperature dependences of the currents associated with the onset of flux motion (lower curve, open dots are data taken in the dilution refrigerator) and with the ordering at high currents (upper curve). Line connecting the upper data points is a fit to $I_{\mathrm{peak}} = I_0 + c'/(T^* - T)$.

a moving solid proposed by Koshelev and Vinokur for a two-dimensional system [8]. According to Koshelev and Vinokur, the current needed to cause the ordering is of the form $I_{\mathrm{peak}} = I_0 + c'/(T^* - T)$, diverging at the clean system's melting temperature. Fitting our $I_{\mathrm{peak}}$ vs $T$ data by this equation generates the solid line connecting these data points in Fig. 2. This fit by $I_{\mathrm{peak}}$ diverges at $T^* = 3.3$ K, which is marked by the vertical line in Fig. 2. The temperature at which our system should undergo a dislocation mediated melting transition can be calculated from known materials parameters and the equation $T_m = A\Phi_0^2 d/256\pi^3\lambda^2$, where $d$ is the film thickness and $A$ is a constant of order 1 which accounts for the renormalization of the shear modulus due to thermal fluctuations [13,14]. Using this equation, we find that the temperature at which our $I_{\mathrm{peak}}$ diverges, 3.3 K, corresponds to a value of $T_m$ calculated using a value of $A = 0.97$, which is a very reasonable value.

To further characterize this ordering, we reexamine the $V$ vs $I$ curves shown in Fig. 1. At higher currents, the $V$ vs $I$ curves all exhibit a well-defined linear region of flux flow. If we extrapolate this linear $V(I) = (I - I_c)R_{\mathrm{ff}}$ back to the current axis, as illustrated in the inset of Fig. 3, the current axis intercept gives us the dynamical critical current $I_c(T)$, which is illustrated in Fig. 3. This extrapolated critical current is proportional to the average pinning force that the vortices feel in the flux flow regime. Therefore, the fact that $I_c(T)$ decreases as the temperature drops below $T^*$ (indicated in Fig. 3 as in Fig. 2) suggests that the rigidity of the moving system of vortices increases as the temperature is lowered below $T^*$. The pinning in these films at low temperatures has previously been shown to be collective [15], so the theory of Larkin and Ovchinnikov [16] can give us a qualitative idea of the origin of this increase in the rigidity of the moving vortex configuration. In this theory, the transverse correlation length is given by $R_c \propto \sqrt{1/I_c}$. Hence, the drop in $I_c(T)$ at low temperatures implies an increase in the correlation area in the flux flow regime.

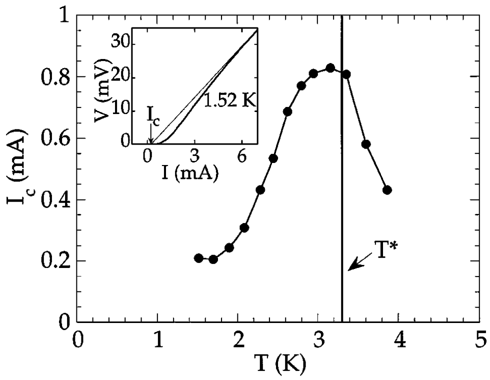


FIG. 3. Critical current vs temperature in an 0.5 kOe applied field. $T^*$ indicated as in Fig. 2. Line connecting the dots is a guide to the eye. Inset: Integrated 1.52 K $V$ vs $I$ curve and the extrapolation from the flux flow regime to obtain the critical current.

The drop in $I_c(T)$ and the peaks in the $\partial V/\partial I$ vs $I$ curves are both observed at temperatures below $T^*$, and both pieces of evidence point to an ordering of the system at high currents in this temperature range. The peak in the differential resistance characterizes the current at which the ordering occurs for a given temperature. The decreasing $I_c(T)$ indicates an increasing order in the moving vortex configuration (in the high current limit beyond the peak) as the temperature is lowered below $T^*$. However, we have no direct evidence indicating that the resulting more ordered state is the crystalline solid state proposed in the simulations of Refs. [8,10].

As noted above, the second striking feature of the data is the crossing points in both the $\partial V/\partial I$ vs $I$ and $V$ vs $I$ curves shown in Fig. 1. We have investigated fields from 0.2 to 2 T and find that, up to a well-defined temperature which decreases as the field is increased, the isotherms exhibit similar crossings in each field. These crossings are quite sharp; the spread of the $\partial V/\partial I$, $V$, and $I$ values about the crossing points is less than 3% of their respective values at the crossing. While such crossing behavior often indicates phase transitions, determining the nature of the crossings in our data will require further investigation. We can, however, draw some simple conclusions. In each field investigated, the crossing of the $\partial V/\partial I$ isotherms occurs before the peak at a value of $\partial V/\partial I$ proportional to the applied field and close to the flux flow resistance. The $V$ vs $I$ isotherms also cross at a value of $V$ proportional to the applied field and corresponding to a resistance within a factor of 2 of the flux flow resistance. The field dependences and resistances of these crossing points suggest that the entire vortex system is in motion at the crossing points. For both the $\partial V/\partial I$ vs $I$ and $V$ vs $I$ curves, the $I$ values at which the isotherms cross in various applied fields follow an $I \propto 1/\ln(H)$ dependence. Such a weak field dependence of the crossing force is characteristic of two-dimensional collective effects.

To further investigate the behavior at low $I$, we measured $\partial V/\partial I$ vs $I$ curves in a dilution refrigerator down to a temperature of 100 mK. Because of the difficulty of heating the sample above $T_c$, all of the curves taken in the refrigerator were measured after an initial cycling of the current. We note that the high $I$ peak in $\partial V/\partial I$ which we associate with the ordering persists to the lowest temperature measured. However, we cannot say anything quantitative about this feature as measured in the refrigerator since, at such low temperatures, the large currents involved produce observable heating in the sample. Nonetheless, a peak is observed, and the fact that $\partial V/\partial I$ drops on the high current side of the peak as $I$ and thus sample heating are increasing indicates that the feature is present and real.

Figure 4 shows several $\partial V/\partial I$ vs $I$ curves measured with $I$ decreasing at temperatures between 600 and 100 mK. These data are well below the current region associated with the peak in $\partial V/\partial I$ discussed above. We see that the initial rise of $\partial V/\partial I$ becomes more abrupt, eventually evolving into a second smaller peak which exhibits a reproducible jagged internal structure. These curves also exhibit hysteresis at the lowest temperatures (below 300 mK in 0.5 kOe), as shown in the insets of Fig. 4.

The abruptness of the initial rise of $\partial V/\partial I$ with increasing $I$ suggests that the vortex configuration is tenuously pinned immediately before this initial rise. We investigate this by varying the rate at which $I$ is swept as hysteresis loops are measured. In doing these measurements, $I$ is always stepped by 1.16 $\mu$A, and the step rate is varied. The insets to Fig. 4 each show ten hysteresis loops, measured with the mixing chamber at 150 mK. The $I$ step interval is 1.5 s in the upper inset and 27.3 s in the lower inset. With the slower sweep rate (lower inset), we see that the initial rise in $\partial V/\partial I$ occurs at different $I$ values for different curves and that $\partial V/\partial I$ exhibits intermediate steps. Further increasing the $I$ step interval results in initial jumps in $\partial V/\partial I$ occurring at even lower values of $I$. With the

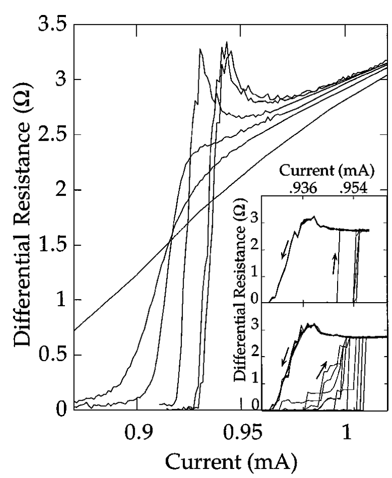


FIG. 4. Differential resistance vs current at 100, 200, 300, 350, 400, and 600 mK in an 0.5 kOe applied field. Insets: Each shows 10 hysteresis loops measured with the mixing chamber at 150 mK in an 0.5 kOe applied field. Arrows indicate increasing or decreasing current. $I$ is swept at a rate of 0.773 $\mu$A/s for the upper inset and 0.0425 $\mu$A/s for the lower inset.

faster $I$ sweep rate (upper inset) no intermediate steps are observed, and the initial jump in $\partial V/\partial I$ generally occurs at higher values of $I$. These data suggest that the widths of the observed hysteresis loops are limited by noise in the system. In fact, we found that deliberately introducing noise into the system could cause $\partial V/\partial I$ to jump between intermediate steps or all the way to its value on the $I$ decreasing part of the loop. The intermediate steps suggest defective flow in which some vortices are moving and others remain pinned.

We now focus on the distinctive jagged structure seen in the lower temperature curves in Fig. 4. This feature is reproducible, even if $H$ and $T$ are varied and then returned to the values of the measurement. This type of fingerprint feature has been observed in 2H-$NbSe_2$ in the field and temperature range of plastic, filamentary vortex motion in that material, and has been interpreted as evidence of such defective flow [6].

At the lowest temperatures (as in the insets of Fig. 4) the fingerprint is observed only in the $I$ decreasing portion of the hysteresis loop. However, at higher temperatures, the $I$ increasing and decreasing portions of the hysteresis loops merge earlier and the fingerprint is observed with $I$ both increasing and decreasing. The fingerprint in the $I$ decreasing portion of the loop is not affected by the $I$ sweep rate, which suggests that all of our sweep rates are slow enough to allow the vortices to relax to an equilibrium configuration as $I$ is reduced.

These low temperature data strongly suggest a tenuously pinned vortex configuration, deforming plastically as some vortices begin to flow while others remain pinned. The power levels are such that, when we measure at the lowest temperatures, the sample is almost certainly at a slightly higher temperature than the mixing chamber of the dilution refrigerator. However, we do not believe that heating is causing the two interesting features of our data: the intermediate steps in the $\partial V/\partial I$ vs $I$ curves and the fingerprint. While heating could cause hysteresis, we would expect heating to lead to runaway increases of $\partial V/\partial I$ (up to at least the flux flow value) as $I$ is increased (and vortices begin to move and heat, thereby depinning more vortices), not the intermediate steps which we observe. Also, the jagged structure of the fingerprint is not likely due to heating, and we have noted that the fingerprint is independent of the current sweep rate. We note that the system which we are studying, in which vortices are mobile in some portions of the sample while pinned in others, will unavoidably generate some thermal gradients in the sample as the mobile vortices induce some local heating. Since these two features of the data so strongly suggest plastic flow, we have included these data with the caveat about heating effects. We again point out that the higher temperature data taken in the cryostat ($T > 1.5$ K) are not affected by self-heating.

To characterize the abrupt onset of plastic flow and at the same time connect the data to the higher temperature, smoother data, we use a voltage criterion. Integrating the differential resistance curves to obtain the $V$ vs $I$ curves, we choose a criterion of $V = 0.1$ mV to characterize the onset of vortex motion at each temperature. The $I_{onset}$ vs $T$ curves, obtained in the dilution refrigerator and in the cryostat, are shown as the lower curves in Fig. 2. We note that choosing a different voltage criterion does not significantly affect the shape of the $I_{onset}$ vs $T$ curves, and that, in the temperature range in which we have data from both of our experimental setups, the curves overlap. We note again that the phase diagram in Fig. 2, characterizing the onset of plastic flow and the ordering at high currents, is qualitatively similar to that proposed by Koshelev and Vinokur for a two-dimensional system [8].

In conclusion, we have investigated the effects of a current on the vortex dynamics in two-dimensional 60 Å films of $Mo_{77}Ge_{23}$. At sufficiently low temperatures, we see evidence that the vortex motion is plastic at low currents. At higher currents, we find evidence that the vortices undergo an ordering which results in a more rigid moving vortex configuration.

We thank V. Vinokur, A. Koshelev, and S. Bhattacharya for useful discussions. This work was supported by the U.S. Air Force Office of Scientific Research, the Center for Materials Research at Stanford University, and the Office of Naval Research.

*Presently at Bell Labs, Lucent Technologies, 600 Mountain Ave., Murray Hill, NJ 07974.

[1] S. Bhattacharya and M. J. Higgins, Phys. Rev. Lett. **70**, 2617 (1993).
[2] S. Bhattacharya and M. J. Higgins, Phys. Rev. B **49**, 10 005 (1994).
[3] W. R. White, A. Kapitulnik, and M. R. Beasley, Phys. Rev. B **50**, 6303 (1994).
[4] U. Yaron *et al.*, Phys. Rev. Lett. **73**, 2748 (1994).
[5] A. C. Marley, M. J. Higgins, and S. Bhattacharya, Phys. Rev. Lett. **74**, 3029 (1995).
[6] S. Bhattacharya and M. J. Higgins, Phys. Rev. B **52**, 64 (1995).
[7] U. Yaron *et al.*, Nature **376**, 753 (1995).
[8] A. E. Koshelev and V. M. Vinokur, Phys. Rev. Lett. **73**, 3580 (1994).
[9] L. Balents and M. P. A. Fisher, Phys. Rev. Lett. **75**, 4270 (1995).
[10] A.-C. Shi and A. J. Berlinsky, Phys. Rev. Lett. **67**, 1926 (1991).
[11] S. Ryu (private communication).
[12] S. Yoshizumi, W. L. Carter, and T. H. Geballe, J. Non-Cryst. Solids **61/62**, 589 (1984).
[13] B. A. Huberman and S. Doniach, Phys. Rev. Lett. **43**, 950 (1979).
[14] D. S. Fisher, Phys. Rev. B **22**, 1190 (1980).
[15] W. R. White, A. Kapitulnik, and M. R. Beasley, Phys. Rev. Lett. **70**, 670 (1993).
[16] A. I. Larkin and Yu. N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).