Current-induced ordering of vortices in two-dimensional amorphous $Mo_{77}Ge_{23}$ films as a function of film thickness and magnetic field

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We present experimental evidence that high currents induce an ordering of the moving vortex configuration in thin films of amorphous $Mo_{77}Ge_{23}$. This ordering is observed for a wide range of film thicknesses and applied magnetic fields. Our experimental results are in qualitative agreement with recently published theories and simulations of dynamic ordering of vortices. [S0163-1829(97)05234-X]

The issue of current-induced phase transformations and, in particular, spatial ordering of vortices has recently received much attention. Experimental,[1–9] theoretical, and simulations investigations[10–17] have shown convincingly that high currents can induce an increase in order of the moving vortex configuration in the flux flow regime.

Previously, we demonstrated this kind of current-induced ordering in an applied field of 0.5 kG in 2D, 60 Å films of amorphous $Mo_{77}Ge_{23}$ with moderate pinning and T_c's of $\sim$5.5 K.[9] Our data showed that, at sufficiently low temperatures, as the current is slowly increased the vortices begin to move in a highly defective manner. Then at higher currents, in the flux flow regime, the order of the moving vortex system abruptly increases. The conclusions drawn from our data were consistent with those drawn from simulations of such a dynamic ordering in 2D systems.[10,11,13,14,16,17]

In this paper we investigate the current-induced ordering of vortices as a function of magnetic field in a 60 Å film, and as a function of film thickness for a fixed magnetic field. Varying these parameters is essentially equivalent to changing the relative strengths of the intervortex interactions and the disorder potential. Our main result is that we see evidence of current-induced orderings in all of the fields and samples studied. For a given sample and field, we can extract from the data a line in the J-T plane characterizing the ordering. Comparing the form of this line to that predicted by the theoretical treatment of Koshelev and Vinokur,[11] we find good agreement in films of high disorder at low magnetic fields, and we find that the agreement breaks down at higher magnetic fields and in less disordered films.

All of our experiments were performed on thin films of amorphous $Mo_{77}Ge_{23}$, grown by multitarget sputtering as described elsewhere.[18] This material is strongly type II, with bulk penetration depth $\lambda(0)=7700$ Å and Ginzburg-Landau coherence length $\xi(0)=55$ Å ($\kappa\approx140$). We studied films of thicknesses 60, 120, and 300 Å with T_c's of 5.5, 6.1, and 6.6 K, respectively. All of these films are strictly 2D with respect to vortex motion. The pinning in all of these films is moderate; the measured critical current densities, using a voltage criterion are $J_c\sim10^4$ A/cm^2, which is less than 1% of the depairing critical current for this material. The films were wet etched into four-point contact 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 I in a perpendicular magnetic field. V vs I curves were obtained by integrating the $\partial V/\partial I$ vs I curves, and a few V vs I curves were measured directly to verify that the integration is valid. The magnetic fields were all well below H_{c2} [$H_{c2}(0)\sim11$ T]. All data were taken with the samples immersed directly in liquid helium to eliminate heating effects.

Figure 1 shows a set of $\partial V/\partial I$ vs J isotherms measured on the 120 Å film in an applied field of 0.5 kG, and the corresponding V vs J isotherms. Such data sets measured on any of the samples in any of the fields mentioned are qualitatively similar to this, and we here describe the common features of the data sets. At high currents, the isotherms all level off at a value of $\partial V/\partial I$ that agrees well with the calculated Bardeen-Stephen flux flow value, which is 2.7 Ω for the sample and field shown in Fig. 1. For each sample and field, the higher temperature $\partial V/\partial I$ vs J isotherms rise monotonically to the flux flow value as J increases. This behavior, exhibited by the highest temperature isotherm shown in Fig. 1, is consistent with the expected flux flow picture. However, below a certain temperature, which is field and film thickness dependent, the $\partial V/\partial I$ vs J isotherms exhibit a peak before leveling off at the flux flow value. This peak corresponds to an inflection point in the V vs J curve and is more pronounced at lower temperatures. Although the data look qualitatively similar for all of the samples and fields we studied, the $\partial V/\partial I$ vs J and V vs J curves, and all of their features, shift to lower current densities with increasing field or film

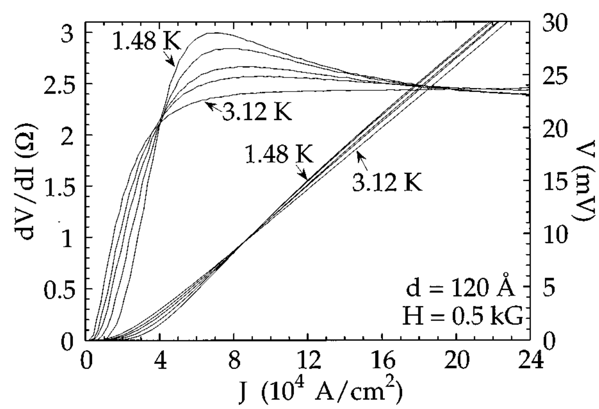

FIG. 1. $\partial V/\partial I$ and V vs J at 1.48, 2.00, 2.41, 2.70, 3.12 K in a 120 Å film in 0.5 kG.

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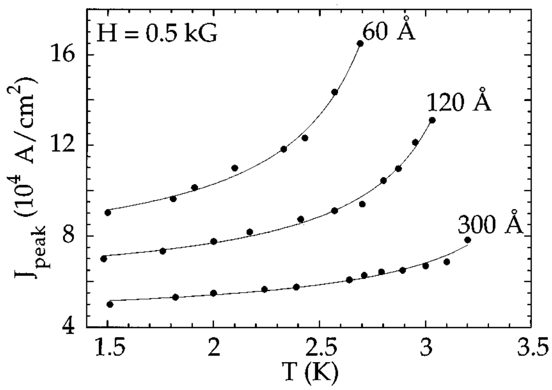

FIG. 2. J_{peak} vs T for the 60, 120, and 300 Å films in 0.5 kG.

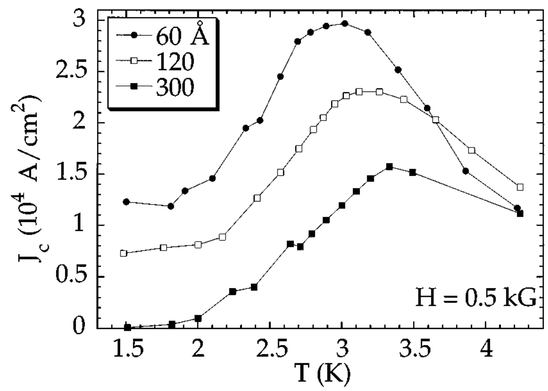

FIG. 3. J_c vs T for the 60, 120, and 300 Å films in 0.5 kG.

thickness. The intriguing crossings in both the $\partial V/\partial I$ vs J and V vs J isotherms are present for all of the samples and fields studied; we will discuss these crossings later.

Peaks in $\partial V/\partial I$ curves such as we observe suggest an ordering of the vortices in the flux flow regime. The basic idea of such a dynamic ordering is that, in a disordered 2D film at low temperatures and zero applied current, the random pinning potential prevents the intervortex interactions from ordering the vortices into a lattice. A current tilts the pinning potential, thereby reducing the pinning effectiveness. At sufficiently high currents, the pinning effectiveness will be sufficiently reduced that the effect of the intervortex interactions will bring about an increase in order in the moving vortex system.

Simulations of 2D systems have characterized the order in a vortex configuration as a function of current.[10,11,13,14,16,17] These simulations generally find that as the current is first applied, $\partial V/\partial I$ increases as vortices become depinned and begin to move plastically. At higher currents, a dynamic ordering of the moving vortices occurs, characterized by a sharp drop in the defect density in the moving lattice and by an inflection point in the simulated V vs I curve which corresponds to a peak in the simulated $\partial V/\partial I$ vs I curve.

The simulations all produce results which are qualitatively similar to our experimental results. While some simulations find that the current-induced ordering results in a perfect vortex lattice,[10,11] others find that some disorder persists in the high current limit.[13,16,17] We see no experimental evidence that the ordering is complete; the fact that we see $\partial V/\partial I$ drop abruptly and then level off suggests that whatever ordering does occur takes place over a limited current range.

Taking the current at the peak of each low temperature $\partial V/\partial I$ vs J isotherm to characterize the dynamic ordering at that temperature, we can draw a J_{peak} vs T curve characterizing the dynamic ordering in each sample for a fixed field. Figure 2 shows such J_{peak} vs T curves for the 60, 120, and 300 Å films in 0.5 kG. These curves are all qualitatively similar to the J vs T line found in the work of Koshelev and Vinokur to separate the region of plastically flowing vortices from the region of a moving crystal. Koshelev and Vinokur find that this J vs T curve should be of the form $J \propto 1/(T^* - T)$, where T^* is the clean system's melting temperature. The solid lines in Fig. 2 are fits to this formula, where we have used T^* as a fitting parameter. These fits give T^* values of 3.1, 3.4, and 3.9, for the 60, 120, and 300 Å films, respectively.

We can compare our experimental T^* values to the theoretical values for the melting temperature. Using known materials parameters, we calculate the temperatures at which our three films would, in the absence of disorder and not considering any effects due to current, undergo a dislocation mediated melting using the formula $T_m = Ac_{66}(T_m, H)da_0^2/4\pi k_b$, where $c_{66}(T,H)$ is the form of Brandt,[19] d is the film thickness, and A is a constant of order one which accounts for the renormalization of the shear modulus due to thermal fluctuations.[20,21] For the purpose of the calculation, we take $A=1$, which is the value found in measurements of melting in thicker films of amorphous $Mo_{77}Ge_{23}$.[22] For the 60, 120, and 300 Å films, the calculated T_m values are 3.3, 4.8, and 6.0 K, and the fitted T^* values are 3.1, 3.4, and 3.9 K, respectively. Thus, while we see in Fig. 2 that all of these fits to the form of the Koshelev-Vinokur equation work reasonably well, for $A=1$, the agreement between the T_m and T^* values becomes less reasonable as the film thickness is increased.[23] We point out that the Koshelev-Vinokur[11] treatment is for the strong pinning limit, and, as we will show below, the disorder in our samples decreases with increasing film thickness. We also point out that the T^* values determined by our fits are quite sensitive to the highest temperature ordering current we measured, especially in the thicker samples in which the increase of the ordering current with temperature is most abrupt.

To further characterize the dynamic ordering, we return to the V vs J curves in Fig. 1. At high currents, these curves are linear as expected in the flux flow regime. Extrapolating this linear flux flow $V(I) = (I - I_c)R_{ff}$ back to the current axis gives us the dynamical critical current $I_c(T)$, which is proportional to the dynamic friction that the pinning sites exert on the moving vortices in the flux flow regime. Figure 3 shows the extrapolated critical current density vs temperature curves for the 60, 120, and 300 Å films in 0.5 kG. For each sample, $J_c(T)$ attains a maximum value near the temperature T^* determined for that sample in this field, and drops as the temperature is lowered below T^*. This suggests that, as the temperature is lowered below T^*, the dynamic friction that the pinning sites exert on the moving vortices drops sharply. This interpretation is consistent with the moving vortices undergoing an ordering at that temperature in the flux flow regime.

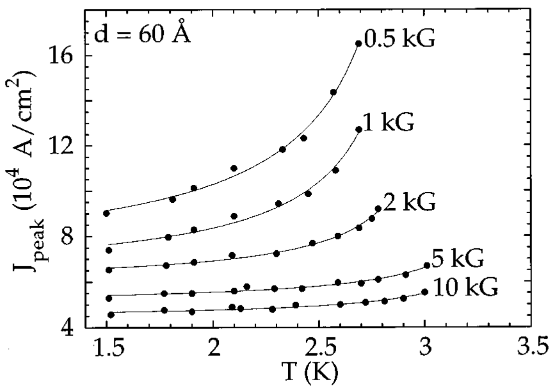

FIG. 4. J_{peak} vs T for the 60 Å film in 0.5, 1, 2, 5, and 10 kG.

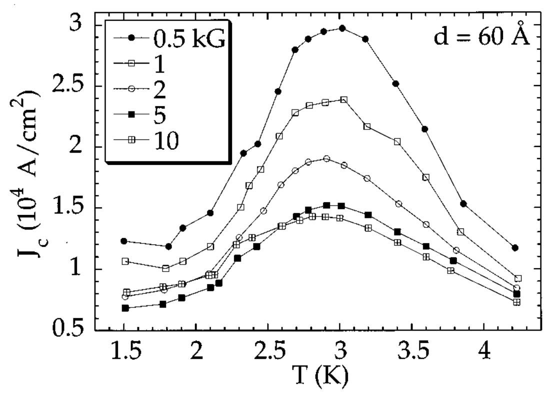

FIG. 5. J_c vs T for the 60 Å film in 0.5, 1, 2, 5, and 10 kG.

Since the pinning in these films at low temperatures has previously been shown to be collective,[24] the theory of Larkin and Ovchinnikov[25] allows us to estimate roughly the extent of the ordering. Using the expression for the transverse correlation length, $R_c \propto \sqrt{1/J_c}$, we can roughly estimate that the drops in $J_c(T)$ imply increases in the transverse correlation lengths by factors of 1.6, 1.8, and 12 in the 60, 120, and 300 Å films, respectively, between each sample's T^* and 1.5 K.

The J_{peak} vs T curves and J_c vs T curves both suggest an ordering in the flux flow regime. While the J_{peak} vs T curves indicate the current at which the dynamic ordering occurs for a given temperature, the drops in $J_c(T)$ indicate that as the temperature is lowered below T^*, there is an increase in order in the moving vortex system in the high current limit beyond the current of the differential resistance peak. We note that the J_{peak} vs T and J_c vs T curves are consistent with the picture of a dynamic ordering occurring when an applied current reduces the pinning effectiveness so that the intervortex interactions are able to bring about the ordering. For these three samples in 0.5 kG and at any temperature, the thicker the film, the lower $J_c(T)$. This indicates that pinning effectiveness decreases as film thickness increases. Therefore, a lower current density should be required to bring about the dynamic ordering in the thicker films, and our J_{peak} vs T curves do, in fact, shift to lower current densities for thicker films.

Now we turn to a study of dynamic ordering as a function of magnetic field in the 60 Å film. Figure 4 shows the J_{peak} vs T curves characterizing the dynamic ordering for this film in fields of 0.5, 1, 2, 5, and 10 kG. Again, the solid curves are fits to the form $J \propto 1/(T^* - T)$ predicted by Koshelev and Vinokur to describe the phase boundary separating regions of defective and nondefective vortex motion. For applied fields of 0.5, 1, 2, 5, and 10 kg, the T^* values obtained from the fits to the J_{peak} vs T curves are 3.1, 3.1, 3.2, 3.5, and 3.5 K, and calculated T_m values are 3.3, 3.3, 3.2, 3.0, and 2.6 K, respectively. We see from the figure that the fits to the Koshelev-Vinokur form work reasonably well, however, for $A=1$, the agreement between the experimental T^* values and the calculated T_m values deteriorates at higher fields.[23] We again point out that the Koshelev-Vinokur treatment[11] is for the strong pinning limit, and that the effect of disorder relative to intervortex interactions is greater in lower fields. We also note again that the fits are very sensitive to the highest temperature ordering currents we measure, especially in the higher fields in which the J_{peak} vs T curves rise much more abruptly with temperature.

Figure 5 shows the J_c vs T curves for the 60 Å film in these fields. Again, for each field, $J_c(T)$ attains a maximum value near that field's T^* and drops as the temperature is lowered below T^*. Again using the Larkin-Ovchinnikov expression to estimate roughly the degree of ordering, we find that the drops in $J_c(T)$ imply increases in the transverse correlation lengths by factors of 1.6, 1.5, 1.6, 1.5, and 1.33 in fields of 0.5, 1, 2, 5, and 10 kG, respectively, as the temperature is lowered from each field's T^* to 1.5 K.

The J_c vs T and J_{peak} vs T curves both suggest a dynamic ordering in the flux flow regime for the 60 Å film in each of these fields. We note that, for this 60 Å film and a given temperature, the higher the field, the lower the $J_c(T)$. This indicates, as we would expect, that the lattice is stiffer at higher fields. In our picture of ordering, we expect a stiffer lattice to require a lower current to reduce the pinning effectiveness sufficiently to allow the intervortex interactions to order the moving vortices, and our J_{peak} vs T curves do move to lower current densities at higher fields.

Finally, we turn to the crossing points, evident in both the $\partial V/\partial I$ vs J and V vs J isotherms of Fig. 1. We find similar crossing points in all samples and fields studied. The crossings are always quite sharp; the spread of $\partial V/\partial I$, V and J values about the crossings is always less than 3% of their respective values at the crossing. Looking at the 60 Å film in various fields, we find that the crossings of both the $\partial V/\partial I$ vs J and the V vs J isotherms occur at J values which can be fit with a $J \propto 1/H^{\alpha}$ form, with α a very small number. The denominator can also be fit with a ln(H) form. In all samples and fields studied, the crossings of the $\partial V/\partial I$ vs J isotherms occur at a value of $\partial V/\partial I$ close to the flux flow value.

While the exact nature of these crossing points is not understood, numerical simulations using parameters appropriate to our 60 Å film in 0.5 kG generate $\partial V/\partial I$ vs I isotherms which strikingly resemble our experimental data and exhibit a similar crossing point.[13] In the simulations, this crossing occurs at a current value at which the hexatic order parameter of the vortex system is at a minimum, and at which the fraction of pinned vortices begins to decrease markedly.

In conclusion, we have found evidence that a dynamic ordering of the vortices in the flux flow regime occurs in our 60 Å film in fields from 0.5 to 10 kG, and in films of thicknesses 60, 120, and 300 Å in an applied field of 0.5 kG. Our data are consistent with the picture, put forth in experiments and simulations, that the ordering occurs when the current suppresses the pinning potential sufficiently to allow intervortex interactions to dominate the disorder potential. Stiffening the lattice by increasing either the film thickness or the applied field reduces the current density required to bring about the dynamic ordering.

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