Anomalous temperature dependence of vortex elastic properties in the flux-flow regime of $Mo_{77}Ge_{23}$/Ge multilayer superconductors

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We report nonlinear electrical response in superconducting/insulating $Mo_{77}Ge_{23}$/Ge multilayers. In low-anisotropy multilayers, we observe an abrupt change in the current-voltage characteristic as a function of temperature. This change corresponds to a sharp drop in the pinning drag force acting on moving vortices in the flux-flow regime at low temperatures. The decrease in pinning drag force may be related to an abrupt increase in the rigidity of the system of moving vortices.

For many years, it has been known that the mean-field phase diagram of an isotropic, homogeneous type-II superconductor includes an Abrikosov lattice of vortices between the upper and lower critical fields. Subsequently, it was recognized[1,2] that thermal fluctuations and static disorder could both modify the lattice phase, particularly in two dimensions. When both effects are present, the interplay between them is complicated and still not completely understood. In cuprate superconductors and artificially layered superconductors, the anisotropic nature of the material enhances[3] the tendency of pinning and thermal fluctuations to modify, or even destroy, the Abrikosov lattice.

In limiting cases, substantial progress has been made in understanding aspects of this problem. One such case is the destruction of long-range vortex translational order by pinning in an isolated two-dimensional superconductor. Here, the collective pinning theory[2] of Larkin and Ovchinnikov provides a relationship between the translational correlation length R_C and a readily measurable quantity, the critical current density J_C, at which the pinning force on a correlation volume is balanced by the Lorentz force arising from the transport current. This theory has been quite successful[4] in understanding the measured critical current densities of relatively thick superconducting films with weak pinning.

In layered superconductors, no simple picture exists for quantitatively relating the translational correlation to the measured critical current densities. Still, the critical current density measures the average pinning force density acting on vortices. If the pinning forces are random, this measurement might reasonably be expected to yield qualitative information about the field and temperature dependence of the correlation volume of collectively pinned vortices.

In this paper, we are concerned with the nature of these correlations in the dynamic, flux-flow state. To this end, we report measurements of the nonlinear electrical response of amorphous $Mo_{77}Ge_{23}$/Ge (superconducting/insulating) multilayer model systems in a perpendicular magnetic field. In the samples discussed here, the superconducting layer thickness remains constant at $d_s = 60$ Å, and the Ge layer thickness varies from $d_i = 25$ Å to $d_i = 65$ Å. For purposes of comparison, we have also fabricated a $d_s = 60$ Å single layer sample that is equivalent to the constituent superconducting layers of each multilayer. In the lower anisotropy multilayers, measurements of the pinning drag force acting on vortices in the flux-flow regime (i.e., the linear portion of the I-V curve well above the usual critical current I_C at which flux motion exceeds some threshold level set by a voltage criterion), show a sharp decrease in the pinning drag force at low temperatures. This sudden decrease may be related to an abrupt increase in the rigidity of the system of vortices.

The procedures for making $Mo_{77}Ge_{23}$/Ge samples and the physical properties and material parameters of this system have been discussed elsewhere.[5–8] Table I describes the samples and their derived parameters.

In all of these samples, there is a low bias region where the response is linear. The inset of Fig. 1 shows a typical example of this low bias resistance as a function of temperature for different samples measured in a perpendicular magnetic field of 5.0 kG. Figure 1 displays the instantaneous slopes $\partial(\ln R)/\partial(1/t)$ of these Arrhenius curves. These curves are qualitatively related to the temperature dependence of the activation barriers, even though simple thermal activation (i.e., with a temperature-independent activation energy) is not universally observed. Reference 7 discusses these data and their implications in detail. The primary conclusion drawn in this reference was that the samples with $M_Z/M_\perp \geq 160$ show qualitatively different behavior than those with $M_Z/M_\perp \leq 50$. In the high-anisotropy ($M_Z/M_\perp \geq 160$) multilayers, the activation barriers are never significantly different from those

TABLE I. Table of material parameters.

Sample number	Number of SC layers	d_S (Å)	d_i (Å)	T_{CO} (K)	$\xi_Z(0)$ (Å)	$M_Z/M_\perp$
291 089-8	1	60		5.39		
291 091-8	10	60	125	5.35		
289 141-8	10	60	65	5.23	~2.5	~500
289 140-5	10	60	55	5.34	~4.2	~160
289 139-6	10	60	45	5.30	7.6	50
289 137-5	10	60	35	5.22	12.3	20
289 136-7	10	60	25	5.35	~25.1	~5

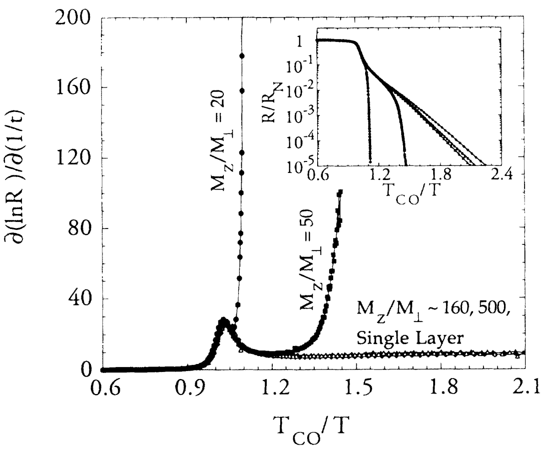

FIG. 1. Instantaneous slopes of Arrhenius curves shown in inset. Inset: Resistive transitions measured in 5.0-kG applied field for a single layer and multilayers with $d_i = \{35, 45, 55,$ and 65 Å$\}$.

in a single layer. This result implies that the vortex discs in each layer of the high anisotropy multilayers are decoupled from those in neighboring layers. In the low anisotropy ($M_Z/M_\perp \leq 50$) multilayers, the activation barriers depart strongly from the single layer result at low temperature, implying that the thermally activated hopping of vortices in different layers at low bias current becomes coupled. In these samples, the activation barriers increase continuously from their single layer values, so only an approximate crossover may be defined between coupled and uncoupled vortex motion. Below, we examine anomalous behavior in the high bias flux-flow regime of these samples. The phenomenon of interest here occurs at temperatures well below the onset of decoupling at low bias, and appears to be distinct from the interlayer coupling seen at low bias.

By measuring dynamic resistance $\partial V/\partial I$ as a function of bias current I, we may observe the nonlinear response of the system. The top panel of Fig. 2 shows $\partial V/\partial I$ vs I for a single-layer sample measured at various temperatures in a 5.0-kG applied field. As expected, this sample shows a smooth crossover from thermally activated flux creep at low bias currents to flux flow at high bias currents. In the flux-flow regime, viscosity limits the vortex velocities; the dynamic resistance is proportional to the perpendicular field and only weakly temperature dependent. The behavior of the $M_Z/M_\perp = 50$ multilayer, (bottom panel of Fig. 2), is distinctly different. Here, a large peak in the dynamic resistance appears abruptly with decreasing temperature. However, the flux-flow resistivity at high bias currents is very close to that of a single layer. Some tendency for dV/dI to continue to increase at high bias can be seen in the data, however.

In the flux-flow regime, the average vortex velocity v is given by $v = (F_L - F_P^d)/\eta$. Here, η is the viscosity, $F_L = J\varphi_0/c$ is the Lorentz force per unit length, and F_P^d is the pinning drag force per unit length, averaged over a correlation volume of the moving vortices. Thus if we numerically integrate $\partial V/\partial I$ to obtain $V(I)$, we may extrapolate the linear $V(I)$ in the flux-flow regime back to the current axis to infer a pinning drag critical current density J_C^d (see Fig. 2 inset). This extrapolated J_C^d is proportional to the average pinning drag force acting on vortices in the flux-flow regime: $F_P^d = J_C^d \varphi_0/c$. Since the effects at pinning are collective, the pinning drag force acting in the flux-flow state may be very different from the pinning forces acting on static vortices, because the intervortex correlations in the flux-flow regime may be different from the static correlations. In the inset of Fig. 2, we show two $V(I)$ curves from the $M_Z/M_\perp = 50$ sample. In the higher-temperature curve, where no peak appears in $\partial V/\partial I$, the extrapolated critical current density is actually substantially higher than in the low-temperature curve, which has a pronounced peak in dynamic resistance. The temperature dependence of the extrapolated J_C^d in various samples is shown in Fig. 3. Here, the sharp drop of J_C^d with decreasing temperature in the $M_Z/M_\perp = 50$ data corresponds to the abrupt appearance of the dynamic resistance peak.

In the $M_Z/M_\perp \sim 160$ sample, $J_C^d(T)$ is essentially equal to that of a single layer, and neither shows an abrupt drop with decreasing temperature. Presumably, a similar result obtains for the $M_Z/M_\perp \sim 500$ sample. It is in-

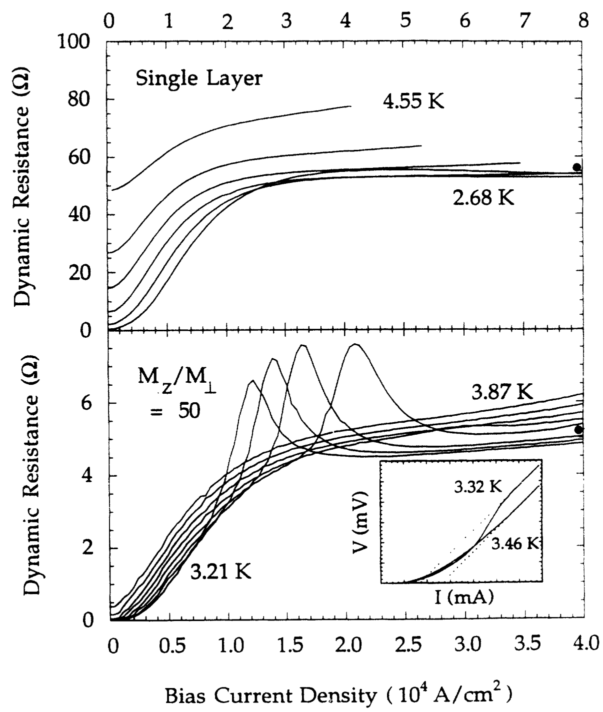

FIG. 2. Dynamic resonance $\partial V/\partial I$ versus bias current density at various temperatures in 5.0-kG applied field for a single layer (top panel) and a $M_Z/M_\perp = 50$ multilayer (bottom panel). The current scale for the top panel appears on the upper current axis. In both panels, the temperatures of the isotherms are approximately evenly spaced, and arrows indicate the Bardeen-Stephen value of the flux-flow resistance at low temperature. The bold dot indicates the flux-flow resistance calculated from Bardeen-Stephen theory. Inset: Numerical integrations of differential curves and extrapolation of critical current from flux-flow regime.

teresting to note that these high anisotropy multilayers also showed no interlayer coupling in their linear response, as discussed previously.[7] In the low anisotropy multilayers, where linear response measurements indicated that vortex discs in adjacent layers become correlated into linelike objects, there also exists a sharp drop in $J_C^d(T)$. In the $M_Z/M_\perp=20$ sample, this jump is shown more clearly in the inset of Fig. 3. While it is difficult to relate reliably to observations made in the linear response to the flux-flow regime, these data are at least suggestive that the drop in $J_C^d(T)$ can occur only when the vortex discs have become correlated into something like vortex lines. Figure 4 offers further evidence for this idea. In this figure, we plot in the H-T plane the interlayer decoupling onset line $T_D(H)$ measured at low bias currents in the $M_Z/M_\perp=50$ sample. In the same figure, we show the field-dependent temperature where the drop in $J_C^d(T)$ occurs. Here, $T_D(H)$ is defined by the criterion that $\partial(\ln R)/\partial(1/t)$ in the multilayer exceeds that in the single layer by 20%. As this graph shows, the drop in $J_C^d(T)$ occurs at temperatures well below those where the vortices in different layers begin to become coupled at low bias currents. Defining $T_D(H)$ by much larger departures from single layer behavior does not substantially change this result.

In Fig. 4, the temperature where the drop in J_C^d occurs is measured between fields of 1.5 and 7.0 kG. Since our determination of J_C^d requires measurements over a large current range in the flux-flow regime, heating prevents reliable quantitative measurements at higher fields. However, $\partial V/\partial I$ curves measured in higher fields do show a strong peak, implying that this phenomenon persists in fields well above 7.0 kG. As shown in the inset of Fig. 4, the side of the drop in $J_C^d(T)$ becomes smaller with de-

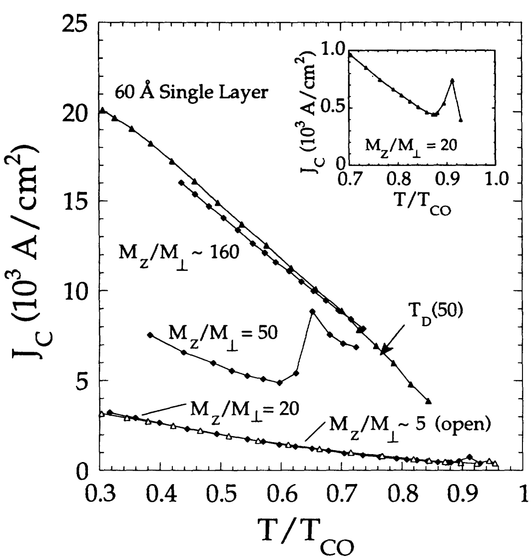

FIG. 3. Measured temperature dependence of critical current densities in 5.0-kG applied field for a single layer and various multilayers. The arrow labeled $T_D(50)$ points to the temperature at which low-bias decoupling occurred in the $M_Z/M_\perp=50$ sample (see Fig. 4). Inset: Closeup of $M_Z/M_\perp=20$ data in the vicinity of mean field T_C.

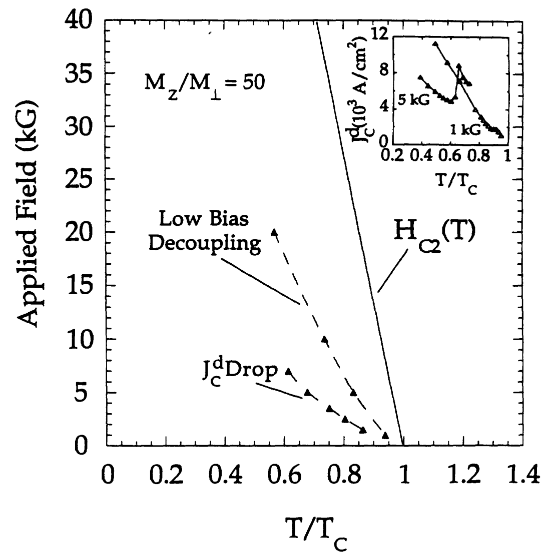

FIG. 4. Interlayer decoupling line $T_D(H)$ for the $M_Z/M_\perp=50$ multilayer compared with the field-dependent temperature where the drop in $J_C(T)$ occurs in the same sample. Inset: $J_C(T)$ for the $M_Z/M_\perp=50$ sample in the applied fields of 1.0 and 5.0 kG.

creasing field and survives only as a flat spot in $J_C^d(T)$ when $H=1.0$ kG. Finally, we note that in the field range shown in Fig. 4, the multilayer samples were heated by ~100 mK as the bias current was increased to its maximum value. Since the drop in $J_C^d(T)$ occurs over a comparable temperature range, we believe that the observed abruptness of the drop is probably limited by heating.

How can we understand the anomalous temperature dependence of the measured pinning drag critical current densities, i.e., the pinning drag forces? One possibility is that the drop in $J_C^d(T)$ merely reflects the crossover in interlayer coupling of vortex motion which is observed in the low bias resistance. This seems unlikely, however, since low bias interlayer coupling occurs continuously and begins at much higher temperature. This point is further emphasized by the fact that $J_C^d(T)$ in the low anisotropy multilayers is less than $J_C^d(T)$ in a single layer over a substantial temperature range above the drop but below the low bias decoupling temperature T_D. Finally, the bottom panel of Fig. 2 shows that while the peak in dynamic resistance appears abruptly as the temperature is decreased, the differential resistance at lower bias currents does *not* change abruptly as a function of temperature. Hence the usual critical density determined by a voltage criterion is unchanged. Thus, we may rule out the possibility that the drop in $J_C^d(T)$ is a simple extension of the interlayer coupling observed in the low bias response.

Shi and Berlinsky have argued[9] that peaks in dynamic resistance may arise from the presence of dislocations in a pinned vortex lattice. In this picture, as the bias current increases and the vortices begin to move, the dislocation density drops sharply, resulting in a dynamic resistance peak. At still higher bias currents, the dislocation density approaches zero, and a linear flux flow I-V is recovered. Dynamic resistance and noise measurements[10] by Bhattacharya and Higgins of $NbSe_2$ have provided support of this point of view. The sharp drop in multilayer critical current densities, however, cannot be explained solely within this framework, because J_C is extrapolated from the linear regime at high bias, where the dislocations are predicted not to exist. While the dynamic resistance measurements reported in Ref. 10 are superficially similar to ours, those data do not appear to show the sharp drop in $J_C(T)$ that exists in our data.

As discussed earlier, the extrapolated J_C^d is proportional to the pinning drag force acting on vortices in the moving state. Qualitatively, we expect that this pinning force depends on the elastic properties of the moving vortices, as well as the magnitude of the random disorder potential. Since the pinning potential must be a smooth function of temperature, we suggest that the sharp drop in $J_C^d(T)$ may represent an abrupt increase in the rigidity of the system of vortices in the flux-flow state. Because the low bias linear response is immeasurably small in the vicinity of the drop, we cannot determine whether this jump in stiffness occurs in the static state as well.

It is possible that such a jump in stiffness signals an ordering (freezing) transition in the system of vortex lines. If such a transition does occur, we cannot use these data to determine whether it is of a continuous or discontinuous nature, since the measured abruptness of the $J_C^d(T)$ drop appears to be limited by heating. In the event of first-order transition, one might expect hysteretic behavior as a function of temperature, in contrast with the measured $\partial V/\partial I$ characteristics, which are nonhysteretic as a function of both temperature and bias current. Measurements of the low bias resistance of high-temperature superconductors, however, have shown[11] that such a hysteresis may be eliminated when very small bias currents are applied. Since our experiments probe the vortices in a grossly invasive fashion, we probably would not observe hysteretic behavior even if a first-order transition did occur. For this reason, and because the low bias resistance is not observable in the region of interest, experiments unrelated to electrical transport would probably be necessary to establish the existence of a "phase" transition.

In conclusion, we have measured the nonlinear electrical response of Josephson coupled $Mo_{77}Ge_{23}$/Ge multilayers. In multilayers where the low-bias resistance indicated that vortices moved independently in each layer, the nonlinear response was also equivalent to that of single layers in parallel. In lower anisotropy samples, where interlayer coupled motion occurs at low-bias currents, we observe a sharp change in the nonlinear response as a function of temperature. Here, the nonlinear response at low temperature includes a peak in differential resistance as the flux-flow regime is approached. This phenomenon appears to coincide with a sudden increase in the rigidity of the system of moving vortices. Since this increase in stiffness occurs abruptly at temperatures well below the onset of interlayer correlated vortex motion, it seems possible that it results from an ordering transition of vortex lines.

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