Model System for Vortex Motion in Coupled Two-Dimensional Type-II Superconductors

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We report linear electrical transport measurements in $Mo_{77}Ge_{23}$/Ge multilayers and a single layer of $Mo_{77}Ge_{23}$ which is nominally the same as the constituent layers of each multilayer. In the multilayers, we observe a crossover from a regime where the vortex motion displays interlayer coupling to a regime where the vortex segments in each layer move effectively independently. Our observations bear some strong resemblances to those in high-temperature superconductors, and we discuss the possible relevance to our system of some concepts developed to interpret the high-temperature superconductors.

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Since the discovery of the high-temperature superconductors, intense interest has arisen about the vortex motion in coupled two-dimensional superconductors. In an isolated homogeneous 2D superconducting film, the idea that thermally excited dislocation-antidislocation pairs can melt the Abrikosov lattice has gained wide acceptance in the last decade.[1-3] Building on this, some have proposed new phase diagrams[4,5] for the vortex system in coupled 2D and highly anisotropic superconductors, in some cases including the presence of disorder, which adds qualitatively new features to the problem. In the high-temperature superconductors, an incomplete understanding of the microscopic nature of the superconducting state, the highly complicated crystal structure, and the inability to vary systematically the magnitude of the Josephson and magnetic interplane coupling considerably complicate the situation. Indeed, the entire approach of modeling the high-temperature superconductors (HTSC) as coupled 2D superconductors remains open to question, since it is not known whether each of the constituent planes in these materials would be superconducting in isolation. Also, because the upper critical fields in the HTSC's become inaccessibly high at low temperatures, only a small fraction of the H-T plane is observable. Clearly, some understanding of the vortex motion in high-quality conventional superconductor/insulator multilayers with comparable anisotropy should provide a valuable reference point in this inquiry.

In this Letter, we examine the zero-bias resistance in perpendicular magnetic fields of periodic amorphous $Mo_{77}Ge_{23}$/Ge multilayers and a single layer of amorphous $Mo_{77}Ge_{23}$ that is nominally the same as the constituent layers of each multilayer. While keeping the superconductor thickness, $d_s=60$ Å, and composition constant, we vary the thickness of the insulating amorphous Ge layer from $d_i=35$ to 65 Å. It is known from independent measurements[6] that the tunneling decay length in amorphous Ge is 8.1 Å. The samples are described in Table I along with a listing of their derived parameters as determined below. All of these films were grown by multitarget magnetron sputtering on a-Si_3N_4/Si substrates. This technique is described in detail elsewhere.[7] As demonstrated previously, excellent layering with controllable interlayer coupling is achieved with these materials using this technique.[8]

From earlier measurements, the bulk zero-temperature magnetic penetration depth is known to be $\lambda(0)=7700$ Å, yielding a bare-film $\lambda_\perp(0)=\lambda^2(0)/d_s=100$ μm; and the Ginzburg-Landau coherence length in thin films where $d_s\sim 60$ Å is $\xi(0)=55$ Å. Of course, there is some uncertainty in the latter figure, because the transition is substantially broadened in very thin films. Also, the zero-temperature critical current of thin films of these materials is of order 10^4 A/cm^2, indicating that they have a moderate level of flux pinning. Because $\lambda_\perp(0)$ is extremely large, a perpendicular magnetic field of several kilogauss will penetrate the superconductor with only very weak spatial variations of B, and the resultant magnetic interlayer vortex coupling will be quite small.[9] As d_i increases, the magnetic coupling falls off much more slowly than the Josephson coupling, so the magnetic coupling must eventually dominate. Combining our own estimates of the Josephson contribution to the small-displacement interlayer vortex coupling with the calculations of Clem,[9] when $H_{c1}\ll H\ll H_{c2}$, we expect the Josephson contribution to be an order of magnitude larger than the magnetic contribution when $d_i=65$ Å, although this estimate in no way affects the conclusions of this paper.

All of these films were patterned by ion-beam milling into four-point measurement structures of length 2.54 mm and width 0.1 mm. Standard low-frequency ac lock-

TABLE I. The samples and their derived parameters.

Sample No.	Number of SC layers	d_s (Å)	d_i (Å)	T_{c0} (K)	$\xi_z(0)$ (Å)	$\xi_\perp(0)$ (Å)	$M_z/M_\perp$
289137	10	60	35	5.44	12.3	55	20
289141	10	60	65	5.30	~2.5	55	~500
289143	1	60	···	5.08	···	55	···

in techniques were used to measure the sample resistance as a function of temperature in various perpendicular fields. All results were checked to confirm the independence of measurement current density and frequency below 10 kHz. The measurement current densities used were typically on the order of 1 A/cm^2. The resistive transition in perpendicular magnetic field of one of the multilayer samples is shown in Fig. 1. Unlike bulk MoGe, the resistive transitions of this multilayer sample broaden substantially as the applied field is increased. Also, the lower part of the transition develops a "kink," the significance of which we shall return to later.

Since the normal-state resistivity of MoGe is temperature independent at low temperatures, we may easily extract the fluctuation conductivity above T_{c0}. For each of our samples, we can fit these data with the fluctuation conductivity calculated using the Lawrence-Doniach model considering only the Azlamazov-Larkin contribution. In the more strongly coupled multilayer, $d_i = 35$ Å, this fit yields a perpendicular coherence length of $\xi_z(0) = 12.3$ Å. The fluctuation conductivity of the weakly coupled multilayer, $d_i = 65$ Å, is consistent with $\xi_z(0) \sim 2.5$ Å, the value extrapolated from the more strongly coupled multilayer using the difference in insulator thicknesses and the measured tunneling length of 8.1 Å in amorphous Ge; but ξ_z obviously cannot be determined with great accuracy when the interlayer coupling is so weak. From these coherence lengths, we derive the Ginzburg-Landau mass ratios given in Table I. On the basis of the tunneling length in amorphous Ge, we would expect the perpendicular coherence lengths for these insulator thicknesses to be 13.2 and 2.8 Å, respectively. The fluctuation conductivity of the single-layer sample has the 2D Azlamazov-Larkin form.

In the upper part of Fig. 2, we replot the data of Fig. 1 in Arrhenius fashion. In the lower part of Fig. 2, we show Arrhenius plots of the resistive transition of the more strongly coupled multilayer. The behavior of the more strongly coupled multilayer bears a striking resemblance to that reported by Palstra *et al.* in YBaCuO,[10] which has a very similar mass ratio (see Ref. 10, Fig. 8). In each of the curves in Fig. 2, a sharp downward kink appears at a field-dependent temperature $T^*(H)$ well below T_{c2}, the temperature at which H_{c2} is equal to the applied field. The significance of this downturn becomes apparent when we overlay the Arrhenius plots both from multilayers and from the single layer at a single representative field in Fig. 3. Above T^*, the resistance of each multilayer is just that of its constituent layers in parallel. Below T^*, the resistance is thermally activated, with an activation energy which is much larger than that of a single layer. *Since T^* is in a region where the sample resistance should be governed by vortex motion, this clearly implies that, above $T^*(H)$, the vortex segments in each layer move, in effect, independently.* The $T^*(H)$

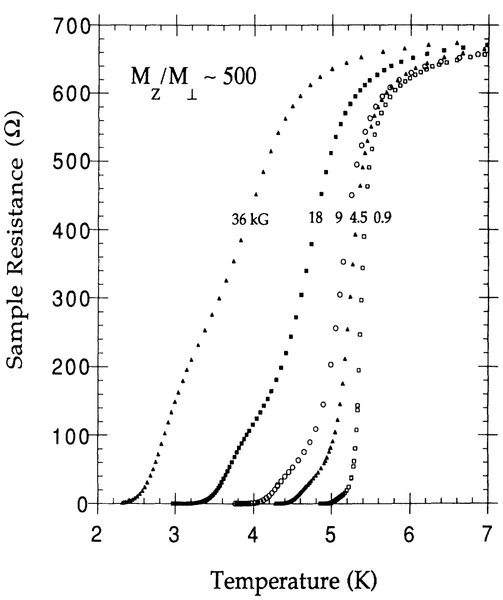

FIG. 1. Sample resistance as a function of temperature for the weakly coupled ($d_i = 65$ Å) MoGe/Ge multilayer sample in different magnetic fields, each perpendicular to the superconducting planes.

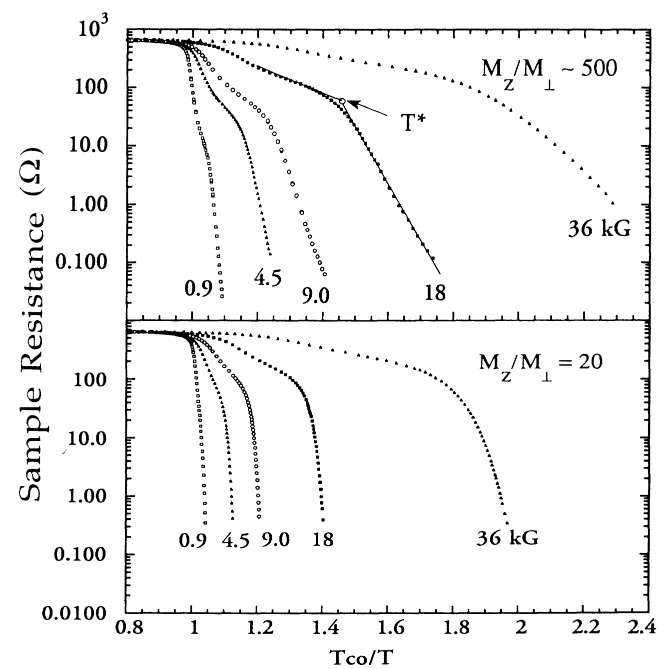

FIG. 2. Arrhenius plots of the sample resistance of two MoGe/Ge multilayers. In the upper plot, of the weakly coupled ($d_i = 65$ Å) multilayer, the slope of each trace defines a roughly constant activation energy at low temperatures. The lower plot, of the more strongly coupled multilayer ($d_i = 35$ Å), shows too much curvature to define a temperature-independent activation energy. The upper plot shows an example of the construction which is used to determine $T^*(H)$.

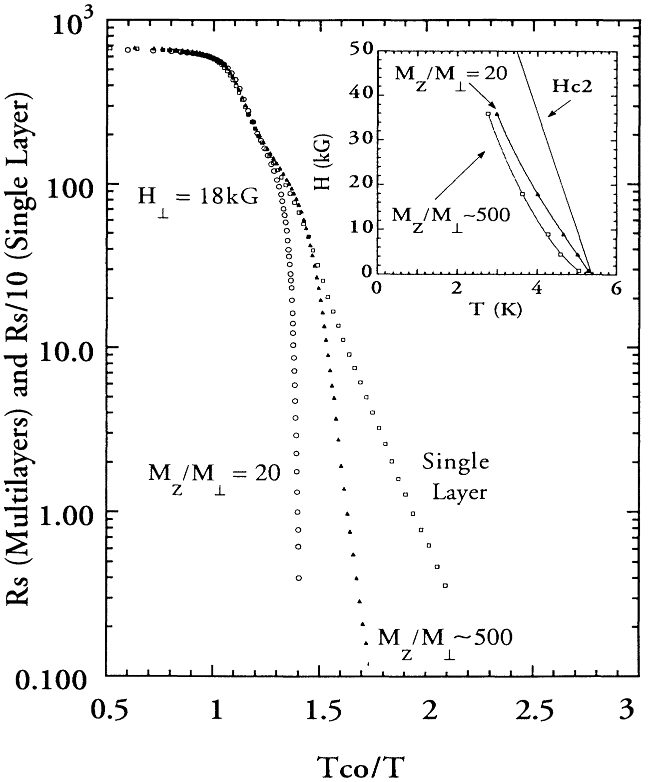

FIG. 3. Arrhenius plots of the sample resistance (scaled by the number of layers each sample) in the single layer and both multilayers. Note that the vertical axis is normalized only by the number of layers. Inset: The lines defined in the H-T plane by $T^*(H)$ of the two multilayer samples.

line defines a crossover from a regime where the vortex motion in a given layer is coupled to motion in the adjacent layers to a regime where the vortex motion displays no interlayer coupling, presumably due to increasing thermal fluctuations. The inset to Fig. 3 shows the $T^*(H)$, or $H^*(T)$, line for both of the multilayers compared with the upper critical field H_{c2}. As expected, $H^*(T)$ increasingly deviates from the $H_{c2}(T)$ line as the interlayer coupling decreases. We note that the downward kink at $T^*(H)$ corresponds to the "foot" evident in Fig. 1 in the high-field data. The appearance of this feature at $T^*(H)$ in these two representations is largely responsible for the similarity of the HTSC and MoGe/Ge data.

Careful examination of Fig. 3 shows a slight inflection even in the single-layer data around $R/R_n = 0.15$. The region between T_{c2} and this inflection point cannot be well described using only a Bardeen-Stephen flux-flow model,[11] so pinning is probably playing some role throughout. We note, however, that this inflection point occurs near the Bardeen-Stephen zero-temperature flux-flow resistivity of $R/R_n = B/H_{c2}(0)$ suggesting that this inflection point separates a free-flux-flow-like region from a region where the flux motion is more strongly influenced by pinning. While Fig. 3 is, in general, representative of the behavior observed at all fields, some differences should be pointed out. Particularly, the inflection point described above moves with field so that it is always in the neighborhood of $R/R_n = B/H_{c2}(0)$.

The $H^*(T)$ line is *not* an irreversibility line. Since we observe linear, frequency-independent resistance well below $H^*(T)$, any irreversibility line must lie substantially lower than $H^*(T)$. We are currently examining the magnetic properties of our MoGe/Ge multilayers using the various approaches applied to the high-temperature superconductors. If an irreversible region is observed, it must occur in the regime where the vortex motion displays interlayer coupling. Also, we note that $T^*(H)/T_{c2}(H)$ increases as the field decreases, so that interlayer-coupled vortex motion occurs increasingly close to T_{c2} at low fields. This is consistent with a vortex-reconnection or related picture, where the important length scale of vortex-line wandering is set by the mean distance between vortices. Particularly, the characteristics of the $H^*(T)$ line appear similar to those of a low-field transition discussed by Glazman and Koshelev,[12] from a vortex-line liquid to a vortex liquid, wherein individual vortex lines lose their integrity. However, because this theoretical picture is strictly applicable only at very low fields, more low-field data are required for quantitative comparison of the $H^*(T)$ line with the predicted phase boundary.

Finally, we turn to the activated behavior in these samples at low temperatures. As shown previously by Graybeal and Beasley,[13] the activation energy in a single layer of MoGe has the form $U(H)/T_{c2}(H) \propto H^{-2/3}$, and $U(9.0\ \text{kG}) = 65.7$ K. The weakly coupled multilayer has a well defined activation energy which is much larger than that of a single layer, and of characteristically different field dependence. In the weakly coupled multilayer, the activation energy has the field dependence $U(H)/T_{c2}(H) \propto H^{-0.54}$, with $U(9.0\ \text{kG}) = 195$ K. This field dependence is manifestly different than the logarithmic field dependence observed by Brunner *et al.*[14] in YBaCuO/PrBaCuO multilayers. The physical origin of this difference is not known. The more strongly coupled multilayer displays a clear downward curvature when plotted in Arrhenius fashion in the lower part of Fig. 2. Thus, one cannot clearly define a temperature-independent activation energy at observable levels of resistivity. As in YBaCuO, the downward curvature in the lower part of Fig. 2 presumably arises from the temperature dependence of the superconducting parameters.[10] Taken together, the data from YBaCuO, BiSrCaCuO,[10] and the two multilayers suggest that, in general, the temperature dependence of the superconducting parameters influences the temperature dependence of the activated behavior more strongly as the interlayer coupling increases.

In conclusion, we have made a model system for studying vortex motion in coupled 2D type-II superconductors. In this system, we can vary the mass ratio continuously, all of the H-T plane is accessible, we know that the description of each of the constituent planes as a 2D superconductor is appropriate, and we know that the interplane coupling arises almost entirely from Josephson coupling. By comparing the zero-bias resistance of multilayers and a single layer, we have observed a crossover at $T^*(H)$ from a regime where the vortex motion in a given layer is correlated to motion in the adjacent layers to a regime where the vortex motion displays no interlayer correlation. As expected, T^* moves closer to T_c as the interlayer coupling increases. At this point, we have not established whether this crossover is related to some thermodynamic phase transition or is kinetic in origin. As the interlayer coupling increases, the temperature dependence of the activation energy becomes more pronounced at observable levels of resistance. While these MoGe/Ge multilayers are obviously very different from the high-temperature superconducting materials, their resistive behaviors are quite similar in some ways, and they may help to elucidate the nature of the flux motion in these materials. In any event, they exhibit a behavior which might reasonably be expected from a Josephson-coupled model of quasi-two-dimensional superconductors.

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