Vortex Dynamics and Instabilities in Layered and Homogeneous Ta/Ge Superconductors

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We present measurements of a dynamically induced instability in the vortex state of an amorphous multilayer and a single alloy layer of Ta/Ge. The critical vortex velocity shows quantitative agreement with the predictions of Larkin and Ovchinnikov calculated using parameters determined independently from the normal state resistivity data. Both samples show a weak field dependence in the critical velocity implying a velocity dependent pinning force in the vortex solid state and a broadening of the transition resulting from the velocity distribution in the liquid state. [S0031-9007(97)03058-5]

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Since the discovery of the high-T_c cuprates much attention has been devoted to the study of vortex motion in layered type II superconductors [1]. In the limit of low applied current, several phases have been proposed such as the vortex glass [2–7] where the vortex solid is pinned by static disorder into a state with zero linear resistivity. However in the equally interesting high current limit the dynamics of the rapidly moving vortex system and its interaction with both static and thermal disorder is less well understood. This Letter demonstrates the existence of a fundamental instability in the vortex system of a Ta/Ge multilayer and a single layer alloy which causes a sudden jump to the normal state as the driving current is increased beyond a critical value J^*. The instability is in quantitative agreement with a prediction by Larkin and Ovchinnikov (LO) [8] of a current induced instability previously seen in both low-T_c [9,10] and high-T_c [11,12] materials. The analysis of this instability is extended for the first time to distinguish between the regime of collective vortex motion in the vortex solid and plastic vortex motion in the vortex liquid. We also consider for the first time the effects of static disorder in the vortex solid state and infer an interesting form for the pinning force as a function of vortex velocity near the instability.

The amorphous film and multilayer of Ta/Ge were prepared by vapor deposition in a vacuum (base pressure $<10^{-9}$ torr) using high purity sources [13]. The multilayer sample was 1250 Å thick with 25 layer pairs consisting of 25 Å of Ge and 25 Å of Ta and the single layer alloy sample was 600 Å thick. Characterization of the multilayer was by Rutherford backscattering, transmission electron microscopy, and x-ray diffraction [14,15]. The composition of the alloy sample was determined by x-ray fluorescence and was chosen such that the highest T_c (2.7 K) was obtained. The multilayer had a lower T_c (1.7 K) determined by the coupling between the thin superconducting layers and the existence of an alloyed region at the layer interface with a higher T_c than the individual Ta layers [14].

dc electrical resistivity measurements were made using a four terminal method on paths of size approximately 5 mm by 1 mm scratched into the films. A temperature stability of better than ± 1 mK was achieved by immersing the sample directly in liquid helium. The angle between the sample and the magnetic field could be set to within 0.1°.

The upper critical field phase diagram [Fig. 1(c)] above 1.3 K was determined by sweeping the temperature at fixed field and for the multilayer sample was extended to 50 mK using a dilution refrigerator. The shape of the upper critical field phase boundary agrees with that predicted by Werthamer, Helfland, and Hohenberg [16]. The slope of the perpendicular upper critical field at T_c along with the zero temperature normal state resistivity ρ_0 imply an in plane coherence length $\xi_{ab}(0)$ of 96 Å and penetration depth $\lambda_{ab}(0)$ of 7000 Å [17]. The parallel critical field data for the multilayer showed a crossover from 2D to 3D behavior as temperature was lowered corresponding to the temperature dependent perpendicular coherence length $\xi_c(T)$ becoming less than the film thickness. From this $\xi_c(0)$ was found to be 69 Å giving an anisotropy parameter ε of 0.7, indicating fairly strongly coupled layers.

Figure 1(a) shows a typical set of IV curves for the multilayer sample at 1.456 K and various fields directed perpendicular to the plane of the layers. Similar data sets have been taken at a large range of fields and temperatures. This sample is in the disordered limit which means that the pinning and bending lengths for the vortices are relatively short [1]. The layered nature of the sample also favors tilt deformations of the vortex

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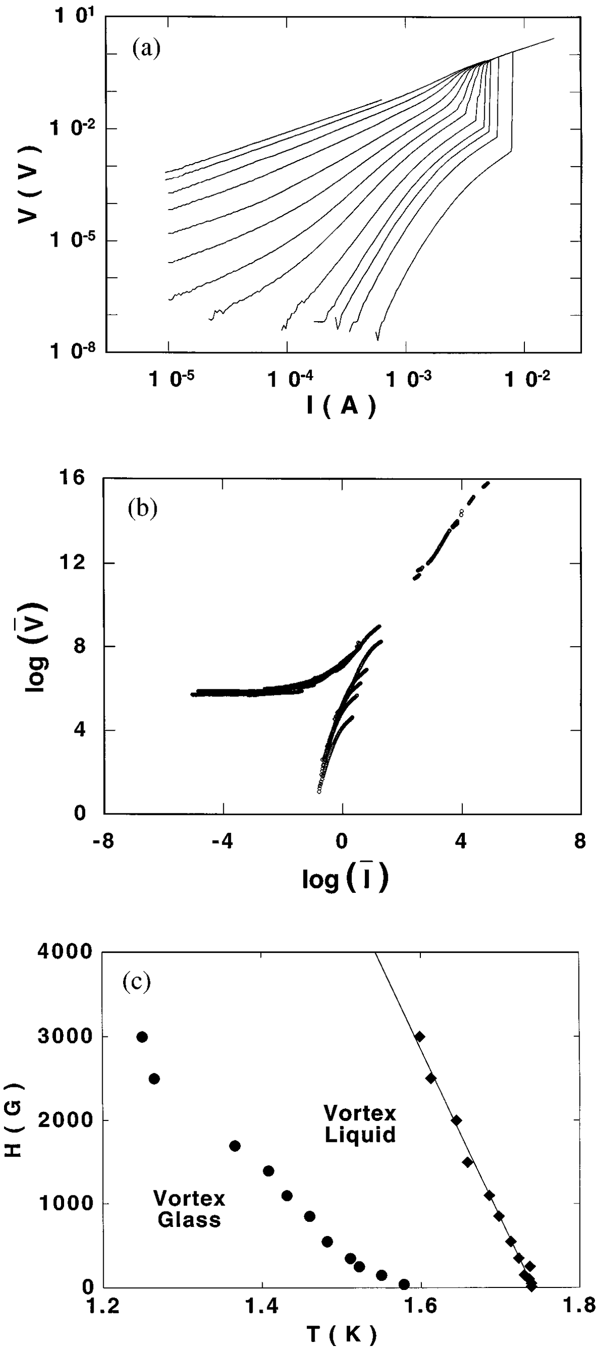

FIG. 1. (a) IV curves for the multilayer sample at 1.456 K and field (right to left) 40, 150, 250, 350, 550, 850, 1100, 1400, 1700, 2100, 2500, 3000, and 3500 G. (b) The same data scaled according to Eq. (3). Note the deviations from scaling behavior of the lower curves at large currents, as discussed in the text. (c) The phase diagram for the multilayer sample near T_c. The triangles denote H_{c2} and the circles H_g. The solid line shows the expected linear behavior of H_{c2} close to T_c.

lattice [1], so the sample is in the 3D limit where the characteristic vortex bending length l_c is shorter than the sample thickness. The relevant model for the 3D vortex solid in the presence of disorder is the vortex glass. Figure 1(b) shows the IV data scaled according to the vortex glass scaling laws

$$\overline{E} = (E/J)\,|1 - (T/T_g)|^{\nu(d-2-z)}, \qquad \overline{J} = J|1 - (T/T_g)|^{\nu(1-d)} \tag{1}$$

The multilayer data generally exhibit excellent scaling, with the scaling parameters $z = 6.0 \pm 0.5$ and $\nu = 1.2 \pm 0.1$ being similar to the majority of previous results for high-T_c systems [3]. Similar scaling has also been observed in a highly disordered low-T_c a-Mo_3Si film of similar dimensions but with different scaling parameters $z = 3.0 \pm 0.3$ and $\nu = 0.67 \pm 0.05$ [5]. It should be noted that the derived parameters z and ν in the Ta/Ge multilayer are the same for all temperatures and fields allowing us to use the rather unconventional method of displaying the scaled data at constant temperature rather than constant field. The vortex glass melting line is shown on the phase diagram in Fig. 1(c).

The scaling analysis clearly indicates that the vortex glass model describes the low current data well. However all of the curves taken below the vortex glass melting line show a deviation from vortex glass scaling behavior at high current density followed by a sudden jump back to the normal state at a sufficiently high current density J^*. For the curves taken in the liquid state this jump back to the normal state response is still observed, but it becomes less and less sharp as the field is increased further above the melting field. We have repeated the measurements by sweeping the currents downward and have observed the same sharp changes in voltage with negligible hysteresis between the upward and downward sweeps despite the fact that the input power levels on either side of the transition differed by up to 5 orders of magnitude. This rules out Joule heating effects as the source of the sudden rise in the voltage at J^*.

The depairing currents calculated using the expression found in Ref. [18] are in all cases too high to be responsible for the sudden voltage upturn. The Josephson behavior [19] used to explain instabilities of some highly anisotropic high-T_c superconductors is not appropriate here as we have observed the voltage upturns in an unlayered alloy as well as a multilayered sample. Recently depinning [20] and vortex lattice crystallization [21] have also been used to explain jumps in the IV curves. However our data show the transition well above T_g in the liquid state where depinning and crystallization effects are not relevant. Furthermore the transition is to the normal state resistance rather than the smaller flux flow value. Thus we conclude that the LO theory is the most promising to pursue in analyzing the high current instability in our samples.

In the LO theory the vortex velocity is determined by a balance between the driving Lorentz force and the vortex viscosity. Eventually as the velocity increases the viscous force reaches a peak and then begins to decline whereupon the vortex system becomes unstable driving the superconductor back into the normal state. The vortex velocity at which this instability occurs is given by

$$v^* = \{D^{1/2}[14\zeta(3)]^{1/4}(1 - t)^{1/4}\}/[\pi \tau_{\text{in}}]^{1/2}, \quad (2)$$

where $D = (v_f d)/3$ is the quasiparticle diffusion coefficient with v_f the Fermi velocity (2.34×10^6 ms^{-1}) and d the electron mean free path (1.5 Å), τ_{in} is the inelastic-scattering time of the quasiparticles, $t = T/T_c$ and $\zeta(3)$ is the Riemann ζ function of 3. The critical velocity v^* is predicted to be field independent in the absence of pinning.

The voltage at which the instability occurs is related to the critical velocity by

$$V^* = v^* \mu_0 H L\,, \quad (3)$$

where L is the length of the current path. The values of v^* for the multilayer are plotted in Fig. 2 at several different temperatures. In the case of the broader transition seen above the melting temperature (where V^* has been defined as the start of the voltage upturn) the corresponding v^* is indeed field independent. Furthermore the critical velocity is in remarkably close agreement with predictions of Eq. (2), 65–75 m/s, based on values of D and τ_{in} determined by the application of weak localization theory to the normal state resistance [15].

Two of the features in the transition at J^* not specifically predicted by the LO theory are a field dependence in v^* below T_g and a broadening of the transition at temperatures above T_g. In order to understand this deviation from LO behavior it is worth considering further the vortex glass model at high currents.

The applied currents probe the vortex structure on a typical length scale of

$$l = (k_B T/\varepsilon \phi_0 J)^{1/2}, \quad (4)$$

where ε is the anisotropy and ϕ_0 the flux quantum [1]. A deviation from vortex glass behavior is expected when the length probed by the current becomes less than the Larkin-Ovchinnikov length (l_{LO}) which measures the size of the short range order in the vortex lattice [6]. Thus l_{LO} can be found from the current density where the IV curve deviates from a power law in Fig. 1(a). This yields a value for l_{LO} at $T_g = 1.456$ K and $H_g = 300$ G of only 300 Å, less than the intervortex spacing of 3000 Å, implying strong disorder in the vortex solid. At higher currents the relevant dissipation processes must involve individual vortices.

Well below T_g the vortex solid has a well defined shear modulus, the individual vortices move with the same average velocity [22] and undergo the LO instability simultaneously. In the melted liquid above T_g the shear modulus goes to zero and the individual vortices are able to move independently past one another. There is a distribution of velocities amongst the vortices and each freely moving vortex undergoes the instability separately upon reaching v^*, leading to a broadened transition.

To help understand the field dependence of v^*, we display in Fig. 3 the field dependence of the resistivity (E/J) measured just below the sudden voltage upturn. The solid line shows the value of the resistivity predicted for free flux flow (ρ_{ff}) according to the Bardeen-Stephen model [23]

$$\rho_{ff} = \rho_n B/H_{c2}\,, \quad (5)$$

where ρ_n is the normal state resistivity. The deviation from free flux flow behavior at low fields can be attributed to pinning, even at these high currents. We propose in this regime a general pinning force of the form $F_P = c(B)f(v)$ where $c(B)$ is a function of the field B, and $f(v)$ is an *increasing* function of the vortex velocity v. The instability occurs when the total force opposing the vortex motion (viscosity plus pinning) reaches a maximum as a

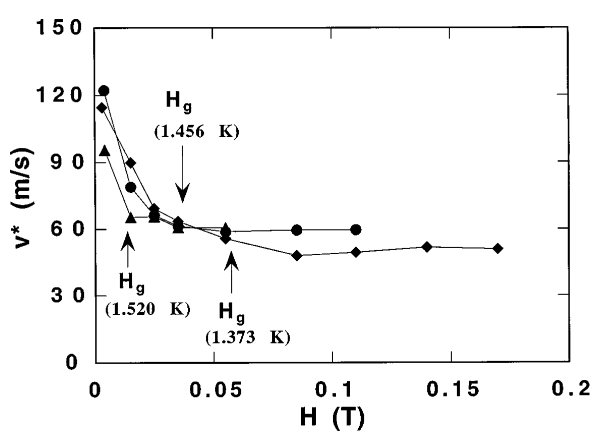

FIG. 2. Critical vortex velocity (v^*) at the LO instability. The data are for 1.373 K (diamonds), 1.456 K (circles), and 1.520 K (triangles) with the corresponding vortex glass melting fields (H_g) shown by the arrows. v^* is field independent only above H_g.

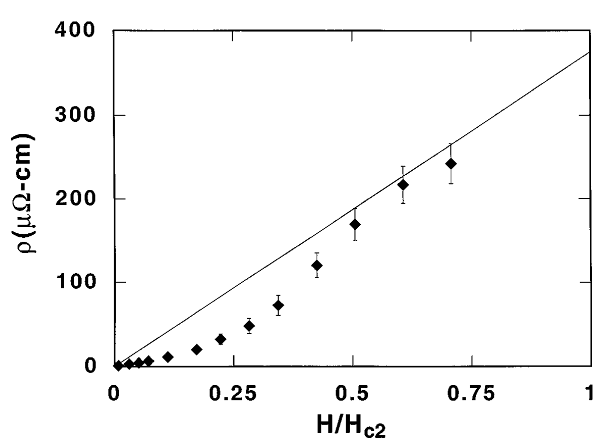

FIG. 3. Resistivity for the multilayer sample measured just below the sudden upturn at J^*. Even at these high currents the resistivity is given by the free flux flow value (solid line) only well above H_g demonstrating the importance of disorder.

function of vortex velocity. With a pinning force which increases with velocity the position of the maximum is moved to a higher velocity than the value of v^* predicted by LO. The size of the shift in v^* is determined by the factor $c(B)$, which is expected to go to zero in the liquid state where pinning is averaged out by thermal disorder, and be a maximum at low fields where the vortices can best accommodate themselves to the pinning potential. Thus the field dependence of the instability is intimately linked to the pinning forces on the vortices, clearly explaining the observed increase in v^* seen below the melting transition in our Ta/Ge samples and also the very similar YBCO data of Xiao and Ziemann [12].

It is interesting to compare the multilayer results with those for the sample with no layering. The alloy sample is considerably thinner and contains no layers to encourage tilt deformations so it is in the 2D limit with l_c larger than the sample thickness. Analysis of the IV curves for this sample shows that the vortex glass scaling breaks down at low currents due to plastic deformations, as expected in two dimensions [4,7,24]. Instead, in the 2D case a Berezinski-Kosterlitz-Thouless (BKT) melting transition is expected, driven by the unbinding of thermally created dislocation-antidislocation pairs [24]. Nevertheless, below the BKT transition the high current behavior of the two dimensional sample should be dominated by the elastic properties of the vortex solid. We do indeed see the same instability in the vortex solid at J^*, with a broadening above the melting line and a distinctive field dependence in v^* below the melting line. The similarity between the two samples with different melting transitions clearly indicates that the features seen in the behavior of the instability at J^* are related only to the existence of a disordered vortex solid phase which undergoes a melting transition to a liquid. The exact nature of the melting transition is not critical.

In conclusion we are able to understand the IV characteristics of both a layered and unlayered Ta/Ge sample across a wide range of applied currents. Both samples show a current-driven instability in the vortex system at a vortex velocity which is in excellent agreement with the predictions of Larkin-Ovchinnikov. The velocity at which the instability occurs shows a field dependence for both samples resulting from the velocity dependence of the pinning force at high currents, illustrating a previously unconsidered role of disorder on the driven vortex lattice. This field dependence disappears above the melting transition of both samples where the transition broadens due to the distribution of velocities in the melted liquid.

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