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Vortex motion in type II superconductors of reduced dimensionality

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Abstract. We apply theory of the destruction by thermal fluctuations of the vortex lattice in Josephson coupled 2D type II superconductors to superconducting $Mo_{77}Ge_{23}$/Ge multilayers. We also report results of mutual inductance measurements at various frequencies of ultrathin $Mo_{77}Ge_{23}$ single layers in the presence of applied DC magnetic fields and bias currents.

Since the observation of anomalous vortex motion in high temperature superconductors, there has been renewed interest in the more general problem of vortex motion in systems of reduced dimensionality in the presence of disorder [1–3]. Ultrathin amorphous Mo–Ge alloy films and MoGe/Ge Josephson coupled multilayers have proved to be an excellent model system for such studies. A universal relation for the zero bias resistance of single films as a function of field and temperature has been reported [4]. More recently, we reported a 2D–3D crossover in the multilayers in which 3D vortex lines break up into 2D disks [5]. In this paper we compare our multilayer results with recent theories of the destruction of vortex lines by thermal fluctuations. We also report new mutual inductance measurements on these systems.

L. I. Glazman and A. E. Koshelev have considered the destruction by thermal fluctuations of the vortex lattice in Josephson coupled 2D type II superconductors with the magnetic field applied perpendicular to the layers [2, 3]. They predict that, at sufficiently low fields, the vortex lattice "melts" in two steps. As the temperature increases, the lattice of vortex lines first melts into a liquid of vortex lines. As the temperature increases still further, the vortex lines themselves lose their integrity, and the vortex singularities in each layer move effectively independently. It was found that this latter crossover occurred at a field B^* defined in the $B-T$ plane by $B^*(T) = \{\alpha_m \phi_0^3/(4\pi)^2 \lambda_c^2 d T_c\}(T_c/T - 1)$. Here, λ_c is a component of the magnetic penetration depth, d is the interlayer spacing, T_c is the mean field superconducting critical temperature, α_m is an adjustable Lindemann parameter and ϕ_0 is the superconducting flux quantum 2.07×10^{-7} G-cm^2. By identifying certain electrical and acoustic transport features in YBaCuO and BiSrCaCuO with B^*, Glazman *et al.* obtain $\alpha_m = 0.12$. As it turns out, the low field region where this two step melting process obtains increases with increasing interlayer coupling.

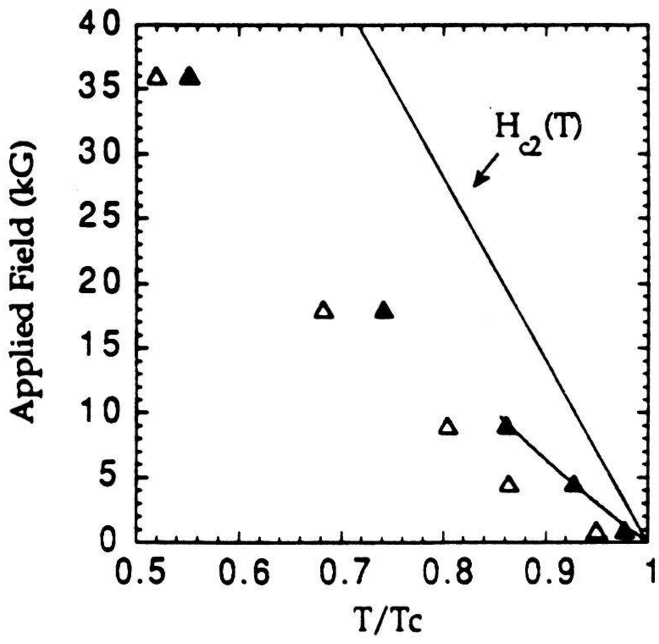

Figure 1
Observed and calculated interlayer decoupling lines.

The 2D–3D crossover observed by us in MoGe/Ge multilayers is shown in Fig. 1. In the more anisotropic multilayer studied there (open symbols in Fig. 1), the low field picture described above should be valid only up to applied fields of a few hundred gauss. For the less anisotropic multilayer (filled symbols in Fig. 1), the low field picture is expected to apply below several kilogauss. Indeed, in this sample a roughly linear relation between B^* and $(T_c - T)$ persisted up to fields of several kilogauss as predicted above. The more anisotropic sample displayed upward curvature of $B^*(T)$ starting below 900 G, as expected. The slope of $B^*(T)$ in the less anisotropic multilayer corresponds to $\alpha_m = 0.08$. Figure 1 compares the observed crossover in the less anisotropic sample at various fields to the theoretical result for B^* (solid line) when $\alpha_m = 0.08$.

While the experiments discussed above detect the onset of interlayer correlated vortex motion by comparison with a single layer, the vortex motion in a single 2D type II superconductor with disorder is still not adequately understood. For this reason, we are performing additional measurements of ultrathin single layer films of $Mo_{77}Ge_{23}$, including mutual inductance measurements in the presence of a DC applied magnetic field and a DC bias current. Without applying DC bias currents, we performed mutual inductance measurements at frequencies between 1.0 kHz and 7.5 Mhz in DC magnetic fields ranging from 0 kG to 10 kG. At all fields, we observed a strong frequency dependence characterized in Fig. 2, which shows the location of the zero bias dissipative peak for various measurement frequencies. By then applying a DC bias current while performing the measurement, we can gain additional insight into the behavior of the vortices in the vicinity of the temperature T_p, where the zero bias dissipation peak occurs. At temperatures substantially below T_p, DC bias currents produce no change in the mutual inductance signal until fairly large currents ($10^3 - 10^4$ A/cm^2) are applied, at which point the dissipation signal begins to rise quite sharply. Since the bias current applies a force to the vortices (or vortex lattice dislocations) which competes with the pinning forces,

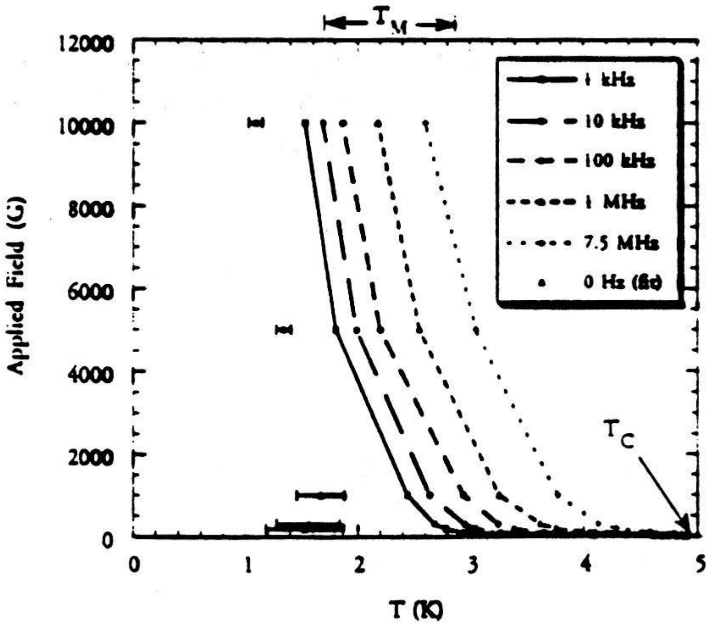

Figure 2
Mutual inductance dissipation peak locations at various measurement frequencies.

we expect a sufficiently large bias current to overcome the pinning potentials, producing dissipative vortex (or dislocation) motion. As expected, the onset of increased dissipation occurs at lower bias current densities as the temperature increases. As it turns out, the temperature where the onset of increased dissipation begins at bias current densities less than 100 A/cm^2, is very close to T_p. Since the AC currents induced by the mutual inductance measurement are typically around 100 A/cm^2, we cannot explore the vortex response at lower current densities. We can, however, roughly identify T_p as the temperature where the very small induced AC currents become able to overcome the pinning forces. Since T_p is so far below the superconducting transition, this raises the question: "Does this reflect a melting transition of the vortex lattice?"

In 2D, the vortex lattice is predicted [6] to melt by thermal excitation of dislocation-antidislocation pairs, with a melting temperature T_M in the range shown at the top of Fig. 2. As the temperature increases above T_M, the vortex positional correlation length is predicted [7, 8] to decrease as $\xi_v = \xi_0 \exp[b[T_M/(T - T_M)]]^{0.37}$ where b is a field independent constant and ξ_0 is an unknown constant. If the vortex (or dislocation) which produces the dissipation in our experiment moves diffusively with diffusivity $D(T, H)$, then we might expect increased dissipation if the lattice is melted on the length scale $(D/\omega)^{1/2}$, where $\omega/2\pi$ is the measurement frequency. This would lead to a frequency dependence of T_p such that $\xi_v(T_p, H) = (D(T_p, H)/\omega)^{1/2}$. By taking $T_M(H)$, b, and D as adjustable parameters, we can fit the frequency dependence of our data above 1.0 kG quite successfully with this model. Additionally, these fits yield roughly field independent values of T_M and b, in accordance with theory. However, since the relevant diffusivity D is that of lattice dislocations, the physically plausible range of values for D is not immediately obvious. Thus, we believe that our data suggest the possibility that we observe the thermal destruction of vortex positional correlations at different length scales by performing the measurement at different frequencies. However, since we have examined only one model of the breakdown of vortex positional correlations, and since we do not have reliable *ab initio* estimates of some model parameters, we must regard this as a preliminary result.

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