Suppressed flux motion in magnesium diboride films

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The mixed-state transport behavior of magnesium diboride films shows a suppression of flux motion that is more severe than is typical for conventional vortex pinning. At currents approaching the pair-breaking value and magnetic fields approaching the upper-critical field, the conductance diverges and the current-resistance and temperature-conductance curves become parallel, showing mainly a shift in the transition due to pair-breaking with minimal signs of flux motion.

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In a type-II superconductor, an applied flux density B or current I has two effects. First the superconductivity is suppressed and the transition temperature T_c shifts downward in the manner[1–3]

$$T_c(B,I) \approx T_c(0,0) - B|dT/dH_{c2}| - I^{2/3}|dT/dI_d^{2/3}|, \qquad (1)$$

where H_{c2} is the upper critical field and I_d is the depairing or pair-breaking critical current, and the slopes are evaluated at $T_c(0,0)$.

The second effect of B and I is that they both broaden the conductance-versus-temperature $G(T)$ transition. The current produces a self-magnetic field, which causes the local T_c to decrease with the distance from the center due to Silsbee's mechanism.[2] Additionally, variations in sample cross section cause the local current density and hence the local T_c to vary. Thus when a sample is cooled from above T_c, G does not jump sharply from its normal-state value G_n to an infinite value just below T_c, but has a finite transition width that increases with I. Note that for very low-value currents $I \ll I_d$—as are typically used—the transition will not be broadened; in this work we use substantial currents $I \sim I_d(T)$.

Similarly, an applied magnetic field broadens $G(T)$, because of flux motion, and limits the maximum G to a finite value given by[2,4]

$$G_f \sim G_n H_{c2}/B. \qquad (2)$$

This $G_f \propto 1/B$ field dependence persists even in the case of highly driven nonlinear and unstable flux flow.[5,6]

The vast majority of published transport measurements are carried out with feeble currents below the depinning threshold I_c, so that broadening with B is prevented by flux pinning. These represent trivial cases where $G(T)$ and $R(T)$ curves in different B appear parallel. However when $I > I_c$, flux motion will cause broadening. For example, Fig. 1 shows $G(T)$ curves for $Y_1Ba_2Cu_3O_7$ films at different flux densities bearing out both the displacement [Eq. (1)] and broadening [Eq. (2)] effects with increasing B (data was taken from Ref. 1). Here $I = 0.5$ mA ($j = 5000$ A/cm^2) is 0.01% of $I_d(0,0)$.

Typically I_c is significantly lower than I_d and has a maximum value for columnar defects whose size, orientation, and distribution match the vortex lattice. Since the vortex separation depends on B, and the radius ξ (coherence length) depends on T, the matching is optimum for specific values of B and T. The maximum critical current density j_c can be estimated as follows: The condensation energy density $H_c^2/8\pi$ times the vortex cross section $\pi\xi^2$ gives the energy per unit length $H_c^2\xi^2/8$. Dividing this by the displacement 2ξ (vortex diameter) gives the maximum pinning force $H_c^2\xi/16$, which equals the critical Lorentz force $F_L = j_c\Phi_0/c$. Using the relation[2] $H_c = \Phi_0/2\sqrt{2}\pi\lambda\xi$ then gives $j_{c,\max} \approx cH_c/32\sqrt{2}\pi\lambda$. In relation to the depairing current density j_d, given by[2,7] $cH_c/3\sqrt{6}\pi\lambda$, we see that

$$I_{c,\max} \approx 0.16 I_d. \qquad (3)$$

This is born out by experience: the very highest pinning niobium compounds have critical currents of about 15% of the depairing value. If the changes in magnetic and kinetic energies of the circulating supercurrents are included,[8] the estimate of I_c can be as much as twice that in Eq. (3); however, in practice I_c values exceeding Eq. (3) have not been observed. For smaller randomly distributed defects, I_c is further lowered by the factor $d^2/4l\xi^2$, where d is the mean defect dimension and l their mean separation. Thus near T_c we expect current densities $\gtrsim 1$ kA/cm^2 to promote flux flow and broaden the transition, as seen for $Y_1Ba_2Cu_3O_7$ in Fig. 1.

The unexpected results on MgB_2 films in the present work are that (1) the $G(T,B)$ curves at different B collapse together showing essentially no B dependent broadening, (2) the $G(T)$ transition widths are abnormally narrow considering the high values of j, and (3) the conductance is abnor-

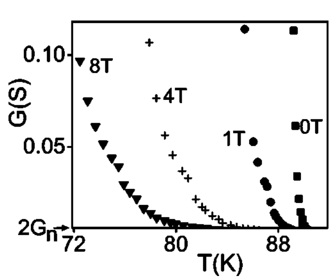

FIG. 1. Conductance vs temperature curves for $Y_1Ba_2Cu_3O_7$ films at different values of $B\perp$ film ($B \parallel c$ axis) at a fixed $I = 0.5$ mA ($j = 5$ kA/cm^2). The normalized B values range $B/H_{c2}(0) \sim 0-6\%$ and $B/H_{c2}(T) \sim 0-30\%$. $G_n = 0.0027$ S. Data from Fig. 20 of Ref. 1.

mally high (i.e., the flux-motion induced voltage vanishes). Since the flux motion is able to freeze out at enormous currents $[I \sim I_d(T)/2]$ and fields $[H \sim H_{c2}(T)/2]$, a conventional pinning mechanism would require a substantial fraction of the sample to be filled by an impurity phase. This is impossible in light of the known purity of the sample and may point to some new and unusual type of hindrance to flux motion. Note that problems with sample quality, I or B inhomogeneity, or other experimental artifacts would have just the opposite effect and would show instead the lack of a universal collapse, broader transitions, and a lower conductance, which is the opposite of what is observed.

The samples are 400 nm thick c-axis-oriented films of MgB_2 on $(1\bar{1}02)$ Al_2O_3 substrates whose fabrication is described elsewhere.[9] X-ray diffraction indicates a highly c-axis-oriented crystal structure normal to the substrate surface with no detectable impurity peaks.[10] The sample purity is also confirmed by scanneling tunneling microscopy (STM).[11] There is no observable weak-link behavior due to grain boundaries, hence their widths are expected to be less than the coherence length over the entire T range. Hence such boundaries would be too narrow to provide the optimum pinning represented by Eq. (3). Altogether, we have studied the transport characteristics of four MgB_2 bridges (S, M, L, N) under a variety of conditions. The films were photolithographically patterned and, in the case of N, the contact pads were further delineated by scribing. Here we show representative $G(0.7T_c \lesssim T \lesssim T_c)$ data on sample N. The normal-state resistivity $\rho_n(T \gtrsim T_c) = 14\ \mu\Omega$ cm, $T_c = 39.6$ K with a transition width of 1 K, and the bridge lateral dimensions are $3 \times 60\ \mu m^2$.

The electrical conductance was measured with a continuous dc source for currents below 50 μA and with a pulsed current source for higher currents. The pulse-repetition rate is about 1 Hz and the results are independent of pulse durations ranging from 0.1 to 7 μs. The worst case Joule temperature rise is $\Delta T_{\text{Joule}} \approx 10$ mK. For the crucial data $(G > 2G_n)$ where flux flow (or lack thereof) is investigated, $\Delta T_{\text{Joule}} < 1$ mK, which is 100 times smaller than the size of the data symbols. The highest self-field of the current at the bridge edge is about 40 G.[12] So for applied $B \gtrsim 0.1$ T we expect a homogeneous flux distribution. Further information about the experimental methods and thermal calculations are given in two review articles.[1,7] A more detailed description of the apparatus as well as a more comprehensive compilation of our data on MgB_2 films is published in a doctoral thesis.[13]

In a previous study[14,15] of the resistive behavior in this system at low temperatures ($T \sim 1$ K and $B \leqslant 14$ T) we found no evidence of flux motion—the current-voltage (I-V) curves at different values of B seemed to all have a similar functional form. This observation seemed puzzling but we dismissed it as being due to some exceptionally strong pinning specific to low temperatures.

In the present work we revisit this issue by investigating the character of the mixed state closer to the transition temperature T_c where there are several advantages:

(1) In this high-temperature range $(T > 0.7T_c)$ it is easy to cover the full ranges of $0 \leqslant B \leqslant H_{c2}$ and $0 \leqslant j \leqslant j_d$.

(2) Vortices are more mobile because of greater thermal activation and weaker pinning; as $T \to T_c$, the condensation energy vanishes and the vortex radius diverges so that the spatially varying pinning potential averages to zero. Furthermore, we concentrate on the $B\perp$ film ($B \| c$ axis) orientation, which ought to have higher flux mobility.

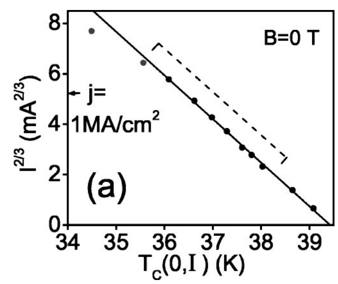

FIG. 2. $I^{2/3}$ vs the mean-field phase boundary $T_c(B=0,I)$ for an MgB_2 film. $T_c(B=0,I)$ is defined at the transition midpoint, i.e., at $G=2G_n$. The arrow shows for reference $j=10^6$ A/cm^2 on the $I^{2/3}$ axis. The bracket shows the ideal range of currents $(I \approx 4-16$ mA) for probing flux motion in the GL regime of Eq. (1).

(3) Near T_c most superconducting parameters show a strong T dependence. This affords a high sensitivity for comparing $G(T)$ curves at different B.

(4) Finally, near T_c, the Ginzburg-Landau (GL) formulation, or one of its variations, can be applied more straightforwardly thereby simplifying the interpretation and analysis of experimental results.

The conductance in the vicinity of the mean-field phase boundary $T_c(B,I)$ [Eq. (1)] and some distance below $(G \lesssim 2G_n)$ is affected by fluctuations. This fluctuation regime has a weak B dependence. The conductance at temperatures below the fluctuation region $(G \gtrsim 2G_n)$ is limited mainly by flux motion and should depend intimately on B. We will use this $G(T) \gtrsim 2G_n$ regime as a sensitive assessment of flux motion.

The first task is to establish the perfect range of currents for detecting flux mobility. Figure 2 shows how the transition temperature shifts with $I^{2/3}$ in zero (self-) magnetic field, following Eq. (1) (without the second right-hand side term containing B). Up to 16 mA, the currents are large enough to cause substantial pair-breaking $(\Delta T_c/T_c > 10\%)$ and yet small enough to fall on the straight line [the near-T_c regime of Eq. (1)]. We will therefore use currents in the range indicated by the bracket.

In the next step we compare $G(T)$ curves at different B values at fixed currents within the optimum window defined above. Figure 3 shows $G(T)$ curves at seven fields perpendicular to the film (parallel to the crystal c axis) at a fixed $I=4.7$ mA. For $B \geqslant 0.16$ T, where the self-field is overwhelmed by the applied B, all five curves have exactly the same shape. Their collapse is shown in panel (b). Figure 4 shows two more examples of $G(T)$ curves in various fields at other fixed currents (8.7 and 15.6 mA). Once again $G(T)$ curves at different fields collapse when shifted horizontally. Besides this abnormal B independence of $G(T)$, the absolute values of G are abnormally high. For example, for the 1.2 T curve in Fig. 3, G should never exceed $G_f \sim 1.3$ S at 28 K [Eq. (2)] or 5 S even at $T=0$—if flux flowed freely—but

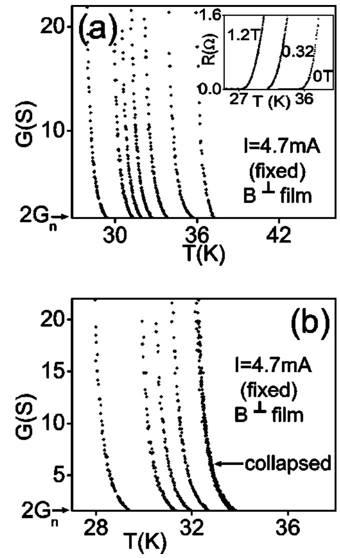

FIG. 3. (a) Conductance vs temperature at different values of B (left to right): 1.2, 0.64, 0.47, 0.32, 0.16, 0.04, and 0 T; highest $B/H_{c2}(T) \sim 0.4$. I is fixed at 4.7 mA ($j \approx 4 \times 10^5$ A/cm^2). Inset shows corresponding $R(T)$ curves for a few fields. The "zero" field ($\lesssim 40$ G) is actually a small residual field plus the current's self-field. (b) Conductance curves for the five highest fields (0.16–1.2) collapsed together onto the 0.16 T curve by simply shifting them horizontally (adding a constant ΔT to each curve).

these limits are completely ignored. Note that at 28 K, where $G=20$ S, I is 40% of I_d, which is likely to exceed any reasonable maximum I_c in light of the discussion related to Eq. (3). The absolute values of j are two to three orders of magnitude higher than for the $Y_1Ba_2Cu_3O_7$ curves in Fig. 1.

The cause of this severe braking of flux motion is not known to us but we hope that our experimental results will generate theoretical activity leading to a solution. We offer

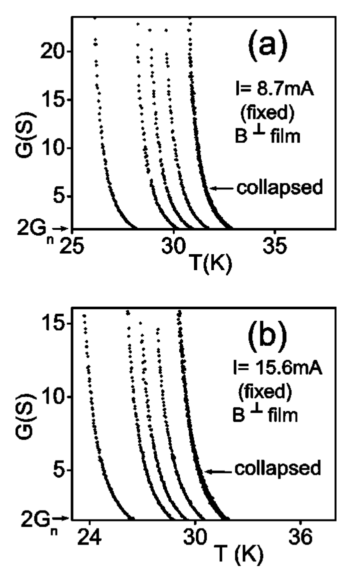

FIG. 4. Conductance vs temperature curves at different values of B (left to right: 1.2, 0.64, 0.47, 0.32, and 0.16 T) at two other values of fixed current ($j \approx 0.7$ and 1.3×10^6 A/cm^2). For both panels the rightmost curve represents the collapse of all five fields.

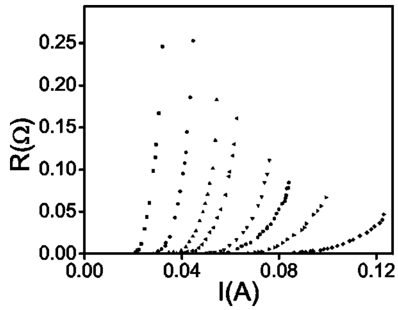

FIG. 5. Resistance vs current curves at $T=20$ K ($\approx T_c/2$). From left to right, $B=1.2$, 0.6, 0.3, 0.2, 0.11, 0.08, 0.06, and 0.033 T; normalized range: $B/H_{c2}(T) \sim 0.4-16\%$. The curves at very low fields show the usual field dependent broadening, while at higher B they become unexpectedly steep and parallel, signaling the freezing of flux motion.

the following tentative speculations at the present time. It is now well-established that MgB_2 is a two-band superconductor with a strong planar σ band and a weaker more three-dimensional π band.[16] The vortices in MgB_2 effectively have two spatial distributions of quasiparticles of each band.[17] There is an intermediate crossover field above which the π-band superconductivity is mostly extinguished and this band then behaves like a quasicontinuous (i.e., vortex free) normal conductor in parallel with the mixed state of the surviving superconducting σ band. This has been imaged by STM[18] and observed as a crossover in the specific heat behavior.[19] It may be worth mentioning that the π band in this system is cleaner than the σ band [as deduced from the shape of $H_{c2}(T)$.[14,20]]. It is possible that this hybrid type I-type II scenario causes a drastic change in the viscous drag coefficient or enhances the conventional pinning mechanism.

While it is not within the scope of the present paper to provide a theory for the observed vortex braking, some light can be shed on these issues in the following way. At sufficiently low B, below the crossover mentioned above, both bands are actively participating in the superconducting state and even the π quasiparticles will be well-localized to the core region. For this case of well-separated cores, the response should show a conventional B dependent broadening besides a pair-breaking shift. We measured R vs I down to very low values of $B/H_{c2}(T)$ ($<1\%$) at several fixed temperatures. A typical set is shown in Fig. 5. The $R(I)$ shape is indeed dependent on B at low values but then becomes steep and parallel at the higher B values, which is opposite to the conventional situation, where the response is steeper at low B and broader at high B.

Although our results are surprising, they are consistent with the results of other groups studying transport in MgB_2 films. Researchers at both Oak Ridge National Laboratory[21] and the University of Wisconsin[22] found I-V curves that were far steeper than in cuprates and showed a small interval between the onset of dissipation and arrival into the normal state. In another study, Gupta *et al.*[23] measured I-V curves (which they ascribed to a vortex-glass) whose $R(I)$ functions seemed like they would merge into ohmic plateaus that

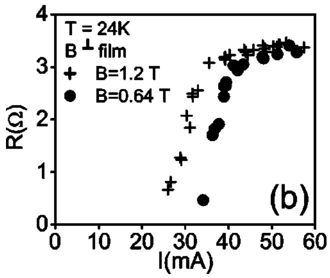

FIG. 6. *I-V* behavior near the $T_c(B,I)$ phase boundary emerges into the normal state instead of a free-flux-flow plateau at high *I*.

would correspond to the free flow of flux[24] if they could have increased their *I* further. We have actually extended their *I-V* curves (by two orders of magnitude in *j*) and have reached the constant $R(I)$ plateaus. An example is shown in Fig. 6. It turns out that the $R(I)$ plateaus have no field dependence and have nothing to do with flux flow, but instead correspond to the normal state. This agrees with the fact that the resistivity parameter ρ_0 that Gupta *et al.* extract from their analysis has no obvious field dependence (their Table I).

In conclusion, our transport measurements on MgB_2 films show a severe suppression of flux motion under a variety of conditions ($T=1.5-39$ K and $B=0.1-14$ T) that seems surprisingly high from a conventional pinning standpoint. We hope that theoretical activity sparked by these results will lead to a complete understanding of the peculiar mixed-state transport behavior of this system.

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