Critical flux pinning and enhanced upper-critical-field in magnesium diboride films

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We have conducted pulsed transport measurements on c-axis oriented magnesium diboride films over the entire relevant ranges of magnetic field \(0 \lesssim H \lesssim H_c\) (where \(H_c\) is the upper critical field) and current density \(0 \lesssim j \lesssim j_d\) (where \(j_d\) is the depairing current density). The intrinsic disorder of the films combined with the large coherence length and three-dimensionality, compared to cuprate superconductors, results in a six-fold enhancement of \(H_c\) and raises the depinning current density \(j_c\) to within an order of magnitude of \(j_d\). The current-voltage response is highly non-linear at all fields, resulting from a combination of depinning and pair-breaking, and has no trace of an Ohmic free-flux-flow regime.

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I. INTRODUCTION

Magnesium diboride (MgB\(_2\)) recently made an impact as a promising new superconductor with a surprisingly high critical temperature \(T_c\) for a simple binary compound. Besides the temperature \(T\), the other principal parameters that define the operational space of a superconductor are magnetic field \(H\) and current density \(j\). Superconductivity perishes above \(H_c(T,j)\) and \(j_d(T,H)\). For most practical applications it is not sufficient for the system to be merely in a superconducting state (presence of a finite order parameter amplitude) but for the system to be in a dissipationless state (constancy of order-parameter phase difference across sample length). Thus from a practical standpoint, the conventional critical current density \(j_c\) is limited by the depinning of vortices and their consequent motion. In the high-\(T_c\) cuprates, the large \(T_c\) is accompanied by high values of \(j_d\) (\(>10^4\) A/cm\(^2\)). However, the layered structure and small coherence length \(\xi\) lead to very weak vortex pinning. Thus between \(j_c\) and \(j_d\), there can be a broad dissipative regime.

MgB\(_2\) has an intermediate \(T_c\) and low values of \(j_d\) and \(H_c\). \(H_c\) \(\sim 10^7\) A/cm\(^2\) at low temperatures and, in single crystals, \(H_c \sim 3\) T parallel to the c-axis. In the films studied here, the intrinsic disorder makes two striking improvements. First of all \(H_c\) is enhanced six-fold. Secondly, pinning is enhanced to the point of raising \(j_c\) to the same order of magnitude as \(j_d\). These observations are consistent with the reduction of \(\xi\) with disorder. Finally MgB\(_2\)’s normal-state resistivity \(\rho_n\) is lower than that of a typical cuprate superconductor (e.g., \(Y_1Ba_2Cu_3O_7\)) by two orders of magnitude. This increases the vortex viscosity by the same factor, so that even when the vortices are depinned, they flow at very low velocities causing insignificant dissipation until \(j_c\) becomes comparable to \(j_d\). All these factors lead to an extremely steep non-linear current-voltage \((IV)\) curve with a complete absence of an Ohmic regime characteristic of free flux flow.

II. EXPERIMENTAL DETAILS

The samples are 400 nm thick films of MgB\(_2\) fabricated using an amorphous boron film was deposited on a (1102) \(Al_2O_3\) substrate at room temperature by pulsed-laser ablation. The boron film was put into a Nb tube with high-purity Mg metal (99.9%) and the Nb tube was then sealed using an argon atmosphere. Finally, the tube was heated to 900 °C for 30 min. in an evacuated quartz ampoule sealed under high vacuum. X-ray diffraction indicates a highly c-axis-oriented crystal structure normal to the substrate surface with no impurity phases. The films were photolithographically patterned down to narrow bridges. In this paper we show data on three bridges, labelled S, M, and L (for small, medium, and large) with lateral dimensions 2.8 x 33, 3.0 x 61, and 9.7 x 172 \(\mu\)m\(^2\) respectively. The lateral dimensions are uncertain by \(\pm 0.7\)\(\mu\)m and the thickness by \(\pm 50\) nm. Fig. 1(a) shows the sample geometry. The horizontal sections of the current leads have enough variation, the film’s own resistance can be used as a thermometer to measure \(R_{th}\) for any pulse duration. Also if \(R(T)\) has enough variation, the film’s own resistance can be used as a thermometer to measure \(R_{th}\) for any pulse duration. For films of \(Y_1Ba_2Cu_3O_7\) (YBCO) on LaAlO\(_3\), which were used for most of our work, we found \(R_{th} \sim 1–10\) nK.cm\(^3\)/W at microsecond timescales. In the case of our MgB\(_2\) films, we expect \(R_{th}\) to be smaller because of sapphire’s very high conductivities.
first principles are not all known for this film-substrate combination and MgB$_2$ has a very flat $R(T)$ below 50 K, so one can’t measure $R_{th}$ as was done for YBCO. We can, however, obtain an upper bound on $R_{th}$ in the following way: Fig. 2(a) shows $IV$ curves for sample L in zero field (This is the largest sample with the lowest surface-to-volume ratio, so that it represents the worst case thermal scenario.). The curves were measured with the sample in different thermal environments. Above some threshold current $I_d$ $\sim$ 650 mA, the system abruptly switches into the normal state. The value of $I_d$ is not sensitive to the thermal environment contacting the exposed surface of the film, confirming that the highly conductive sapphire, together with the greatly reduced heat input during the short pulse, prevents the film’s temperature from rising significantly (It has been shown by Stoll et al. that if there is sample heating, the thermal environment makes a significant difference because it will provide an additional path for the heat to flow through.). Fig. 2(b) shows the top portion of one of the $IV$ curves. The resistance jumps directly to the full normal-state value (The arrow indicates the first data point with non-zero resistance; the dashed line corresponds to $V = R_n I$). It is argued elsewhere that this jump to the normal state occurs due to pairbreaking by the current. At the point the system is just driven normal, the power density reaches $p = jE = 1.01$ GW/cm$^3$ (arrow in Fig. 2(b)). This sets a gross upper bound of $R_{th} \sim 7$ nK.cm/W. Note that the main bottle neck of heat conduction is the film-substrate boundary resistance which is not strongly temperature dependent. In the present work, typical $p$ values are two orders of magnitude lower than the critical $1$ GW/cm$^3$ and so we expect the temperature rise to be a small fraction ($\sim 1\%$) of $T_c$.

The magnetic field is applied normal to the film (parallel to the $c$ axis) and the self field of the current ($\leq 50$ G) is much lower than the applied fields used in this work. Further details of the measurement techniques have been published in a previous review article and other recent papers.

III. RESULTS AND ANALYSIS

Fig. 3 shows the resistive transitions at a low continuous current of $I = 1.4 \mu A$ in different fixed magnetic fields. Panel (a) shows the full curves for sample M, whereas for sample S we show the central region of the transition in panel (b). Both the resistance and the magnetic field is applied normal to the film (parallel axis) and the self field of the current (c axis) and the self field of the current ($\leq 50$ G) is much lower than the applied fields used in this work. Further details of the measurement techniques have been published in a previous review article and other recent papers.

We now turn to the in-field $IV$ curves to investigate the nature of flux motion. In a system with weak flux pinning, the resistance goes through alternate regimes of Ohmic ($V \propto I$) and non-Ohmic behavior. At very low driving forces (low $j$) there can be observable resistance due to thermally activated flux flow (TAFF) or flux creep. Then one encounters a non-linear response as current-driven depinning sets in; in effect the number of mobile vortices is rising. This is incipient flux flow. At sufficiently larger $j$, the vortex motion is effectively free from the influence of pinning and the response becomes Ohmic again. We previously introduced the term free flux motion.

![FIG. 1: (a) Sample geometry used for resistance measurement. At low values of $j$ the wide lead areas add a constant resistance of about 15% of the total value. At high $j$ this contribution is frozen out. (b) Pulse waveforms under worst-case conditions ($j = 0.7$ MA/cm$^2$, $E = 83$ V/cm, and $p = jE = 803$ MW/cm$^3$ on the plateau). The resistance rises to (90% of) its final value in about 50 ns from the (10%) onset of $I$.](image1)

![FIG. 2: Zero-field $IV$ curves for sample L show an abrupt switch to a state of full normal-state resistance, $R_n$, by currents of pair-breaking magnitudes. (a) The switch to a dissipative state is not significantly influenced by the thermal environment. (b) Top portion of the curve in superfluid He$^4$. The resistive portion of the measured curve extrapolates to the $V = R_n I$ dashed line.](image2)
resistivity should correspond to the canonical $\rho_f \sim \rho_n B/H_{c2}$ Bardeen-Stephen expression. As one goes beyond FFF, non-linearity can set in because of heating of the electron gas or changes in the electron distribution function. Finally at yet higher currents, pair-breaking destroys superconductivity and drives the system normal. Here the resistance again ceases to change with current, being characteristic of the normal state, and so the response becomes Ohmic one more time. These stages of dissipation have been described in our previous review article. In $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_7$, the depinning critical current is sufficiently weak compared to the pair-breaking value that all of the regimes can be observed.

In MgB$_2$ the situation is very different. Fig. 3(a) shows the $R(I)$ curves of the present MgB$_2$ samples. After the onset of dissipation, the resistance quickly rises to the full normal-state value. It should be noted that the plateaus do not correspond to FFF but to the normal state. Accordingly the resistance value changes very little with the applied $B$, especially for the curves at lower fields. The overall shapes of the curves are almost independent of field. When the curves of the previous panels are shifted vertically and horizontally by constant amounts they can be made to overlap as shown in Fig. 3(b).

Fig. 3 shows the raw and shifted curves for the other two samples.

These steep IV characteristics in MgB$_2$ are similar to those for niobium alloys but are markedly different from those in the cuprates. The latter can be understood in terms of MgB$_2$’s lower temperature scale and much greater pinning (due to its higher isotropy and ten times larger vortex cross section). Hence thermal activation and current driven depinning are desired until $T_\text{FF}$ but to the normal state. Accordingly the resistance continues to hold for the $R=0.84 \Omega$ and $R=1.76 \Omega$ criteria.

FIG. 3: Resistive transitions of two MgB$_2$ bridges at indicated flux densities. $I=1.4 \mu$A. (a) Sample M; midpoint $T_c$’s lie on the dashed line through $R = R_n/2 = 1.95\Omega$. (b) Similar set for sample S. Dashed lines run through $R = R_n/2 = 1.22\Omega$, and also through the lower and higher resistive criteria $R = 0.84\Omega$ and $R = 1.76\Omega$.

FIG. 4: $H_{c2}$ versus $B$ for three samples. The solid straight lines are linear fits to the data. The dashed lines correspond to the WHH function. Panel (b) shows $H_{c2}$ for sample S defined at two other criteria. The linear behavior of $H_{c2}(T)$ continues to hold for the $R=0.84 \Omega$ and $R=1.76 \Omega$ criteria.

FIG. 5: Resistance versus current curves for sample M. Flux densities are indicated from left to right. The sample was immersed in superfluid helium and $T = 1.5K$ for all data. (a) Raw data. (b) Same data linearly shifted so as to collapse onto a single common curve.
FIG. 6: Resistance versus current curves for samples S and L. Flux densities are indicated from left to right. The sample was immersed in superfluid helium and shifted data. Panels in the left column show raw data and panels in the right column show linearly shifted data.

applications, this implies that the practically useable current densities are much higher than might be inferred from the $j_d$ of the material, since substantial flux dissipation is deferred until $j_c$ becomes comparable to $j_d$.

IV. CONCLUSIONS

We have investigated the low-temperature ($T \ll T_c$) in-field transport behavior of MgB$_2$ and present the first measurement of the full dissipation curves (i.e., $0 \leq j \lesssim j_d$ and $0 \leq R_{T=0} \lesssim R_n$) for this system. MgB$_2$ films made by the two-step laser-ablation process have an intrinsic pinning of a critical magnitude, such that the principle dissipation and resulting IV curves arise mainly from intrinsic mechanisms such as pair-breaking. The onset of dissipation is within an order of magnitude of the pair-breaking current, even at flux densities of a few teslas—the resistance rising quickly to the full normal-state value as the current is increased beyond $j_c$. The same disorder that enhances pinning, also enhances $H_{c2}$ and qualitatively changes its temperature dependence because of the two-band nature of the superconductivity in this material. As explained by the theory of Gurevich, $H_{c2}(0)$ extrapolates to a higher value than would be expected for WHH behavior, and the slope, $dH_{c2}/dt$, is relatively constant. Our measurements of $H_{c2}$ are consistent with this predicted unusual dependence. Both the enhancement in $H_{c2}$ and the critically pinned flux make such MgB$_2$ films more promising for applications, besides providing a cleaner and more intrinsic view of a superconductor’s current-voltage response in the mixed state.

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15. The value of the current density at which this jump occurs, $\sim 2 \times 10^7$ A/cm$^2$, is roughly comparable to the theoretical estimate of $j_d(0) = cH_c(0)/[3\sqrt{\pi}\lambda(0)] \sim 6 \times 10^7$ A/cm$^2$.

16. Sometimes large departures can occur for exceptional situations such as superclean systems and narrow vortex cores where the internal energy-level spacing exceeds their widths.

17. The slight shift in plateau resistance at the highest fields can be understood in terms of spreading of resistance outside the bridge area and into the current-lead areas as explained in the experimental section. Fields approaching $H_{c2}$ start driving the whole film normal at relatively low currents so that the resistance of the wider current-lead areas is not frozen out. This causes the normal-state plateau to rise slightly at the highest fields.