Critical currents, pinning, and edge barriers in narrow YBa$_2$Cu$_3$O$_{7-\delta}$ thin films

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(Received 23 October 1989)

Current transport behavior is reported for narrow strips (down to approximately 1 μm) of YBa$_2$Cu$_3$O$_{7-\delta}$ thin films deposited and lithographically patterned by various means. A systematic increase in the critical current densities is observed in the narrowest strips, suggesting the possible presence of an edge barrier-to-flux entry in these films. The critical currents are found to be near the depairing limit as calculated for these particular films. The critical currents are observed to decrease with increasing temperature, consistent with a flux-creep model. Also, current-voltage characteristics are measured at various temperatures. These characteristics are consistent with exponential behavior in the low-temperature region, but are better fit by power-law behavior at the high temperatures. Flux-pinning energies at zero temperature derived from these data range from 20 to 200 meV depending on the method used. The high-temperature power-law behavior may reflect inhomogeneities along the length of the strips.

I. INTRODUCTION

Current transport in thin films of the high-$T_c$ oxide superconductors is of both fundamental and technological interest. It is of particular importance to establish the mechanisms governing the magnitude of the critical current density $J_c$. Toward this end, it is instructive to measure the current-voltage (I-V) characteristics over a broad range of temperatures, as well as to estimate the critical current density. Especially, transport in narrow strips is informative because it is sensitive to macroscopic inhomogeneities along the films and to the affect of film edges on transport. We have studied the current transport behavior of patterned strips of in situ deposited YBa$_2$Cu$_3$O$_{7-\delta}$ (Y-Ba-Cu-O) thin films as a function of the strip width in the range of 1–13 μm. We find that high critical current densities $J_c$ can be retained in such narrow strips, and that there is even a systematic increase in $J_c$ in the narrowest strips. At low temperatures the I-V characteristics can be fit either by exponential behavior or power-law behavior. Above ~50 K, the fit to a power law is better. All in all, however, we find the low-temperature behavior is best understood in terms of flux creep, and we use this data to estimate the pinning energies present in these films.

II. SAMPLE PREPARATION, EXPERIMENTAL RESULTS, AND DISCUSSIONS

Thin films of Y-Ba-Cu-O were deposited in situ by two means: pulsed laser ablation$^1$ and single target magnetron sputtering.$^2$ The substrates used were MgO(100), yttria-stabilized zirconia (YSZ) (100) or SrTiO$_3$ (100). The oxygen pressure and substrate temperature during deposition are 200 m torr and approximately 700 °C in laser ablation, and 10 m torr with 40 m torr Ar mixture and approximately 650 °C in sputter deposition, respec-

![FIG. 1. Resistive transition of laser ablated films of YBa$_2$Cu$_3$O$_{7-\delta}$ on YSZ ($d$=800 Å, Sample No. A1 to A3). The resistive $T_c$ of these samples are approximately 87 K.](image)

**FIG. 1.** Resistive transition of laser ablated films of YBa$_2$Cu$_3$O$_{7-\delta}$ on YSZ ($d$=800 Å, Sample No. A1 to A3). The resistive $T_c$ of these samples are approximately 87 K.
TABLE I. List of sample YBa$_2$Cu$_3$O$_{7-\delta}$ thin-film preparation conditions and their physical properties. \( P(\text{O}_2) \) is the pressure of oxygen gas in the chamber, \( T(\text{sub}) \) is the substrate temperature. Also listed are the film thickness, patterning method, patterned strip width, resistive \( T_c(R=0) \), extrapolated critical current density and resistivity at 100 K.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Deposition method</th>
<th>Substrate</th>
<th>( P(\text{O}_2) ) (m torr)</th>
<th>( T(\text{sub}) ) (°C)</th>
<th>Thickness (Å)</th>
<th>Patterning method</th>
<th>Width (µm)</th>
<th>( T_c ) (K)</th>
<th>( J_c(0)^a ) (A/cm$^2$)</th>
<th>( \rho(100\text{ K}) ) (µΩ cm)</th>
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<tbody>
<tr>
<td>A1</td>
<td>Laser</td>
<td>ZrO$_2$</td>
<td>200</td>
<td>700</td>
<td>800</td>
<td>CE$^b$</td>
<td>1.9</td>
<td>87.5</td>
<td>1.9 x 10$^7$</td>
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<td>ZrO$_2$</td>
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<td>700</td>
<td>800</td>
<td>CE</td>
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<td>ZrO$_2$</td>
<td>200</td>
<td>700</td>
<td>800</td>
<td>CE</td>
<td>7.4</td>
<td>86.5</td>
<td>8.2 x 10$^6$</td>
<td>90</td>
</tr>
<tr>
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<td>SrTiO$_3$</td>
<td>200</td>
<td>700</td>
<td>1200</td>
<td>CE</td>
<td>1.4</td>
<td>86</td>
<td>3.2 x 10$^6$</td>
<td>90</td>
</tr>
<tr>
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<td>700</td>
<td>1200</td>
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<td>650</td>
<td>300</td>
<td>CE</td>
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<td>94</td>
<td>1.2 x 10$^6$</td>
<td>130</td>
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<tr>
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<td>300</td>
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<td>650</td>
<td>300</td>
<td>CE</td>
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<td>56</td>
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<td>115</td>
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<tr>
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<td>650</td>
<td>2200</td>
<td>IM$^c$</td>
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<td>650</td>
<td>2200</td>
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<tr>
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<td>80</td>
<td>1.6 x 10$^2$</td>
<td></td>
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</tbody>
</table>

$^a$Extrapolated critical current densities.

$^b$Chemical etching.

$^c$Ion etching.

Thick films (C1 to C3), \( T_c \) decreased approximately by 25 K after etching, and the resistivity showed a dependence on the width. The origin of this deterioration is not clear.

Figure 2 shows the critical current densities of laser ablated films A1 to A3 on YSZ as a function of temperature and strip width. The critical current densities at 10 K of the 1.9-, 6.0-, and 7.4-µm-wide strips are approximately 1.6 x 10$^7$, 7.0 x 10$^6$, and 8.0 x 10$^6$ A/cm$^2$, respectively. The critical current density of the narrowest strip is higher than those of the other strips by a factor of 2. This increase in critical current for the narrower strips is also observed in some of the other samples, independent of how they were deposited or patterned, as shown in Table I.

The observed independence of the temperature dependence of the resistivity on strip width indicates that no major damage was incurred during lithographic processing, and that few macroscopic inhomogeneities are present in the films. For the wide strips where \( J_c \) is independent of strip width, bulk pinning presumably pertains. We believe the increase for the smallest width represents the effect of the edge barrier to vortex entry that is expected to play a role in strips whose width \( w \) approaches the transverse penetration depth \( \lambda_{\perp} = \lambda^2 / d \), where \( d \) is the film thickness. The increase of \( J_c \) with decreasing strip width occurs unambiguously in sample series A and C. It is less evident, or even absent, for the others. Note, however, that the thicknesses of samples A and C are less than those of samples B and D. Thus they have significantly larger \( \lambda_{\perp} \)'s and would be expected to exhibit larger edge barrier.

The temperature dependence of \( J_c \) observed in the strips is very similar to that reported within single Y-Ba-Cu-O grains by Mannhart et al.$^3$ This suggests that the grain boundaries are not determining the critical currents in these films. Like Mannhart et al., we can estimate the pinning energy in the strips by using a flux-creep model. Fits of our data to the flux-creep expression of Tinkham,$^4$

\[
J_c(t) = J_c(0)(1 - \alpha t - \beta t^2)
\]

for small \( t \) (\( \equiv T/T_c \)) yield values of \( \alpha \approx 1 \) and \( \beta \approx 0.3 \). The values of the pinning energy \( U(0) \) at \( T=0 \) determined from the expression,

\[
a = \frac{[kT/U(0)]\ln(E_0/E)}{	ext{characteristic electric field derived in Ref. 3, and } k \text{ is the Boltzmann constant. We will return later to the question}}
\]
of edge barriers versus bulk pinning, but clearly bulk pinning governs \( J_c \) in the wider strips. The values below 100 meV correspond to the samples whose \( T_c \)'s were reduced in the patterning process. We observe a distribution of the pinning energy for a given film (i.e., for different widths) and from film to film.

It is instructive to compare the magnitude of the observed critical current densities with the depairing value \( J_{c}^{db} \), and that expected in very narrow strips \((w < \lambda_i)\) due to the edge barrier \( J_{c}^{eb} \). It can be shown that in magnitude\(^5\)

\[
J_{c}^{db} \approx J_{c}^{eb} = \frac{e \Phi_0}{16\pi^2\lambda_i^2 \xi}.
\]  

Using \( \lambda_i \approx 2500 \) Å as measured by our group in similar films\(^b\) and taking \( \xi \approx 20 \) Å, we obtain \( J_{c}^{eb} = 1 \) to \( 2 \times 10^8 \) A/cm\(^2\). In a film thickness of 800 Å, we also obtain \( \lambda_i \approx 0.75 \) µm, which suggests we are not yet in the \( w < \lambda_i \) limit. Nonetheless, it is evident that these films have \( J_c \)'s approaching their maximum possible values. Moreover, the increase in \( J_c \) as \( w \) decreases seems clearly related to an edge barrier effect.

Let us estimate the strip width dependence of \( J_c \) to first-order assuming the critical state model. According to this assumption, the current density is enhanced at the edges of the film over the value in the center, which is governed by bulk pinning alone. Correspondingly

\[
J_c = J_c^e \left( \frac{2a}{\lambda_i/w} \right) + J_c^b,
\]  

where \( J_c^e \) and \( J_c^b \) are the critical current densities corresponding to the edge barrier and to bulk pinning, respectively, and \( a \) is an adjustable dimensionless parameter. We assume that these pinning effects are additive. Of course, in the case of \( w \ll \lambda_i \), the critical current density is expressed as

\[
J_c = J_c^e + J_c^b.
\]

Figure 4 shows a fit of the data for sample \( A1 \) to \( A3 \) to Eq. (3). The fitting parameters are \( J_c^b = 4.1 \times 10^8 \) A/cm\(^2\) and \( J_c^e \lambda_i \approx 1.2 \times 10^3 \) A/cm. If we assume \( J_c^e \) is given by Eq. (2), then \( a \approx 0.16 \).

In Fig. 5, the typical \( I-V \) curves are shown for the laser ablated 800-Å thick film \( A2 \) at seven different temperatures. There exist several schools of thought for the transition from the zero resistance to finite voltage state of the high-temperature superconductors. According to the flux-creep model\(^4,7,8\) the voltage induced by thermal activation of flux over the pinning barriers is expressed in the low-temperature region as

\[
V = V_0 \exp[-U(T)/kT + U(0)I/kTI_c(0)],
\]  

where \( V_0 \) is a parameter, and \( U(0) \) and \( I_c(0) \) the extrapolated value of the pinning energy and critical current at \( T = 0 \). Other points of view include models based on inhomogeneities\(^3\) and a vortex glass\(^10,11\) concept. For both of these models, the \( V \) versus \( I \) characteristics exhibit a power-law dependence \( V \propto I^n(T) \). Figures 6(a)–6(d) show the data of Fig. 5 plotted both as \( \ln V - I \) and \( \ln V - \ln I \) reflecting these two basic \( V \) versus \( I \) dependencies. These data are further parametrized in Figs. 7 and 8 where we showed the dependence of \( d(\ln V)/dI \) versus \( 1/T \), and \( d(\ln V)/d(\ln I) \) versus \( T \). We return to the possible interpretation of these curves in the following.
FIG. 7. Experimental relation between $d(\ln V)/dI$ and $1/T$ for samples A1 and A2. The values of $d(\ln V)/dI$ are obtained from the slope of semilog plots such as Figs. 6(a) and 6(b).

As can be seen in Fig. 6, at low temperatures the data are equally well fit by either an exponential or power-law $V$ versus $I$ relation. At high temperatures, the fit to a power-law dependence is distinctly superior. The crossover comes about 50–60 K where the temperature dependence of $d(\ln V)/dI$ and $d(\ln V)/d(\ln V)I$ clearly change character. Whether the crossover at this temperature represents an intrinsic temperature behavior or the presence of oxygen deficient regions ($60 \text{ K} < T_c < 90 \text{ K}$) in the films is not entirely clear. In one of our films (B1 and B2), this change in behavior could be seen directly in the temperature dependence of $J_c$, itself, which would seem to suggest some kind of inhomogeneity.

It is interesting to compare the pinning energy derived from the above-mentioned $J_c-T$ relation with those derived from the $I-V$ characteristics assuming the flux-creep picture. In general, the pinning energy in Eq. (5) depends on the magnetic flux density $B$. In this experiment, how-

FIG. 6. Typical results for semilog plot and log-log plot in the transition region of the $I-V$ characteristics of sample A2. (a) and (c) show those in the high-temperature region, and (b) and (d) are those in the low-temperature region.

FIG. 8. Experimental data $d(\ln V)/d(\ln I)$ vs temperature. The data show a power-law behavior in the samples A1 and A2. The values of $d(\ln V)/d(\ln I)$ are found from the slope of log-log plot shown in Figs. 6(c) and 6(d) as examples.
ever, we can neglect the dependence of $U$ on $B$, as well as
that of $J_c$ on $B$ because there is no external magnetic
field, and the self-field due to the bias current is of order
10 G at most. Then, at low temperatures the slope of the
$\ln V-\ln I$ relation is given by
\begin{equation}
\frac{d(\ln V)}{dI} = \frac{U(0)}{kTc(0)}.
\end{equation}
In Fig. 7, the experimental relation between $d(\ln V)/dI$ and $1/T$ is shown. As seen in the figures, at low tempera-
tures the values of $d(\ln V)/dI$ increase almost linearly
with $1/T$, in agreement with Eq. (6). This agreement,
along with the linear temperature dependence of $J_c$ at
low temperatures, strengthens the case for a flux-creep in-
terpretation of our data at low temperatures. At higher
temperatures, $d(\ln V)/dI$ is seen to increase with temper-
aturer. As we have already suggested, the behavior in this
regime may reflect inhomogeneities. On the other hand,
within the flux-creep model,
\begin{equation}
\frac{d(\ln V)}{dI} \propto \frac{U(T)}{J_c(T)} \propto X(T),
\end{equation}
where $X(T)$ is the characteristic length scale over which
the pinning energy varies. The data require that $X(T)$
diverges as $T\to T_c$. This is reasonable since both $\lambda$ and $\xi$
diverge at $T\to T_c$.

From the data of Fig. 7 below 50 K and using Eq. (6),
we obtain the pinning energy $U(0)\approx 20-50$ meV for
the laser ablated films of different strip width. These values
are a factor of 3-5 smaller than the values obtained from
the temperature dependence of $J_c$ on the same samples.
The voltage range (and hence the rate of flux creep) over
which the pinning energies are determined is different for
these two measurements, however. Perhaps this can ac-
count, in part, for the difference in the inferred pinning
energies, the lower values corresponding to the higher
transport current. Whether inhomogeneities could play a
role here is not known.

It is also interesting to compare the pinning energies
found here with those obtained by Ferrari et al. [13] who in-
ferred the distribution of pinning energies in similar
Y-Ba-Cu-O in situ thin films from $1/f$ flux noise data.
These authors find a distribution that peaks below 100
meV, in acceptable agreement with the values found here.

In interpreting the physical meaning of these pinning
energies, it is important to stress that in the experiments
reported here, and in the flux noise experiments of Ref.
13, the magnetic fields involved are so small that the vor-
tices in the material are sufficiently far apart that collec-
tive effects are not important. It is the depinning energy
of individual vortices that is being measured in these ex-
periments. This is in contrast to experiments done in
substantial magnetic fields, where interactions between
the vortices are important. This same argument rules out
vortex glass behavior [10,11] as the origin of the power-law $V$
versus $I$ behavior seen at high temperatures in our sam-
ple, since this model depends on the existence of interac-
tion between vortices as we understand it.

Also, we note that the physical interpretation of the
pinning energies quoted here is subject to some ambigu-
ities. First, since both edge and bulk pinning are present,
it is not obvious a priori which energy (or combination of
the two) we measure. In the widest films this ambiguity
is minimal, and it is likely that we measure the bulk pin-
ning energy. Second, it is not known over what length of
the vortex the pinning energy pertains. For such thin
films, it seems most likely that the vortex moves as a
whole along its entire length in any given thermally ac-
tivated event. In this case, the pinning energy should be
proportional to the film thickness. This point was not
checked in these experiments, however.

Finally, as we have pointed out above, at high tempera-
tures the $I-V$ characteristics appear to follow a power-law
dependence. Plummer et al. [9] have shown that such be-
havior can follow from a distribution of critical currents
along a superconducting filament or strip. In this model,
\begin{equation}
\frac{d(\ln V)}{d(\ln I)} = \alpha(T) = 0.6\left(\frac{J_c}{\sigma}\right)^{5/3},
\end{equation}
where $J_c$ is the mean critical current density along the
filament and $\sigma$ is the variance in the distribution. Within
this picture, the decrease of $\alpha(T)$ with temperature seen
in Fig. 8 reflects the decrease of $J_c$ with $T$. While it is not
possible to conclude with certainty that inhomogeneities
govern the $I-V$ curves at high temperatures, this inter-
pretation seems plausible, particularly given the possible evi-
dence for some oxygen-deficient regions in our films. In
any event, it is clear that there is a distinct change in the
behavior of the pinning at $\sim 50$ K. Also, given the likel-
hood of some inhomogeneities in these complicated ma-
terials, it would seem necessary to rule out inhomoge-
neities before turning to more intrinsic mechanisms.

III. CONCLUSION

The transport current behavior has been measured in
narrow Y-Ba-Cu-O films. An increase of $J_c$ has been ob-
served with decreasing the strip width, even before the
width becomes comparable to $\lambda_c$. This result suggests
the presence of the edge barrier, which impedes the entry
of flux into the sample. If we take the strip width smaller
than $\lambda_c$, it may be possible to reach the transport depar-
ing critical current density ($=4\times10^5$ A/cm$^2$ if we take
$\lambda_c \approx 1500$ Å). We have obtained pinning energies of
50-200 meV from the temperature dependence of $J_c$, and
of 20 to 50 meV from the $I-V$ characteristics in the low-
temperature region. The difference of the values of the
pinning energies imply the existence of a distribution of
pinning energies. We find that the $I-V$ curves of our sam-
ple in the high-temperature region exhibit power-law be-
havior, which may reflect inhomogeneities along the
length of the strips.

ACKNOWLEDGMENTS

We thank H. J. Snobland for his help, and are grateful to
B. Lairson and J. Z. Sun for useful discussions. This
work was supported by the U.S. Office of Naval
Research, the U.S. Air Force Office of Scientific
Research, and the NEC Corporation through the support of
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Only the length scale of the pinning potential enters because, as argued elsewhere in this paper, it is the pinning of individual vortices that we measure here, not so-called flux bundles.