Linewidth dependence of critical current density in $Y_1Ba_2Cu_3O_7$ thin-film microbridges

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A study of the dependence of the transport critical current density (J_c) on the width of $Y_1Ba_2Cu_3O_7$ thin-film microbridges with widths down to 2 μm has been made. No evidence of edge pinning, which leads to larger J_c's in narrower microbridges, was found. Due to the limitation in resolution of photolithography encountered in common usage, a tapered or radiation damaged edge was always present, which may have introduced a significant error in the cross section and hence in the estimation of J_c. By normalizing the critical current (I_c) to the room-temperature resistance of the microbridge, we can eliminate this mask-defined cross-sectional error.

One of the most important structural properties of high-temperature superconducting (HTS) thin films is their critical current density (J_c). However, the structure of the pinning centers in thin films, which determine J_c, is not yet well understood due to the many possible sources of pinning defects such as stacking faults, twin boundary, etc. Edge pinning was suggested by Tahara *et al.*,[1] when they found that J_c of $Y_1Ba_2Cu_3O_7$ (YBCO) thin-film microbridges systematically increases with narrower bridge width. It is expected that edge pinning will become important for bridge widths w comparable to and smaller than the effective magnetic penetration depth $\lambda_{\rm eff} = \lambda_c^2/\delta$, where δ is the film thickness and λ_c the penetration depth for shielding of fields parallel to the c-axis (i.e., for shielding supercurrents flowing in the CuO_2 basal planes). For given film dimensions δ and w, this condition is met when the temperature falls within a temperature range ΔT of the critical temperature (T_c), where ΔT is given by $\Delta T = T_c\lambda^2(0)/2w\delta$. For the present films the effect should be strongest for temperatures within about 2 K of T_c. In the experiments of Tahara *et al.*,[1] thin films of varying quality, deposited by different techniques, were used. As is well known, even samples from the same deposition run may differ from one to another in structural properties, J_c or T_c due to differences in thermal contact between the substrate and the holder and due to the nonuniformity of the plume of the sputtered material, etc. So the observed J_c changes with bridge width may be due to many reasons. In order to make a meaningful comparison between the J_c's of different microbridges, it is important that they have identical structural and magnetic (bulk-pinning) properties, so that other sources of variation in J_c may be excluded.

In this letter we report the dependence of J_c on the width of microbridge lines 2, 5, and 10 μm. Scanning electron microscopy (SEM) revealed tapered edges on all three bridges after patterning, which introduce some uncertainty in the cross sectional area used to calculate J_c. We demonstrate that the bridges possess virtually identical normal state properties, and utilize this fact to normalize out the geometrical uncertainties. Differences in J_c between the bridges are then found to be of second order and the values are consistent with our self-field-induced flux-creep model.[2]

Epitaxial YBCO thin films with thicknesses of 0.2 μm were deposited onto (100) $LaAlO_3$ substrates by an optimized laser ablation process.[3] Briefly, the film was deposited at a substrate temperature of 770 °C in O_2 at 200 mTorr pressure. The excimer laser was operated with KrF at 248 nm with a repetition rate of 25 Hz. Films with uniformity across an area up to 3.5×3.5 cm^2 can be produced. The films have a c-axis orientation as confirmed by x-ray diffraction. Critical temperature ($\rho = 0$) is 90 K. $J_c = 3\times 10^6$ A/cm^2 at 77 K. Standard photolithography with negative photoresist (Olin Hunt HNR 120 process) and Ar-ion milling were used to etch thin films into a four-point-probe pattern, with bridge widths between 2 and 10 μm. J_c measurement is conducted at Oak Ridge National Laboratory, using an 8-T superconducting cryostat. Temperature was varied between 74 and 300 K by using liquid nitrogen only.

The resistance was measured as a function of temperature for all three bridges, the transition width of all three curves are less than 1 K. The linear T dependence of resistivity and extrapolation to origin indicate excellent conductivity. After normalizing to their room-temperature resistance values, the three curves essentially collapse onto one another (Fig. 1), matching extremely well near the transition region. This indicates that the resistivities and T_c values of all the bridges are the same, and further confirms the uniformity of the film. However, J_c is the most significant indicator of flux pinning forces in HTS materials. The measured I_c of the three lines and their J_c's estimated by

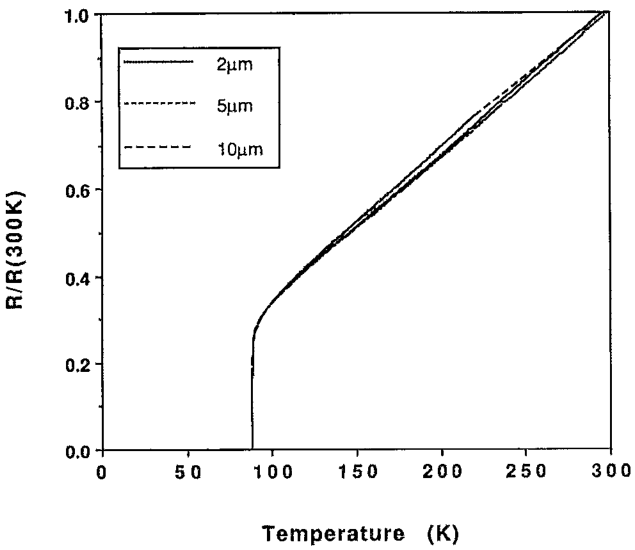

FIG. 1. Resistive transition of three microbridges. Resistance is normalized by their room temperature values, respectively.

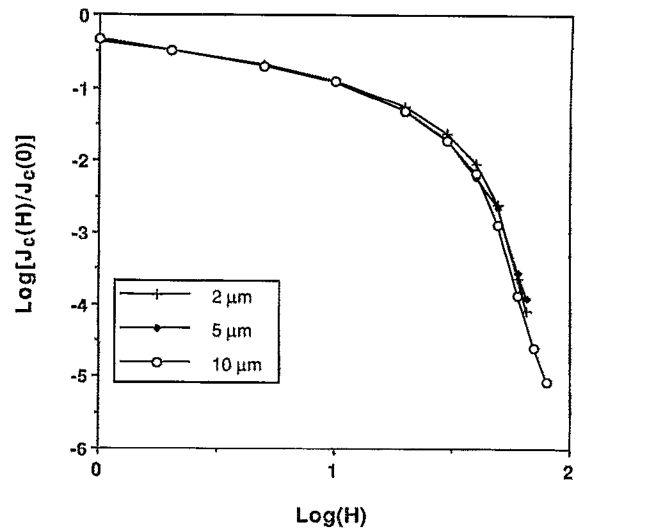

FIG. 2. J_c of three bridges at 77 K show similar dependence on magnetic field (H in kOe). Normalizing to zero-field values eliminates the MDCS error.

using the mask defined cross section (MDCS) are listed in Table I. The narrower the line, the larger the apparent J_c. This is due to the systematic error in narrower bridges, since almost the same J_c can be observed if we normalize our current to $R(300\text{ K})$, i.e.

$$J_c^{5\mu\text{m}}=\{R(300\text{ K})^{5\ \mu\text{m}} I_c^{5\ \mu\text{m}}/[R(300\text{ K})^{10\ \mu\text{m}} I_c^{10\ \mu\text{m}}]\} J_c^{10\ \mu\text{m}},$$

and use the J_c estimated by MDCS for the 10- μm line as a standard, since the tapered or radiation damaged edge introduces less cross-sectional error in wider lines.

Since the pinning action is expected to show up more clearly under an external magnetic field, we have measured J_c at 77 K in magnetic fields up to 8 T applied parallel to the c-axis direction. The results are plotted in Fig. 2 using reduced variable $\log[J_c/J_c(0)]$ and $\log(H)$. J_c is normalized by the zero-field values to eliminate the error introduced by MDCS. The nearly identical decrease of J_c with magnetic field strongly supports the contention of similar pinning in all the bridges. We have used only liquid nitrogen to cool down the sample, since at 77 K, the significant (about a factor of 2) J_c difference already show up in the measurement of Ref. 1 and it is not temperature dependent. Also, unlike the results reported in Ref. 1 where different $J_c(T)$ relations are observed for bridges of different widths, Fig. 3 shows an almost identical $I_c(T)R(300\text{ K})$ relation between 2- and 5-μm bridges (the 10-μm line was damaged during measurement so that data is not available). The resulting temperature dependence is very similar to that reported within a single YBCO grain by Mannhart *et al.*[4] The quantity $I_c(T)R(300\text{ K})$ is a relatively better indication of the magnitude of J_c than $I_c(T)$/MDCS.

All the above experimental results tend to support the insignificance of the edge pinning over the range of bridge widths employed here. In Table I, the weak dependence of J_c on linewidth may well be explained by the weak dependence of self-field on linewidth, as will be shown later, and from our self-field-induced flux-creep study,[2] J_c under zero external field is limited by the self-field generated by the transport current. Due to the loop nature of the self-mag-

TABLE I. Zero field J_c values at 77 K calculated based on MDCS and room-temperature resistance, respectively.

	2 μm	5 μm	10 μm
I_c (mA)	19.6	35.8	63.5
MDCS (cm^2)	4×10^{-9}	1×10^{-8}	2×10^{-8}
J_c (10^6 A/cm^2) (I_c/MDCS)	4.9	3.58	3.18
$R(300\text{ K})$ (kΩ)	4.76	2.69	1.44
J_c (10^6 A/cm^2) [$I_cR(300\text{ K})$]	3.24	3.34	3.18

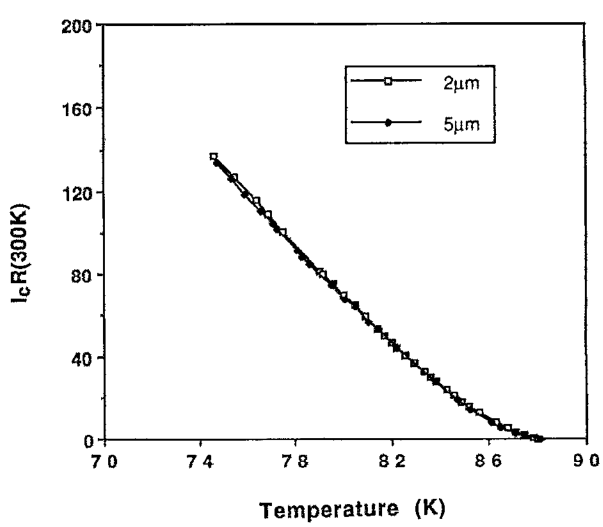

FIG. 3. Same $J_c(T)$ dependence for 2- and 5-μm bridges using $R(300\text{ K})$ as a substitute for cross section.

netic-field, anisotropic properties of YBCO material need to be considered.[5] The self-field orientation is then divided into two categories, one parallel to the c-axis direction $H_{s\parallel}$ and another perpendicular to the c-axis direction $H_{s\perp}$. The self-field $H_{s\perp}$ can be derived from Ampere's law $4\pi Jw\delta/10 = H_{s\parallel}2\delta + H_{s\perp}2w$ in practical units, and

$$H_{s\parallel} = (2J/5)[\delta/2 \ln(1 + w^2/\delta^2) + w \tan^{-1}(\delta/w)]$$

by straightforward integration, where w is the bridge width and δ is the film thickness. Generally $W \gg \delta$ can be assumed, so $H_{s\perp} = \pi J\delta/5$ and $H_{s\parallel} = (J\delta/5)[\ln(1 + w^2/\delta^2) + 1]$, both strongly dependent on bridge thickness and only weakly dependent on bridge width.

In conclusion, no evidence of edge pinning in YBCO thin films was found in our experiment. The J_c of YBCO microbridges with different widths show the same temperature and magnetic field dependence. We believe that the product of the critical current and room-temperature resistance is a better indicator of the magnitude of J_c for an etched thin-film bridge, instead of I_c/MDCS, which introduces a significant error as the line gets narrower down to the 1-μm regime.

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