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Critical Current Behavior in Narrow $YBa_2Cu_3O_{7-\delta}$ Thin Films

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Critical current measurements are reported for narrow strips (down to ~1.0 μm) of $YBa_2Cu_3O_{7-\delta}$ 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 edge pinning in these films. The critical currents are found to be near the depairing limit for these particular films. The critical currents are found to decrease with increasing temperature near zero temperature as in the flux creep formula of Tinkham. The pinning energy derived in the flux creep regime of a 6 μm wide strip is found to be approximately 100 meV.

The critical current density Jc in thin films of the high-Tc oxide superconductors is of fundamental and technological interest. It is of particular importance to establish the mechanisms governing the magnitude of Jc. We have studied the critical currents of patterned strips of $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films as a function of the strip width in the range 1 to 13 μm. We find that high critical current densities can be retained in such narrow strips, even after lithographic patterning, and that there is a systematic increase in Jc in the narrowest strips.

Thin films of YBCO were deposited in-situ by pulsed laser ablation[1] and single target magnetron sputtering[2] on MgO, ZrO_2 or $SrTiO_3$. The oxygen pressure and substrate temperature during deposition are 200 mtorr and approximately 700 C in laser ablation, and 10 mtorr and approximately 650 C in sputter deposition, respectively. Critical currents for the films with thickness ranging from 300 Å to 2200 Å were measured on lines, typically 1-13 μm wide and 1.5 mm long, which had been patterned by standard photoresist lithography and ion milling or chemical etching using dilute nitric acid. Critical current densities were obtained by the division of the maximum zero-voltage current (dc conventional 4-terminal measurement, critical voltage = 0.4 μV (≈ 3 μV/cm)) by the cross-sectional area of the strips.

Figure 1 shows the critical current densities of the laser ablation films on ZrO_2 as a function of temperature and strip width. The critical current density at 10 K of the 1.9 μm wide strip is approximately 1.6×10^7 A/cm^2, which is higher than those of the other strips by a factor of 2. The patterned strips show sharp resistive transitions with zero resistance at 87K as shown in Fig. 2. We find normal resistivities of $\rho(100K)\approx95$ μΩ-cm and $d\rho/dT \approx 0.6$ μΩ-cm/K in these strips. The increase in the critical current is also observed in the other samples, independent of how they were deposited or patterned.

As seen from the data above, the resistive transitions of these strips are essentially independent of strip width. This indicates that no grain inhomogeneities are present in the films and that no major damage was incured during lithographic processing. The critical currents are high and, as already noted, increase for the narrowest strips. For the wide strips, Jc is independent of strip width and presumably reflects bulk pinning. We believe the increase for the smallest width represents the affect of edge pinning (or edge barrier to vortex entry) that is expected to play a role when the width w approaches the transverse penetration depth $\lambda_\perp=\lambda^2/d$ where d is the film thickness.

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The temperature dependence of Jc observed in the wide strips is very similar to that reported within a single YBCO grain by Mannhart, et al[4]. This suggests that the grain boundaries are not determining the critical currents in these films. Fits of our data to the flux creep expression of Tinkham[3]

$$Jc(t) = Jc(0)\,(1-\alpha t-\beta t^2)$$

for small t yield value of $\alpha \approx 1$ and $\beta \approx 0.3$, apparently identical to the results in Ref.4. Not suprisingly the values of the pinning energy determined from the value of $\alpha=(k\,T/Up)\ln E_0/E$, are also similar and of order 0.1 to 0.15eV. Here E is the electric field criterion used to define Jc and E_0 is a characteristic electric field derived in Ref.4.

It is instructive to compare the magnitude of the observed critical current densities with the depairing value Jc^{dp}, and that expected in very narrow strips ($w < \lambda_\perp$) due to edge pinning Jc^{ep}. It can be shown that in magnitude (Ref.5)

$$Jc^{dp} \approx Jc^{ep} = c\Phi_0/16\pi^2\lambda^2\xi \quad .$$

Using $\lambda \approx 2500$Å as measured by our group in similar film and taking $\xi \approx 15$Å, we obtain Jc^{ep} = $1\text{-}2\times10^8$ A/cm^2. In a film thickness of 800Å, we also obtain $\lambda_\perp \approx 0.75$ μm, which suggests we are not yet in the $w < \lambda_\perp$ limit.

Nonetheless, it is evident that these films have Jc's approaching the maximum possible values for our films. Moreover, the increase in Jc as w decrease seems related to edge pinning. Note that if we take $\lambda \approx 1500$Å, as reported for the best materials, $Jc^{dp} \approx 4\times10^8$ A/cm^2.

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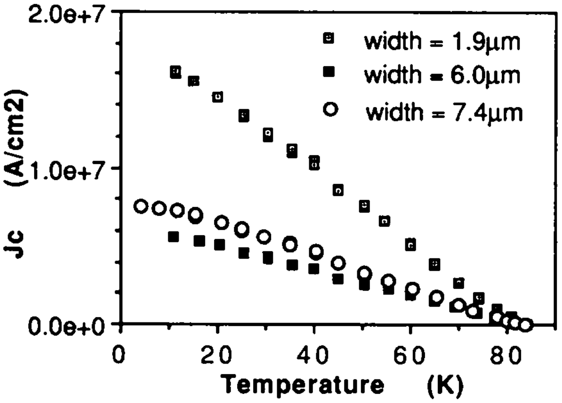

Fig.1 Temperature dependence of Jc for laser ablated films on ZrO_2 (d = 800Å).

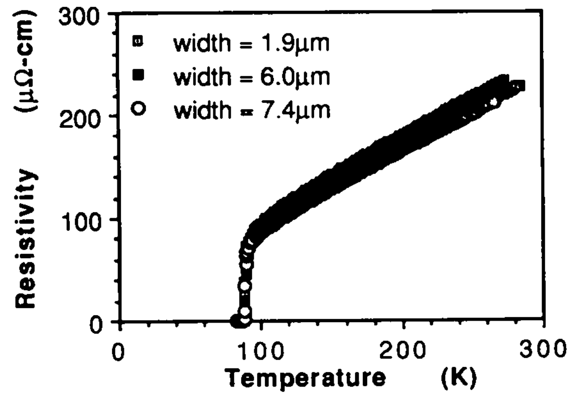

Fig. 2 Resistive transition of laser ablated films on ZrO_2 (d = 800Å).

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