CRITICAL CURRENT DENSITY MEASUREMENTS OF THIN FILMS OF YBaCuO

L.H. Allen, J.H. Claassen, and P.R. Broussard
Naval Research Laboratory
Washington, D.C. 20375-5000

INTRODUCTION

The discovery of high-\(T_c\) superconducting transition temperatures in metallic oxides with a perovskite crystal structure has generated much interest in device applications. The critical current density is an important figure of merit for applications such as magnet technology, AC power line transmission, and high frequency interconnects. Since devices for these applications will function in many different environmental conditions, a thorough study of \(J_c\) as a function of temperature and field is needed.

The films were deposited on (100) single crystal SrTiO\(_3\) substrates in an UHV system (background pressure of 10\(^{-6}\) mbar with all sources on). Yttrium and copper were evaporated from electron beam guns and barium fluoride from a Knudsen cell. The substrates' temperature was raised to 50 °C and molecular oxygen was introduced at the substrates for the film growth. When removed from the chamber, the films were amorphous and insulating and were then annealed in flowing wet oxygen to get the correct crystal structure. A more detailed description of the film preparation is given by Broussard, et al. in these proceedings.\(^1\)

In this paper we present results for two films: one which has essentially the stoichiometric composition, \(\text{YBa}_2\text{Cu}_3\text{O}_7\), referred to as "1-2-3," and an off-stoichiometric film which has barium-rich and copper-poor, \(\text{YBa}_2\text{Cu}_3\text{O}_y\), referred to as "1-3-2." The compositions were determined using an "elastic" Rutherford backscattering spectroscopy technique, which uses higher energy alpha particles than is usual. X-ray diffraction was used to analyze the crystalline phases present in our films. The "1-2-3" film has grains of \(\text{YBa}_2\text{Cu}_3\text{O}_7\) with both \(\text{c}\)- and \(\text{a}\)-axes oriented normally to the substrate. In addition, grains of the "248" phase identified by Marshall, et al.\(^2\) are present with \(\text{c}\)-axis oriented normally to the substrate. The "1-3-2" film also has grains of the \(\text{YBa}_2\text{Cu}_3\text{O}_y\) with \(\text{c}\)- and \(\text{a}\)-axes oriented normally to the substrate in addition to some unreacted BaF\(_2\). The microstructure of the "1-2-3" film was studied by shining polarized light onto the film surface and observing how the light reflects. Grains with orthorhombic structures such as the superconducting phase of YBaCuO will produce a maximum intensity reflection when rotated 90° from an orientation that produces a minimum reflection. The entire surface of our film went from light to dark with a 90° rotation, suggesting that the orthorhombic crystal structure of the film has in-plane order on the length scale of at least a few millimeters (the size of the microscope's field of view). A resistive technique was used to measure the room temperature resistivity (\(\rho\)), resistance ratio (RR) between 298 K and 100 K, and the superconducting transition temperature (\(T_c\)) of the films. The "1-3-2" film has \(\rho = 696 \mu\text{Q}\cdot\text{cm}, \text{RR} = 2.9, \text{and} \Delta T_c = 3\) K with \(R = 0\) by 88 K. For the "1-3-2" film, \(\rho = 3.2 \text{mQ}\cdot\text{cm}, \text{RR} = 2.6, \text{and} \Delta T_c = 79\) K and was 6 K wide.

The annealed films were patterned for the critical current density measurement into a four-probe geometry which was 80 \(\mu\text{m}\) wide with 940 \(\mu\text{m}\) between the voltage leads. Standard photolithographic techniques were used to apply the pattern and a dilute mixture of hydrochloric acid with water (1:9) used to etch the films. Measurements of \(\rho\) before and after the patterning showed no change for the films, indicating that the procedure did not damage the materials. (For off-stoichiometric compositions, evidence that suggests otherwise is presented in the next section.) Contact to the films was made by first sputtering a 1000 Å
layer of gold onto the contact pads of the pattern, and then layering a freshly-cut piece of indium, a gold wire, followed by another piece of indium on top of that. Contact resistances of better than $1\,\Omega$ were achieved with this technique, which resulted in less than a 50 mK rise in temperature for the largest current ($0.5\,\text{A}$) we used.

**J_c RESULTS**

A standard transport technique was used to measure the critical currents. At fixed temperature and field, a constant current was passed through the film while we monitored the voltage drop between the voltage leads. We used a one microvolt criteria to determine the critical current. Using a profilometer to measure the films' thicknesses gave 5900 Å for the "1-2-3" film and 1.06 μm for the "1-3-2" film, and allowed us to calculate $J_c$.

Fig. 1 is a plot of the temperature dependence of $J_c$ in ambient field for both the films. At 4.2 K, the critical current density of the stoichiometric film is $1.04 \times 10^6\,\text{A/cm}^2$. As temperature increases, $J_c$ slowly decreases until above 55 K where it falls off more rapidly. By 77 K, $J_c$ has dropped to $3.5 \times 10^5\,\text{A/cm}^2$. The "1-3-2" film's $J_c$ is lower, $1.64 \times 10^5\,\text{A/cm}^2$, and also rolls over in temperature at $\approx 15\,\text{K}$. Also in Fig. 1, the $J_c$ of the "1-2-3" film approaches zero close to the 88 K which was the $T_c$ obtained with a resistance measurement. If the "1-3-2" curve has the same shape as the "1-2-3" curve, then $T_c$ as determined by $J_c$ going to zero is much lower than the 79 K measured resistively. This may indicate that off-stoichiometric material is more sensitive to an etching process than stoichiometric material.

For the "1-2-3" film, the $J_c$ data for temperatures greater than 50 K follow a power law dependence

$$J_c = (1 - t)^n$$

as shown in Fig. 2. A least squares fit of log $J_c$ to log $(1-t)$ is illustrated by the straight line in Fig. 2 and yields a value for $n$ of 3.27 with a standard deviation of 0.06 and a linear correlation coefficient of 0.9988. Furthermore, if we leave $T_c$ as an adjustable parameter, the best fit to the data (lowest correlation coefficient) is obtained when $T_c$ is 88K ± 1 K, which is the same value obtained with a resistance measurement. Recently, Deutscher and Muller have proposed that Josephson tunneling that occurs at the twin boundaries inside the grains of high-$T_c$ oxides will dominate the transport process. They predict a power law dependence with $n = 2.0$. Our results do not support their prediction, but we find no theories in the literature that propose a closer value to ours.

To obtain the field dependence of $J_c$, the films were placed in a Bitter magnet and oriented so the field was perpendicular to the film surface. Fig. 3 shows the results for the "1-2-3" film. At 4.2 K, $J_c$ was not strongly affected by field, and for fields as high as 90 kOe was reduced less than a factor of 10 from the ambient field value. By 77 K, however, only a few kOe was needed to sharply diminish $J_c$.

The pinning force is related to $J_c$ by

$$F = \frac{1}{2} \left( \frac{J \times B}{J_c} \right)$$

and Fig. 4 is a plot of field dependence of the pinning force at 4.2 K. As indicated, the pinning forces are very high, $\approx 10^9\,\text{dyn/cm}^2$, which is comparable to the values obtained for commercially used materials such as Nb$_2$Sn and NbTi alloys. Up to 90 kOe, $F_p$ is still increasing and has not reached the maximum which is characteristic of $F_p(H)$ curves. Assuming that YBaCuO has a similar $H_c2$ as EuBaCuO for which a lower limit of $H_c2$ has been
established at 275 kOe by Tajima, et al. then at 90 kOe the reduced field (h) was \( \approx \frac{1}{3} \). For superconducting systems such as Nb3Sn, the maximum in \( F_p \) occurs for \( h \) between 0.3 and 0.5, which suggests that greater magnetic fields may be needed to observe the maximum in \( F_p(H) \) for YBaCuO.

To close, we note that the "1-2-3" film was "burned out" when a transient voltage spike was applied, creating a crack across the current path. Interestingly, when SEM was used to inspect the crack, "charging" was observed in the region around it, which is an indication of semiconducting or insulating material. In the YBaCuO system, non-metallic transport properties have been correlated with a tetragonal crystal structure that is oxygen deficient compared to the superconducting phase. A portion of this region was identified as a potential weak spot before the \( J_c \) measurement and may already have been tetragonal, but the fatal pulse appears to have enlarged the tetragonal region and in the process produced the crack.