Critical-Current Measurements in Epitaxial Films of $YBa_2Cu_3O_{7-x}$ Compound

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We have grown epitaxial films of the $YBa_2Cu_3O_{7-x}$ compound on $SrTiO_3$ substrates. The superconducting critical current in these films at 77 K is in excess of 10^5 A/cm^2 and at 4.2 K in excess of 10^6 A/cm^2.

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Over the last fifteen months the superconducting transition temperature has increased by a factor of 4 to approximately 100 K. This development was initiated by the remarkable observations of Bednorz and Müller,[1] who showed that in $La_{2-x}Ba_x(Sr,Ca)Cu_4O_9$, with the K_2NiF_4 structure, the superconducting transition temperature was in the range of 30–40 K. Shortly after these results were reproduced in a number of laboratories,[2–5] Chu and his associates[6] showed that the application of pressure increased the transition temperature to 52 K and, furthermore, in the Y-Ba-Cu-O systems, transition temperatures as high as 100 K could be obtained.[7] Over the last few months a very large number of publications have appeared addressing various aspects of superconductivity in these materials.

One of the weak points that has often been cited about this class of superconducting materials is their small critical current. Although a number of publications have appeared on this subject, the value of the critical current is still small relative to the more familiar metallic alloys. For example, the highest published[8] value at 77 K known to these authors is approximately 10^3 A/cm^2. The range of potential utility of these materials is determined by the critical current. We have prepared epitaxial films of these materials and find that the critical current at 4.2 K is in excess of 10^6 A/cm^2 and at 77 K is in excess 10^5 A/cm^2. The value of 4.2 K compares favorably with some of the best metallic alloys and we believe it can be increased even further.

Epitaxial films with a nominal composition of $YBa_2Cu_3O_{7-x}$ were prepared by the evaporating of Y, Ba, and Cu from three separate electron-beam sources in a vacuum of approximately 10^{-4} to 10^{-3} Torr comprised primarily of O_2. The substrate was $SrTiO_3$ with a [100] direction perpendicular to the plane of deposition. During deposition the substrate was kept at approximately 400 °C. The procedure for our making these films is similar to that described earlier.[9,10] As deposited, the films showed a broad peak in the x-ray diffraction pattern characteristic of a highly disordered or an amorphous atomic arrangement. These films were annealed at approximately 900 °C in O_2 to obtain epitaxial films. This was confirmed both by x-ray diffraction and electron-microscopy examination. The c axis of the orthorhombic structure was primarily perpendicular to the plane of the film. However, a fraction of the film had crystalline orientation with the c axis in the plane of the film. In addition to the orthorhombic structure there were trace amounts of a second phase present. The details of the film structure will be described in later publications. Figure 1 shows the typical change in resistance with temperature of our samples. Perhaps the most notable feature of these data is the relatively sharp transition to total superconductivity. The width of the transition temperature (10% to 90%) is about a degree. The film became totally superconducting at 90 K.

Critical-current measurements were made in two ways. In one method, the magnetic properties of a film with a thickness of 10^{-4} cm were measured in a field perpendicular to the plane of the film and the critical current deduced from the maximum value of the trapped flux. In the second method, a dc or a pulsed current was passed through a film approximately 10^{-4} cm thick by 3×10^{-2} cm wide. A four-point-probe measurement was made and the onset of a voltage greater than a microvolt was used as a measure of the critical current. The continuous-current and the pulsed-current methods gave the same results. Unfortunately this approach could not be used below 70 K because of the large currents required and the relatively high values of the total contact

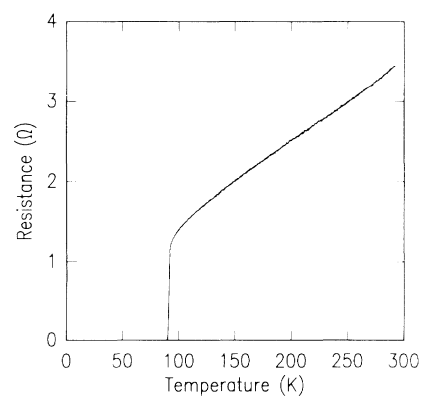

FIG. 1. The resistance vs temperature for a typical sample. The temperatures at the onset of superconductivity and the complete lack of resistance are ~105 and 90.2 K, respectively. The width of the transition from 10% (92 K) to 90% (91 K) of the resistance is 1 K.

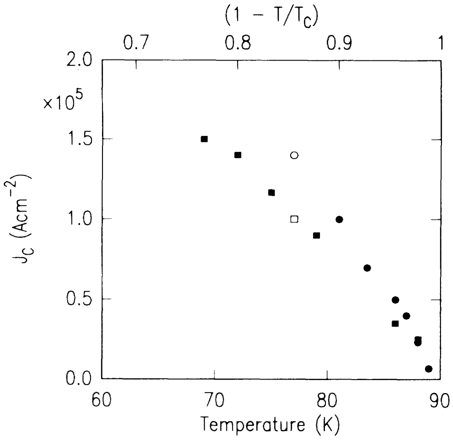

FIG. 2. The critical-current density vs temperature for two samples measured directly. The two values measured at 77 K were taken with the sample immersed in liquid nitrogen and are shown with open symbols.

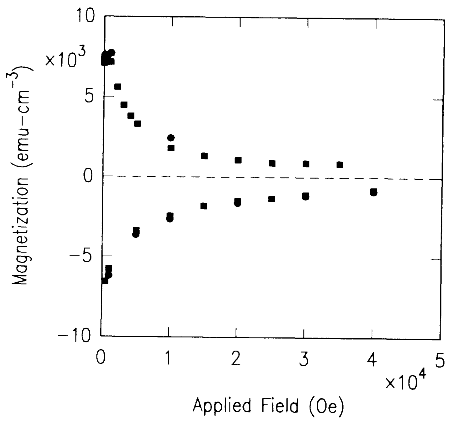

FIG. 3. The volume magnetization vs applied field at 4.4 K for two samples.

resistance for the current leads, $\sim 40\ \Omega$. The critical current of two different samples is shown in Fig. 2. In one of these samples the critical current at liquid-nitrogen temperature was in excess of 1.5×10^5 A/cm^2.

The magnetic field measurements were made on samples approximately 0.1 cm$\times$0.3 cm$\times10^{-4}$ cm in width, length, and thickness. We report here the results of the perpendicular field measurements as these are relevant to the current flowing in the plane of the film, or the direction of highest critical current density.[11] The measurements were made on a SHE Corporation SQUID magnetometer. The sample was initially cooled in zero field to 4.4 K and subsequently a field of 3.7 Oe was applied. A large diamagnetic response was observed. The sample was warmed in this field and a sharp drop in the diamagnetic response was observed at the transition temperature. The width of the magnetic transition was comparable to the width of the resistive transition.

In Fig. 3 we show the sample magnetization versus applied field for fields up to 40 kOe measured with the sample at 4.4 K. On removing the applied field, the resultant positive moment is associated with trapped flux and circulating currents in the film. We can deduce the critical current from these data and the expression[12] $J_c=30M/R$, where M is the volume magnetization in units of emu/cm^3, R is the radius of the sample in cm, and J_c is the critical current density in A/cm^2. At 4.4 K and zero applied field this yields a value of 1.6×10^6 A/cm^2 with use of a geometrical mean for the radius. This value decreases to about 4.2×10^5 A/cm^2 in an applied field of 10 kOe (not corrected for demagnetization effects). Figure 4 shows the magnitude of the magnetization as a function of temperature with zero applied field for another sample. At temperatures of 30 and 70 K, magnetic hysteresis loops similar to those of Fig. 3 were measured with identical results for the magnetization indicated in Fig. 4. If we accept the temperature dependence shown in Fig. 4 and scale it to the directly measured critical-current density above 70 K, we obtain a value of 2×10^6 A/cm^2 for the critical-current density at 4.2 K, in agreement with magnetization measurements. We believe that the critical currents estimated from the above magnetization data are less than the actual critical currents because penetration-depth effects, important in thin films, have not been taken into account. Our estimates, therefore, are a lower limit.

In summary we have shown that the superconducting critical currents in this class of high-temperature superconductors can be remarkably high.

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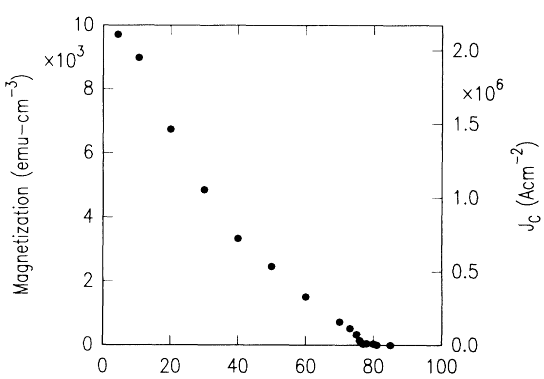

FIG. 4. The volume magnetization vs increasing temperature for a sample. The applied field was first reduced to zero from a large value and the temperature was then increased. The y-axis scale on the right was obtained with use of the equation described in the text and with the mean radius of the sample, or 0.14 cm.

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