Temperature-independent, constant E-J relation below T_c in the current-induced resistive state of polycrystalline $YBa_2Cu_3O_{7-x}$

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Restoration of the resistive state of bulk $YBa_2Cu_3O_{7-x}$ between 4.2 K and T_c was investigated by transport measurements using $J > J_c$. Unlike the low-T_c type-II superconductors, where restoration of the normal-state resistivity is obtained by exceeding J_c by a fraction of J_c, a constant value of resistivity, which was several to many times smaller than that of the normal-state value, was obtained when J_c was exceeded in bulk $YBa_2Cu_3O_{7-x}$ samples. This constant E-J slope remained constant up to ten times the transport J_c. Even more surprisingly, this value was constant for a given sample between 4.2 K and T_c. Near T_c we observed two breaks in the E-J behavior, which we believe correspond to the inter- and intragrain J_c's with the high J_c in agreement with reported values obtained by magnetization. Microstructural results imply that the mechanism for the observed behavior may be weak-link related.

I. INTRODUCTION

Since the discovery[1,2] of high-T_c superconductors many investigations have been undertaken to understand the resistive transition of these materials in the vicinity of T_c in the limit of very small measuring current under varying magnetic fields for single crystal,[3,4] ceramic,[5] and thin-film[6–8] samples. An interpretation to the experimental data was offered in the light of thermally activated flux creep in the case of the single crystals and thin films,[9,10] and in the light of weak-link coupling[5] in the case of the ceramic samples.

In classic type-II superconductors, normal-state resistivity ρ_n (resistivity just above T_c, before the onset of superconductivity) is restored by exceeding the critical current density J_c by a small fraction of J_c almost in all cases.[11,12]

In ceramic high-T_c superconductors this phenomenon has not been investigated, to our knowledge. Here we report experiments on the temperature dependence of the current-induced resistive state below T_c in polycrystalline bulk $YBa_2Cu_3O_{7-x}$ samples. The resistivity restored by exceeding J_c several fold was several to many times smaller than the normal-state resistivity, and even more surprisingly it was constant between 4.2 K and T_c. It seems that the resistivity restored in this manner depends on the processing of the samples.

We have also observed two very different critical current densities by direct transport measurements. The first one (denoted as J_{c1} in Fig. 2) is the weak-link-limited, intergrain J_c, and the second one (denoted as J_{c2} in Fig. 2), corresponds to the intragrain magnetization J_c.

EXPERIMENT

A set of bar-shaped samples, nominally $0.5\times0.8\times24$ mm^3, was cut from $YBa_2Cu_3O_{7-x}$ pellets of the same thickness, which were prepared by a solid-state reaction process using commercial Grace powder. Silver pads were painted on the pellets before heat treatment to facilitate low-resistivity contacts. Bar-shaped samples were then separately given a final heat treatment at increasing temperatures for the same period before the final oxygenation. Stranded thin silver wires were soldered (In–50 wt % Sn) to the silver contact pads as current leads. A contact resistivity of about 10 $\mu\Omega\,cm^2$ was easily achieved.

A computer-controlled dc-pulse technique[13] with a four-probe arrangement was used to determine J_c (a 1-μV/cm electric-field criterion was used), and to obtain I-V characteristics. After measuring J_c as a function of temperature and applied magnetic field, E-J (I-V) curves were obtained by exceeding J_c several fold to see the restoration of normal-state resistivity. Low contact resistances and a very short pulse rise times, nominally 3–9 msec., were necessary to avoid the Joule-heating effects. J_c results and current-pulse-induced bifurcation of J_c on these samples are presented elsewhere.[14] For comparison, restoration of normal-state resistivity in a Nb–50 wt % Ti, Cu-clad wire was also investigated in the same way.

RESULTS

Figure 1 shows a typical J_c versus T curve for one of these $YBa_2Cu_3O_{7-x}$ bulk samples. E-J curves for the same sample as in Fig. 1 are presented in Fig. 2 when the temperature is close to T_c. Note that some resistance appears when J_c is exceeded, but this value is several times smaller than that at only few degrees above T_c. The resistivities at 100 and 92 K and just above J_c are $\rho_{100\,K}=0.53$ mΩ cm and $\rho_{92\,K}=0.13$ mΩ cm, and thus $\rho_{100\,K}/\rho_{92\,K}=4$. Figure 3 shows E-J curves at temperatures between 4.2 and 100 K. Note that the slope does remain approximately constant below T_c despite a 90-K

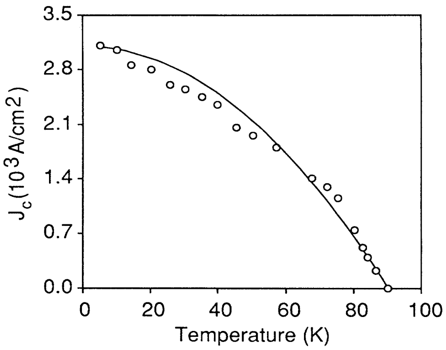

FIG. 1. Typical J_c vs T curve of one of the bulk $YBa_2Cu_3O_{7-x}$ samples studied (sample size was $0.5\times0.8\times24$ mm^3, and a 1-μV/cm criterion was used) at ambient fields. The solid line is $J_c=J_c(0)[1-(T/T_c)^2]$, where $J_c(0)=3.1\times10^3$ A/cm^2.

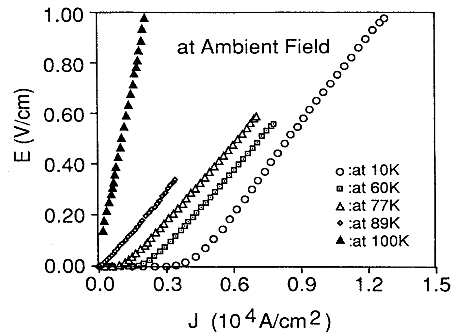

FIG. 3. E vs J curves for the same sample (as in Fig. 1). Note that the slope (resistivity) stays constant between T_c and 4.2 K, and several times smaller than the slope above T_c.

change in temperature. Figure 4 shows E-J curves for another sample. We have again a temperature independent slope between T_c and 4.2 K which is, in this case, 22 times smaller than that of above T_c.

Figure 5(a) shows E versus J curves at 100 K for three different $YBa_2Cu_3O_{7-x}$ samples made in the same way except for the final heat treatment. The sample B and C were heat treated 10 and 20 °C higher than the sample A, respectively, for the same period of time. Figure 5(b) shows E versus J curves at 10 K for the same three samples as in Fig. 5(a). Note that the resistivity in the current-induced resistive state follows the same order as in the normal state, but does not scale with the normal-state resistivity.

Figure 6 shows the current-induced transition into normal state for a Nb–50 wt. % Ti wire. The wire was single core, Cu clad, and 0.3 mm in diameter. As seen from the E-J curves above and below T_c (12 K), normal-state resistivity is restored rather sharply by exceeding J_c by a small amount.

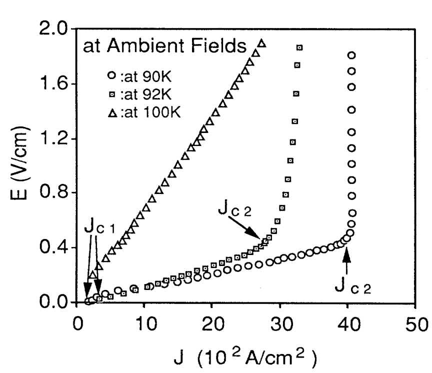

FIG. 2. E vs J curves for the same sample (as in Fig. 1) at temperatures just above and below T_c as marked. Note the two different J_c's marked. J_{c1} here refers to the standard critical current density at which the first measurable voltage drop appears across the sample (a 1-μV/cm electric-field criterion was used in our measurement), and J_{c2} is the second break in the E-J curves, observed by direct transport measurement, and it compares well with the reported magnetization J_c values for this sort of samples.

X-ray diffraction studies show no phases other than $YBa_2Cu_3O_{7-x}$ in these samples. Scanning electron microscopy (SEM) and optical microscopy studies indicate that apart from increasing average grain size with increasing final heat treatment temperature, the general grain morphology looks the same for all the samples studied. As the final annealing temperature goes up, the pore density decreases in the samples. The starting grain size in the powder and in sample A was about 1 μm, and the grain size in sample C was about 10 μm. Microprobe (wavelength dispersive spectroscopy) analysis show that the grains in all the samples have stoichiometric composition. The samples with the highest heat treatment occasionally shows CuO and Y_2BaCuO_x in very small quantities at the grain boundaries. When these phases are present they are usually elongated along the grain boundaries.

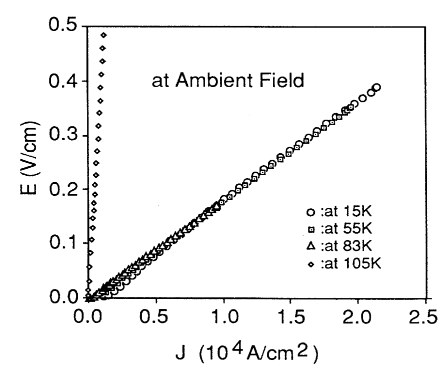

FIG. 4. E vs J curves for another sample. Again there is one constant slope below T_c, which is several times smaller than that of above T_c.

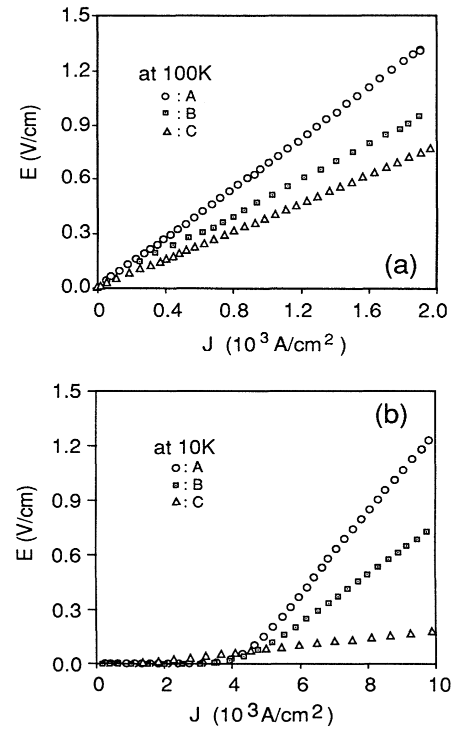

FIG. 5. (a) E vs J curves above T_c for the samples A, B, and C. The sample B and C were the same as A, except their final heat treatment temperature was 10 and 20 °C higher, respectively. (b) E vs J curves at 10 K for the same samples A, B, and C as in (a). Note that current-induced differential resistivity follows the same order as in the normal state.

DISCUSSION

As seen from Fig. 1 critical current densities of the samples used in this investigation are respectable for the bulk sintered ceramic $YBa_2Cu_3O_{7-x}$ superconductors. The solid line is $J_c = J_c(0)\ [1-(T/T_c)^2]$, where $J_c(0) = 3.1 \times 10^3\ A/cm^2$.

It is evident from Fig. 2 that for T just several degrees below T_c two critical current densities can be deduced from such E-J curves. The first one is only approximately $10^2\ A/cm^2$, and comparable with the reported transport J_c's for bulk sintered $YBa_2Cu_3O_{7-x}$ samples.[15,16] The second one is 3×10^3 and $4 \times 10^3\ A/cm^2$ at 92 and 90 K, respectively. The latter ones are well in agreement with the reported magnetization J_c values for polycrystalline bulk $YBa_2Cu_3O_{7-x}$ samples. Therefore we think that the first one (marks as J_{c1} in Fig. 2) is the weak-link-limited[17] intergrain J_c, and the second ones (marked as J_{c2}) are the true bulk transport J_c of the interior of the grains (intragrain J_c). Below 90 K it was not possible to observe the second J_c's for these samles because of the experimental current range limit (120 A) and the sample sizes studied. This was one of the reasons we chose to look into the effect in the immediate vicinity of T_c and in the absence of an applied magnetic field. Thus field-induced flux flow is highly unlikely. Magnetic-field-induced flux flow results in constant slope in E-J curve, and this slope depends on the magnitude of the field in the very weak pinning regime.[18] Since the slope remains constant up to ten times the J_c in our experiment, the self-field-induced flux flow is not a possible mechanism, otherwise one would expect the slope to increase with the increasing self-field (sample current). One could see some evidence of this in the transitions in Fig. 6. Transition becomes steeper as it takes place at higher sample currents.

Even in this immediate vicinity of T_c the temperature-independent constant resistive state has been clearly observed. The transition from zero resistance to this constant resistance is rather sharp, suggesting a very small spread in the J_c of the limiting weak links.

As seen from Figs. 3 and 4, although the weak-link-limited J_c is exceeded five and ten times, respectively, the slopes of the E-J curves remain constant. It seems that for a given bulk $YBa_2Cu_3O_{7-x}$ sample there is a constant resistivity below T_c for a large range in J above J_c. This current-induced resistivity remains constant between T_c and 4.2 K. This might indicate that the resistance of a weak link in these samples above their J_c is temperature independent. It seems that as the grain size goes up and pore density goes down, both the normal-state resistivity and current-induced resistivity below T_c go down. Thus the current-induced resistivity below T_c seems to decrease with the decreasing grain boundary surface area per unit volume.

As seen from Fig. 6 the current-induced transition process for a Nb–50 wt. % Ti wire seems to be as expected, and normal-state resistivity is restored by exceeding J_c by a small fraction of J_c. This transition is very much similar in character to the second break off in the E-J curves of $YBa_2Cu_3O_{7-x}$ samples (see Fig. 2).

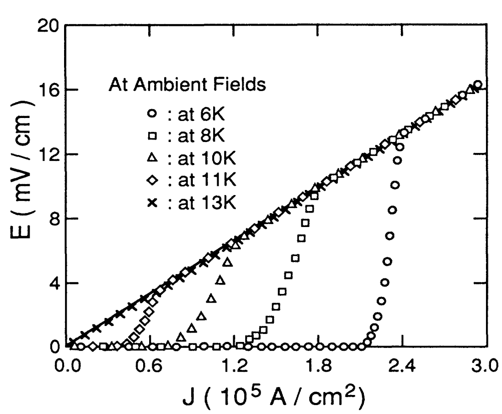

FIG. 6. E vs J curves at temperature above and below T_c as marked for a typical type-II superconducting wire (Nb–50 wt. % Ti). Note that the full normal-state resistivity is restored by exceeding J_c by a small amount.

CONCLUSIONS

The restoration of normal-state resistivity by exceeding J_c was investigated for $YBa_2Cu_3O_{7-x}$ ceramic samples and compared with that of classical type-II superconductors. From the immediate vicinity of T_c to 4.2 K a temperature- and current density-independent resistivity was restored when J_c is exceeded in $YBa_2Cu_3O_{7-x}$ ceramic samples in contrast to classical type-II superconductors. These resistivities were several times to several tens of times smaller than the normal-state resistivities of these samples.

Two critical values of J were observed near T_c, the first corresponding to the transport, weak-link-limited intergrain J_c's and the second corresponding to magnetization, intragrain J_c's reported for bulk sintered $YBa_2Cu_3Co_{7-x}$ samples.

The normal-state resistivity just above T_c and the constant resistivity value below T_c were different for each sample, and they both seem to be related to the grain boundary surface area per unit volume. Since this investigation was done at ambient fields, the constant slope of the E-J curves is not likely to be due to field-induced flux flow. Since these slopes are temperature independent between T_c and 4.2 K, they also exclude the thermally activated flux creep as a responsible mechanism. It is probably the total resistance of the network of weak links operative throughout the sample in this transport measurements.

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