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Upper critical fields and anisotropy limits of high-T_c superconductors $R_1Ba_2Cu_3O_{7-y}$, where R = Nd, Eu, Gd, Dy, Ho, Er, and Tm, and $YBa_2Cu_3O_{7-y}$

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The upper critical fields $B_{c2}(T)$ were measured up to 28 T for $R_1Ba_2Cu_3O_{7-y}$, where R = Nd, Eu, Gd, Dy, Ho, Er, and Tm, and for $YBa_2Cu_3O_{7-y}$. The midpoints $(dB_{c2}/dT)_{T=T_c}$ cluster about (2.8 ± 0.2) T/K, the T_c's $=(93 \pm 2)$ K show a slight systematic decrease from Nd to Tm, and the extrapolated values of $B_{c2}(0)$ cluster about (160 ± 20) T. The wide range of normal-state resistivities indicates that they are not intrinsic to the superconductor. The anisotropy $A = B_{c2\parallel}/B_{c2\perp}$ is estimated to be less than 12 based on the data for the resistive transition. Criteria for the midpoint resistive transition are also reexamined.

In this Rapid Communication we present high-field data with applied fields up to 28 T on the high-T_c superconductors $R_1Ba_2Cu_3O_{7-y}$, with R = Nd, Eu, Gd, Dy, Ho, Er, and Tm and $YBa_2Cu_3O_{7-y}$. The T_c's are clustered within a few degrees about 92 K, the slopes of the midpoint critical fields $(dB_{c2}/dT)_{T=T_c}$ cluster about 2.8 T/K, but the resistivities near T_c for the rare-earth compounds range from 200 to 2000 $\mu\Omega$ cm. The large variation in resistivity is not reflected in the superconducting properties. The rapid and nearly linear temperature dependence of the normal-state resistivity and the very broad nature of the resistive transition in a magnetic field present difficulties in defining $B_{c2}(T)$. Our present results define the resistive transitions using extrapolations of the resistivities from the linear region well above T_c. The resulting midpoint $(dB_{c2}/dT)_{T=T_c}$ is more consistent and much higher than that obtained earlier by us[1] and others. The anisotropy of B_{c2} in $YBa_2Cu_3O_{7-y}$ at 4.2 K is estimated to be less than 12 based on these high-field data.

These materials were prepared at Bell Communications Research as described in Ref. 2 and are the same samples used in Ref. 2 or sections cut from the same batch. All the compounds measured are single phase, except for Nd which has a few percent of a second unidentified phase. Although compounds with R = Sm, Yb, and Lu were also prepared, the upper critical fields were not measured in these because good electrical contacts were not obtained, although mechanical removal of the surface layer did not alleviate the problem. We assume this problem is due to a surface oxide.

The upper critical fields $B_{c2}(T)$ were measured resistively with a standard dc four-probe technique in transverse dc magnetic fields in water-cooled magnets up to 20 T or in the 30 T Hybrid magnet at the Francis Bitter National Magnet Laboratory facility. The samples were small ($0.5 \times 3 \times 8$ mm^3) rectangular polycrystalline slabs with low porosity. The leads were attached with Ag paint and a low dc current density (<300 μA/cm^2) was applied. A general-purpose temperature-controlled cryostat furnished by the facility was used for measurements to 20 T. Measurements were made in the same manner described earlier for Y-Ba-Cu-O.[1] The midpoint of the resistive transition was obtained at constant temperature and swept field.

The large temperature dependence of the resistance of these high-T_c materials makes it difficult to define the midpoint of the transitions which are broadened radically in applied fields. If measurements are taken at temperatures near T_c, as has been done by us and others for Y-Ba-Cu-O, then one would define $\rho_N(T)$ below T_c as the dashed line (labeled as l) in Fig. 1, and the resulting resistivity as $\rho_{Nl}(T)$. However, if the resistivity is extrapolated from temperatures well above T_c (above about 115 to 120 K) then one would define $\rho_N(T)$ below T_c as the dash-dotted line (labeled as h), determined from the extrapolation as shown in the expanded T scale of the inset of Fig. 1. We have chosen what we believe to be the more reasonable definition as the h extrapolation with the midpoint 0.5 $\rho_{Nh}(T)$. [If the l extrapolation were chosen, $\rho_{Nl}(T)$ would become negative as T approached zero; clearly an inappropriate procedure.] Figure 1 shows the results for the $ErBa_2Cu_3O_{7-y}$ specimen. However, the general features are reflected in all the $RBa_2Cu_3O_{7-y}$ data. The corresponding midpoints are indicated in the figures as $0.5R_{Nh}$ and $0.5R_{Nl}$. Because the resistive transitions broaden rapidly in an applied magnetic field, the criterion $0.5R_{Nl}(T)$ gives a lower $B_{c2}(T)$ and a lower $(dB_{c2}/dT)_{T=T_c}$ than $0.5R_{Nh}(T)$.

Figure 2 shows the resultant $B_{c2}(T)$ data for the $NdBa_2Cu_3O_{7-x}$ specimen using the l and h extrapola-

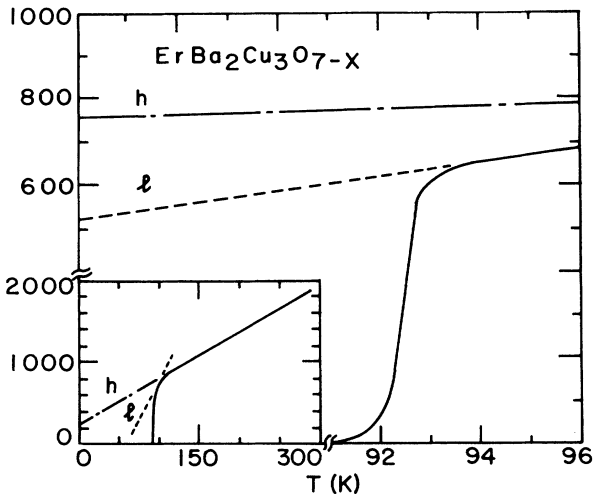

FIG. 1. Comparison of extrapolations of linear variation of normal-state resistance vs temperature T in $RBa_2Cu_3O_{7-x}$ with R = Er as an example. The upper dash-dotted line (h) indicates the linear extrapolation from above about 115 K, whereas the lower dash (l) line is obtained close to T_c where previous work was examined. The inset shows the comparison over a large T range.

tions. Both methods give a linear $B_{c2}(T)$ which extrapolates to nearly the same value of T_c at $B_0=0$. It is clear in Fig. 2 that the $(dB_{c2}/dT)_{T=T_c}$ is substantially different for the l and h extrapolation procedure. We also show the $0.9R_{Nl}$ data which give a higher slope and an increased extrapolated value of T_c. The corresponding $0.9R_{Nh}$ is not plotted because it is difficult to define [and would result in very high values of $(dB_{c2}/dT)_{T=T_c}$ and T_c]. The question here is whether the upper portion of the resistive transition reflects a small superconducting fraction well above the rapid drop in resistance. The change in resistance of $YBa_2Cu_3O_{7-y}$ was less than 1% at 116 K for fields up to 20 T, suggesting that at this temperature any superconducting contribution is quite small.

Another characteristic feature of the broad resistive transition is illustrated in Fig. 2. A knee is observed near the bottom of the transition. The field at which the knee occurs, where the resistance starts to increase rapidly (labeled FOOT), also shows a linear variation with T (about 0.7 T/K). The combination of the various linear dependences shows that there is a large broadening of the transition as a function of field and that all the various features have approximately linear variations with T near T_c. Thus there is a range of criteria which can be used to discuss these materials, and extremely high fields are needed to examine the full transition below T_c. For this paper we choose to use the h extrapolation and the midpoint data defined as $0.5R_{Nh}$.

A comparison of T_c, $(dB_{c2}/dT)_{T=T_c}$, and $B_{c2}(0)$ is shown in Fig. 3 for the rare-earth series. Here $B_{c2}(0)$ is an extrapolation to zero temperature assuming the $0.5R_{Nh}$ extrapolation and the standard WHH theory with no Pauli-spin pair breaking. T_c is the value obtained by extrapolating $0.5R_{Nh}$ vs B_0 to $B_0=0$. As shown in Fig. 2, this value of T_c is quite close (≤ 0.5 K) to that obtained by extrapolation of $0.5R_{Nl}$. Figure 3 shows that the compounds $RBa_2Cu_3O_{7-x}$ are characterized by a nearly constant $T_c=93\pm2$ K and a nearly constant $(dB_{c2}/dT)_{T=T_c}$ $\simeq 2.8\pm0.2$ T/K. Consequently the $B_{c2}(T)$ data, along with the previously reported T_c, susceptibility, and oxygen-doping[2] data suggest that the magnetic rare-earth

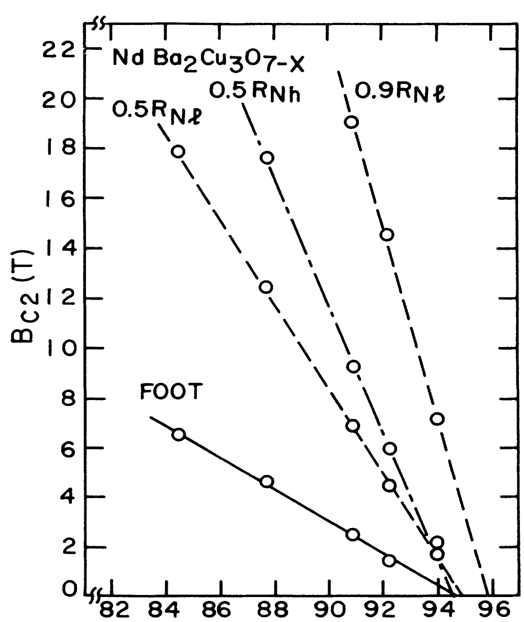

FIG. 2. Extrapolated data for upper critical field B_{c2} vs T for $NdBa_2Cu_3O_{7-y}$ using the midpoint for the h and l extrapolation $0.5R_{Nh}$ and $0.5R_{Nl}$ and for $0.9R_{Nl}$.

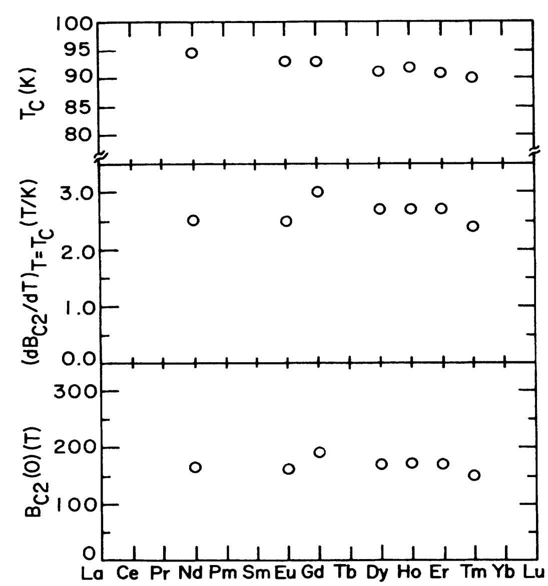

FIG. 3. Comparison of results for $RBa_2Cu_3O_{7-y}$ specimens vs R. Top: critical temperature T_c; center: $(dB_{c2}/dT)_{T=T_c}$ for $0.5R_{Nh}$; bottom: calculated $B_{c2}(0)$ based on data above.

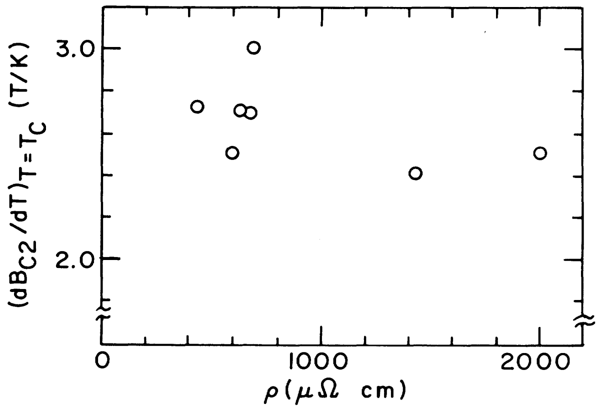

FIG. 4. Midpoint slope $(dB_{c2}/dT)_{T=T_c}$ vs resistivity ρ for different $R\mathrm{Ba_2Cu_3O_{7-y}}$ specimens.

ions do not interact with the conduction electrons in the compounds $R\mathrm{Ba_2Cu_3O_{7-x}}$. It has been suggested that the insensitivity of superconducting properties to the presence of magnetic rare-earth ions is a result of the large distance between the magnetic ions and the superconducting electrons, which is possible if the electrons in Cu-O chains are responsible for the superconductivity. The systematic small decrease of T_c versus rare-earth atom correlates with the lattice parameter change.[2]

Despite the insensitivity of $B_{c2}(0)$ and T_c to the rare-earth ion in the $R\mathrm{Ba_2CuO_{7-y}}$ series, there is a large variation in the resistivity as indicated in Ref. 2. Figure 4 shows a plot of $(dB_{c2}/dT)_{T=T_c}$ vs ρ at T_c. There is a cluster of the data near 400 to 600 $\mu\Omega$ cm, but the Sm and Nd compound have ρ values of $\sim$1400 and 2000 $\mu\Omega$ cm. Using 200 $\mu\Omega$ cm as an upper limit of resistivity for the $\mathrm{YBa_2Cu_3O_{7-y}}$ would result in a correspondingly higher value of γ than that in Ref. 1. (The high resistivity material, R=Nd, has a second phase present which may have contributed to the very high ρ.) Examination of Fig. 4 indicates that ρ is not directly correlated with magnetic scattering.

From the standard theory for $B_{c2}(T)$ we would expect that the slope would increase linearly with increasing resistivity if all other parameters which affect the superconductivity (such as T_c, the density of states, the electron carrier density, etc.) remained constant throughout the series $R\mathrm{Ba_2Cu_3O_{7-x}}$. In the dirty limit, the change in resistivity from 200 to 2000 $\mu\Omega$ cm would cause the slope to increase tenfold. However, if we demand that the change from 200 to 2000 $\mu\Omega$ cm in the resistivity is to have less than a 10% effect on the slope (as is observed), then the material would have to have an electron carrier density of less than 10^{19} $\mathrm{cm^{-3}}$; a value which is two orders of magnitude too small. Alternatively, for the slope to remain nearly constant, the material would have to be sufficiently in the clean limit. Consequently, the slope is not straightforwardly related to the measured resistivity. One possibility is that the resistivity is dominated by the intergranular conduction, whereas the superconductivity properties are determined by the intragranular resistivity. Recent studies suggest that the relatively small critical current density in polycrystalline Sr-Ba-Cu-O (Refs. 3 and 4) and Y-Ba-Cu-O (Ref. 5) may result from such intergranular conduction. Based on our data, we suggest that the upper limit of ρ in $R\mathrm{Ba_2Cu_3O_{7-y}}$ is 200 $\mu\Omega$ cm. Single-crystal data would provide a definitive measure of the intrinsic ρ.

We have also examined single-phase $\mathrm{YBaCu_3O_{7-x}}$ material and find $(dB_{c2}/dT)_{T=T_c}=2.9$ T/K for the h midpoint, $T_c=91.4$ K, and the extrapolated $B_{c2}(0)=180$ T. The $0.9R_{Nh}$ values yield $(dB_{c2}/dT)_{T=T_c}=5.3$ T/K, $T_c=93.1$ K, and $B_{c2}(0)=340$ T. These values are higher than presented earlier by us for a multiphase specimen,[1] mainly because we are using the h criterion. If we use the range $(dB_{c2}/dT)_{T=T_c}$ from 2.2 to 6 T we obtain $B_{c2}(0)$ from 140 to 380 T. In an attempt to outline the possible range of the anisotropy of B_{c2} we examined the onset of resistance at 4.2 K and high field. The assumption is that the crystallites with layers parallel to B_0 establish the upper limit of $B_{c2\parallel}$ and that those crystallites with the layer planes perpendicular to B_0 will become normal (and resistive) at a lower field $B_{c2\perp}$. The onset of resistance gives a lower bound estimate of $B_{c2\perp}$ because other mechanisms can also lead to an early onset of the resistive state. We found zero resistance ($<5\times10^{-2}$ $\mu\Omega$ cm at <0.1-μV level) up to 28 T. Using $B_{c2\perp}=28$ T for the lowest limit we conclude that the anisotropy $A=B_{c2\parallel}/B_{c2\perp}$ is less than $\frac{340}{28}\simeq12$. If we choose to argue that $B_{c2\parallel}=2[B_{c2\parallel}(\text{midpoint})-B_{c2\perp}]/B_{c2\perp}$ then $A\leq2[140-28]/28\simeq8$. Several of the $R\mathrm{Ba_2Cu_3O_{7-y}}$ specimens were also examined at 4.2 K and all showed zero resistance up to 20 T setting a conservative upper limit of $A<\frac{340}{20}=17$ for this class. Data of Ekin *et al.*[6] gave zero values of resistance for $\mathrm{YBa_2Cu_3O_{7-y}}$ up to $\simeq4$ T at 77 K. If this is used as a lower limit of B_{c2} for our data then $A<13$, using $B_{c2\parallel}$ at $0.9R_{Nh}$. We should note that the anisotropy of B_{c2} in a single crystal on $\mathrm{Nb_3Sn}$ and $\mathrm{V_3Si}$ (Ref. 7) and the layered $\mathrm{NbSe_2}$ (Ref. 8) is independent of temperature. The present estimates suggest that this may also be the case for $\mathrm{YBa_2Cu_3O_{7-y}}$ and that the anisotropy in B_{c2} is ≤13 over the range 77 to 4.2 K. Recently, Santhanam *et al.* reported[9] an anisotropy of 30 in the *critical current density* J_c of single-crystal $\mathrm{YBa_2Cu_3O_{7-y}}$ which is above our present estimates of the B_{c2} anisotropy. Although J_c is affected by B_{c2}, other materials properties contribute to the pinning mechanisms in addition to the B_{c2}.

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