PHYSICAL REVIEW B VOLUME 35, NUMBER 13 1 MAY 1987

Upper critical fields of high-T_c superconducting $Y_{2-x}Ba_xCuO_{4-y}$

T. P. Orlando and K. A. Delin
Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

S. Foner* and E. J. McNiff, Jr.
Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

J. M. Tarascon, L. H. Greene, W. R. McKinnon, and G. W. Hull
Bell Communications Research, Red Bank, New Jersey 07701
(Received 9 March 1987)

We have measured the upper critical field $B_{c2}(T)$ of $Y_{2-x}Ba_xCuO_{4-y}$ with $x=0.4$ near T_c in dc fields up to 20 T and at 77 K with pulsed fields to 45 T. The data yield $(dB_{c2}/dT)_{T=T_c}=1.3$ T/K and $T_c=89.5$ K for the midpoint of the resistive transitions, and $(dB_{c2}/dT)_{T=T_c}=5\pm1$ T/K and $T_c=95.1$ K for the onset. The estimates for $B_{c2}(0)$ range from 80 to 320 T. Pulsed-field data suggest that a fraction of the material is still superconducting above 45 T at 77 K.

Some of the high-T_c superconducting oxygen-defect perovskites have also proven to be very high-field superconductors. Measurements up to 45 T on $La_{1.85}Sr_{0.15}CuO_{4-y}$ suggest that the upper critical field B_{c2} can be as high as 140 T at zero temperature.[1] These high-field measurements give support to low-field measurements with applied fields B_0 up to 6 T.[2-4] Recently, superconductivity at 93 K has been reported by Wu *et al.* for Y-Ba-Cu-O, and their low-field data up to 5.7 T suggest that this material is also a very high-field superconductor.[5] In this Communication we present high-field data with B_0 up to 45 T on $Y_{2-x}Ba_xCuO_{4-y}$ with $x=0.4$. We observe that very high critical fields and calculations of $B_{c2}(T)$ based on our data near T_c indicate that $B_{c2}(0)$ can range from 80 to 320 T, for the midpoint and onset data, respectively. Many of the issues involved in measuring and calculating $B_{c2}(T)$ are the same as discussed in more detail in Ref. 1 for La-Sr-Cu-O. These data are in excellent agreement with the low-field data of Wu *et al.*[5] with $x=0.8$, suggesting that these mixed-phase materials produce a similar superconducting phase over a range of nominal compositions.

The materials were prepared at Bell Communications Research as described in Ref. 6. The characteristics of the samples discussed in this Communication are similar to their $x=0.25$ and 0.20 samples.

The upper critical fields $B_{c2}(T)$ were measured resistively with a standard four-probe technique in transverse dc magnetic fields up to 20 T in water-cooled magnets at the Francis Bitter National Magnet Laboratory facility. Ag paint was used to attach the leads to the small rectangular polycrystalline slabs. Tests were made to ensure that the $B_{c2}(T)$ data were not sensitive to the low applied dc current ($<300\ \mu A/cm^2$). The resistive measurements were made in a laboratory temperature-controlled cryostat available to users and supplied by the facility. The sample was in contact with He gas in the cryostat and the temperature was monitored with capacitance and platinum thermometers. Most of the data were taken at fixed values of B_0 and swept T, and selected points were taken at fixed T while varying B_0. The data for $B_{c2}(T)$ near T_c are shown in Fig. 1.

This material, like La-Sr-Cu-O, has a transition width which increases markedly as T is decreased below T_c, making it difficult to accurately define the transition unless fields on the order of 20 T or more are available. In Fig. 1 the width of the transition is indicated by showing the data for the midpoint ($0.5R_N$) and the onset ($1.0R_N$) of the resistive transition, where R_N is the resistance above T_c. The data for the midpoint yield $(dB_{c2}/dT)_{T=T_c}=1.3$ T/K and $T_c=87.5$ K. Data for the onset are subject to much more scatter due to the very broad nature of the transition; nevertheless, our best estimates are

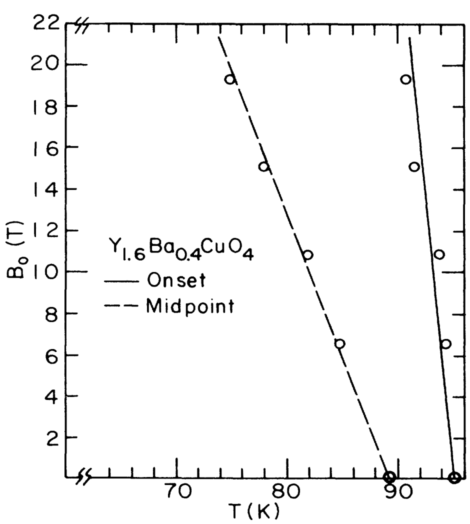

FIG. 1. Upper critical fields B_{c2} vs temperature for the superconducting phase in $Y_{2-x}Ba_xCuO_{4-y}$ with $x=0.4$ nominally.

that $(dB_{c2}/dT)_{T=T_c}=5\pm1$ T/K with $T_c=95.1$ K. Pulsed-field measurements with an rf loss technique up to 45 T and with the sample immersed in liquid N_2 suggest that portions of the sample are still superconducting above 45 T at 77 K, consistent with the onset data above. However, the small fraction of superconductor and the large breadth of the transition resulted in a corresponding small signal which was difficult to detect. The onset limit set by the pulsed-field data is indicated by an arrow in Fig. 2. Again, as for La-Sr-Cu-O, the cause of the increased breadth of these resistive transitions as a function of B_0, whether due to inhomogeneities, anisotropy, or both, is not clear.

The range of $B_{c2}(T)$ predicted by the midpoint and onset data is shown in Fig. 2, where we have used the standard theory for a three-dimensional dirty type-II superconductor.[7] $B_{c2}(0)$ ranges from 80 to 320 T. Moreover, each upper bound assumes that the spin-orbit scattering parameter $\lambda_{so}=\infty$, and the lower bound assume that $\lambda_{so}=0$. In addition to λ_{so}, the temperature dependence of the normal-state resistivity[1] $\rho(T)$ and the value of the antisymmetric Fermi-liquid parameter[8,9] also affect the estimates of $B_{c2}(T)$. The data of Wu *et al.*[5] show that $\rho(T)$ decreased by about 20% from above T_c to zero temperature, indicating that $B_{c2}(0)$ could be correspondingly smaller than projected in the figures. These and other corrections, which are often assumed negligible, may contribute substantially to the behavior of the superconducting layered perovskites. However, because the only available data (even at 20 to 30 T) are near T_c, it is difficult to draw precise conclusions by extrapolation over such large ranges of temperature and field. It is interesting to note that at 77 K (the boiling point of liquid nitrogen) B_{c2} (77 K) ranges from 16 to 84 T. Of course, the assessment of the practical applications of these high fields at 77 K must await the development of materials with a more substantial fraction that is superconducting.

Our data up to 20 T give results nearly identical to the data of Wu *et al.*[5] Both give slopes at the midpoints of 1.3 T/K and slopes at 90% ($0.9R_N$) of 3 T/K. The very similar values of T_c and slopes for Wu *et al.*[5] materials with $x=0.8$ compared to our sample with $x=0.4$ suggest that the same superconducting phase is being produced over a wide range of nominal compositions. In addition, our samples with $x=0.2$ to 1.0 all have essentially the same T_c values, which further support this observation.

The Ginzburg-Landau coherence length $\xi_{GL}(0)$ can be calculated from the slope of $B_{c2}(T)$ and T_c. For the midpoint data $\xi_{GL}(0)=1.7$ nm, and for the onset, 0.9 nm. These lengths, especially 0.9 nm, are of the order of the interelectron spacing $n^{-1/3}$, suggesting that superconducting fluctuations could be important. Because only a small fraction of the sample is superconducting, the normal-

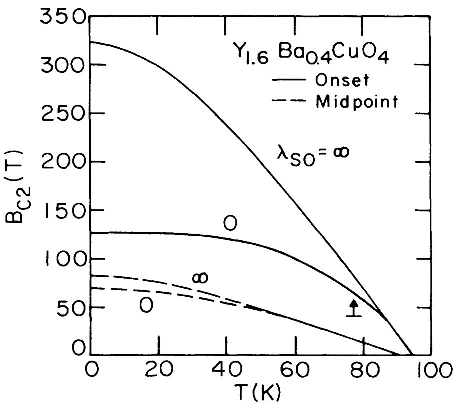

FIG. 2. Calculated upper ($\lambda_{so}=\infty$) and lower ($\lambda_{so}=0$) bounds for $B_{c2}(T)$ using $B_{c2}(T)$ for midpoint (dashed curves) and onset (solid curves). The arrow represents the data from pulsed fields up to 45 T at 77 K, which indicates that there is a fraction of the sample superconducting above this point.

state resistivity is not known. If we assume a range of $\rho=500-2000$ $\mu\Omega$ cm, which is comparable to La-Sr-Cu-O at 90 K,[2] we estimate that the electronic coefficient of the heat capacity γ ranges from 200–2000 erg cm^{-3}K^{-2}, depending upon the choice of dB_{c2}/dT and assumed electron carrier concentration ($n=10^{21}-10^{22}$ cm^{-3}). Even with this broad range, γ is comparable to values for other low carrier density materials like Ba-Pb-B-O (Refs. 10 and 11) and Nb-N.[12] In addition, with $n=10^{22}$ cm^{-3} the material is in the dirty limit; whereas, with $n=10^{21}$ cm^{-3} the material is between the clean and dirty limits. Consequently, n becomes an important materials parameter suggesting that superconducting properties might be varied by controlling fabrication processes that change n. However, the sensitivity of the superconducting parameters due to n calls for caution in estimating parameters only from $(dB_{c2}/dT)_{T=T_c}$, T_c, and ρ.

Note added in proof. Immediately after submission of this Communication, the superconducting phase was identified as $YBa_2Cu_3O_{8-x}$, [see Y. LePage, W. R. McKinnon, J. M. Tarascon, L. M. Greene, G. W. Mull, and D. M. Hwang, preceding paper, Phys. Rev. B **35**, 7245 (1987)].

We wish to thank J. M. Rowell, J. H. Wernick, T. H. Geballe, and M. J. Neal for valuable discussions. Three of us (J.M.T., K.A.D., and T.P.O.) acknowledge support of the National Science Foundation (NSF) Industry-University Cooperative Research Program through NSF Contract No. DMR-8403493. The Francis Bitter National Magnet Laboratory is supported by the NSF.

*Also at Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139.

[1]T. P. Orlando, K. A. Delin, S. Foner, E. J. McNiff, Jr., J. M. Tarascon, L. H. Greene, W. R. McKinnon, and G. W. Hull, Phys. Rev. B **35**, 5347 (1987).

[2]J. M. Tarascon, L. H. Greene, W. R. McKinnon, G. W. Hull, and T. H. Geballe, Science (to be published).

[3]D. W. Capone II, D. G. Hinks, J. D. Jorgensen, and K. Zhang,

Appl. Phys. Lett. **50**, 543 (1987).
[4]R. Cava, R. B. van Dover, B. Batlogg, and E. A. Rietman, Phys. Rev. Lett. **58**, 408 (1987).
[5]M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu, Phys. Rev. Lett. **58**, 908 (1987).
[6]J. M. Tarascon, L. H. Greene, W. R. McKinnon, and G. W. Hull, this issue, Phys. Rev. B **35**, 7115 (1987).
[7]A. L. Fetter and P. C. Hohenberg, in *Superconductivity,* edited by R. P. Parks (Marcel Dekker, New York, 1969), Vol. II, p. 866.
[8]J. A. X. Alexander, T. P. Orlando, D. Rainer, and P. M. Tedrow, Phys. Rev. B **31**, 5811 (1985).
[9]T. P. Orlando, E. J. McNiff, Jr., S. Foner, and M. R. Beasley, Phys. Rev. B **19**, 4545 (1979).
[10]B. Batlogg, Physica B **126**, 275 (1984).
[11]K. Kitazawa, S. Uchida, and S. Tanaka, Physica B **135**, 505 (1985).
[12]C. Geibel, H. Rietshel, A. Jounod, M. Pelizzone, and J. Müller, J. Phys. F **15**, 405 (1985).