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Low-temperature thermal conductivity of $YBa_2Cu_3O_{7-\delta}$

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The thermal conductivity of $YBa_2Cu_3O_{7-\delta}$ has been measured between 0.1 and 7 K. The data are similar in magnitude and temperature dependence to data for other sintered ceramics.

We have made low-temperature measurements of the thermal conductivity of the high-T_c superconducting ceramic $YBa_2Cu_3O_{7-\delta}$, where $\delta \cong 0.2$.

The sample was prepared by mixing and grinding $BaCO_3$, Y_2O_3, and CuO powders as described elsewhere.[1] It had a transition temperature of 91.6 K determined from the midpoint of the resistive transition. The 10–90% transition width was 2.6 K, and zero resistance was observed at 87.0 K. For the thermal conductivity measurement, a piece in the shape of a rectangular rod was cut from a pressed disk, and had dimensions $25 \times 1.6 \times 2.3$ mm^3.

Data were taken using a two-heater one-thermometer method with 120-Ω strain gauges employed as heaters[2] and a 100-Ω carbon resistor used to measure temperature. The accuracy of the measurement, limited by the uncertainty of the geometry of the sample, is $\sim 2\%$.

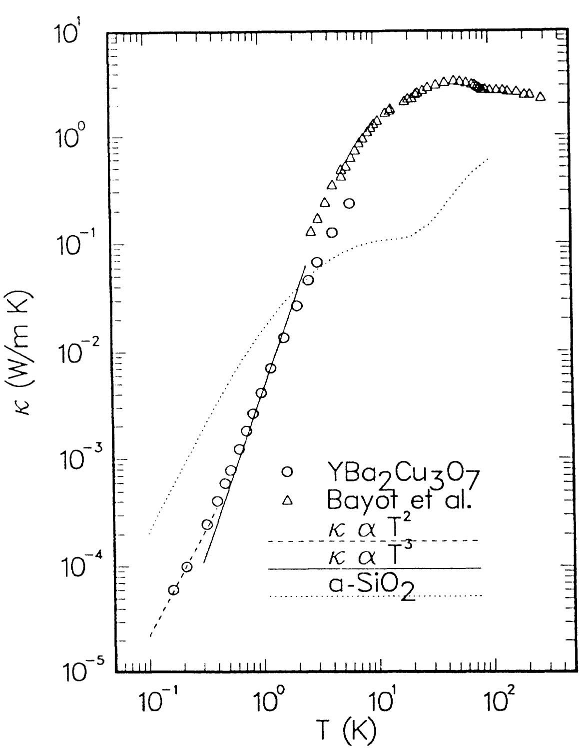

FIG. 1. Thermal conductivity κ of $YBa_2Cu_3O_{7-\delta}$. ○ denotes present data, △ denotes data of Ref. 3. The lines are explained in the text.

The measured thermal conductivity κ is shown by the circles in Fig. 1. Data taken at higher temperature by Bayot *et al.*[3] on a sample reported to have the same composition, are also plotted. Shown for comparison, and to stress the small magnitude of the data, is glassy SiO_2. As can be seen, the present data and those of Ref. 3 have the same temperature coefficient where they overlap, but the present data are roughly a factor of 2 lower in magnitude. This discrepancy will be discussed later. At the lowest temperature ($T < 0.3$ K) κ varies approximately as T^2 (dashed in Fig. 1), whereas at higher temperatures the slope increases to indicate a dependence closer to T^3 (solid line in Fig. 1). Both the magnitude and temperature dependence of the present data are characteristic of insulating sintered ceramic materials in general.[4]

We can estimate the magnitude and temperature dependence of κ at low temperatures by considering the structure of the ceramic. The sample was highly porous, with measured density (4430 ± 110 kg/m^3) only $\sim 70\%$ of the predicted theoretical[5] value (6310 kg/m^3). Measurements on other porous materials[6] indicate that below 1 K, phonons are scattered predominantly by the pores. This scattering can both limit the phonon mean free path and exclude heat flow from some of the sample volume. In the first case, it can be shown that for spherical pores of radius R in a material of porosity r,

$$\kappa \approx 2.72 \times 10^{10} \frac{R}{v^2 r} T^3 \text{ (W/m K)} , \quad (1)$$

where v is the phonon velocity, and v^2 is averaged over all modes. Using the measured longitudinal phonon velocity[7] and assuming the material to be isotropic (Poisson's ratio

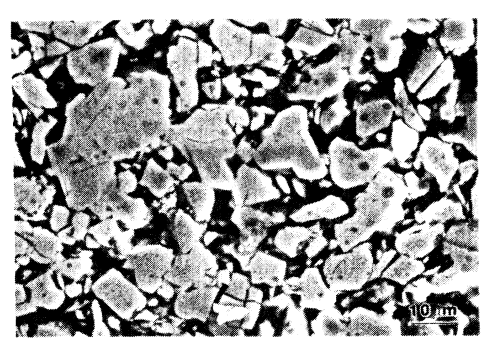

FIG. 2. Scanning electron micrograph of a polished and etched portion of the sample used in the measurements.

is 1/3) we can compute an average velocity and hence gain an estimate of the pore radius R. Consider the second effect of the pores, namely, the exclusion of heat flux from portions of the sample volume. The conductivity of the bulk material may be calculated from that of the porous medium using models from the literature.[8] Again, using the approximation of spherical pores,[9] we find that for a porosity of $r = 0.3$, the conductivity of the bulk is nearly twice that of the porous material. This factor may account, at least partially, for the discrepancy between the present data and those of Ref. 3, in that Bayot *et al.* may have used a more compact sample. Unfortunately, however, they provided no information concerning the density of their sample. Using the bulk conductivity (calculated from the solid line in Fig. 1), we find from Eq. (1) that $R \approx 2\ \mu$m, which is consistent with the scanning electron micrograph shown in Fig. 2, and with a transmission electron microscope study of a thin foil from the sample. The computed phonon mean free path of $\approx 4\ \mu$m is also consistent with the average grain size seen in Fig. 2. The T^2 dependence of κ below 0.3 K is seen in many other sintered ceramics,[4] but as yet has no satisfactory explanation.

In conclusion, we have measured the low-temperature thermal conductivity of $YBa_2Cu_3O_{7-\delta}$ and find it to be similar in magnitude and temperature dependence to that of other sintered ceramics. A good estimate of the magnitude and temperature dependence of compact $YBa_2Cu_3O_{7-\delta}$ may be made by consideration of the granular nature of the material.

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[1]S. E. Inderhees, M. B. Salamon, T.A. Friedmann, and D.M. Ginsberg, Phys. Rev. B **36**, 2401 (1987).

[2]D. Moy and A. C. Anderson, Cryogenics **23**, 330 (1983).

[3]V. Bayot, F. Delannay, C. Dewitte, J.-P. Erauw, X. Gonze, J.-P. Issi, A. Jonas, M. Kinany-Alaoui, M. Lambricht, J.-P. Michenaud, J.-P. Minet, and L. Piraux, Solid State Commun. **63**, 983 (1987).

[4]R.H. Tait, Ph.D. thesis, Cornell University, 1975 (unpublished). Note that $YBa_2Cu_3O_{7-\delta}$ is superconducting over the entire temperature range of these measurements, and the only process of thermal conduction when $T \ll T_c$ is via lattice vibrations, as is the case for insulating materials.

[5]R. Beyers, G. Lim, E. M. Engler, R. J. Savoy, T. M. Shaw, T. R. Dinger, W. J. Gallagher, and R. L. Sandstrom, Appl. Phys. Lett. **50**, 1918 (1987).

[6]M. P. Zaitlin and A. C. Anderson, Phys. Rev. B **12**, 4475 (1975).

[7]A. Migliori, Ting Chen, B. Alavi, and G. Grüner, Solid State Commun. **63**, 827 (1987), extrapolated to 0 K, $v_l \approx 7\times10^3$ m/s.

[8]R. E. Meredith and C. W. Tobias, J. Appl. Phys. **31**, 1270 (1960).

[9]It can be shown that the mean free path is not a strong function of the model selected. See, for instance, E. P. Roth and A. C. Anderson, J. Appl. Phys. **47**, 3644 (1976).

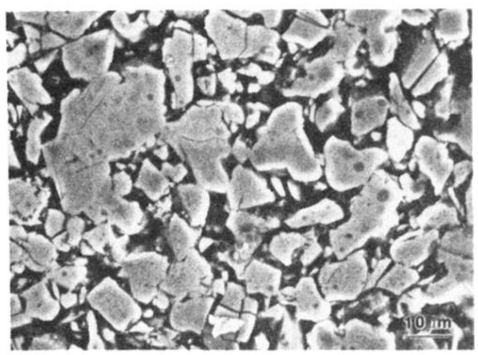

FIG. 2. Scanning electron micrograph of a polished and etched portion of the sample used in the measurements.