RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 40, NUMBER 1 1 JULY 1989

Low-temperature thermal conductivity of single-crystal $Bi_2Sr_2CaCu_2O_8$

Da-Ming Zhu, A. C. Anderson, E. D. Bukowski, and D. M. Ginsberg
Department of Physics and Materials Research Laboratory, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801
(Received 16 February 1989)

The thermal conductivity κ of a single crystal of superconducting $Bi_2Sr_2CaCu_2O_8$ has been measured at temperatures from 0.03 to 9 K. Below 2 K, where κ displays a T^2 dependence, the results agree in both temperature dependence and magnitude with that of a single-crystal superconducting $YBa_2Cu_3O_{7-x}$ or $HoBa_2Cu_3O_{7-x}$, and are remarkably similar to the thermal conductivity of glasses.

Since the discoveries of high-T_c superconducting compounds,[1,2] a number of studies have been made on their thermal conductivities.[3] Most of these studies have been done on sintered materials. Because of differences in sample porosity (and possibly some other effects), the results from sintered materials vary considerably from sample to sample. Although this variation provides evidence that the thermal conductance is provided mainly by phonons,[3,4] it has not been possible to extract the intrinsic temperature dependence of the thermal conductivity. It is, therefore, desirable to make thermal-conductivity measurements on single-crystal samples. To the best of our knowledge, only one group has measured the thermal conductivity of single-crystal superconducting samples at low temperatures.[5] Their results show that the thermal conductivities of single-crystal superconducting $YBa_2Cu_3O_{7-x}$ and $HoBa_2Cu_3O_{7-x}$ have a T^2 temperature dependence and nearly the same magnitude below 3 K. We find the same behavior for single-crystal superconducting $Bi_2Sr_2CaCu_2O_8$ which belongs to a newly discovered family of high-T_c compounds.[6] These results suggest that the T^2 dependence of the thermal conductivity below a few kelvin may be common to high-T_c materials.

The sample was grown by a self-flux method,[7] with excess copper oxide serving as the flux. The starting materials were high-purity (99.995% or better) Bi_2O_3, $SrCO_3$, and CuO. A mixture of these reagents with cation ratios 2:2:1:2 (Bi:Sr:Ca:Cu) was ground in an agate mortar until no visible inhomogeneities remained. The ground mixture was placed in a platinum crucible and heated in air in a box furnace at 980 °C for 10 h. This was followed by cooling in 150 h to 830 °C and then to 500 °C in 5 h, with subsequent furnace cooling to room temperature. The result was a mass of shiny, micalike crystals embedded in a black flux. The crystals were easily removed from the mass, and proved to be quite pliable and easily cleaved. Oxygen annealing was found to substantially improve sample quality,[7] as exhibited by magnetic measurements of a sample before and after annealing. This annealing was performed in flowing oxygen at 600 °C for 78 h, followed by quenching to room temperature. The sample's superconducting transition was then characterized with a superconducting quantum interference device (SQUID) magnetometer; the results are shown in Fig. 1. The onset temperature of 84 K and the sharpness of the transition suggest that the sample is single-phase material. This is consistent with the observation made by other workers that crystals in this system tend to form preferentially with the same stoichiometry as that of the starting material.[8]

The sample was approximately $0.21 \times 1.6 \times 4.0$ mm^3 in size with the c axis perpendicular to the faces of the largest dimensions. Thermal conductivity was measured parallel to the a-b plane using a conventional steady-state heat-flow method with two heaters and one thermometer. Two strain gauges were employed as the heaters,[9] and a carbon resistor, reduced in size, was used as the thermometer.[10] Thermal contacts between the heaters and the sample were made with 0.15-mm-diam copper wires. The wires were welded to a thin copper foil to which the strain gauges were glued. An insulated, thin copper foil was placed between the sample and the carbon thermometer to ensure temperature uniformity. A small amount of GE7031 varnish was used for attaching the heaters and the thermometer to the sample, and the sample to a dilution refrigerator. The absolute accuracy of the measured

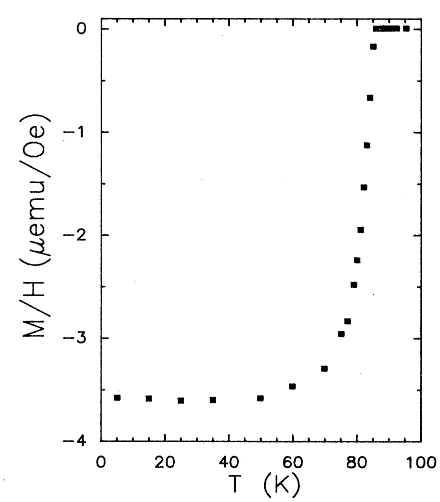

FIG. 1. The magnetic moment divided by applied magnetic field for the single-crystal sample of $Bi_2Sr_2CaCu_2O_8$, showing a superconducting transition near 84 K, measured as the sample was cooled in a field of 14 Oe.

 © 1989 The American Physical Society

thermal conductivity, which is limited mainly by the irregular geometry of the sample, was estimated to be about 15%.

Figure 2 shows the measured thermal conductivity. Between 0.03 K and about 2 K, a least-squares fit of these data to a power law gives $\kappa=(0.15\pm0.02)T^{2.0\pm0.02}$ W/mK. Above 2 K, the thermal conductivity increases more slowly than T^2. Figure 3 compares the thermal conductivity of $Bi_2Sr_2CaCu_2O_8$ with those of single-crystal $YBa_2Cu_3O_{7-x}$ and $HoBa_2Cu_3O_{7-x}$. As can be seen, the thermal conductivities of these three different materials have essentially the same temperature dependence and magnitude.

A low-temperature T^2 dependence of the electronic thermal conductivity is predicted for superconductors having a highly anisotropic energy gap.[11] However, as mentioned above, results on sintered samples suggest that the dominant heat carriers below 10 K in high-T_c materials are phonons, not electronic excitations.[12]

A T^2 dependence of the phonon thermal conductance can arise from the scattering of phonons by electronic excitations, a behavior which can be observed in normal metals if the contribution to κ by electrons is small.[13] For a superconductor with a sufficiently anisotropic energy gap, such phonon scattering might occur. However, without any detailed information about the energy gap in these high-T_c materials, it is difficult to judge whether such a mechanism is applicable.

A T^2 phonon thermal conductance is known to be characteristic of amorphous solids, and can be very well described by a phenomenological tunneling model of two-level systems.[14] In brief, all glassy materials that have been studied show a T^2 dependence in their thermal conductivities below about 1 K, and the magnitudes of their thermal conductivities vary only within a factor of 5 or so for different materials. For comparison, we plot the thermal conductivities[15,16] of vitreous silica and glassy $Zr_{0.7}Pd_{0.3}$ in Fig. 3. As may be noted, the thermal conductivities of the high-T_c materials are remarkably similar to those of the glasses. It had been previously proposed that the T^2 behavior of the thermal conductivity of the high-T_c crystals may be phonons scattered from two-level systems, as in glasses.[3,5] Acoustic measurements support this explanation, showing that the sound velocity changes in these high-T_c materials follow a logarithmic temperature dependence,[17,18] which is another characteristic of glasses.[14] Furthermore, in the La-Sr-Cu-O and Y-Ba-Cu-O systems, a linear term in the specific heat is demonstrated.[3] A linear term has been observed in all glassy materials studied so far, and is also expected in the tunneling model of two-level systems.[14] Therefore, this linear term might be associated with the T^2 dependence in the thermal conductivity. Recent studies report that a linear term is absent in the specific heat of Bi-Ca-Sr-Cu-O compounds.[19-24] However, the uncertainties quoted for these studies would mask a linear term which is smaller than that of other high-T_c compounds, but still of the same order of magnitude as the linear term found in glasses. Of course, the $Bi_2Sr_2CaCu_2O_8$ sample is a single crystal, not an amorphous solid. However, "glassy" behavior has been documented for a spectrum of disordered crystals.[25]

In summary, we have measured the thermal conductivity of a single crystal of superconducting $Bi_2Sr_2CaCu_2O_8$ compound. The results give a T^2 dependence below 2 K. Both this temperature dependence and the magnitude of the thermal conductivity found in this study are close to those observed in single-crystal superconducting YBa_2-

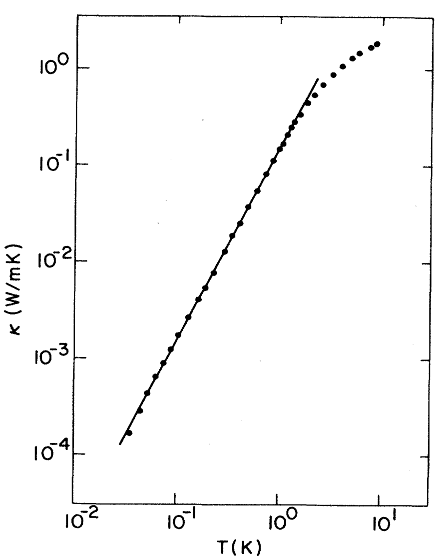

FIG. 2. The thermal conductivity of the single crystal of superconducting $Bi_2Sr_2CaCu_2O_8$. The straight line is a least-squares fit to the data below 1.6 K, and gives $\kappa=(0.15\pm0.02)T^{2.0\pm0.02}$ W/mK.

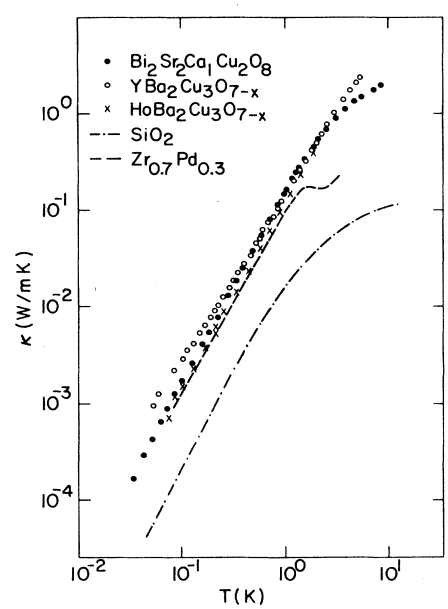

FIG. 3. Comparison of the thermal conductivities of single-crystal superconducting $Bi_2Sr_2CaCu_2O_8$, $YBa_2Cu_3O_{7-x}$ (Ref. 5), and $HoBa_2Cu_3O_{7-x}$ (Ref. 5) with the thermal conductivities of vitreous silica (Ref. 15) and a superconducting metallic glass $Zr_{0.7}Pd_{0.3}$ (Ref. 16, $T_c\simeq2.5$ K).

Cu_3O_{7-x} and $HoBa_2Cu_3O_{7-x}$ compounds, suggesting that this phenomenon may be a feature common to all high-T_c materials. The mechanism which causes this temperature dependence is unknown, but may be related to the two-level states found in glasses and in certain disordered crystals.

This work was supported in part by the Department of Energy, Division of Materials Science under Contract No. DE-AC0276ER01198 through the University of Illinois Materials Research Laboratory (D-M.Z. and A.C.A.), and in part by the National Science Foundation under Grant No. NSF-DMR-86-12860 (E.D.B. and D.M.G.).

[1]J. G. Bednorz and K. A. Müller, Z. Phys. B **64**, 189 (1986).

[2]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).

[3]For a brief review, see H. E. Fischer, S. K. Watson, and D. G. Cahill, Comments Condens. Mater. Phys. **14**, 65 (1988).

[4]J. J. Freeman, T. A. Friedmann, D. M. Ginsberg, J. Chen, and A. Zangvil, Phys. Rev. B **36**, 8786 (1987).

[5]J. E. Graebner, L. F. Schneemeyer, R. J. Cava, J. V. Waszczak, and E. A. Rietman, in *High-Temperature Superconductors,* edited by M. B. Brodsky *et al.*, 1987 MRS Fall Meeting Symposium Proceedings, Vol. **99** (Materials Research Society, Pittsburgh, 1988), p. 745.

[6]H. Maeda, Y. Tanaka, M. Fukutomi, and T. Asano, Jpn. J. Appl. Phys. **27**, L209 (1988).

[7]D. S. Ginley, B. Morosin, R. J. Baughman, E. L. Venturini, J. E. Schirber, and J. F. Kwak (unpublished).

[8]P. D. Han (private communication).

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

[10]M. Steinback, P. J. Anthony, and A. C. Anderson, Rev. Sci. Instrum. **49**, 691 (1978).

[11]C. M. Varma, J. Appl. Phys. **57**, 3604 (1985).

[12]If phonons are the dominant heat carriers in our sample, the thermal conductivity should approach a T^3 dependence below about 0.1 K as phonons are scattered predominantly by the sample surfaces. The absence of a T^3 dependence could be explained by specular scattering of phonons from the smooth, shiny surfaces of this sample. See T. Klitsner and R. O. Pohl, Phys. Rev. B **36**, 6551 (1987).

[13]A. C. Anderson and S. G. O'hara, J. Low. Temp. Phys. **15**, 323 (1974).

[14]For a review, see *Amorphous Solids,* edited by W. A. Phillips (Springer-Verlag, Berlin, 1981).

[15]T. L. Smith, P. J. Anthony, and A. C. Anderson, Phys. Rev. B **17**, 4997 (1978).

[16]J. E. Graebner, B. Golding, R. J. Schutz, F. S. L. Hsu, and H. S. Chen, Phys. Rev. Lett. **39**, 1480 (1977).

[17]B. Golding, N. O. Birge, W. H. Haemmerle, R. J. Cava, and E. Rietman, Phys. Rev. B **36**, 5606 (1987).

[18]P. Esquinazi, C. Duran, C. Fainstein, and M. N. Regueiro, Phys. Rev. B **37**, 545 (1988).

[19]K. Kumagai and Y. Nakamura, Physica C **152**, 286 (1988).

[20]S. L. Yuan, J. W. Li, W. Wang, Q. Z. Ran, G. G. Zheng, W. Y. Guan, and J. Q. Zheng, Mod. Phys. Lett. B **2**, 885 (1988).

[21]S. J. Collocott, R. Driver, C. Andrikidis, and F. Pavese, Physica C **156**, 292 (1988).

[22]M. Sera, S. Kondoh, K. Fukuda, and M. Sato, Solid State Commun. **66**, 1101 (1988).

[23]R. A. Fisher, S. Kim, S. E. Lacy, N. E. Phillips, D. E. Morris, A. G. Markelz, J. Y. T. Wei, and D. S. Ginley, Phys. Rev. B **38**, 11 942 (1988).

[24]R. Caspary, A. Hohr, H. Spille, F. Steglich, H. Schmidt, R. Ahrens, G. Roth, H. Rietschel, Y. F. Yan, and Z. X. Zhao, Europhys. Lett. **8**, 639 (1989).

[25]For a review, see A. C. Anderson, Phase Trans. **5**, 301 (1985).