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SUPERCONDUCTING AND NORMAL STATE PARAMETERS OF $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ SINGLE CRYSTALS: A COMPARISON WITH $Ba_2YCu_3O_7$

B. BATLOGG, T. T. M. PALSTRA, L. F. SCHNEEMEYER, R. B. VAN DOVER and R. J. CAVA

AT&T Bell Laboratories, Murray Hill, NJ 07974, USA

ABSTRACT

Magnetic and magnetotransport properties were studied on $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ single crystals. The normal state resistivity in the a-b plane varies linearly with temperature and extrapolates to zero at $T = 0$. The slopes of the upper critical field are -4.5 ± 1 (-0.55) T/K for H perpendicular (parallel) to the c-axis. The coherence length is calculated to be ~ 30Å in the a-b plane but only ~ 4Å perpendicular to it. ξ_c is thus shorter than the 12Å spacing between the Cu-O double layers. From H_{c1} and H_{c2} data, the Sommerfeld parameter γ is deduced.

Introduction

As the family of cuprate based high T_c superconductors grows,[1–4] it appears necessary for the development of an understanding to establish the properties which these compounds have in common. Already a first glance at the crystal structure of the Bismuth cuprates suggests that only the Cu-O layers are important for superconductivity: Unlike in the $Ba_2YCu_3O_7$ type structure, no Cu-O chains are present in this structure.[5–7] Further insight will come from the knowledge of the basic properties of the normal and superconducting state.

Here we report the results of single crystal studies, mainly the anisotropies of critical fields, which allow us to calculate microscopic and macroscopic parameters. All numerical values are found to be very similar to the ones for $Ba_2YCu_3O_7$. Most interestingly, the coherence length perpendicular to the Cu-O layers, $\xi_c = 4$Å, equals approximately the Cu-O double layer thickness, but is substantially shorter than the spacing between the double-layers (12Å).

Resistivity

A hallmark of the cuprate high T_c superconductors is their normal-state resistivity which varies linearly with temperature and extrapolates to zero at $T = 0$.[8] And indeed, the same behavior is also observed for the Bi-cuprate (Fig. 1). Particularly noteworthy is the low value for the in-plane resistivity of good quality single crystals, approximately 140 $\mu\Omega$ cm at room temperature. (This value is somewhat uncertain due to the ambiguity in measuring the geometry of the thin, few μm thick, crystals. The flux-growth technique is described in Ref. 9.) Single crystals of $Ba_2YCu_3O_7$ have higher resistivities, but a recent analysis concluded that their intrinsic resistivity would be ~ 150 $\mu\Omega$ cm at room temperature.[10] The resistivity in the Bi-cuprates thus appears to be close to the

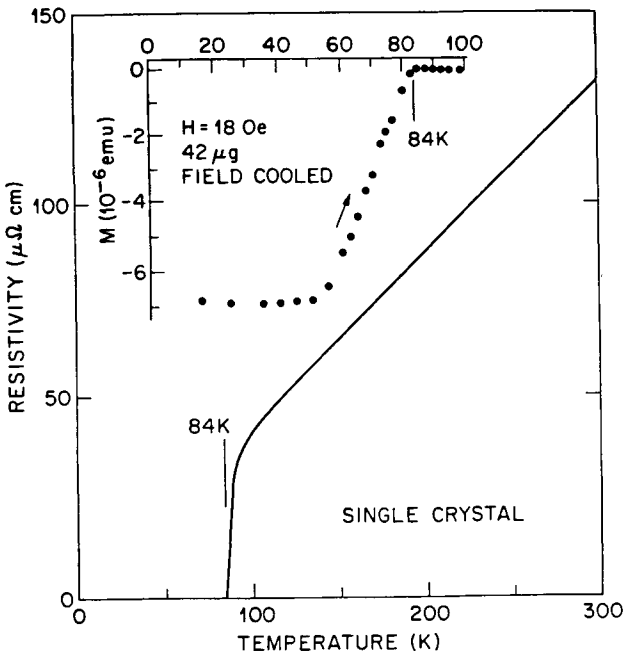

Fig. 1 Resistivity in the a-b plane of a single crystal. The insert shows the Meissner signal, which corresponds to $\sim 70\%$ of the ideal value.

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proposed "intrinsic" values for the 1-2-3 compound and one might speculate if it is determined by the 2-dimensional Cu-O layers only. Pronounced deviations from the linear temperature dependence are observed close to T_c.

Lower critical field H_{c1}

The lower critical field was measured in a SQUID magnetometer with the magnetic field parallel to the a-b plane, minimizing thus the effects of demagnetizing fields. A typical magnetization curve is shown in Fig. 2 and H_{c1} was defined as the field where M(H) starts to deviate from linearity. An independent estimate for H_{c1} comes from the observation of a time dependent magnetization. When the field is increased above this value, the magnetization varies with time and this provides an independent estimate of H_{c1}. The temperature dependence of H_{c1} is given in Fig. 3 for single crystal and polycrystalline samples. At the lowest temperature, H_{c1} is 17 ± 2 mT, which is only slightly higher than 12 ± 1 mT measured for $Ba_2YCu_3O_7$ single crystals in the same geometry.[11] The results for the single and polycrystal samples are very similar, which is unexpected and needs further study. It is most likely due to preferred orientation of the crystallites.

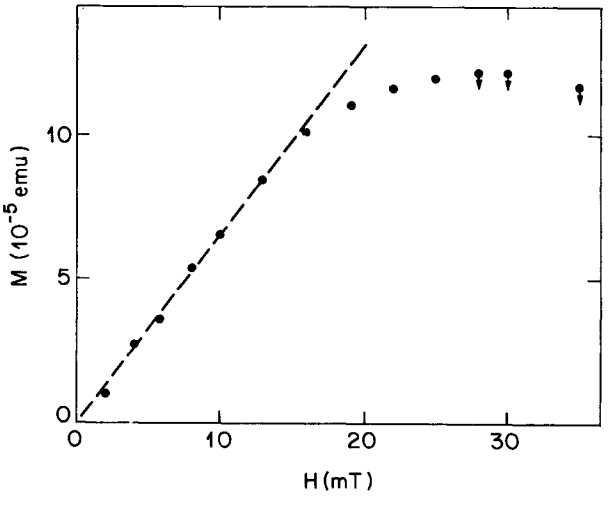

Fig. 2 Magnetization curve to determine the lower critical field H_{c1}. The arrows on the highest field points indicate time dependence of the magnetization.

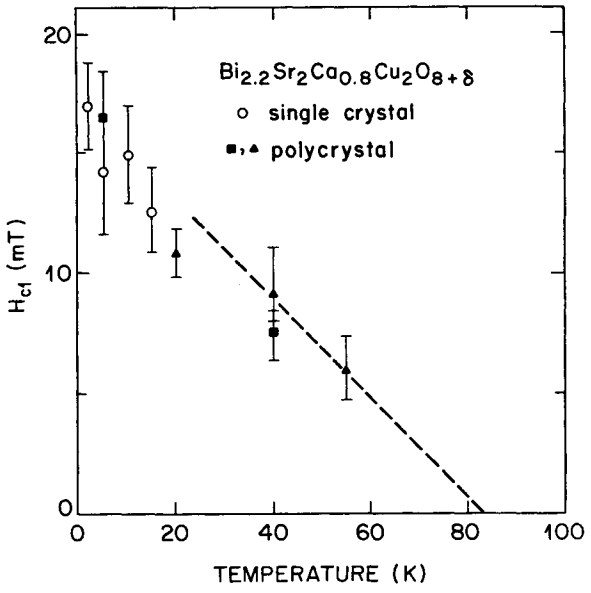

Fig. 3 Temperature dependence of the lower critical field H_{c1}.

Upper critical field H_{c2}

The upper critical field H_{c2} was studied by dc resistivity measurements in fields up to 10T oriented either parallel or perpendicular to the basal plane which also carried the current. The current density was 2.5 A/cm^2. A calibrated Pt thermometer was used to measure the temperature, and detailed corrections for magnetoresistance were applied.

A typical set of data is shown in Fig. 4, consisting of a zero field and the 5T curves for the two different field directions. The dashed lines indicate how T_c was defined in a field: extrapolation of the straight portion of R(T) to R = 0. Any such definition is somewhat arbitrary. Our choice was only guided by the corresponding data on 1-2-3 single crystals, which also show a broadening of the transition, but no rounding towards the lowest temperatures.[12] Even as the transition broadened, the R = 0 temperature remained well defined. The dashed lines in Fig. 4 therefore are an approximation of such a well defined transition. Here we are mainly interested in comparing the Bi-cuprate with the 1-2-3 compound, and thus adopted the described method to determine T_c (H). A complete set of R(T) in various fields is shown in Fig. 5, and the resulting $H_{c2}-T$ phase diagram is given in Fig. 6. H_{c2} varies non-linearly with temperature in the lower field region. The slopes obtained for 5 – 10T are: −0.55 T/K for H

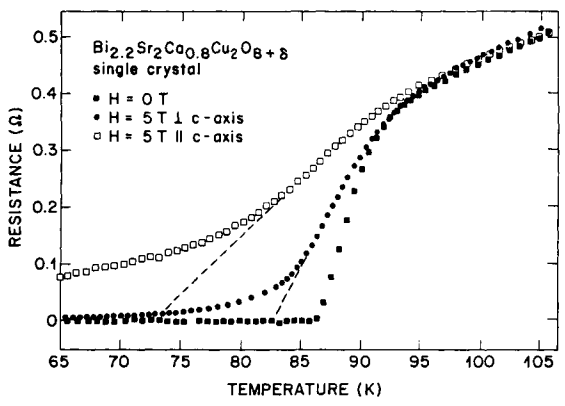

Fig. 4 An example of the resistive transition and its dependence on the orientation of the magnetic field with respect to the a-b plane of the crystals. The dashed lines show the definition of T_c for the broadened curves. This procedure was adopted to facilitate comparison with H_{c2} measurements of $Ba_2YCu_3O_7$ single crystals.

parallel to c and -4.5 ± 1 T/K for H perpendicular to c. These values, together with the H_{c1} data, can be used to calculate several parameters describing the Bi-cuprate superconductor. The zero-temperature upper critical fields $H_{c2}(0)$ can be evaluated by extrapolation using the WHH theory.[12] Although we only know $H_{c2}(T)$ close to the transition temperature, we feel encouraged to use this extrapolation scheme since recent measurements on 1-2-3 single crystals in a pulsed field found that H_{c2} (T) follows indeed a WHH-like curve over the full temperature range.[14] In particular the upturn of the H_{c2} curves is observed only close to T_c. Thus we find $H_{c2}^{\parallel}(0) = 31.5$T and $H_{c2}^{\perp}(0) = 260 \pm 60$T, respectively. The Pauli limiting field H_p of 153T is smaller than $H_{c2}^{\perp}(0)$ but larger than the average $\bar{H}_{c2}(0)$ of 128T, calculated within the framework of anisotropic Ginzburg-Landau theory.

Discussion

The thermodynamic critical field $H_c(0)$ may be estimated with the additional assumption that the anisotropy of H_{c1} is similar to the anisotropy of H_{c2}, which appears to be true for the 1-2-3 superconductor.[11,14] A suitable average than leads to $\bar{H}_c(0) = 1 \pm 0.2$T, and an averaged Ginsburg-Landau parameter $\bar{\kappa}_{GL}$ of $\sim 90 - 95$, describing this extreme type II superconductor. The electronic density of states, given by the Sommerfeld parameter γ, can

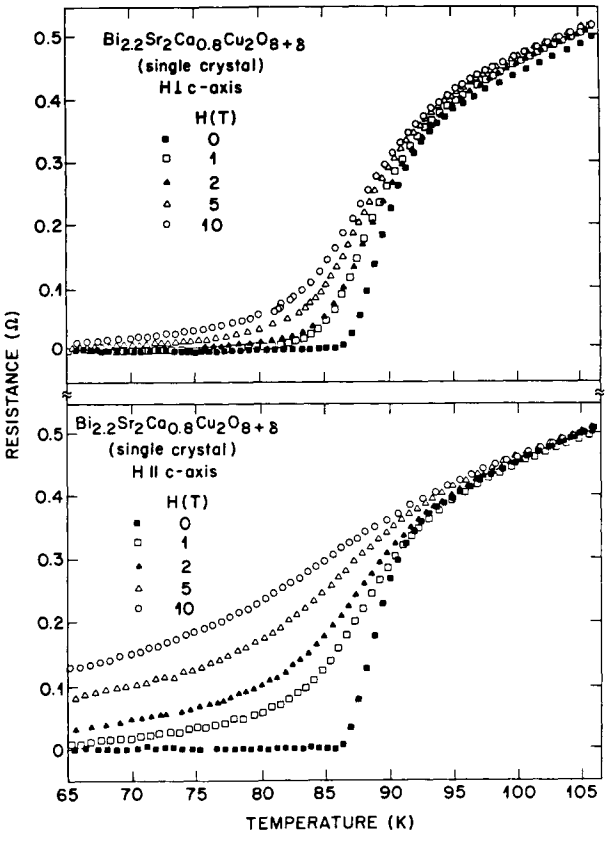

Fig. 5 Summary of R(T) curves for the two field orientations.

also be deduced from $\bar{H}_c(0)$, and amounts to $\sim 11 \pm 2$ mJ/mole K^2. As pointed out before, the T_c of the high T_c superconductors is 3 – 5 times higher than of conventional superconductors with similar electronic density of states.[15,16]

The superconducting coherence length ξ is a microscopic quantity of great interest and can be evaluated from H_{c2} using the standard expressions. Assuming isotropy in the a-b plane, the coherence length in the plane $\xi_{a,b}$ is 31Å, and 4Å perpendicular to it. These results are remarkable for two reasons. First, the absolute values are, within experimental uncertainty, the same as for $Ba_2YCu_3O_7$.[11,12,14–17] Secondly, the coherence length perpendicular to the Cu-O layers ($\xi_c \sim 4$Å) is substantially shorter than the spacing between the Cu-O double layers (~ 12Å). Also, ξ_c is approximately the same as the thickness of the Cu-O double layers formed by the (Cu-O) – Ca – (CuO)

"sandwich". A coherence length ξ_c of ~ 4Å for both classes of compounds suggests that superconductivity is essentially rooted in the Cu-O double layers. Are the structural elements separating these layers only passive building blocks which provide the proper "environment" for superconductivity to occur in the planar network of corner-sharing Cu-O pyramids?

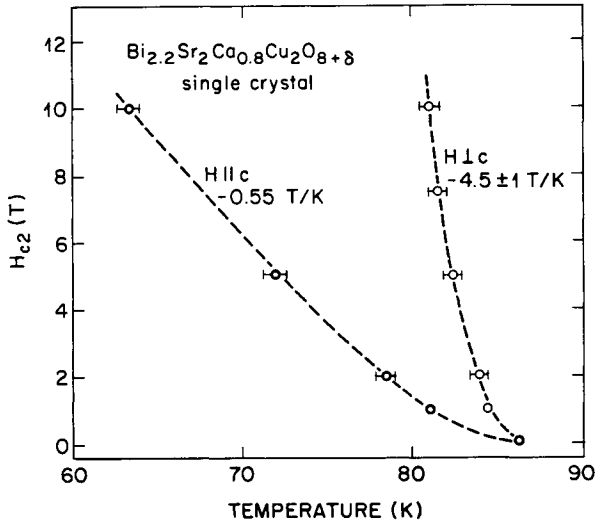

Fig. 6 Temperature dependence of the upper critical field.

Table 1

Physical properties of $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$

Measured quantities	
Transition temperature	$T_c = 84$K
Normal state resistivity	$\rho_{300} = 140\mu\Omega$cm
Upper critical field H_{c2}	
H∥c	$-dH_{c2}^{\parallel}/dT = 0.55$T/K
$H_{\perp c}$	$-dH_{c2}^{\perp}/dT = 4.5 \pm 1$T/K
Derived quantities	
Upper critical field at T = 0	$H_{c2}^{\parallel}(0) = 32$T
	$H_{c2}^{\perp}(0) = 260 \pm 60$T
Thermodynamic critical field (averaged)	$\overline{H}_c(0) = 1 \pm 0.2$T
Coherence length	$\xi_{a,b} = 31$Å
	$\xi_c = 4$Å
Sommerfeld parameter (from $\overline{H}_c(0)$)	$\gamma = 11 \pm 2$ mJ/K^2 mole f.
κ_{GL}	$\kappa = 90 - 100$

Summary

In conclusion, we have established through magnetic and magnetotransport measurements on single crystals that the title compound is a highly anisotropic type II superconductor. The coherence length ξ_c is only ~ 4Å perpendicular to the Cu-O layers, which are separated ~ 12Å by Bi-O layers. The Bi-cuprate and the 1-2-3 compounds are very similar metals and superconductors which points to the Cu-O double layers as the essential structural elements. The electronic density of states is calculated from the thermodynamic critical field ($H_c(0) \sim 1$T) and is found to be in the same range as in the other high T_c superconductors ($\gamma \sim 10$ mJ/mole K^2).

It can be concluded, therefore, that the Cu-O layers are the most important building block in high T_c superconductors. Superconducting and normal state properties are very similar in the Bi-cuprates and in $Ba_2YCu_3O_7$, and are apparently dominated by the physics of the Cu-O layers.

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