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Upper critical field and resistivity of single-crystal $EuBa_2Cu_3O_y$: Direct measurements under high field up to 50 T

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A wide-temperature-range profile of the H_{c2}-T curve for the superconducting 1:2:3 compound is presented. The data were obtained from a $EuBa_2Cu_3O_y$ single crystal under a pulsed magnetic field up to 50 T along the c axis. H_{c2} at 4.2 K is 27.5 ± 2.5 T for the onset of the resistivity. The residual resistivity is roughly estimated to be about 50 $\mu\Omega$ cm. The magnetoresistance is positive and the general features of the superconducting properties except T_c are well sketched by the Bardeen-Cooper-Schrieffer dirty-limit model. The anisotropies in H_{c2} and the resistivity are also discussed.

It is generally accepted that high magnetic-field studies on the high-T_c superconductors will give much information about the intrinsic properties of the transport phenomena.[1] In practice, however, this has been difficult because the expected $H_{c2}(T)$ near 0 K is very high and much work has been done without looking at the whole profile of the H_{c2}-T curve. The experimental studies for single crystals[2-9] and sintered powder samples[10-12] show only the extrapolated $H_{c2}(T)$ and resistivity curves based on data near T_c. As the present status of electronic band calculations[13,14] and other various theories[15] do not give a sufficient explanation of the intrinsic mechanism of high-T_c superconductivity, it is highly desirable to have complete information about the electrical and magnetic responses of high-T_c superconducting materials.

The present paper gives the wide-temperature-range profile of the H_{c2}-T curve and the residual resistivity of 1:2:3 compound. The experiment was performed using a $EuBa_2Cu_3O_y$ single crystal under a pulsed magnetic field up to 50 T down to liquid-helium temperature. A clear change from the superconducting state is found even at 4.2 K when the magnetic field is applied along the c axis. Then, the coherent length ξ is determined with high accuracy and one can also check the validity of the Werthamer-Helffand-Hohenberg (WHH) theory and the anisotropic Ginzburg-Landau (GL) theory in the 1:2:3 compounds.

$EuBa_2Cu_3O_y$ single crystals with a mean size of $1100 \times 560 \times 22$ μm were grown from molton Eu-Ba-Cu-O compounds.[16,17] As-grown crystals were annealed in an oxygen atmosphere at 900–950 °C for 5–10 h and then cooled down slowly to room temperature. Annealed crystals show a twinning structure.[8,18,19] The largest facet is the a-b plane which is perpendicular to the c axis. Sample resistivity was measured using the usual four-terminal method except for measurement along the c direction. The electrical contact was obtained by using gold wires of 25 μm in diameter with conductive silver paste on the gold films evaporated on the largest facet of the crystal. Contact resistances were between 10^{-2} and 10^{-1} $\Omega\,mm^2$ for the area of 560×170 μm^2. Resistivity measurements without magnetic field were made by using the low-frequency (73 Hz) ac four-terminal method. Temperature was measured with a calibrated platinum resistance thermometer. A highly qualified single crystal of $EuBa_2Cu_3O_y$ with a superconducting transition temperature of 94 K was obtained and the transition width was within 1 K. Magnetoresistance was measured by using the dc four-terminal method in a temperature range from 4.2 K to room temperature under a pulsed magnetic field up to 50 T at the Research Center for Extreme Materials in Osaka University where the sample temperature was measured with a calibrated thermocouple of Au-Fe/Ag. The pulsed width of the magnetic field was 0.4 msec. The measurement conditions in the pulsed magnetic field are described in detail in an earlier paper.[11]

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Magnetic-field dependence of the parallel resistance in the a-b plane with the magnetic field H along the c axis from 310 to 4.2 K is shown in Fig. 1.[20] The magnetoresistance $MR_{\perp}$ defined by $\rho_{\parallel}(T,H)-\rho_{\parallel}(T,0)$ is positive and is approximately linear up to 50 T in the temperature range above T_c. Figure 2 shows the corresponding $\rho_{\parallel}$ when H is parallel to the a-b plane. The magnetoresistance in this case, $MR_{\parallel}$, is slightly smaller than $MR_{\perp}$. However, the negative magnetoresistance observed by Oussena *et al.* in sintered powder $YBa_2Cu_3O_y$ (Ref. 12) sample was not found in this experiment.

Figure 3 shows the temperature dependence of $H_{c2\perp}(T)$ and $H_{c2\parallel}(T)$ obtained from Figs. 1 and 2 where $\perp$ and $\parallel$ represent the magnetic-field directions referred to the a-b plane. The $H_{c2}(\rho=0)$ is defined as magnetic field at the onset point of the resistance shown by notation A in Fig. 2. The estimated $H_{c2}(\rho=\frac{1}{2})$, which is normally used for sintered powder samples, is also shown.[21] The $H_{c2}(\rho=\frac{1}{2})$ is defined as notation B shown in Fig. 2. The $H_{c2\perp}(T)$ curve exhibits a slightly upward curvature near T_c which is very often observed in layered superconductors.[22,23] The value of $H_{c2\perp}(0)$ is estimated to be 27.5 ± 2.5 T. This value is close to 26.5 T which is evaluated by the WHH theory, i.e., the dirty-limit Bardeen-Cooper-Schrieffer (BCS) relation of $H_{c2}(0)=0.69T_c \times (dH_{c2}/dT)$ (Ref. 24) with the observed $dH_{c2\perp}/dT$ of 0.41 T/K obtained around $T/T_c=0.65$–0.85. This value is quite close to the value estimated by Worthington *et al.*[3] This means that the WHH theory is effective in the case of this 1:2:3 compound. On the other hand, $H_{c2\parallel}(T)$ drastically increases with decreasing temperature and is measured only above 79 K. The extrapolated $H_{c2\parallel}(0)$ using the same relation is 245 ± 20 T where $dH_{c2\parallel}/dT$ is 3.8 T/K around $T/T_c=0.8$–0.9. The $H_{c2\parallel}(T)$ also exhibits upward curvature near T_c.

The $dH_{c2\parallel}/dT$ value of 3.8 T/K in the present $EuBa_2Cu_3O_y$ crystal is almost the same as the previously reported values of 3.8 T/K,[7] 3.3 T/K,[6] and 3.9 T/K (Ref. 9) for single-crystal $YBa_2Cu_3O_y$ measurements while $dH_{c2\perp}/dT$ obtained in the present study is 0.41 T/K which differs from the previous values of 0.54 T/K (Ref. 7) and 0.56 T/K,[6] and 1.1 T/K.[9] According to the WHH theory, dH_{c2}/dT is strongly dependent on resistivity. The difference of $dH_{c2\perp}/dT$ in various single crystals seems to depend on ρ. The observed ρ in the present study near T_c is 170 $\mu\Omega$ cm (-0.41 T/K) which is lower than the previously reported value of 800 $\mu\Omega$ cm (-1.1 T/K) for $YBa_2Cu_3O_y$ (Ref. 9) and of 410 $\mu\Omega$ cm (-0.7 T/K) for $EuBa_2Cu_3O_y$.[8] It may be said that highly qualified material shows a low $dH_{c2\perp}/dT$ value. However, Orlando *et al.* investigated the relation between ρ and dH_{c2}/dT by using sintered powder samples and concluded that the

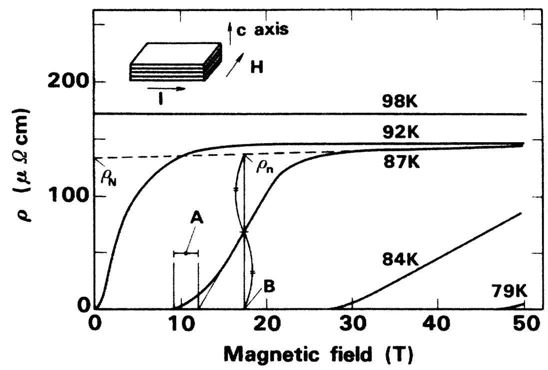

FIG. 2. Magnetic-field dependence of the resistivity in the a-b plane, when the field is in the plane. Definitions of the onset point A and the midpoint B are schematically shown.

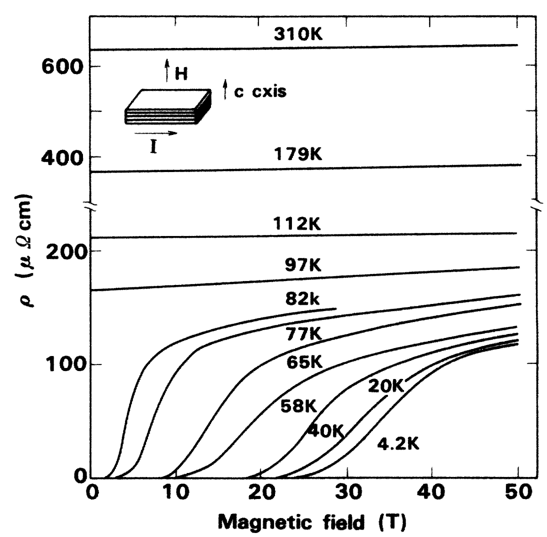

FIG. 1. Magnetic-field dependence of the resistivity ρ in the a-b plane at various temperatures. The field is applied along the c axis.

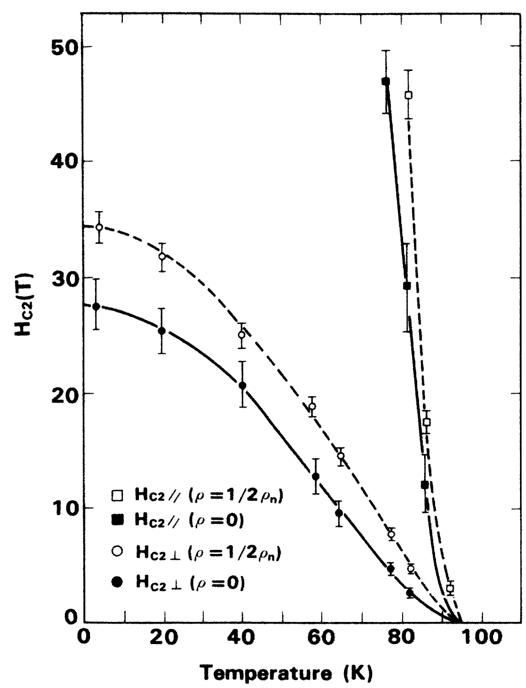

FIG. 3. Upper-critical field H_{c2} vs temperature T for single-crystal $EuBa_2Cu_3O_y$.

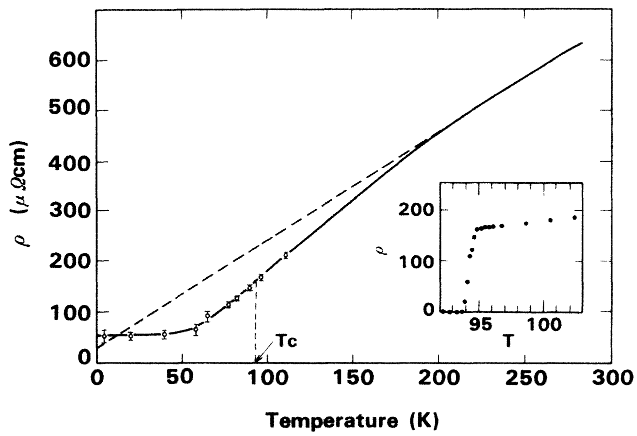

FIG. 4. Temperature dependence of the normal resistivity in the *a*-*b* plane. Error bars come from the ambiguity of the substraction of magnetoresistance. The inset shows the resistivity near T_c without magnetic field. The dashed straight line is a linear extrapolated value from the higher-temperature data above 170 K.

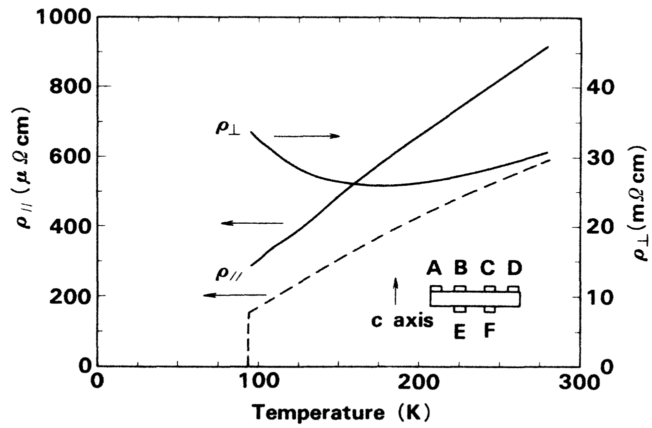

FIG. 5. Temperature dependence of the resistivity tensor measured by the Montgomery method where terminals *B*, *C*, *E*, and *F* are used for the cross measurement. The dashed line is obtained by the four-terminal method where terminals *A*, *B*, *C*, and *D* are used.

resistivities were not an intrinsic property of the superconductivity because the dH_{c2}/dT ws not a function of resistivity.[10] The detailed measurements using single crystals will be necessary for understanding the relation between dH_{c2}/dT and ρ.

The coherent length tensor is calculated from the estimated $H_{c2\perp}(0)$ and $H_{c2\parallel}(0)$ data using the relations given by $H_{c2\perp}=\Phi_0/2\pi\xi_\parallel^2$, $H_{c2\parallel}=\Phi_0/2\pi\xi_\parallel\xi_\perp$, where Φ_0 is the flux quantum. The obtained values are $\xi_\parallel(0)=35$ Å, $\xi_\perp(0)=3.8$ Å.

It should be noted that two-dimensional behavior is not ruled out because $\xi_\perp$ is much smaller than the unit-cell length along the *c* axis.[25] The observed $\xi_\perp$ value is critical[26] even if the Cu-O chain were responsible for the superconductivity. Although three-dimensional behavior is reported by Freitas *et al.*,[27] the possibility of two-dimensional character and dimensional crossover should be investigated in the future. The observed anisotropic ratio of $H_{c2\parallel}/H_{c2\perp}$ is 9.3 at 80 K in accordance with previously reported data[28] of the reciprocal ratio, $H_{c1\perp}/H_{c1\parallel}=10$. This fact means that the anisotropic GL theory can be applicable to the 1:2:3 compounds.

The zero-field normal resistivity curve in the *a*-*b* plane can be roughly estimated by combining the high-field results with the data above T_c as is shown in Fig. 4, where the observed linear and positive magnetoresistance is substracted from the high-field data and the residual resistivity is estimated as about 50 $\mu\Omega$ cm.[29] With the exception of magnetoresistance the outline of $\rho(T)$ can be understood by the normal-metal model. The linear magnetoresistance is a little unusual but is sometimes found in magnetic materials.[30] The spin-fluctuation effect, i.e., negative magnetoresistance[31] is not found.

The anisotropic resistivity above T_c is also measured and the results are shown in Fig. 5. The Montgomery method[32] was used to separate each resistivity. The temperature dependence roughly agrees with the observed data of $YBa_2Cu_3O_y$ single crystal given by Tozzer *et al.*[33] The resistivity along the *c* axis is semiconductive near T_c. This observed peculiarity should be investigated in the future.

In conclusion, it should be noted that a high-quality single crystal of $EuBa_2Cu_3O_y$ shows a clear type-II superconductivity under a strong magnetic field up to 50 T. The wide-temperature-range profile of the H_{c2}-T curve shows that the WHH theory based on the BCS dirty-limit model well explained the experimental results whose coherent lengths were $\xi_\parallel=35$ Å and $\xi_\perp=3.8$ Å. The estimated in-plane normal resistivity down to liquid-helium temperature does not show any peculiarity and the magnetoresistance is positive. The remaining or rather enhanced problem is why the superconducting critical temperature T_c is so high in such a "normal" metal.

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[21]$H_{c2}(\rho=\frac{1}{2})$ has some ambiguity because it is difficult to determine the normal resistivity at low-temperature range. However, our rough estimation of $H_{c2}(\rho=\frac{1}{2})$ is very useful when the data are compared with sintered powder samples.

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