Upper Critical Field and Resistive Tail in High-T_c Cuprates(High-T_c Superconducting Materials Research)

著者	Koike Yoji, Noji Takashi, Saito Yoshitami, Kobayashi Norio, Nakanomyo Takashi, Goto Takayuki, Fukase Tetsuo
journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	37
number	1/2
page range	151-160
year	1992-11
URL	http://hdl.handle.net/10097/28404

Upper Critical Field and Resistive Tail in High-T_c Cuprates*

Yoji Koike[a], Takashi Noji[a], Yoshitami Saito[a], Norio Kobayashi[b],
Takashi Nakanomyo[b], Takayuki Goto[b] and Tetsuo Fukase[b]
[a]Department of Applied Physics, Faculty of Engineering,
Tohoku University, Sendai
[b]Institute for Materials Research, Tohoku University, Sendai
(Received August 7, 1992)

Synopsis

The electrical resistivity under magnetic fields has been investigated for $Pb_2Sr_2Y_{1-x}Ca_xCu_3O_8$, single-crystal $Bi_2Sr_2CaCu_2O_8$ and low-T_c $(La,Eu)_{2-x}(Ba,Sr)_xCuO_4$. The upper critical field and the resistive tail in the lower portion of the superconducting transition curve are discussed.

I. Introduction

Since the discovery of high-T_c superconductivity in La-Ba-Cu-O,1) many kinds of high-T_c superconductors with two-dimensional CuO_2 sheets in their crystal structures have been found. As the superconducting transition temperature T_c is high, the upper crirical field H_{c2} is naturally high, compared with convetional superconductors. Therefore, high magnetic fields are necessary to investigate not only H_{c2} but also physical properties in the normal state at low temperatures.

In this article, we review our several studies on high-T_c cuprates using the high-magnetic-field facilities of Tohoku University. H_{c2} and the resistive tail in a magnetic field are studied for $Pb_2Sr_2Y_{1-x}Ca_xCu_3O_8$.2,3) The anisotropy of H_{c2} and the resistive tail are studied for single-crystal $Bi_2Sr_2CaCu_2O_8$.4) H_{c2} at low temperatures is studied for low-T_c $(La,Eu)_{2-x}(Ba,Sr)_xCuO_4$.

II. H_{c2} and resistive tail of $Pb_2Sr_2Y_{1-x}Ca_xCu_3O_8$

The compound $Pb_2Sr_2Y_{1-x}Ca_xCu_3O_8$ discovered by Cava et al.5) has double CuO_2 pyramidal layers in the crystal structure, and the stack of layers along the c-axis is expressed as $-Y_{1-x}Ca_x-CuO_2-SrO-PbO-Cu-PbO-SrO-CuO_2-$. There are two kinds of Cu with different valences; one is about +2 for the pyramidal CuO_2 layers and the other is +1 for the oxygen-free Cu layer, as contained in $YBa_2Cu_3O_6$. The compound

---

* The 1896th report of Institute for Materials Research

$Pb_2Sr_2YCu_3O_8$ is an insulator developing antiferromagnetic ordering of Cu^{2+} spins,[6] but the superconductivity appears when holes are doped by the partial substitution of Ca for Y. That is, T_c appears at $x > 0.1$ and takes a maximum value ($T_{c,onset} = 83$ K, $T_{c,zero} = 75$ K) at $x = 0.5$.

Ceramic samples of good quality were synthesized by a solid-state reaction, as described in detail in the literature.[3,7] Resistivity measurements were carried out by a DC four-point probe method.

Figure 1 shows the temperature dependence of ρ of $x = 0.5$ in various magnetic fields. The superconducting transition curve becomes very broad by the application of a magnetic field. This behavior is similarly observed for the parallel and perpendicular fields relative to the current direction, suggesting that the broadening of the transition curve in magnetic fields is not attributed to the simple flux-flow resistance due to the Lorentz force. Figure 2 displays $H_{c2}(T)$, defined at the midpoint of the transition curve. H_{c2} is proportional to $T_c - T$, though it shows slight positive curvature near T_c. The value of $-dH_{c2}/dT$ is estimated as 1.7 - 1.8 T/K, which is comparable to those of $Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_{10}$[8,9] and $Tl_2Ba_2Ca_2Cu_3O_{10}$[10] and smaller than those of $YBa_2Cu_3O_7$[11] and $La_{1.85}Sr_{0.15}CuO_4$.[12] H_{c2} at 0 K, $H_{c2}(0)$, is estimated using the

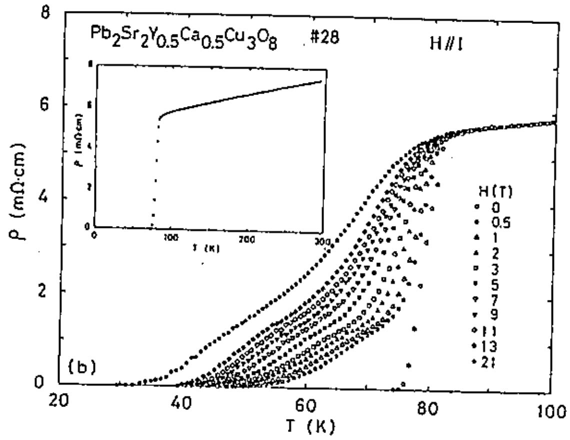

Fig. 1. Temperature dependence of ρ of $Pb_2Sr_2Y_{0.5}Ca_{0.5}Cu_3O_8$ in magnetic field parallel to the current direction. The inset shows data in zero field.

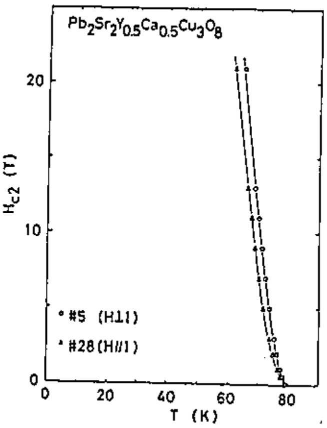

Fig. 2. Temperature dependence of H_{c2} of $Pb_2Sr_2Y_{0.5}Ca_{0.5}Cu_3O_8$. H_{c2} is defined at the midpoint of the transition curve. Magnetic fields are perpendicular to the current direction for sample #5 (o) and parallel for sample #28 (Δ).

relation $H_{c2}(0) = 0.69T_c|dH_{c2}/dT|_{Tc}$ given by the WHH theory for the type II superconductivity in the dirty limit.$^{13)}$ The value of $H_{c2}(0)$ is 85 - 96 T. The Ginzburg-Landau coherence length at 0 K, $\xi(0)$, is estimated from the following equation, $H_{c2}(0) = \phi_0/2\pi\xi^2(0)$, where ϕ_0 is the superconducting flux quantum. The value of $\xi(0)$ is estimated as 19 - 20 Å. These values of H_{c2} and $\xi(0)$ are comparable to those of ceramic samples of other high-T_c superconductors.

The resistive tail in magnetic fields shown in Fig. 1 is well expressed as $\rho = \rho_0\exp(-U_0/T)$, as shown in Fig. 3. The thermal activation energy U_0 has been thought to be related to the potential energy of flux pinning and the resistive tail has been discussed using the model of flux creep and flow. The model, however, cannot be simply applied to our data, because the resistive tail and the value of U_0 are not so dependent on the field direction relative to the current direction, though the flux-flow resistance due to Lorentz force should be influenced by the configuration of the magnetic field and the sample current. If the magnetic flux does not enter a sample straight in the vortex state and is bent by grain boundaries and/or

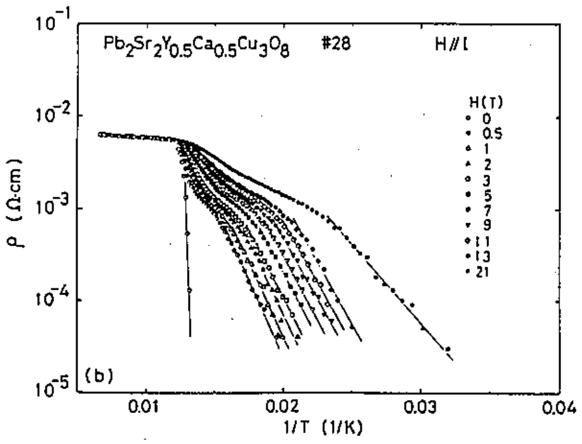

Fig. 3. Plot of log ρ vs T^{-1} for data shown in Fig. 1. U_0 is given by the slopes of the solid lines.

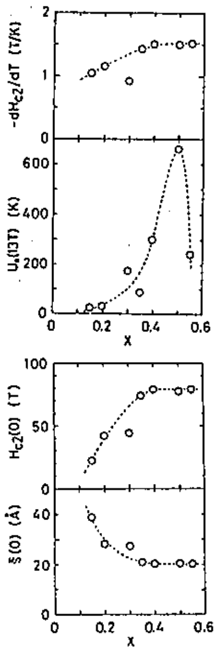

Fig. 4. Variations with x of $-dH_{c2}/dT$, $H_{c2}(0)$, $\xi(0)$ and U_0 at 13 T for $Pb_2Sr_2Y_{1-x}Ca_xCu_3O_8$.

the crystallographic anisotropy, the model of flux creep and flow may be essentially true to explain the resistive tail. The value of U_0 is close to those of $Bi_2Sr_2CaCu_2O_8$[14-16] and $TlBa_2CaCu_2O_y$[17] and smaller than that of $YBa_2Cu_3O_7$.[16] This may suggest that U_0 is related to the crystallographic anisotropy, for the anisotropy of $Pb_2Sr_2Y_{0.5}Ca_{0.5}Cu_3O_8$ is similar to those of $Bi_2Sr_2CaCu_2O_8$ and $TlBa_2CaCu_2O_y$ and larger than that of $YBa_2Cu_3O_7$.

Variations with x of $-dH_{c2}/dT$, $H_{c2}(0)$ and $\xi(0)$ are shown in Fig. 4. These take maxima or minima around x = 0.5, correlating with T_c. Figure 5 shows the magnetic field dependence of U_0. It is not so dependent on the magnetic field strength, but is strongly dependent on x, as shown in Fig. 4. U_0 takes a clear maximum at x = 0.5. According to the model of flux creep and flow, U_0 is simply considered to be proportional to the condensation energy of superconductivity. Therefore, it may be reasonable that U_0 takes a maximum at x = 0.5 where T_c takes a maximum. It is, however, not yet certain why U_0 is not so dependent on the magnetic field strength.

In conclusion, transport properties of $Pb_2Sr_2Y_{1-x}Ca_xCu_3O_8$ under magnetic fields are very similar to those of other high-T_c superconductors with pyramidal CuO_2 layers, such as $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_8$. It may be no exaggeration to say that the pyramidal CuO_2 layer controls almost all properties of these materials including T_c.

III. Anisotropy of H_{c2} and resistive tail of single-crystal $Bi_2Sr_2CaCu_2O_8$

The compound $Bi_2Sr_2CaCu_2O_8$ has double CuO_2 pyramidal layers in the crystal structure, similar to $Pb_2Sr_2Y_{1-x}Ca_xCu_3O_8$. The CuO_2 layers construct two-dimensional conduction layers. Therefore, it is expected that physical properties are very anisotropic.

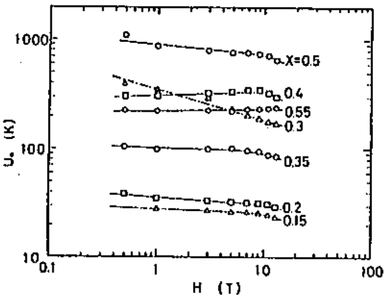

Fig. 5. Magnetic field dependence of U_0 of $Pb_2Sr_2Y_{1-x}Ca_xCu_3O_8$.

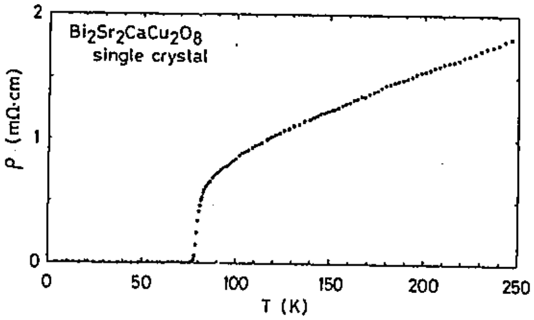

Fig. 6. Temperature dependence of ρ of single-crystal $Bi_2Sr_2CaCu_2O_8$.

Single crystals of $Bi_2Sr_2CaCu_2O_8$ were grown from molten Bi-Sr-Ca-Cu-O using excess CuO as flux, as described in detail in the literature.[4] Resistivity measurements were carried out by a DC four-point probe method with a current flowing perpendicular to the c-axis.

Figure 6 shows the temperature dependence of ρ. T_c defined at the midpoint of the transition curve is 80.6 K. In the high temperature region, T-linear dependence of ρ is observed. The resistivity begins to deviate from the T-linear dependence about 150 K far from T_c. This is considered to be due to the enhancement of the superconducting fluctuation originating from the two-dimensional nature and the very short coherence length. The excess conductivity over the normal conductivity σ_n, which is the inverse of the extrapolated value of the T-linear part of ρ in the high temperature region, is shown as a function of reduced temperature in Fig. 7. In the vicinity of T_c, the excess conductivity $\sigma-\sigma_n$ is proportional to $(T-T_c)^{-1/2}$, suggesting that the superconducting fluctuation in the vicinity of T_c is three-dimensional. According to the theory of Aslamazov and Larkin,[18] the excess conductivity in the three-dimensional system is given by $\sigma-\sigma_n = \{e^2/32\hbar\xi(0)\}\{(T-T_c)/T_c\}^{-1/2}$. From this equation $\xi(0)$ is eastimated as 14 Å.

The superconducting transition in magnetic fields is very

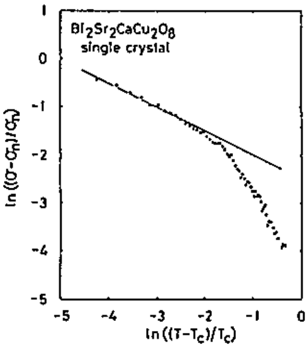

Fig. 7. Temperature dependence of the excess conductivity of single-crystal $Bi_2Sr_2CaCu_2O_8$. The solid line is the prediction of the theory for three-dimensional systems.

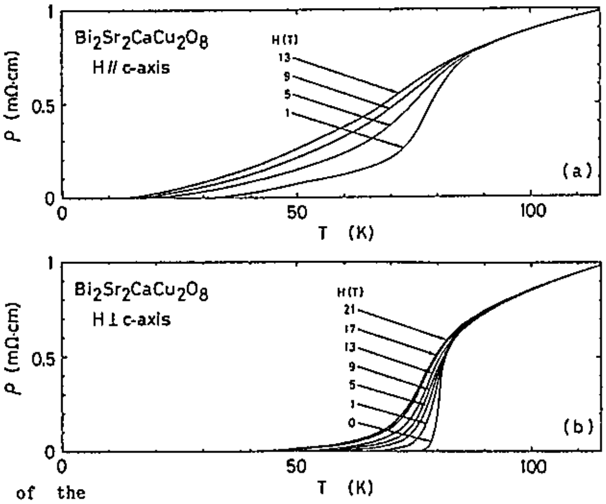

Fig. 8. Superconducting transition in magnetic fields of single-crystal $Bi_2Sr_2CaCu_2O_8$.
(a) H // c-axis. (b) H ⊥ c-axis.

anisotropic, as shown in Fig. 8. The temperature dependence of H_{c2} is shown in Fig. 9. Various parameters obtained from our measurements are listed in Table 1. Those of $YBa_2Cu_3O_7$ 19) and $(La_{1-x}Sr_x)_2CuO_4$ 20) are also listed for reference. The anisotropy of H_{c2} is as large as 9 - 19. This is the minimum value, for the anisotropy will become large by more careful sample alignment. In any case, the anisotropy is larger than 5.1 of $YBa_2Cu_3O_7$. This may be reasonably understood as due to the crystallographic anisotropy, because $Bi_2Sr_2CaCu_2O_8$ is most easily cloven among high-T_c cuprates. The value of $H_{c2}^{\perp}(0)$ estimated from the WHH theory is 270 - 400 T for H ⊥ c-axis. So far as we know, this is the highest value among those of various kinds of superconductors. This value exceeds the Pauli paramagnetic limiting field $H_p(0)$ = 150 T, calculated from the equation, $H_p(0) = 1.84T_c$, where $H_p(0)$ and T_c are in the units of T and K, respectively. The coherence lengths at 0 K, $\xi_{/\!/}(0)$ along the c-axis and $\xi_{\perp}(0)$ perpendicular to the c-axis, are estimated as listed in Table 1 from the following equation:21) $H_{c2}^{/\!/}(0) = \phi_0/2\pi\xi_{\perp}^2(0)$ and $H_{c2}^{\perp}(0) = \phi_0/2\pi\xi_{/\!/}(0)\xi_{\perp}(0)$. The value of $(\xi_{\perp}^2(0)\xi_{/\!/}(0))^{1/3}$ is 13 - 18 Å, which is in good agreement with $\xi(0)$ estimated from the excess conductivity due to the superconducting fluctuation as mentioned before. The value of $\xi_{/\!/}(0)$ is

Table 1. Superconducting parameters of single crystals of high-T_c cuprates.

	$Bi_2Sr_2CaCu_2O_8$	$YBa_2Cu_3O_7$ 19)	$(La_{1-x}Sr_x)_2CuO_4$ 20)
T_c	80.6 K	79 K	30 K
$-dH_{c2}^{\perp}/dT$	4.9-7.3 T/K	2.7 T/K	4 T/K
$-dH_{c2}^{/\!/}/dT$	0.39-0.55 T/K	0.52 T/K	0.3 T/K
$H_{c2}^{\perp}/H_{c2}^{/\!/}$	9-19	5.1	13
$m_{/\!/}/m_{\perp}$	80-360	26	170
$H_{c2}^{\perp}(0)$	270-400 T	40 T	83 T
$H_{c2}^{/\!/}(0)$	21-29 T	28 T	6 T
$H_P(0)$	150 T	150 T	55 T
$\xi_{\perp}(0)$	34-40 Å	35 Å	74 Å
$\xi_{/\!/}(0)$	2.1-3.6 Å	6.8 Å	5.4 Å
s	8.8 Å	3.3 Å	1.8 Å
γ	0.29-0.85	22	46

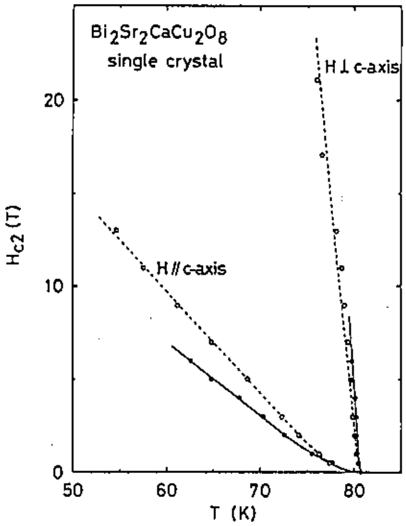

Fig. 9. Temperature dependence of H_{c2} of single-crystal $Bi_2Sr_2CaCu_2O_8$. H_{c2} is defined at the midpoint of the transition curve. Open and closed circles correspond to different samples.

2.1 - 3.6 Å and much smaller than the spacing between the conductive CuO_2 layers s = 8.8 Å for $Bi_2Sr_2CaCu_2O_8$. The parameter γ given by $\gamma = (4\xi_{/\!/}(0)/s)^2/\pi$, characterizing the relative two-dimensionality of superconductivity, is much smaller than those of $YBa_2Cu_3O_7$ and $(La_{1-x}Sr_x)_2CuO_4$ as listed in Table 1 and moreover smaller than the unity. This suggests that the dimensional crossover from three-dimensional superconductivity to two-dimensional superconductivity may occur with decreasing temperature in this compound.[22] The dimensional crossover, which is characterized by the divergent increase of H_{c2}, is expected to appear at H_{c2} = 4.5 - 9.5 T where $\xi_{/\!/}(T) = s/\sqrt{2}$. Unfortunately, such a symptom is not observed within our experimental accuracy. More detailed work may be necessary. It is also of great intereat to measure H_{c2} in magnetic fields that are as high as possible and to investigate the competition between the quasi-two-dimensional superconductivity and the Pauli paramagnetic limit.

As for the superconducting transition in magnetic fields, it is remarkable that the resistive tail is much broader than that of single-crystal $YBa_2Cu_3O_7$. As shown in Fig. 10, the resistive tail is well expressed as $\rho = \rho_0 \exp(-U_0/T)$. Therefore, this broadness will be not due to some inhomogeneity but due to the flux creep and flow. Magnetic field dependence of U_0 is shown in Fig. 11. U_0 is roughly

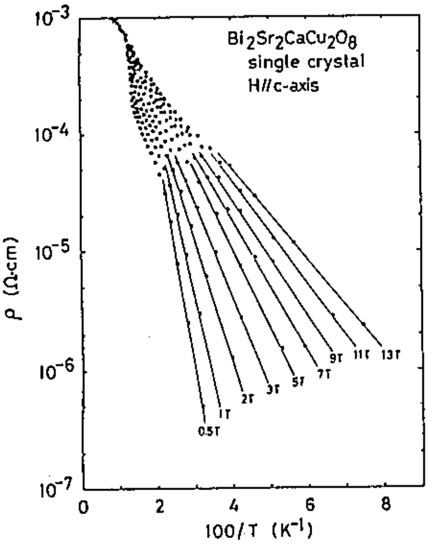

Fig. 10. Plot of log ρ vs T^{-1} for data shown in Fig. 8(a). U_0 is given by the slopes of the solid lines.

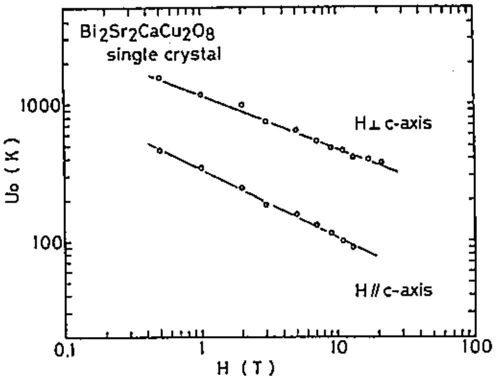

Fig. 11. Magnetic field dependence of U_0 of single-crystal $Bi_2Sr_2CaCu_2O_8$.

proportional to $H^{-0.5}$ for H // c-axis and $H^{-0.4}$ for H ⊥ c-axis. It may be reasonable that flux creep and flow are important in this compound, because U_0 is small on account of the short coherence length and because the measured temperature T is higher than that of for conventional superconductors.

IV. H_{c2} of low-T_c $(La,Eu)_{2-x}(Ba,Sr)_xCuO_4$

In high-T_c cuprates, it is very difficult to study galvanomagnetic properties in the normal state at low temperatures, because H_{c2} is extraordinarily high. Here, we chose low-T_c cuprates and carried out resistivity measurements at low temperatures down to 30 mK in high manetic fields up to 27 T to study the galvanomagnetic properties, combinig a ^3He-^4He dilution refrigerator with the hybrid magnet.

Ceramic samples of $La_{1.88}Ba_{0.12}CuO_4$ (T_c = 6.2 K), $(La_{0.9}Eu_{0.1})_{1.85}Ba_{0.15}CuO_4$ (T_c = 5.9 K) and $(La_{0.7}Eu_{0.3})_{1.85}Sr_{0.15}CuO_4$ (T_c = 3.65 K) were synthesized by a solid-state reaction. Resistivity measurements were made by a DC four-point probe method.

Figure 12 displays the typical field dependence of ρ at low

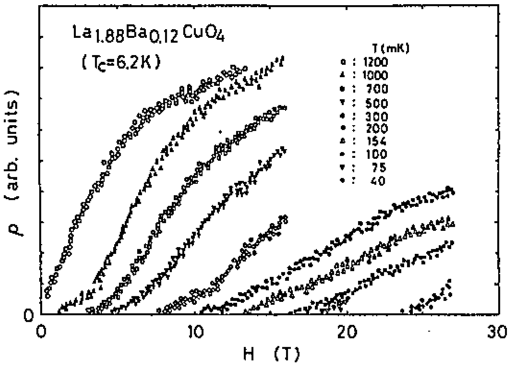

Fig. 12. Magnetic field dependence of ρ of $La_{1.88}Ba_{0.12}CuO_4$ at low temperatures.

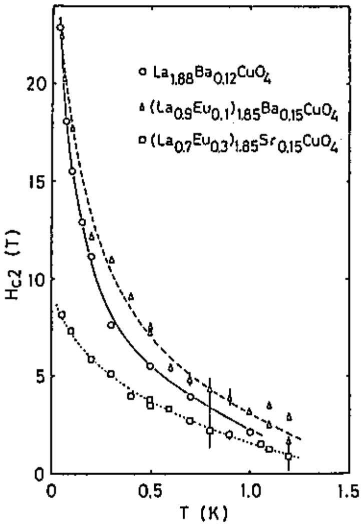

Fig. 13. Temperature dependence of H_{c2} of
$La_{1.88}Ba_{0.12}CuO_4$ (T_c=6.2K),
$(La_{0.9}Eu_{0.1})_{1.85}Ba_{0.15}CuO_4$ (T_c=5.9K),
$(La_{0.7}Eu_{0.3})_{1.85}Sr_{0.15}CuO_4$ (T_c=3.65K).
The definition of H_{c2} is described in the text.

temperatures. The superconducting transition is observed, but unfortunately the galvanomagnetic property in the normal state is not discussed, for the superconducting transition is not completed within the experimental field range. It is necessary to choose more low-T_c samples to study the galvanomagnetic properties.

As for H_{c2}, the temperature dependence of H_{c2} is obtained at low temperatures down to $t \equiv T/T_c \sim 0$, as shown in Fig. 13. Here, H_{c2} is defined as the field, where the extrapolated line of the steepest part of the ρ vs H plot reaches the zero resistivity. It is found that H_{c2} increases very much at low temperatures and shows positive curvature, but the origin remains an open question.

Acknowledgements

The authors would like to acknowledge the collaboration of Prof. S. Hayashi and Messrs. M. Masuzawa, H. Sunagawa, H. Kawabe, T. Hanaguri and T. Nomoto on the work reviewed in the article. They are also grateful to Profs. Y. Muto and K. Watanabe and the staff of HFLSM and the Cryogenic Center of Tohoku University for the use of the high-magnetic-field facilities. This work was supported by a Grant-in-Aid for Scientific Research on Priority Areas, Mechanism of Superconductivity, from the Ministry of Education, Science and Culture, Japan.

References

1) J.G. Bednorz and K.A. Müller, Z. Phys. B64 (1986) 189.
2) Y. Koike, M. Masuzawa, H. Sunagawa, T. Noji, H. Kawabe, N. Kobayashi and Y. Saito, Jap. J. Appl. Phys. 29 (1990) L408.
3) Y. Koike, M. Masuzawa, T. Noji, H. Sunagawa, H. Kawabe, N. Kobayashi and Y. Saito, Physica C170 (1990) 130.
4) Y. Koike, T. Nakanomyo and T. Fukase, Jap. J. Appl. Phys. 27 (1988) L841.
5) R.J. Cava et al., Nature 336 (1988) 211.
6) T. Oashi, K. Kumagai and K. Kadowaki, J. Phys. Soc. Jpn. 59 (1990) 1549.
7) M. Masuzawa, T. Noji, Y. Koike and Y. Saito, Jap. J. Appl. Phys. 28 (1989) L1524.
8) Y. Muto, N. Kobayashi and T. Sasaki, The Science of Superconductivity and New Materials, ed. S. Nakajima, World Scientific, Singapore (1989) 98.
9) H. Kumakura, K. Togano, M. Uehara, H. Maeda, K. Takahashi and E. Yanagisawa, Jpn. J. Appl. Phys. 27 (1988) L1514.
10) H. Iwasaki, N. Kobayashi, Y. Koike, M. Kikuchi, Y. Syono, K. Noto

and Y. Muto, Jpn. J. Appl. Phys. 27 (1988) L1631.

11) Y. Muto, N. Kobayashi and Y. Syono, Novel Superconductivity, ed. S.A. Wolfand and V.Z. Kresin, Plenum Publishing Co., New York (1987) 787.

12) N. Kobayashi, T. Sasaoka, K. Oh-ishi, T. Sasaki, M. Kikuchi, A. Endo, K. Matsuzaki, A. Inoue, K. Noto, Y. Syono, Y. Saito, T. Masumoto and Y. Muto, Jpn. J. Appl. Phys. 26 (1987) L358.

13) N.R. Werthamer, E. Helfand and P.C. Hohenberg, Phys. Rev. 147 (1966) 295.

14) T.T.M. Palstra, B. Batlogg, L.F. Schneemeyer and J.V. Waszczak, Phys. Rev. Lett. 61 (1988) 1662.

15) Y. Jia and J.A. Wilson, Solid State Commun. 71 (1989) 191.

16) N. Kobayashi, H. Iwasaki, H. Kawabe, K. Watanabe, H. Yamane, H. Kurosawa, H. Masumoto, T. Hirai and Y. Muto, Physica C159 (1989) 295.

17) H. Iwasaki, N. Kobayashi, M. Kikuchi, T. Kajitani, Y. Syono, Y. Muto and S. Nakajima, Physica C159 (1989) 301.

18) L.G. Aslamazov and A.I. Larkin, Phys. Lett. 26A (1968) 238.

19) S. Hayashi, H. Komatsu, T. Inoue, T. Ōno, K. Sasaki, Y. Koike and T. Fukase, Jap. J. Appl. Phys. 26 (1987) L1197.

20) Y. Hidaka, Y. Enomoto, M. Suzuki, M. Oda and T. Murakami, Jap. J. Appl. Phys. 26 (1987) L377.

21) D.R. Tilley, Proc. Phys. Soc. 85 (1965) 1177.

22) R.A. Klemm, A. Luther and M.R. Beasley, Phys. Rev. B12 (1975) 877.