Systematic characterization of upper critical fields for MgB$_2$ thin films by means of the two-band superconducting theory

Satoru Noguchi$^{1,2}$, Akihiro Kuribayashi$^1$, Tatsunori Oba$^3$, Hiroki Iriuda$^3$, Yoshitomo Harada$^{2,7}$, Masato Yoshizawa$^{3,4}$, Shigeaito Miki$^{2,5}$, Hisashi Shimakage$^{2,5}$, Zhen Wang$^{2,5}$, Kazuo Satoh$^{2,6}$, Tsutomu Yotsuya$^{2,6,8}$ and Takekazu Ishida$^{1,2}$

$^1$ Department of Physics and Electronics, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan
$^2$ Institute for Nanofabrication Research, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan
$^3$ Graduate School of Engineering, Iwate University, 4-3-5 Ueda, Morioka, Iwate 020-8551, Japan
$^4$ JST Satellite Iwate, 3-35-2 Iioka-shinden, Morioka, Iwate 020-0852, Japan
$^5$ National Institute of Information and Communications Technology, 588-2 Iwaoka-cho, Nishiku, Kobe, Hyogo 651-2429, Japan
$^6$ Technology Research Institute of Osaka Prefecture, 2-7-1 Ayumino, Izumi, Osaka 594-1157, Japan
E-mail: noguchi@pe.osakafu-u.ac.jp

Received 12 November 2008, in final form 11 January 2009
Published 30 March 2009
Online at stacks.iop.org/SUST/22/055004

Abstract
We present experimental results for the upper critical fields $H_{c2}$ of various MgB$_2$ thin films prepared by molecular beam epitaxy, multiple-targets sputtering, and co-evaporation deposition. Experimental data for the $H_{c2}(T)$ are successfully analyzed by applying the Gurevich theory of dirty two-band superconductivity in the case of $D_\pi/D_\sigma > 1$, where $D_\pi$ and $D_\sigma$ are the intraband electron diffusivities for the $\pi$ and $\sigma$ bands, respectively. We find that the parameters obtained from the analysis are strongly correlated to the superconducting transition temperature $T_c$ of the films. We also discuss the anomalous narrowing of the transition width at intermediate temperatures confirmed by the magnetoresistance measurements.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, multiband superconductivity has attracted much attention, as a novel metallic superconductor MgB$_2$ discovered at the beginning of the 21st century [1] has been revealed by numerous experimental and theoretical studies not only to show the highest $T_c$ among intermetallic compounds but also to be a prototype two-band superconductor [2–9]. The superconductivity of MgB$_2$ occurs in both the $\sigma$ and $\pi$ bands of the hexagonal B layer which has a similar electronic structure to graphite [10, 11]. The $\sigma$ band, contributing to a chemical bond between B atoms, is a two-dimensional orbital localized in the $ab$-plane of the hexagonal structure. On the other hand, the $\pi$ band is an antibonding orbital along the $c$-axis, which spreads out three-dimensionally. Therefore, the interaction between $\sigma$ and $\pi$ bands is very weak and then two superconducting gaps open below the superconducting transition temperature $T_c$ in both bands.
The two-band superconducting character in MgB_2 appears in the temperature dependence of the upper critical field _H_{c2}, which shows an upward curvature below _T_c. The superconducting anisotropy parameter _γ determined from the ratio of _H_{c2} for the _ab-direction to that for the _c-direction also shows a temperature dependence. The _γ value for the single crystal increases with decreasing temperature [12]. Drastic enhancement of _H_{c2} is observed in dirty samples such as nonmagnetic impurity doped MgB_2 bulks and/or films, where _γ becomes small showing a variety of the temperature dependence [7, 8, 13–15]: in the case of a high resistivity film, _γ reduces with decreasing temperature [7]. These behaviors are not explained by just the dimensional crossover as usually discussed in the layered superconductors [16], but by the superimposition of _H_{c2} with two distinct superconducting gaps [5, 9].

There are mainly two disorder effects on the superconducting properties due to nonmagnetic impurities and/or crystal imperfection: one is suppression of _T_c by weakening the superconducting coupling and the other is enhancement of the initial slope of _H_{c2} at _T_c by reducing the electron mean free path [17]. In dirty MgB_2 bulks and films there is very clever situation in which the great intraband scattering raises _H_{c2} and the small interband scattering slightly suppresses _T_c. The shape of the _H_{c2}(T) curve is changed depending on whether intraband scattering in the _σ or the _π band is larger. Gurevich gave the formula for _H_{c2}(T) curves in the framework of dirty two-band superconductivity [6, 9]. He calculated the _H_{c2}(T) curves by using the parameters of the interband scattering _g_ and the diffusivities _D_σ and _D_π in the _σ_ and _π_ bands including the anisotropy [9]. These parameters are good milestones for summarizing the experimentally obtained _H_{c2}(T) curves and in discussing the two-band superconductivity.

In this work we present experimental and calculated results of the _H_{c2}(T) phase diagram of various MgB_2 thin films on some different substrates prepared by molecular beam epitaxy (MBE), multiple-targets sputtering and co-evaporation deposition. We measured magnetoresistance over the whole region of the _H_{c2}(T) curves by using a pulsed magnet up to 37 T. In order to obtain the best fitting parameters of the Gurevich theory to experimental data we took a differential plot, (−_dH_{c2}/dT) versus _T_c because this plot emphasizes the temperature dependence of the _H_{c2}(T) curve. We found that the parameters obtained from the analysis are strongly correlated to the _T_c of the films. Moreover, we present another interesting result on the transition width. In the process of magnetoresistance measurements at several temperatures, we found that the resistive transition width does not increase monotonically with decreasing temperature but has a minimum at a certain temperature below _T_c. We discuss the peculiar behavior in the temperature dependence of the transition width obtained from magnetoresistance measurements.

2. Experimental details

_H_{c2} was determined from measurements of the magnetoresistance by a dc four-terminal method at several temperatures below _T_c down to 1.5 K under a pulsed magnetic field up to 37 T using a home-made pulsed magnet system. Magnetoresistance was measured in the field direction of both _H || _ab-plane and _H || _c-axis to obtain the superconducting anisotropy of the films. A block diagram for the _H_{c2} measurements is shown in figure 1. In order to avoid excessive electric noise and heat-inflow to the sample, a battery is used as a current source in a proper electric circuit. Currents of 1–40 mA are applied to MgB_2 films, depending on the resistance of the samples, to obtain a signal of about 3 mV from the normal resistance. The magnetic field is applied by triggering a thyristor switch of a LCR circuit from a delay pulse generator. The pulsed width of the magnetic field is 10 ms. A field trace is obtained by integrating the voltage data recorded in a digital oscilloscope from a field pick-up coil. A stray signal from the lead wires is canceled by using a compensation coil and a bridge circuit.

Six as-grown MgB_2 thin films were used in the magnetoresistance measurements. Four MgB_2 films were prepared by the Iwate group using an MBE apparatus with
Figure 2. Photograph of MgB$_2$ thin film #6 used in the $H_{c2}$ measurements. The film width is 0.2 mm and the length between terminals is 2 mm.

Table 1. Fabrication conditions of MgB$_2$ thin films.

| Film | Thickness (nm) | $\rho(40$ K $)$ ($\mu\Omega$ cm) | Substrates | Apparatus |
|------|----------------|-------------------------------|------------|-----------|
| #1   | 100            | 9.2                          | MgO(100)   | MBE       |
| #2   | 300            | 35                           | Si(111)    | MBE       |
| #3   | 200            | 40                           | ZnO(0001) + 10 nm Ti | MBE |
| #4   | 200            | 4                            | ZnO(0001) + 50 nm Ti | MBE |
| #5   | 160            | 270                          | c-Al$_2$O$_3$ | Sputter |
| #6   | 700            | 44                           | c-Al$_2$O$_3$ | Co-evaporation |

The co-evaporation conditions of a low deposition rate in ultra-high vacuum without post-annealing [18–20]. Two of them were deposited on MgO(100) (#1) and Si(111) (#2) substrates at 200$^\circ$C and the others were deposited on Ti buffer layers on ZnO(0001) substrates at 200$^\circ$C. The difference of the latter two films is the thickness of the Ti buffer layers; one is 10 nm (#3) and the other is 50 nm (#4). The film thickness and the resistivity at 40 K are listed in table 1. The structure and crystallinity were checked by x-ray diffraction. It was revealed that the c-axis of the MgB$_2$ is oriented in a perpendicular direction to the film surface. Especially, film #4 is found to have an excellent alignment with the in-plane orientation [20].

The other two MgB$_2$ films were prepared by the NICT group. They were deposited on the c-plane of a sapphire substrate: one is fabricated by using a carousel-type multiple-target sputtering system without any buffer layers [21], denoted as #5, and the other by using a co-evaporation method (#6) [22]. They have a smooth surface as grown at low-substrate temperatures and their c-axis is also well oriented in a perpendicular direction to the film surface. The film thickness and the resistivity at 40 K are also listed in table 1. The co-evaporation film (#6) was fabricated to the shape of a four-terminal pattern as shown in figure 2.

3. Results

The magnetoresistance curves of the MgB$_2$ film #3 at several temperatures for $H \parallel c$-axis are shown in figure 3(a) as a typical example of the experimental data. No hysteresis is observed. The $H_{c2s}$ were defined as the midpoint of the resistive transition and the transition widths were defined as the fields between 10% and 90% of the normal resistance. The differential data $dR/dH$ are plotted as a function of the magnetic field in figure 3(b). We find that the peak fields in figure 3(b) coincide with the $H_{c2s}$ at each temperature. The peak width, which is almost proportional to the inverse of the peak height, also corresponds to the transition width. So a maximum in the peak height observed at 26 K means that the transition becomes sharp at that temperature.

From the magnetoresistance measurements, we obtained the $H_{c2}(T)$ phase diagrams of six films, which are shown in figure 4. Error bars in the figure correspond to the fields between 10% and 90% of the normal resistance. The superconducting anisotropy parameter $\gamma_H = H_{c2(0)}^{ab}/H_{c2}^{c}$ as a function of temperature was obtained as shown in the inset of the figure, where $H_{c2}^{ab}$ and $H_{c2}^{c}$ are the $H_{c2}$ for $H \parallel ab$-plane and $H \parallel c$-axis, respectively. The $\mu_0H_{c2}^{ab}(0)$s are 20–40 T, which are apparently larger than those for MgB$_2$ single crystal.
This indicates that the superconducting coherence length is effectively reduced through the reduction of the electron mean free path due to some kind of disorder in fabricating the films. As for the anisotropy, the values of $\gamma_M$ are between 1 and 3 depending on the films, smaller than that of single crystal MgB$_2$. $\gamma_M$ decreases with increasing temperature, as shown in the inset of the figure. This is a basis for determining the ratio of the diffusivities for the $\sigma$ and $\pi$ bands as analyzed later. These experimentally obtained results of $T_c$, $\mu_0H_{c2}^{(ab)}(0)$, $\mu_0H_{c2}^{(c)}(0)$ and $\gamma_M(0)$ are listed in Table 2.

### Table 2. Experimentally obtained values of some superconducting characteristics and the best fitting parameters of the Gurevich calculation to the experimental data.

| No. | $T_c$ (K) | $\mu_0H_{c2}^{(ab)}(0)$ (T) | $\mu_0H_{c2}^{(c)}(0)$ (T) | $\gamma_M(0)$ | $g$ | $D_\sigma$ (cm$^2$ s$^{-1}$) | $D_{ab}^{(ab)}$ (cm$^2$ s$^{-1}$) | $D_{c2}^{(c)}$ (cm$^2$ s$^{-1}$) | $\eta^{(c)}$ | $\eta^{(ab)}$ |
|-----|-----------|-----------------|-----------------|---------------|----|----------------|----------------|----------------|--------|--------|
| #1  | 35.1      | 29.1            | 15.3            | 1.91          | 0.077 | 20.88          | 1.48          | 0.38          | 22.78  | 14.1   |
| #2  | 34.5      | 35.4            | 20.0            | 1.78          | 0.089 | 6.92           | 1.08          | 0.35          | 11.3   | 6.4    |
| #3  | 30.4      | 38.6            | 19.5            | 1.98          | 0.197 | 3.85           | 0.70          | 0.11          | 13.8   | 5.5    |
| #4  | 37.1      | 25.3            | 11.4            | 2.23          | 0.042 | 44.16          | 2.28          | 0.45          | 43.9   | 19.4   |
| #5  | 28.8      | 23.0            | 16.3            | 1.41          | 0.265 | 4.20           | 0.65          | 0.19          | 12.1   | 6.5    |
| #6  | 36.9      | 30.3            | 18.6            | 1.62          | 0.046 | 22.78          | 1.60          | 0.50          | 25.4   | 14.3   |

The values of $g$ in Table 2 were determined by fitting the Gurevich theory to the experimental data of $\mu_0H_{c2}^{(ab)}$ and $\gamma_M(0)$.

### 4. Analysis

Experimentally obtained data for $H_{c2}(T)$ and $\gamma_M$ were calculated by fitting the Gurevich theory [6, 8, 9] based on two-gap Usadel equations, in which impurity scattering is introduced as the intraband electron diffusivities and the interband scattering. The calculations were performed using the application software Mathematica (Wolfram Research Co.). For two-gap superconductivity, $T_c$ is not affected by intraband scattering, but decreased with increasing interband scattering parameter $g$. We assume $T_0 = T_c(g = 0) = 40$ K and then determine the value of $g$ from the Gurevich theory [9] as follows:

$$U\left(\frac{g}{\lambda_0}\right) + \frac{(\lambda_0 + w \ln t_c) \ln t_c}{p + w \ln t_c} = 0,$$

$$U(x) = \psi(1/2 + x) - \psi(1/2),$$

$$2p = \lambda_0 + [\lambda_\pi - 2\lambda_\sigma \gamma_\sigma / (\lambda_\sigma + \lambda_\pi)] / \gamma_\pi, \quad \gamma_\pi = \gamma_\sigma \pm \gamma_\pi,$$

$$\lambda_\pi = \lambda_0 \pm \lambda_\pi,$$

$$\lambda_0 = (\lambda_\pi^2 + 4\lambda_\sigma \lambda_\pi)^{1/2},$$

$$w = \lambda_\sigma \lambda_\pi / \lambda_\pi \lambda_\sigma,$$

$$g = h \gamma_\pi / 2\pi k_B T_0,$$

$$t_c = T_c / T_0.$$
On the other hand, the shape of the \( \eta \) \( \sigma \) and \( \eta \) \( \pi \) are the intraband superconducting coupling constants of the \( \sigma \) and \( \pi \) bands, respectively. \( \lambda_{\sigma \pi} \) and \( \lambda_{\pi \sigma} \) are the interband superconducting coupling constants and \( \gamma_{\sigma \pi} \) and \( \gamma_{\pi \sigma} \) are the interband scattering rates. There is a constraint among these interband parameters so as to satisfy the symmetry relation to the partial densities of states \( N_\sigma \) and \( N_\pi \) in the \( \sigma \) and \( \pi \) band, respectively:

\[
\frac{\lambda_{\sigma \pi}}{\lambda_{\pi \sigma}} = \frac{\gamma_{\sigma \pi}}{\gamma_{\pi \sigma}} = \frac{N_\pi}{N_\sigma}, \tag{10}
\]

where \( N_\pi/N_\sigma \sim 1.3 \) for MgB\(_2\) [6]. We use the values of \( \lambda_{\sigma \sigma}, \lambda_{\pi \pi}, \lambda_{\sigma \pi} \) and \( \lambda_{\pi \sigma} \) fixed to be 0.81, 0.285, 0.119 and 0.09, respectively, in the following calculations [4, 9]. In this way, we determined the values of \( g \) for six films using the experimentally obtained \( T_c \) as listed in table 2.

The equation for calculating \( H_{C2} \) is presented as follows:

\[
(\lambda_0 + \lambda_i)[\ln t + U(x_+)] + (\lambda_0 - \lambda_i)[\ln t + U(x_-)] + 2w[\ln t + U(x_+)]/[\ln t + U(x_-)] = 0, \tag{11}
\]

\[
\lambda_i = [\omega_0 - \gamma_\pi - \lambda_\pi - 2\lambda_{\pi \pi} - \gamma_\pi - 2\lambda_{\pi \pi} - \gamma_\pi] / \Omega_0, \tag{12}
\]

\[
x_h = h(\omega_\pi + \gamma_\pi) / 4\pi k_B T, \tag{13}
\]

\[
\Omega_0 = [\omega_0 + \gamma_\pi] / 4\gamma_\pi \gamma_\sigma \tag{14}
\]

\[
\omega_\pi = (D_\sigma \pm D_\pi ) / \gamma_\pi \Omega_0 \tag{15}
\]

where \( t = T/T_0 \) and \( \phi_0 \) is the flux quantum. \( D_\sigma \) and \( D_\pi \) are the intraband electron diffusivities in the \( \sigma \) and \( \pi \) bands, respectively. Since the \( \pi \) band has much more of a three-dimensional nature than the \( \sigma \) band, we assume isotropic diffusivity in the \( \pi \) band; \( D_\pi = D_\pi^{(ab)} = D_\pi^{(c)} \). In the \( \sigma \) band, on the other hand, anisotropic diffusivities along the \( c \)-axis and \( ab \)-plane are introduced; \( D_\sigma = D_\sigma^{(ab)} \) for \( H \parallel c \)-axis, while \( D_\sigma = \sqrt{D_\sigma^{(ab)} D_\sigma^{(c)}} \) for \( H \parallel ab \)-plane. \( D_\sigma^{(ab)} \) and \( D_\sigma^{(c)} \) are the diffusivities along the \( ab \)-plane and the \( c \)-axis, respectively.

The ratio \( D_\pi/D_\sigma = \eta \) is defined as \( \eta^{(ab)} = D_\pi / \sqrt{D_\sigma^{(ab)} D_\sigma^{(c)}} \) for \( H \parallel ab \)-plane and \( \eta^{(c)} = D_\pi / D_\sigma^{(ab)} \) for \( H \parallel c \)-axis, respectively.

In the calculation, the absolute value of \( D_\pi \) is roughly determined from the value of \( H_{C2}(0) \) for each field direction. On the other hand, the shape of the \( H_{C2}(T) \) curve is mainly dependent on the parameter \( \eta \). In the case of \( \eta \ll 1 \), the curve shows a steep increase at a low temperature near 0 K, while in the case of \( \eta \gg 1 \), the initial slope of the \( H_{C2}(T) \) curve at \( T_c \) is suppressed, as shown in the inset of figure 5. As \( \eta = 1 \), the \( H_{C2}(T) \) curve is identical to the curve for a single-band superconductor. This situation is much clearer in the differential plot, \( -dH_{C2}/dT \) versus \( T/T_c \), as shown in figure 5. Therefore, we first obtained the best-fit parameters by fitting the calculation curve to the experimental data shown in figure 4 and then referred the \( -dH_{C2}/dT \) plot as shown in figure 6 to confirm that the fitting is the best. It becomes quite important in these advanced analyses that we measure the magnetoresistance at a lot of temperatures for each film. In this way, we successfully obtain the calculation curves drawn by solid lines in figures 4 and 6, which show fairly good agreement with the experimental data points. The obtained parameters are listed in table 2.

5. Discussions

The results of the analysis as listed in table 2 show the case of \( \eta > 1 \) for all MgB\(_2\) films, which means that the films have a cleaner \( \pi \) band than \( \sigma \) band. This is also confirmed in the temperature dependence of \( \gamma_\eta \) as shown in the insets of figure 4, where \( \gamma_\eta \) decreases with increasing temperature, which is explained as the case of \( \eta > 1 \) in the Gurevich theory [6]. There are many reports of the disorder effect on \( H_{C2} \) by doping a nonmagnetic impurity to MgB\(_2\) bulks and films. For example, \( H_{C2} \) can attain values up to 60 T in the C substitution system [8]. On the contrary, our films were fabricated with no artificially doped impurity to get high grade films for device applications. Nevertheless, even films such as ours show an enhancement of the \( H_{C2} \), which suggests that the structural disorder is more dominant than the substitution of nonmagnetic impurity atoms. Several factors that cause the structural disorder are deviation of the stoichiometry, mismatch of the lattice constants between MgB\(_2\) and substrates (which causes a strain or distribution of the interatomic distance), randomness of in-plane orientation, degradation by oxygen and water attack, and so on. It seems quite natural that the effect of the structural disorder is equally introduced in both \( \sigma \) and \( \pi \) bands as well as in the interband scattering.

In order to make the disorder effect clear, we plot several parameters obtained from this study against the \( T_c \) as shown in figure 7. The experimental parameters, \( \mu_0 H_{C2}^{(ab)}(0) \) and \( \gamma_\eta \) exhibit no \( T_c \) dependence as shown in the upper graph of figure 7. On the other hand, the parameters obtained from the analysis, \( D_\pi, D_\pi^{(ab)} \) and \( D_\pi^{(c)} \), decrease clearly with decreasing \( T_c \). \( D_\pi^{(ab)} \) and \( D_\pi^{(c)} \) show an exponential dependence on the \( T_c \), as drawn by solid lines in the middle graph of figure 7. \( D_\pi \) decreases much faster than \( D_\pi^{(ab)} \) and \( D_\pi^{(c)} \) with decreasing \( T_c \). As for the resistivity, \( \rho \) increases roughly with decreasing \( T_c \) as shown in the bottom graph of the figure. As a conclusion, even in two-band superconductors \( T_c \) of the films is found to be a good parameter to evaluate the diffusivity which is directly related to the crystalline quality of the superconducting films, as well as the residual resistivity.
Next, we show that the conclusion remains unchanged when we adopt the other definition of the $H_{c2}$. Many groups have reported the $H_{c2}(T)$ phase diagram of MgB$_2$ bulks and/or films obtained from resistivity measurements. Some of them have used $H_{c2}$ defined as an onset or 90% of the magnetoresistive transition [7, 8, 13, 14]. However, we consider that the midpoint definition is more relevant from an experimental point of view in the systematic measurements and characterizations of various MgB$_2$ thin films fabricated by different methods [23]. Nevertheless, it is worth checking how parameters obtained from fitting the theoretical calculation to the experimental data are varied by differences in the definition of $H_{c2}$. The magnetoresistance curves of film #3 are rather sharp, as shown in figure 3, so we obtained each $H_{c2}(T)$ determined from midpoint, 90% and 99% of the normal resistance ($R_n$). Although the $T_c$s and the $H_{c2}(0)$s are different according to the definition, the temperature dependences of the $H_{c2}$ among three definitions are very similar to one another. We also analyzed each type of $H_{c2}(T)$ data by fitting the Gurevich theory. Obtained parameters are listed in table 3.

| #3 | $T_c$ (K) | $g$ | $D_\pi$ (cm$^2$ s$^{-1}$) | $D_{a}^{(ab)}$ (cm$^2$ s$^{-1}$) | $D_{c}^{(c)}$ (cm$^2$ s$^{-1}$) |
|----|----------|----|--------------------------|-------------------------------|-------------------------------|
| Midpoint | 30.4 | 0.197 | 3.85 | 0.70 | 0.11 |
| 90% $R_n$ | 31.3 | 0.168 | 4.05 | 0.72 | 0.14 |
| 99% $R_n$ | 32.4 | 0.137 | 6.19 | 0.68 | 0.20 |

and characterized by these data in figure 7 we find that they plot near the solid line of the figure. Accordingly, the conclusion of the cleaner $\pi$ band is not changed by any differences in the definition of $H_{c2}$.

Finally, we briefly discuss the transition width in the magnetoresistance measurements [24]. So far as we know there have been no discussions on the transition width in the two-band superconductivity. As shown in figure 3, the

---

Table 3. Several parameters fitting the Gurevich calculation to the experimental data of MgB$_2$ film #3 for different definitions of $H_{c2}$.

---

Figure 6. $-dH_{c2}/dT$ versus $T$ plots of six films for the field direction $H \parallel ab$-plane and $H \parallel c$-axis. Solid lines are fitting curves using the Gurevich theory with the same parameters as shown in figure 4.

Figure 7. Plots of several parameters obtained from this study against the $T_c$. 

| $\mu H_{c2}(0)$ | $D_{\pi}$ (cm$^2$ s$^{-1}$) | $D_{a}^{(ab)}$ (cm$^2$ s$^{-1}$) | $D_{c}^{(c)}$ (cm$^2$ s$^{-1}$) |
|------------|--------------------------|-------------------------------|-------------------------------|
| #1 | #2 | #3 | #4 | #5 | #6 |

---

6
magneto resistivitve transition becomes sharp at 26 K and broad below that temperature. If we interpret this behavior only in terms of the $H_{c2}(T)$ phase diagram, it may be seen that the $H_{c2}(T)$ curve shows an upward curvature. When the superconductivity in the $\pi$ band is destroyed by an applied field, the normal core appears partly to form a vortex pinning center. The pinning mechanism of MgB$_2$ films has been speculatedly discussed from the mixed-state transport measurements by Arcos and Kunchur [25]. Although the transition width is often related to the local $T_c$ variations due to some inhomogeneities, it may be attributed to two-band superconducting characteristics.

6. Conclusion

We have presented experimental results on the $H_{c2}(T)$ for the $H \parallel ab$-plane and $H \parallel c$-axis of various as-grown MgB$_2$ thin films prepared by molecular beam epitaxy, multiple-target sputtering and co-evaporation deposition. The results were well described by the Gurevich theory of dirty two-gap superconductivity. We extracted empirical parameters on the diffusivity of superconducting electrons for the $\sigma$ and $\pi$ bands from the $H_{c2}(T)$ calculation. All films were categorized as $D_\pi/D_\sigma > 1$, namely the cleaner $\pi$ band case. We found that the parameters obtained from the analysis are strongly correlated with the $T_c$ of the films. Accordingly, $T_c$ is a good parameter for characterizing the quality of the films from the point of view of superconducting properties as well as the residual resistivity.

Acknowledgments

We would like to thank A Gurevich for critical reading of this manuscript. This work was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan (grant no. 19206104).

References

[1] Nagamatsu J, Nakagawa N, Muranaka T, Zenitani Y and Akimitsu J 2001 Nature 410 63
[2] Choi H J, Roundy D, Sun H, Cohen M L and Louie S G 2002 Nature 418 758
[3] Choi H J, Roundy D, Sun H, Cohen M L and Louie S G 2002 Phys. Rev. B 66 020513(R)
[4] Golubov A A, Koritsus J, Dolgov O V, Jepsen J, Kong Y, Andersen O K, Gibson B J, Ahn K and Kremer R K 2002 J. Phys.: Condens. Matter 14 1353
[5] Golubov A A and Koshelev A E 2003 Phys. Rev. B 68 104503
[6] Gurevich A 2003 Phys. Rev. B 67 184515
[7] Gurevich A et al 2004 Supercond. Sci. Technol. 17 278
[8] Braccini V et al 2005 Phys. Rev. B 71 012504
[9] Gurevich A 2007 Physica C 456 160
[10] Kunchur M N, Wu C, Arcos D H, Ivlev B I, Choi E-M, Boyer L L 2001 Phys. Rev. Lett. 86 4656
[11] Liu A Y, Mason I and Kortus J 2001 Phys. Rev. Lett. 87 087005
[12] Lyard L et al 2002 Phys. Rev. B 66 180502(R)
[13] Jung M H, Jaime M, Lacerda A H, Boebinger G S, Kang W N, Kim H J, Choi E M and Lee S I 2001 Chem. Phys. Lett. 343 447
[14] Ferrando V, Manfrinetti P, Marre D, Putti M, Sheikin I, Tarantini C and Ferdeghini C 2003 Phys. Rev. B 68 094517
[15] Noguchi S, Miki S, Shimakage H, Wang Z, Satoh K, Yotsuya T and Ishida T 2005 Physica C 426–431 1449
[16] Lawrence W E and Doniach S 1971 Proc. 12th Int. Conf. on Low Temp. Phys. (Kyoto, 1970) ed E Kanda (Tokyo: Keigaku) p 361
[17] Helfand E and Werthamer N R 1964 Phys. Rev. Lett. 13 686
[18] Harada Y, Takahashi T, Iriuda H, Kuroha M, Nakanishi Y and Yoshizawa M 2005 Physica C 426–431 1453
[19] Takahashi T, Harada Y, Iriuda H, Kuroha M, Oba T, Seki M, Nakanishi Y, Ecchigoya J and Yoshizawa M 2006 Physica C 445–448 887
[20] Harada Y, Yamaguchi H, Takahashi T, Iriuda H, Oba T and Yoshizawa M 2007 IEEE Trans. Appl. Supercond. 17 2883
[21] Saito A, Kawakami A, Shimakage H and Wang Z 2002 Japan. J. Appl. Phys. 41 L127
[22] Shimakage H, Saito A, Kawakami A and Wang Z 2004 Physica C 408–410 891
[23] Kunchur M N, Wu C, Arcos D H, Ivlev B I, Choi E-M, Kim K H P, Kang W N and Lee S I 2003 Phys. Rev. B 68 100503(R)
[24] Noguchi S, Kuribayashi A, Harada Y, Yoshizawa M, Miki S, Shimakage H, Wang Z, Satoh K, Yotsuya T and Ishida T 2008 J. Phys. Chem. Solids 69 3240
[25] Arcos D H and Kunchur M N 2005 Phys. Rev. B 71 184516