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Two-band effect in superconducting parameters and their anisotropies of MgB_2 single crystals

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MgB_2 단결정의 초전도 상수와 그 이방성에 나타난 두 개의 띠의 영향

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Abstract

We have studied superconducting parameters of MgB_2 single crystals from reversible magnetization measurements with the magnetic field both parallel and perpendicular to the *c*-axis of the crystals. The temperature dependence of the London penetration depth, $\lambda_{ab}^{-2}(T)$, obtained from the Hao-Clem analysis on reversible magnetization, shows a clear discrepancy from single-band theories. It is also found that the anisotropies of the London penetration depth, γ_λ, slowly increases with temperature while the anisotropy of the upper critical field, γ_H, decreases with temperature. These behaviors are in sharp contrast with the behavior of superconductors with a single band. The temperature dependence of λ_{ab}^{-2}, and the opposite temperature dependences of γ_λ and γ_H can be well explained with the theory of the two-band superconductivity.

Keywords : MgB_2, Two-band superconductor, Magnetization, Anisotropy, Upper critical field, Penetration depth

1. Introduction

The recent discovery of superconductivity in MgB_2 [1] has attracted great attention from the scientific community. Besides rather high transition temperature (T_c) of 39 K in such a simple compound, one factor that makes MgB_2 more interesting and unique is its multi-band property. Band-structure calculations have demonstrated that the Fermi surface consist of two sets of disconnected bands: quasi-two-dimensional (2D) σ bands and three-dimensional (3D) π bands [2].

The superconducting properties of the two sets of

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bands are quite different due to the orthogonality of the σ and the π bands. The superconducting gap have been calculated and have been observed to be 5.5–8 meV on the strongly superconducting σ bands and to be 1.5–3.5 meV on the weakly superconducting π bands [3]. The two-gap nature has been verified by a numerous experiments [4-7].

The two-gap nature was revealed to influence superconducting properties of this material significantly. For example, the anisotropy of the upper critical field ($\gamma_H \equiv H_{c2}^{ab}/H_{c2}^{c}$) was experimentally found to have a strong temperature dependence [8, 9]. This is totally unexpected according to the one-gap Ginzburg-Landau theory, in which the anisotropy defined as $\gamma \equiv \gamma_\lambda = \gamma_H$ should be constant. Therefore, the temperature dependence of γ_H is thought to result from the interplay of two bands. According to the detailed theoretical studies, at low temperatures, the large gap from the σ bands dominates γ_H while the smaller gap from the π bands becomes important in determining γ_H at high temperatures, resulting in decrease of γ_H [10, 11].

Another consequence of the multi-band nature of MgB_2 is that the anisotropy of the penetration depth (γ_λ) may no longer be described by a single parameter. In MgB_2, since the penetration depth depends on the total number of charge carriers from both the σ band and the π band, while H_{c2} is mainly determined by the σ band, γ_λ is not necessarily the same as γ_H [12, 13]. According to Kogan's calculation [13], γ_λ is isotropic at low temperatures and increases to 2.5 near T_c. This behavior was verified qualitatively when an estimate of γ_λ in small-angle neutron-scattering (SANS) measurements on MgB_2 polycrystals [14] and single crystals [15] revealed an isotropic γ_λ over limited ranges of temperature and the field, but not quantitatively.

In this paper, we investigated the temperature dependence of the upper critical field, the penetration depth, and their anisotropies, γ_H and γ_λ , of MgB_2 single crystals by measuring reversible magnetization for $H \parallel c$ and $H \parallel ab$. The reversible magnetization was analyzed by using the Hao-Clem model for $H \parallel c$ and by using the London model for $H \parallel ab$. The values of $\gamma_\lambda(T)$ obtained within a limited temperature range were supplemented by the anisotropy of the lower critical field ($\gamma_{H_{c1}}$) from M-H loops. We observed that γ_λ and γ_H revealed an opposite temperature dependence; γ_λ increased with temperature while γ_H decreased with temperature. Together with the temperature dependence of λ_{ab}^{-2} , these results provide a strong experimental support for the two-band superconductivity of MgB_2.

2. Experiments

Single crystals were grown using a high pressure technique, which is explained in detail in previous reports [16, 17]. Two sets of single crystals were investigated using magnetization measurements. In the first set, 10 hexagonal-shaped single crystals, with typical dimensions of 200 × 100 × 25 μm^3 were collected on a substrate with their *c* axis perpendicular to the substrate surface. In the second set, a flat but not hexagonal-shaped single crystal with dimensions of 800 × 300 × 60 μm^3 was mounted with its *c* axis perpendicular to the substrate. These two sets of crystals did not show any significant difference upon the magnetization analysis reported below. Therefore, in the following we discuss the data obtained from the second set.

Magnetization measurements were carried out by using a superconducting quantum interference device magnetometer (Quantum Design, MPMS-XL) with the magnetic fields up to 5 T.

3. Results and Discussion

Figure 1 shows the temperature dependence of the reversible magnetization, $4\pi M(T)$, measured in the

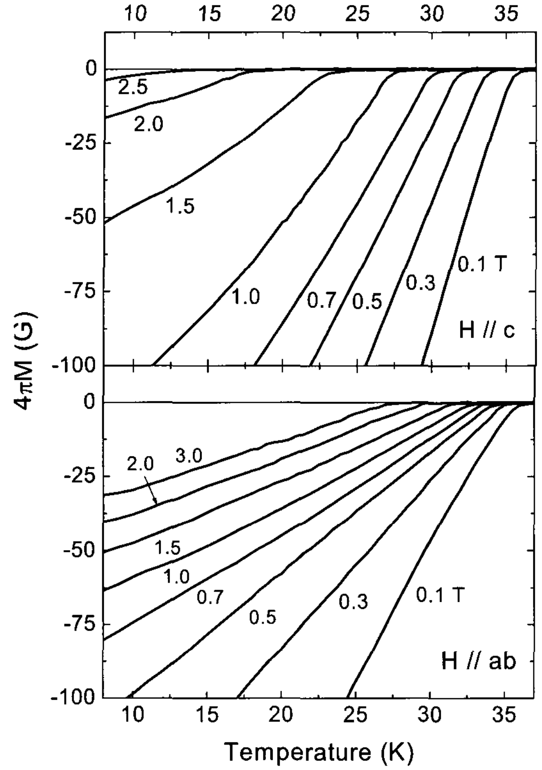

Fig. 1. Temperature dependence of $4\pi M(T)$ for $H \parallel c$ and $H \parallel ab$.

field range 0.1 T $\le H \le$ 2.5 T for $H \parallel c$ and in the range 0.5 T $\le H \le$ 3 T for $H \parallel ab$, respectively. The irreversible fielsd $H_{irr}(T)$, where the ZFC and FC magnetizations start to diverge, were determined by using a criterion of $M_{FC}/M_{ZFC} = 0.95$ from the $4\pi M(T)$ curves obtained at different fields. The magnetization curves shifted to lower temperatures as the fields were increased in both field directions. Observed systematic shift of the magnetization is a typical mean field behavior in conventional superconductors, but it is quite different from the high-T_c superconductors. To analyze reversible magnetization data for $H \parallel c$, we used the Hao-Clem model [18], which considers not only the electromagnetic energy outside of the vortex cores, but also the free energy changes arising from the cores, since the applied fields are comparable with $H_{c2}^{c}(0)$. Experimental $4\pi M$ vs. H data obtained at each temperature were fitted to the Hao-Clem model with $H_c(T)$ and κ as parameters. If the value of κ is appropriately chosen, the values of $H_c(T)$ should be the same for different fields, and the optimum value of κ is obtained to give the smallest deviation of $H_c(T)$.

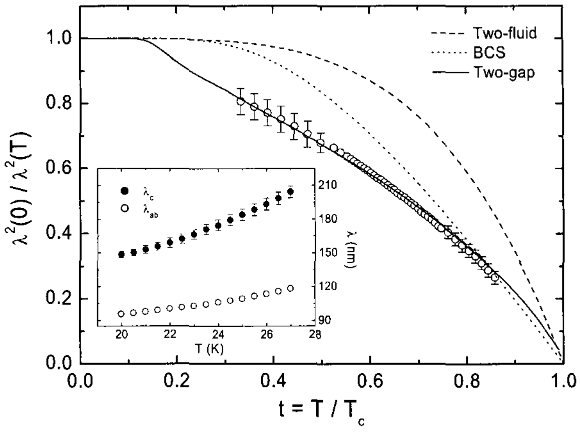

Fig. 2. Temperature dependence of $\lambda_{ab}^2(0)/\lambda_{ab}^2(T)$ calculated from the Hao-Clem model. The solid line represents the two-gap model. The theoretical curves by the two-fluid model (dashed) and the BCS model (dotted) are also drawn. Inset: temperature dependence of the in-plane (λ_{ab}) and the out-of-plane penetration depth (λ_c).

Employing the values of H_c (T) and κ_{ab} obtained from the Hao-Clem model, we calculated the magnetic penetration depth, $\lambda_{ab}(T)$, using the relation $\lambda_{ab}(T) = \left[\kappa\phi_0 / 2\sqrt{2}\pi H_c(T)\right]^{1/2}$. Figure 2 shows the temperature dependence of $\lambda_{ab}^2(0)/\lambda_{ab}^2(T)$, which represents the normalized superfluid density of MgB_2.

For a system like MgB_2 which is found to have two different bands, the existence of two gaps should be reflected in $\lambda_{ab}(T)$ in the following way; the large gap has a significant impact on $\lambda_{ab}(T)$ at higher temperatures, while the temperature dependence of λ_{ab} for $T << T_c$ would be dominated by the small gap. Therefore, we tried to apply the two-gap model [18] to describe our $\lambda_{ab}(T)$ data. Here, the theoretical $\lambda_{ab}(T)$ was calculated using

$$\lambda_{ab}^{-2}(T)/\lambda_{ab}^{-2}(0) = 1 - 2\left[c_1 \int_{\Delta_s}^{\infty} \left(-\frac{\partial f}{\partial E} \right) D_s(E) dE + \right. \\ \left. + (1 - c_1) \int_{\Delta_L}^{\infty} \left(-\frac{\partial f}{\partial E} \right) D_L(E) dE \right] \quad (1)$$

where c_1 is a parameter determines the contribution of the small gap to the total superfluid density, Δ_s is the small gap, Δ_L is the large gap, f is the Fermi-Dirac distribution function, and $D_{S(L)}(E) = E / \left[E^2 - \Delta_{S(L)}{}^2 \right]^{1/2}$. The two-gap model using Eq. (1) describes our $\lambda_{ab}{}^2(0)/\lambda_{ab}{}^2(T)$ relatively well over the whole temperature region as plotted as a solid line. A little plateau and then a downward curvature up to ~ 0.5 T/T_c reflect higher contribution of small gap to the superfluid density. Our data show obvious discrepancies from both the two-fluid model $\lambda^2(0)/\lambda^2(T) = 1 - (T/T_c)^4$ and a single-gap BCS theory as also depicted in Fig. 2.

In order to investigate the anisotropy of λ, we calculated $\lambda_c(T)$ by analyzing the reversible magnetization data for $H \parallel ab$. Contrary to $H \parallel c$, the simpler London model can be utilized for $H \parallel ab$ because $H_{c2}{}^{ab}(0)$ is much larger than the applied magnetic fields. According to Kogan [21], the free energy of a uniaxial superconductor for which the anisotropy of the upper critical field, $\gamma_H = H_{c2}{}^{ab} / H_{c2}{}^{c}$, is different from the anisotropy of the penetration depth, $\gamma_\lambda = \lambda_c / \lambda_{ab}$, is given by

$$F = \frac{\phi_0 B \Theta_\lambda}{32\pi^2 \lambda_{ab}^2} \ln\left(\frac{2\sqrt{3}\gamma_H^{-2/3} \phi_0 \Theta_\lambda}{\xi^2 B \left(\Theta_\lambda + \Theta_H \right)^2} \right) \quad (2)$$

where $\Theta_{\lambda,H}(\theta) = \left(\sqrt{\sin^2\theta + \gamma_{\lambda,H}^2 \cos^2\theta} \right) / \gamma_{\lambda,H}$, and θ is the angle between the c-axis and the induction B. From the relation $M = -\partial F / \partial H$, magnetization can be calculated. For $H \parallel ab$, the magnetization gives

$$\frac{\partial M}{\partial \ln H} = \frac{\phi_0}{32\pi^2 \lambda_{ab} \lambda_c} \quad (3)$$

if it is assumed that the logarithmic term in the magnetization does not change drastically. When this equation is combined with $\lambda_{ab}(T)$, $\lambda_c(T)$ can be determined, and the result is shown in the inset of Fig. 2. For comparison, $\lambda_{ab}(T)$ is included in the same figure. As can be seen in Fig. 2, the difference between $\lambda_{ab}(T)$ and $\lambda_c(T)$ gradually increases as the temperature is increased, which implies that γ_λ increases as temperature is increased. According to the theoretical predictions [12, 13], γ_λ is almost isotropic at low temperatures and increases to the same value as γ_H near T_c.

To further investigate the anisotropy of λ at low temperatures, we directly measured the lower critical fields H_{c1} by using *M-H* loops. In the *M-H* loops, H_{c1} was selected from the first penetrating fields at which a deviation from Meissner shielding occurs and the demagnetization effect was carefully considered in calculating H_{c1}. Figure 3 displays the temperature dependence of H_{c1} in both field directions. Contrary to the H_{c2}, H_{c1} is almost isotropic. As a result, the anisotropy of H_{c1} defined as $\gamma_{H_{c1}} = H_{c1}{}^{c} / H_{c1}{}^{ab}$ is nearly temperature independent except at temperatures near T_c as shown in the inset of Fig. 3.

To compare the temperature dependences of γ_λ and γ_H, we summarize all the quantities in Fig. 4.

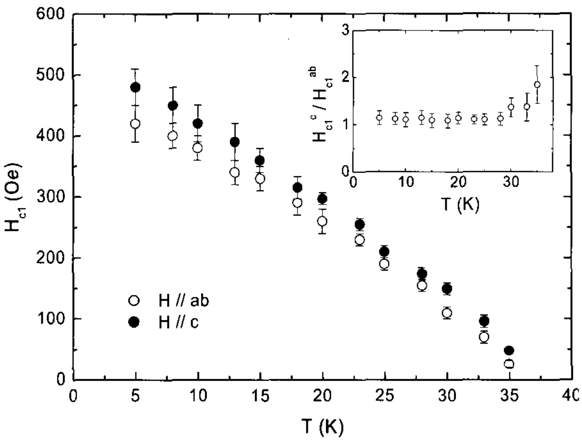

Fig. 3. Temperature dependence of H_{c1} for $H \parallel c$ and $H \parallel ab$ as obtained from the *M-H* loops. Inset: temperature dependence of the anisotropy of H_{c1}.

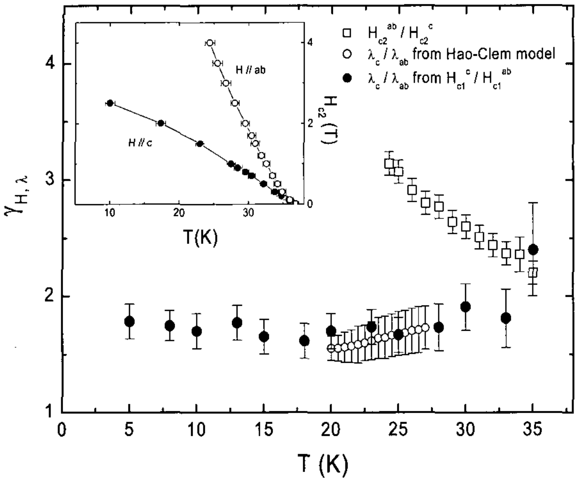

Fig. 4. Temperature dependence of the anisotropy of λ (γ_λ) that was obtained from reversible magnetization and direct measurement of H_{c1}, and the anisotropy of H_{c2} (γ_H). Inset: temperature dependence of H_{c2}

The values of γ_H were deduced from the values of $H_{c2}(T)$, which were determined from the onset of the diamagnetic response at $4\pi M(H_{c2})=0$ as shown in the inset of Fig. 4. Since $\gamma_\lambda(T)$ obtained from the reversible magnetization was in the limited temperature range, we added $\gamma_\lambda(T)$ obtained from $\gamma_{H_{c1}}$. When $\gamma_{H_{c1}}$ is converted into γ_λ using $H_{c2}(T)$, the values become very consistent with those deduced from the reversible magnetization. In contrast to the behavior of γ_H which decreases with temperature and approaches 2, γ_λ increases with temperature and shows a tendency to converge to the value of γ_H at temperatures near T_c. According to the theoretical predictions [10, 11], the decrease in γ_H is due to different contributions from the σ and the π bands at different temperatures. On the contrary, since the penetration depth depends solely on the carrier density of the π band at low temperatures, γ_λ is almost isotropic and increases only weakly with temperature due to the effect of two different bands [11, 12]. Eventually, the values of γ_H and γ_λ approach the same value at $T=T_c$, and as for one-gap superconductors, a common value of the anisotropy can be determined. This overall behavior is clearly shown in Fig. 4 and our data directly support the theoretical predictions.

4. Conclusion

Temperature dependence of the upper critical field, the penetration depth, and their anisotropies, γ_H and γ_λ, of MgB$_2$ single crystals was investigated by measuring reversible magnetization for $H \parallel c$ and $H \parallel ab$. The reversible magnetization was analyzed by using the Hao-Clem model for $H \parallel c$ and by using the modified London model for $H \parallel ab$. We have shown that both γ_λ's obtained from the reversible magnetization and from the lower critical fields slowly increase with temperature, while γ_H reveals an opposite behavior. All three anisotropies approach a common value of 2 at $T \sim T_c$. The temperature dependence of the anisotropies as well as the temperature dependence of penetration depth agree well with the theoretical predictions based on the two-band superconductivity.

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