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The Anisotropy of the London Penetration Depth and the Upper Critical Field in C-doped MgB_2 Single Crystals from Reversible Magnetization

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Abstract

We have studied the anisotropy of the London penetration depth of carbon doped MgB_2 single crystals, which was obtained from reversible magnetization measurements with the magnetic field both parallel and perpendicular to the c-axis. Similar to the pure MgB_2, the anisotropy of the upper critical field γ_H decrease with temperature while the anisotropy of the London penetration depth γ_λ slowly increases with temperature. However, the temperature dependence of γ_H is drastically reduced and the value of γ_λ becomes nearly ~1 as C is introduced. These results indicate that C substitution increases impurity scattering mainly in the σ bands. The temperature dependence of the anisotropies agree well with the theoretical predictions with impurity scattering.

Keywords : C-doped MgB_2, reversible magnetization, upper critical field, penetration depth

1. Introduction

It is now well established that MgB_2 is a two-gap superconductor with two-band: quasi-two-dimensional σ bands and three-dimensional π bands [1-3]. One of the consequences of the two-band nature is the strong temperature dependence of the anisotropy of the upper critical field ($\gamma_H \equiv H_{c2}^{ab}/H_{c2}^{c}$) [4], which is in contrast to the single-gap Ginzburg-Landau theory. The strong temperature dependence of γ_H is thought to result from the interplay of two bands. Theoretical works have revealed that two different bands affect the behavior of γ_H such a way in which the anisotropic σ bands dominate in low temperature region while at temperatures near T_c, contribution from the isotropic π bands increases [5-7].

Another consequence of the multi-band nature of MgB_2 is that the anisotropy of the penetration depth (γ_λ), as well as the anisotropy of H_{c2}, may no longer be described by a single parameter [7-10]. In MgB_2, γ_λ is not necessarily the same as γ_H 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. According to Kogan's calculation based on weak-coupling theory [8], γ_λ is isotropic at low temperature and increases to 2.5 near T_c. That behavior was confirmed by the first-principle calculations for the electronic structure and the

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electron-phonon interaction [11], which showed that the effect of impurity scattering changed the exact value of γ_λ. The above anomalous behaviors of $\gamma_H(T)$ and $\gamma_\lambda(T)$ for MgB_2 single crystals were confirmed by magnetization measurements [12, 13].

When impurity scattering increases, the behavior of H_{c2} is modified. According to the dirty-limit two-gap theory, the shape of the $H_{c2}(T)$ curve depends on the diffusivities of the σ and the π bands. $H_{c2}(0)$ is determined by a minimum diffusivity(dirtier bands) while $H_{c2}(T)$ is controlled by a maximum diffusivity (cleaner bands) at $T \approx T_c$. When the σ bands are dirtier, an upward curvature should appear near T_c, and γ_H should decrease with temperature. In contrast, when the π bands are dirtier, a huge increase in $H_{c2}(T)$ should appear at low temperatures without an upward curvature near T_c, and γ_H should increase with temperature.

In this paper, we investigated the effect of C doping on the temperature dependence of the anisotropies of the penetration depth γ_λ, and the upper critical field γ_H of MgB_2 single crystals by measuring reversible magnetization for both $H \parallel c$ and $H \parallel ab$. The reversible magnetization was analyzed by using the Hao-Clem model and the London model for $H \parallel c$ and $H \parallel ab$, respectively. γ_H and γ_λ were found to show an opposite temperature dependence as shown in pure MgB_2; γ_H decreases with temperature while γ_λ gradually increases with temperature. However, temperature dependence of γ_H is greatly reduced and γ_λ becomes more isotropic as C is introduced. These results agree well with the dirty-limit two-band theory.

2. Experiments

$Mg(B_{0.95}C_{0.05})_2$ single crystals were grown using a high pressure technique, which is explained in detail in previous reports [14, 15]. Concentration of C was determined by using both electron probe X-ray microanalysis and electron dispersive X-ray spectroscopy. 12 relatively hexagonal-shaped single crystals with typical dimensions of 200 × 100 × 25 μm^3 were collected on a substrate with their *c* axis aligned perpendicular to the substrate surface. The values of the transition temperature T_c and the transition width ΔT_c determined from the low-field magnetization were 26 K and 2.4 K, respectively.

The measurement of the reversible and the irreversible magnetization were carried out by using a superconducting quantum interference device magnetometer (Quantum Design, MPMS-XL) with the fields up to 5 T applied parallel and perpendicular to the *c* axis of the sample.

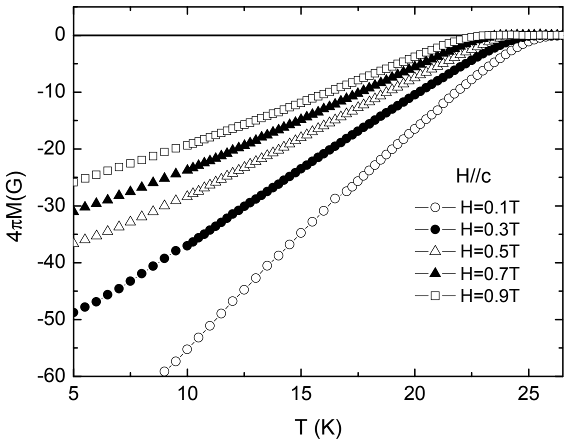

Fig. 1. Temperature dependence of the reversible magnetization, $4\pi M(T)$, of C-doped MgB_2 single crystals for various field ranges of $H \parallel c$ (data for only low fields are shown).

3. Results and Discussion

Figure 1 shows, as an example, the temperature dependence of the reversible magnetization, $4\pi M(T)$, measured in the field range $0.1\ \mathrm{T} \le H \le 0.9$ T with $H \parallel c$. The reversible region was determined in the temperature ranges at which the criterion $M_{FC}/M_{ZFC} \ge 0.95$ holds [16]. The reversible curves shifted to lower temperatures as the field was increased.

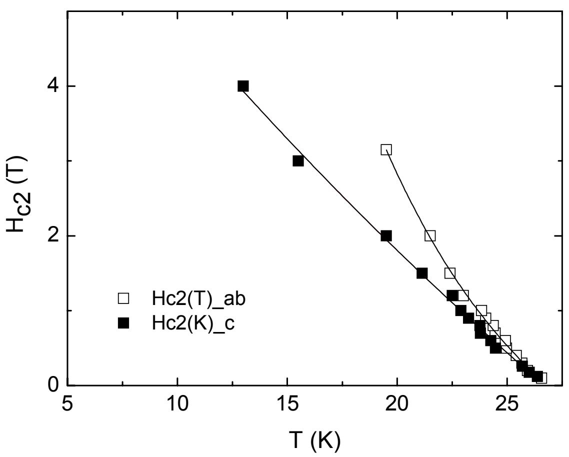

Fig. 2. Temperature dependence of the upper critical field for $H \parallel c$ and $H \parallel ab$ determined from the $4\pi M(T)$ curves. Solid lines are guide for eyes.

The temperature dependence of the upper critical fields of C-doped MgB_2 for $H \parallel c$ (H_{c2}^{c}) and for $H \parallel ab$ (H_{c2}^{ab}) defined as the onset of the diamagnetic response at $4\pi M(H_{c2}) = 0$ were presented in Fig. 2. Temperature dependence of H_{c2}^{c} and H_{c2}^{ab} were found to be similar to those of pure MgB_2; H_{c2}^{c} is almost linear and H_{c2}^{ab} presents a positive curvature near T_c, leading to a decrease of the anisotropy of $H_{c2}(T)$ as the temperature approaches to T_c. While pure MgB_2 single crystals show a linear decrease in $H_{c2}^{c}(T)$ near T_c, a close inspection reveals an upward curvature with C doping, which is consistent with the dirty-limit two-gap theory.

To analyze reversible magnetization data for $H \parallel c$, we used the Hao-Clem model [17]. Since the applied fields are comparable with $H_{c2}^{c}(0)$, only the Hao-Clem model, which considers not only the electromagnetic energy outside of the vortex cores, but also the free energy changes arising from the cores, can permits a reliable description of the reversible magnetization in the *entire* mixed state. However, for $H \parallel ab$, the simpler London model can be utilized because $H_{c2}^{ab}(0)$ is much larger than the applied magnetic fields, therefore the contribution of the core energy may not be as significant as it is for $H \parallel c$.

According to Kogan [18], 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

$$F = \frac{\phi_0 B \Theta_\lambda}{32\pi^2 \lambda_{ab}^2} \ln\left(\frac{2\sqrt{3}\gamma_H^{-2/3}\phi_0 \Theta_\lambda}{\xi^2 B \left(\Theta_\lambda + \Theta_H\right)^2} \right) \qquad (1)$$

where $\Theta_{\lambda,H}(\theta) = \left(\sqrt{\sin^2\theta + \gamma_{\lambda,H}^2 \cos^2\theta}\right) / \gamma_{\lambda,H}$, ϕ_0 is the flux quantum, λ_{ab} is the in-plane penetration depth, and θ is the angle between the c-axis and the induction B. For $H \parallel c$ and $H \parallel ab$, the free energy becomes

$$F(\theta = 0) = \frac{\phi_0 B}{32\pi^2 \lambda_{ab}^2} \ln\left(\frac{\sqrt{3}\gamma_H^{-2/3}\phi_0}{2\xi^2 B} \right)$$

and

$$F(\theta = \frac{\pi}{2}) = \frac{\phi_0 B}{32\pi^2 \lambda_{ab}\lambda_c} \ln\left(\frac{2\sqrt{3}\gamma_H^{-2/3}\phi_0 \gamma_\lambda^{-1}}{\xi^2 B \left(\gamma_\lambda^{-1} + \gamma_H^{-1}\right)^2} \right) \qquad (2)$$

respectively. These results reduce to that of the original London model when the various anisotropies are equal to each other. With these equations, we calculated both the in-plane and the out-of-plane penetration depth.

From the relation $M = -\partial F / \partial H$, the magnetization can be calculated. For $H \parallel ab$, the magnetization gives

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

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. Figure 3 shows $\lambda_{ab}(T)$ and $\lambda_c(T)$

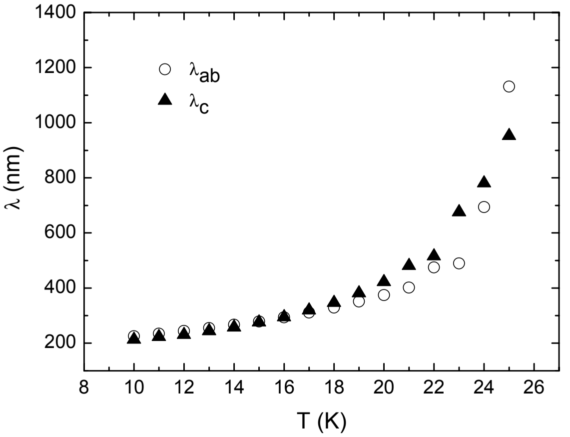

Fig. 3. Temperature dependence of the in-plane[$\lambda_{ab}(T)$] and out-of-plane[$\lambda_c(T)$] penetration depth. $\lambda_c(T)$ was calculated using the London model, and $\lambda_{ab}(T)$ was calculated using the Hao-Clem model. λ_c and λ_{ab} are almost isotropic.

calculated from the Hao-Clem model and the London model, respectively. A notable feature is that λ_{ab} and λ_c are nearly isotropic in low temperature region and start to diverge as the temperature is increased, which implies that the anisotropy of λ is closed to ~1 at low temperatures and slowly increases with the temperature. This tendency agrees well with the theory with two gaps.

We compared the temperature dependence of γ_λ and γ_H in Fig. 4. The values of γ_H were deduced from the values of $H_{c2}(T)$ shown in Fig. 2. Since $\gamma_H(T)$ obtained from the reversible magnetization was in the limited temperature range, we added $\gamma_H(T)$ obtained from the transport measurements. The temperature dependence of γ_H and γ_λ are observed to be similar to those of pure MgB_2; γ_H decreases with temperature, and γ_λ is nearly temperature independent and converges to the value of γ_H near T_c. Two differences are observed in C-doped MgB_2. First, the temperature dependence of γ_H is drastically reduced, which reflects that the anisotropic σ bands become more isotropic with C-doping. Second, the value of γ_λ decreases to ~1 over the temperature region measured. According to

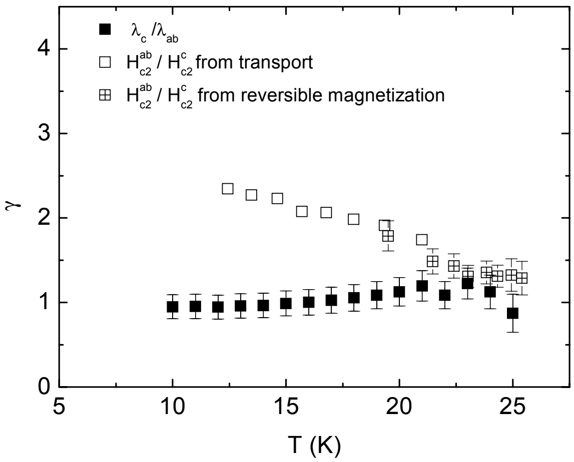

Fig. 4. Temperature dependence of the anisotropy of λ(γ_λ) and the anisotropy of H_{c2} that were obtained from reversible magnetization and transport measurements.

the theoretical calculation [11], impurity scattering could change the exact value of γ_λ and impurities in the π band drastically enhance γ_λ. Combined with the reduced temperature dependence of γ_H, this result provides an experimental support for relative increase of impurity scattering in the σ bands than in the π bands due to C-doping.

4. Summary

We have investigated the anisotropies of the penetration depth and the upper critical field of 10% C-doped MgB_2 single crystals, obtained from the reversible magnetization for magnetic fields applied both perpendicular and parallel to the *c*-axis of the crystals. The reversible magnetization was analyzed using the Hao-Clem model for $H \parallel c$ and using the modified London model for $H \parallel ab$. The anisotropy of the upper critical field decreases with temperature while the anisotropy of the penetration depth remains nearly constant with temperature and two anisotropies converge at a value of 1 near T_c. The reduced temperature dependence of γ_H and the smaller value of γ_λ, compared to those in pure MgB_2, indicate that C substitution enhances impurity scattering mainly in the σ bands over the π bands. The temperature dependence of the anisotropies agrees well with the theoretical predictions with impurity scattering.

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