Intrinsic pinning effect and its enhancement by Al substitution in MgB$_2$ single crystals

T Nojima$^1$, M Chotoku$^1$, K Takahashi$^1$, H-G Lee$^2$ and S-I Lee$^2$

$^1$Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
$^2$Department of Physics, Sogang University, Seoul 121-742, Republic of Korea

E-mail: nojima@imr.tohoku.ac.jp

Abstract. Anisotropic behavior of pinning properties in MgB$_2$ and Mg$_{0.88}$Al$_{0.12}$B$_2$ single crystals has been studied using torque $\tau = (M \times H)$ magnetometry as a function of magnetic field $H$ and angle $\theta$ between the $H$ direction and the $c$ axis. When the direction of $H$ is apart from the $ab$ plane, we do not observe remarkable pinning effect. On the other hand, as $\theta$ approaches 90$^\circ$, the hysteresis in $\tau(H)$ and $\tau(\theta)$ curve suddenly increases and shows the sharp maximum at $\theta = 90^\circ$, which remind us of the so-called intrinsic pinning. However, it is found that this pinning effect is irrelevant to the change of anisotropy $\gamma$ with temperature in MgB$_2$, and is strongly enhanced in Mg$_{0.88}$Al$_{0.12}$B$_2$ in spite of the decrease of $\gamma$ with Al substitution. These results may indicate another plane-like pinning mechanism, which is extrinsic and become effective by Al substitution.

1. Introduction

The discovery of the superconductivity in MgB$_2$ with a transition temperature $T_c \sim 39$ K [1] has attracted a lot of researches to understand its superconducting mechanism and phenomenology. From the viewpoint of vortex matter physics, the layered crystal structure in MgB$_2$ is one of the features to be noted. The theoretical calculation [2, 3] suggested that the orbitals arising from the boron network plane form the conduction bands causing the superconductivity. It is natural to consider that there exits a periodic modulation of the order parameter along the $c$ axis with the maximum at the boron layers. From this fact, one may expect the strong layer pinning, which is known as intrinsic pinning in high-$T_c$ cuprates [4], also in MgB$_2$ for vortices parallel to the boron plane. Indeed, the sharp hysteresis peak at a filed $H_{\parallel ab}$, implying the existence of layer pinning, is reported in some torque measurements [5, 6]. However it should be noted that in MgB$_2$ the coherence length along the $c$ axis $\xi_c \sim 2$ nm [7], which corresponds to the vortex core radius, is 6 times longer than the $c$ axis lattice constant of 0.35 nm even at low temperatures $T$. It is not so clear that in this situation, the intrinsic pinning works effectively.

Since the intrinsic pinning effect has a close relation with electronic anisotropy $\gamma$, the study of pinning anisotropy with respect to $\gamma$ will give an crucial information to the question remaining to be solved. It is reported that in MgB$_2$, $\gamma$ determined as $H_{c2}^{/\parallel ab}/H_{c2}^{/\parallel c}$ decreases with increasing $T$ due to the two-gap effect [6] with $H_{c2}^{/\parallel ab}$ and $H_{c2}^{/\parallel c}$ the upper critical field parallel to the $ab$ plane and the $c$ axis, respectively. This two-gap nature may be useful to study the relation between the intrinsic pinning and the anisotropy near $H_{c2}$ if the pinning effect operates. The chemical substitution may give another way for this subject. According to the previous reports, $H_{c2}^{/\parallel c}$ changes only slightly due to Al substitution for Mg sites, whereas it results in the remarkable decrease of $H_{c2}^{/\parallel ab}$. The behaviour can be explained...
with a clean limit model, in which the disorder due to Al substitution does not influence $H_{c2}/c$, or the scattering of conduction carries, so much [8, 9]. The decrease of $\gamma$ only due to the increase of $\xi_c$ may be a good advantage for the comparative study of the intrinsic pinning.

In this work, the dependence of the anisotropic pinning properties on temperature and Al substitution was examined by measuring the magnetic torque of MgB$_2$ and Mg$_{0.88}$Al$_{0.12}$B$_2$ single crystals. We will discuss the origin of the layer pinning observed in angular dependence.

2. Experimental

Single crystals of MgB$_2$ and Mg$_{0.88}$Al$_{0.12}$B$_2$ were grown by a high pressure synthesis method [10]. For the measurements, we selected the crystals with the typical size of $\sim 100 \times 100 \times 50 \mu m^3$ for MgB$_2$ and $\sim 50 \times 50 \times 30 \mu m^3$ for Mg$_{0.88}$Al$_{0.12}$B$_2$. They show the superconducting transition with $T_c = 37.0$ K and 30.6 K, respectively, which are consistent with the values reported for polycrystalline samples [8, 9].

The magnetic torque $\tau$ was measured using a piezo-resistive cantilever developed commercially for the AFM [11] as a function of $H$ and the angle $\theta$ between the $c$ axis and the direction of $H$. In this method, the magnetic torque $\tau = |M \times H|$ with $M$ the magnetization occurring on the sample attached on the sensitive cantilever can be detected by the piezo resistance deposited on it.

3. Results and discussions

Figure 1 shows the typical $\tau(\theta)$ curve for MgB$_2$ at $T = 4.2$ K and $H = 1.2$ T, which is normalized by $\tau_{eq \text{max}}$, the maximum in $\tau_{eq}(\theta) = (\tau_{up}(\theta)+\tau_{down}(\theta))/2$ with $\tau_{up}(\theta)$ and $\tau_{down}(\theta)$ denoting $\tau(\theta)$ in the $\theta$ increasing and decreasing processes, respectively. As a whole, the hysteresis in $\tau(\theta)$ is very small, indicating that the background pinning in this sample is very weak. However, looking at the data carefully, we note that a small but sharp hysteresis peak is observed within the region of $\theta = 90\pm1^\circ$. This lock-in-like peak in $\tau(\theta)$ have been reported by some groups using the single crystals [5,6], although the peak size is different from sample to sample. In the inset of figure 1, $\tau(H)/\tau_{eq \text{max}}$ curves at various $\theta$ are plotted as a function of $H/H_{c2}$ (In this figure $\tau_{eq \text{max}}$ denotes the maximum in $\tau_{eq}(H)$ which is the average between field-up and field-down process). The similar trend is also obtained in $\tau(H)$ with $\theta$ fixed. When the $H$ direction is apart from the $ab$ plane, the hysteresis in $\tau(H)$ is very small. On the other hand, at $\theta = 89.5^\circ$ a large hysteresis emerges. These results may remind us of the intrinsic pinning effect.

In order to examine the angular dependence with the quantity proportional to critical current

![Figure 1](image-url)
density, the magnetization hysteresis $\Delta M$ is estimated using the relation [12],

$$M(H) = A \frac{\tau(H)(\sin^2 \theta + \gamma^2 \cos^2 \theta)^{1/2}}{H \sin 2\theta},$$  \hspace{1cm} (1)$$

with $A$ an angular-independent constant. The anisotropy $\gamma$ was derived by fitting $H_{c2}(\theta)$ using the GL effective mass model $H_{c2}(0^\circ)/(\cos^2 \theta + (1/\gamma)^2 \sin^2 \theta)^{1/2}$, as shown in the inset of figure 2. We note that the relation of equation (1) is suggested for the thermal equilibrium condition. But in case that the pinning effect is not so strong, it can be a good approximation. In figure 2, $\Delta M$ at $H = 0.7H_{c2}$ is plotted as a function of $\theta$ for $T = 4.2$ K and 30 K. The sharp increase of $\Delta M$ above $\theta = 89^\circ$ is indicative of the lock-in-like pinning and is consistent with the data in figure 1. However, comparing the data of $\Delta M(\theta)$ for two different temperatures, we note that the degree of anisotropy in the pinning property is almost the same in spite of the big difference in $\gamma$. As $\xi_c$ usually increases with increasing temperature, the decrease of $\gamma$ at 30 K should give an additional effect on the extension of vortex core along the $c$ axis, which weakens the intrinsic pinning. The layer pinning observed may come from different origin.

The effect of Al substitution on $\tau(\theta)$ is shown in figure 3. The hysteresis is not so large at $H$ directions highly tilted from the $ab$ plane, indicating the aluminium atoms or the sites around them do not act as effective pinning centers for vortices crossing the boron plane. On the other hand, when $\theta$ approaches the direction of the $ab$ plane, it is found that the hysteresis in $\tau(\theta)$ suddenly increases and shows the sharp peak at $\theta = 90^\circ$, which is much stronger than that for the pure MgB$_2$. As reported for polycrystalline sample, the anisotropy decrease with Al substitution [9], which should give the negative effect on the intrinsic pinning. Indeed, in our Al substituted sample $\gamma$ estimated with $H_{c2}(88^\circ)/H_{c2}(10^\circ)$ is 3.4 at $T = 4.2$ K. Therefore, the origin of strong layer pinning in the substituted samples is not intrinsic pinning.

All the samples measured in this work show the layer pinning effect, the development of which seems to deviate from the concept of the intrinsic pinning. In addition, the strength of it may depend on sample by comparing our results with reported ones. Although our results do not necessarily indicate the absence of the intrinsic pinning in MgB$_2$, it is possible to argue that the effect of the intrinsic pinning is weak as expected and there is an additional contribution of extrinsic pinning to the lock-in-like pinning observed, which is enhanced by Al substitution. The origin of the strong layer pinning is now open question. Considering the long $\xi_c$, the plane-like non-superconducting islands may be distributed in the crystal.

![Figure 2. Angular dependence of magnetization hysteresis $\Delta M$ for $T = 4.2$ K and 30 K$^\circ$. The inset shows the angular dependence of $H_{c2}$ at the same temperatures. Solid lines are fits by the GL effective mass model.](image-url)
4. Conclusion

Using torque magnetometry we observed the sharp hysteresis peak at the field direction parallel to the boron layer for pure and Al doped MgB$_2$ single crystals, which reminds us of the intrinsic pinning. However, the layer pinning effect is found to be independent of the electronic anisotropy. We suggest the contribution of extrinsic mechanism to the layer pinning.

Acknowledgements

We thank S. Nakamura for useful discussions, and Y. Watanabe, S. Tanno, K. Hosokura, H. Miura and A. Ogata for the low temperature apparatus. The measurements at high fields were performed at High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University. This work is supported by Grant-in-Aid for Scientific Research (20540343) from JSPS.

References

[1] Nagamatsu J, Nakagawa N, Muranaka T, Zenitani Y and Akimitsu J 2001 Nature 410 63
[2] Kortus J, Mazin I I, Belashchenko K D, Antropov V P and Boyer L L 2001 Phys. Rev Lett. 86 4656
[3] Choi H J, Roundy D, Sun H, Cohen M L and Louie S G 2002 Nature 418 758
[4] Tachiki M and Takahashi S 1989 Solid State Commun. 72 1083
[5] Takahashi K, Atsumi T, Yamamoto N, Xu M, Kitazawa H and Ishida T 2002 Phys. Rev. B 66 012501
[6] Angst M, Puzniak R, Wisniewski A, Jun J, Kazakov S M, Karpinski J, Roos J and Keller H 2002 Phys. Rev. Lett. 88 167004
[7] Zehetmayer M, Eisterer M, Jun J, Kazakov S M, Karpinski J and Weber H W 2004 Phys. Rev. B 70 214516
[8] Putti M, Ferdeghini C, Monni M, Pallecchi I, Tarantini C, Manfrinetti P, Palenzona A, Daghero D, Gonnelli R S and Stepamov V A 2005 Phys. Rev. B 71 144505
[9] Angst M, Bud’ko S L, Wilke R H T and Canfield P C 2005 Phys. Rev. B 71 144512
[10] Kim H J, Lee H S, Kang B, Chowdhury P, Kim K H, Park M S and Lee S I 2005 Phys. Rev. B 71 174516
[11] Ohmichi E and Osada T 2002 Rev. Sci. Instr. 73 3022
[12] Farrell D E, Bonham S, Foster J, Chang Y C, Jiang P Z, Vandervoort K G, Lam D J and Kogan V G 1989 Phys. Rev. Lett. 63 782