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# Domination of glassy and fluctuation behavior over thermal activation in vortex state in $MgB_2$ thin film

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# $MgB_2$ 박막에서의 열적 활성화에 비해 두드러진 볼텍스 유리화 및 열적 요동현상의 연구

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**Abstract**

We have investigated the mixed-state magnetoresistance of high quality c-axis-oriented $MgB_2$ thin film for magnetic field from 0.5 T to 5.0 T, applied normal to ab-plane. The temperature dependence of magnetoresistance was well described by vortex glass and fluctuation theories for different temperature regimes. We observed glassy exponent of $\nu(z-1) \sim 3$ and upper critical field of $H_{c2}(0) \sim 35$ T, which is consistent with previous data obtained from direct $H_{c2}(0)$ measurements. Interestingly, the thermally activated flux flow region was observed to be very narrow, suggesting that the pinning strength of this compound is very strong. This finding is closely related to the recent reports that the bulk pinning is dominant in $MgB_2$ and the critical current density of $MgB_2$ thin film is very high, comparable to that of cuprate superconductor. The present results further suggest that $MgB_2$ is beneficial to technical applications.

*Keywords*: $MgB_2$, thin film, magnetoresistance, vortex glass, thermal fluctuation

## I. Introduction

The reversible region in high-$T_c$ cuprate superconductors (HTS) is very large compared with that in conventional superconductors because of the large anisotropy ratio ($\gamma$), short coherence length ($\xi$) and high transition temperature of HTS. Due to these factors, HTS showed the complex vortex-phase diagram in the mixed state. However, the reversible properties have restricted the practical applications of HTS due to the flux-flow resistance[1]. As the vortices move, flux-flow resistance starts to occur and the transition width becomes broad.

Recently, $MgB_2$, which is discovered to be a superconductor with high $T_c \sim 40$ K has attracted great interests not only in basic scientific fields but also in practical applications[2]. On the technological point of view, this compound has a lot of potential. It is easily fabricated in the form of wires and cables and already the fabrication of Fe-clad $MgB_2$ tapes was demonstrated[3]. Also, $MgB_2$ is a good metal with a high charge carrier density in the normal state[4].

Moreover, negligible grain boundary effect[5] was observed in $MgB_2$ that is quite different from HTS. Therefore, high upper critical fields and critical current densities are the only requirement for direct applications of $MgB_2$. Nevertheless, these values are diversely scattered and strongly depend on the synthesis method. For the $MgB_2$ synthesized in the sealed Ta tube[6], $H_{c2}(0)$ is 12.5 T and $J_c(0)$ is around $10^5$ A/cm$^2$, which are lower than those of $Nb_3Sn$. For $MgB_2$ sintered in high temperature and high pressure[7,8], $H_{c2}(0)$ is up to 26.5 T but $J_c(0)$ is comparable to the samples of Ref. 6. On the contrary, for the c-axis-oriented high quality $MgB_2$ thin film[9,10], $H_{c2}(0)$ is 29 ~ 39 T and $J_c(0)$ is reported to be $10^7$ A/cm$^2$ at 15 K, suggesting that $MgB_2$ film is much more suitable for the applications under an intense magnetic field and a high current flow.

For the origin of high current density in c-axis-oriented $MgB_2$ film, vortex-glass phase is proposed[11] as in an untwined single crystal of YBCO after inducing a sufficiently high density of pinning centers. In HTS, however, a thermally activated flux-flow (TAFF) was observed in the wide temperature region[12], which is occupied most of the reversible part. Thus, the temperature for practical applications is limited to low temperature.

To investigate the TAFF behavior in vortex state and to elucidate the enhanced pinning properties in $MgB_2$ thin film, we have investigated the mixed-state magnetoresistance of high quality c-axis-oriented $MgB_2$ thin film for magnetic field from 0.5 T to 5.0 T, applied normal to ab-plane. Our main observation is that the resistive transition is described by the 3D thermal fluctuation near $T_c$ and vortex glass theory in the low dissipative part of resistive transition. However, the TAFF region is observed to be very narrow, which is contrasted with that observed in HTS.

## II. Experiments

The sample preparation was described elsewhere[13]. The $MgB_2$ film used in our measurement was confirmed c-axis oriented normal to the substrate surface and a single phase by the X-ray diffraction measurement. The standard photolithography technique was adapted to align the electrical pads and to obtain well-defined geometry, and then the sample was chemically etched in an acid solution, $HNO_3$ (50%) and pure water (50%) is applied. The sample dimension is 2 mm x 1 mm x 0.4 nm. The contact resistance in each electrical pad is less than 1 Ω. To measure longitudinal voltage, we used a low noise nanovoltmeter (HP 34420A) and achieved voltage resolution of 10 nV under applied current of 4 mA. The magnetic field is applied normal to ab-plane by using superconducting magnet system (Maglab2000 Oxford Ltd.) We tested the current dependence of all our measurements for the various currents of 0.4 mA, 4.0 mA and 40 mA. Onset transition temperature is 39.2 K at 0.4 mA and zero field.

## III. Results and discussions

Fig. 1 shows the typical resistive transition under magnetic field from 0.5 T to 5.0 T. The onset temperature decreases with magnetic field. To examine the TAFF in $MgB_2$ film, Fig. 1(b) is displayed in Arrhenius form. The Arrhenius plot possesses the upward curvature for all the current investigated in our measurements. This implies that the activation energy U in $\rho = \rho_0 \exp(-U/kT)$ increases with temperature. This is different from the usual behavior of the TAFF. For HTS in the TAFF region, the Arrhenius plot has linear slope.

The upward curvature in $MgB_2$ thin film suggests that the thermally activated region is reduced or diminished. The increase of activation energy with decreasing temperature implies that the vortex state is entering the vortex-glass state. To test a possible description of vortex-glass model in the low dissipation part of the resistive transition, we applied vortex-glass theory to our resistivity data. According to the vortex-glass theory[14], the glass transition is characterized by vortex glass correlation length $\xi \sim |T-T_G|^{-\nu}$ and correlation time $\tau_G \sim \xi^z$ where ν is a static exponent and z is a dynamic exponent as the vortex glass temperature is approached. In the scaling regime, the resistance vanishes as $R \sim |T-T_G|^{\nu(z-1)}$. Therefore, inverse logarithmic derivative of resistivity is given by

$$\left(\frac{d\ln\rho_{xy}}{dT}\right)^{-1} = \frac{1}{\nu(z-1)}(T-T_G) \quad (1)$$

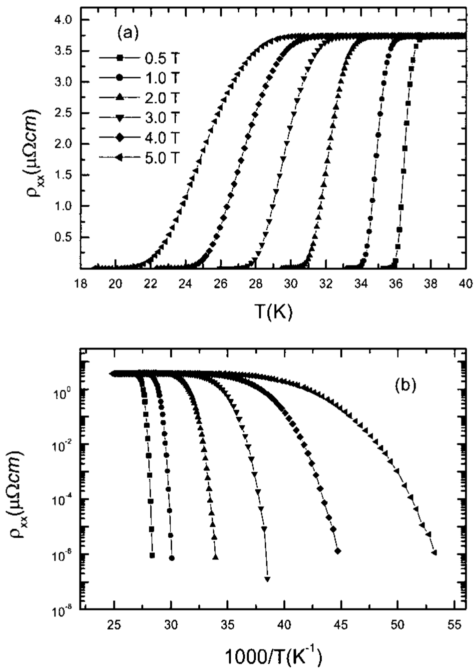


Fig. 1(a) Magnetoresistance of $MgB_2$ film in mixed state for magnetic field from 0.5 T to 5.0 T, applied normal to ab-plane. (b) Arrehenius plots of Figure 1(a)

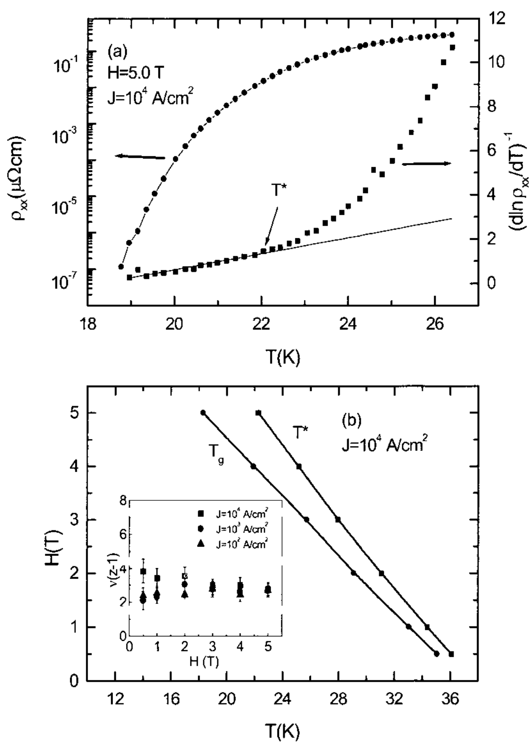


Fig. 2 (a) Temperature dependence of resistivity and its inverse logarithmic derivatives with respect to temperature at H=5.0 T and J=$10^4$ A/$cm^2$. The slope of a linear fitting defines critical exponent and its intercept gives $T_G$. (b) Phase diagram for $MgB_2$ thin film at J = $10^4$ A/$cm^2$. Inset shows the critical exponent with magnetic fields and current densities.

Fig. 2(a) shows the temperature dependence of the resistivity and its inverse logarithmic derivative at H = 5 T. The inverse logarithmic derivative with respective to temperature is a clear straight line in temperature up to T*. The slope defines the critical exponent and the intercept gives the glass temperature $T_G$[17, 18]. It is clear that low dissipation part of resistivity is well described by vortex-glass theory and the critical region is between $T_G$ and T*. From this analysis, we can draw the phase diagram and calculate the critical exponent ν(z-1). Fig. 2(b) shows the phase diagram drawn by this analysis at J=$10^4$ A/$cm^2$ and the inset is the critical exponent ν(z-1) with magnetic field. The regime between $T_G$ and T* is the critical fluctuation region of vortex glass state. The critical exponent depends slightly on field in low field but it is almost constant and ν(z-1) is around 3 in high field. This value is consistent with the previous reported value of 3.5 in I-V characteristics[11] within experimental errors and confirms a three dimensional (3D) vortex glass state in a $MgB_2$ film.

In HTS above the critical region of vortex-glass state, wide free or TAFF regions were observed[12]. Experimental manifestation of this TAFF is the straight line in Arrhenius plots in the thermally activated region. As mentioned above, however, the activation energy in our $MgB_2$ thin film increases with decreasing temperature. This means that above the critical region of vortex glass state, effects of glass state persist.

At the high temperature region near $T_c$, it is well known that the thermal fluctuation of order parameter amplitude makes resistive transition broad[20]. Therefore, we assumed that above the critical region of vortex glass state, the fluctuation of order parameter is the major factor that causes the transition broad. To test our assumption, we have attempted to scale the resistivity above the critical

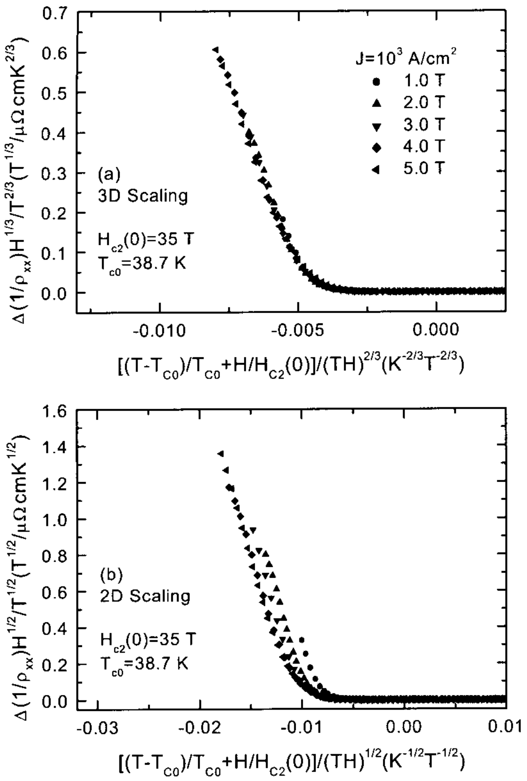


Fig. 3 (a) 3D Scaling analysis for thermal fluctuation theory with magnetic field from 1.0 T to 5.0 T. We obtained $H_{c2}(0)$ = 35 T and $T_{c0}$=38.7 K. These values are irrespective of applied current densities. (b) 2D scaling analysis with same parameters

region using Ullah and Dorsey's formulas[16]. Fig. 3(a) and (b) is the scaled curves for 2D and 3D parameters, respectively. The background was subtracted by a polynomial fitting above $T_c$. We have considered a possible magnetoresistance in a normal state although the magnetoresistance is very small in our samples. First, we optimized the scaling in 3D formula. In 3D scaling analysis, we obtained $T_{c0}(0)$ = 38.7 K and $H_{c2}(0)$ = 35 T and scaling is perfect above critical region of vortex glass state. The parameter values are consistent with the direct $H_{c2}(0)$ and $T_c$ measurement. Fig. 3(b) shows our attempt to 2D scaling with the same $H_{c2}(0)$ and $T_{c0}(0)$ values of 3D scaling analysis, not adjusting the parameter values. The 2D scaling is not so good as that in 3D scaling with the same fitting parameters. This implies that thermal fluctuation is 3D-like and that the anisotropy is probably small. The anisotropy determined by direct $H_{c2}$ measurement of $MgB_2$ thin film is below 2 [Refs. 9 and 10].

The resistive transition of $MgB_2$ thin film is described by vortex glass theory in the low dissipation part and by thermal 3D fluctuation theory above critical region of vortex glass state. However, the TAFF region which occupied large portions of reversible part in HTS was observed to be very narrow, suggesting that the pinning strength of this compound is very strong. This is why the TAFF region is reduced by vortex glass state. In HTS, proton irradiations induce the vortex glass state and simultaneously enhance pinning strength[15]. Therefore, our results support the previous report that the critical current density of $MgB_2$ thin film is comparable to that of cuprate superconductors and that the increasing pinning strength is because vortex state enters the glass region. Also, our findings are closely related to another previous report that bulk pinning is dominant in $MgB_2$ up to $0.9T_c$ [Ref. 19].

## IV. Conclusions

We have investigated the mixed-state magnetoresistance of high quality c-axis oriented $MgB_2$ thin film for magnetic field up to 5 T. The low dissipation part of resistive transition was well described by vortex glass theory. We have found out the glass transition temperature and critical region of vortex glass state. The critical exponent ν(z-1) is consistent with the previously reported value. The TAFF region is very narrow, suggesting that vortex state starts to be glassy above critical region of vortex glass state. Near $T_c$, we have interpreted our results based on the thermal fluctuation theory and have got reasonable values of the fitting parameter, $H_{c2}(0)$ = 35 T, which is well consistent with data obtained direct $H_{c2}(0)$ measurement. Since the pinning strength of $MgB_2$ thin film is very strong, the TAFF region is reduced and vortex glass region is enhanced.

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## References

[1] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. Lett. **12**, 145 (1964).
[2] J. Nagamatsu *et al.,* Nature, **410**, 63 (2001).
[3] S. Soltanian *et al.,* cond-mat/0105152 (2001).
[4] W N. Kang *et al.,* Appl. Phys. Lett. **79**, 982 (2001).
[5] D. C. Labalestier *et al.,* Nature **410**, 563 (2001).
[6] D. K. Finnemore *et al,*. Phys. Rev. Lett. **86**, 2420 (2001).
[7] C. U. Jung *et al.,* Appl. Phys. Lett. **78**, 4157 (2001).
[8] Y. Takano *et al.,* Appl. Phys. Lett. **78**, 2914 (2001).
[9] M. H. Jung *et al.,* Science submitted (2001).
[10] S. Paitnaik *et al.,* cond-mat/0104562 (2001).
[11] Hyeong-Jin Kim, W. N. Kang, Eun-Mi Choi, Kijoon H. P. Kim, and 10. Sung-Ik Lee, Phys. Rev. Lett. **87**, 087002-1 (2001).
[12] Wan-Seon Kim *et al.,* Phys. Rev. B, **61**, 11 317 (2001); and references therein.
[13] W. N. Kang *et al.,* Science, **292**, 1521 (2001).
[14] M. P. A. Fisher, Phys. Rev. Lett. **62**, 1415 (1989); D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991).
[15] A. M. Petrean *et al.,* Phys. Rev. Lett. **84**, 5852 (2000).
[16] S. Ullah and A. T. Dorsey, Phys. Rev. Lett. **65**, 2066 (1990).
[17] J. Herrmann *et al.,* Phys. Rev. B, **54**, 3610 (1996).
[18] Yu. Eltsev and O. Rapp, Phys. Rev. B, **57**, R3237 (1998).
[19] Mun-Seog Kim *et al.,* Phys. Rev. B, **64**, 012511 (2001).
[20] U. Welp *et al.*, Phys. Rev. Lett. **67**, 3180 (1991).