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Origin of High Critical Current density in MgB 2 thin films

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MgB_2 박막에서 높은 임계전류의 근원

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Abstract

We have fabricated high-quality c-axis-oriented MgB_2 thin films by using a pulsed laser deposition technique. The thin films grown on (1 $\bar{1}$ 0 2) Al_2O_3 substrates show an onset transition temperature of 39.2 K with a sharp transition width of ~ 0.15 K. X-ray diffraction patterns indicate a c-axis-oriented crystal structure perpendicular to the substrate surface. We observed high critical current densities (J_c) of ~ 16 MA/cm^2 at 15 K and under self-field, which is comparable to or exceeds those of cuprate high-temperature superconductors. The extrapolation J_c at 5 K was estimated to be ~ 40 MA/cm^2, which is the highest record for MgB_2 compounds. At a magnetic field of 5 T, the J_c of ~ 0.1 MA/cm^2 was detected at 15 K, suggesting that this compound is very promising candidate for the practical applications at high temperature with lower power consumption. As a possible explanation for the high current-carrying capability, the vortex-glass phase will be discussed.

Keywords : MgB_2, thin film, critical current density

I. Introduction

The recent discovery of the binary metallic MgB_2 superconductor [1] with a remarkably high transition temperature T_c = 39 K has attracted great both basic scientific interest [2] - [6] and practical application [7] – [17]. The strongly linked nature of the inter-grains [7] with high charge carrier density [6] in this material is further advantages for use in technological applications. Recently, the upper critical field (H_{c2}) of 29 - 39 T [8], [9], which is much higher than that of previous reports, was observed, suggesting that MgB_2 is of considerable for practical application in superconducting solenoids using mechanical cryocoolers such as closed cycle refrigerators. In addition to higher T_c and H_{c2} in MgB_2, the magnitude of critical current density (J_c) is also very important factor for use in practical applications.

To explain the complex phase in the vortex state for cuprate high-T_c superconductors (HTS), Fisher *et al.* [11] proposed the theory of a vortex-glass superconductivity by considering both pinning and collective effects of vortex lines. According to this theory, a diverging coherence length (ξ) near vortex-glass transition (T_g) can be described by $\xi \sim |T-T_g|^{-\nu}$ and coherence time scale ξ^z, where ν is the

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static exponent and z is the dynamic exponent; thus *I-V* curves can be expressed by a universal scaling function. For HTS, experimental evidences of vortex glass phase have been reported [12]. Moreover, a vortex glass transition was observed in an untwinned single crystal of $YBa_2Cu_3O_7$ after inducing a sufficiently high pinning centers, suggesting that a vortex glass phase is one of origins for high J_c [13].

In this paper, we report high current-carrying capability in high quality MgB_2 thin films, which is confirmed by direct current-voltage (*I-V*) measurements as functions of magnetic fields and temperatures. Moreover, as a possible origin of this high J_c in MgB_2 thin films, the vortex glass phase will be considered.

II. Experimental

The MgB_2 thin films were grown on Al_2O_3 ($1\ \bar{1}\ 0$

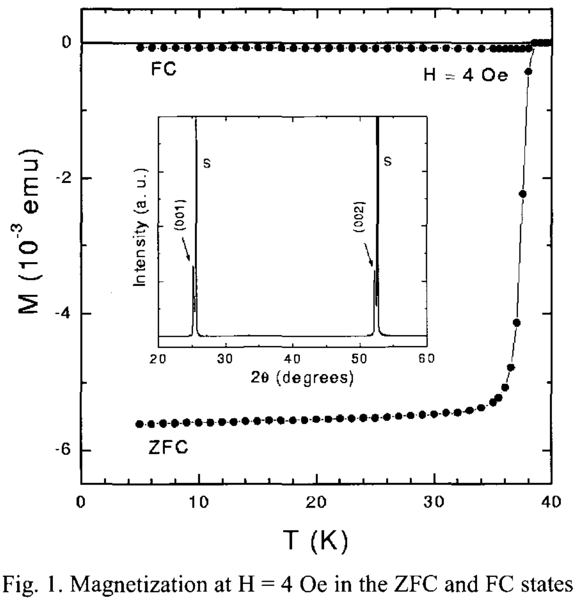

Fig. 1. Magnetization at H = 4 Oe in the ZFC and FC states of MgB_2 thin films grown on Al_2O_3 substrates. A very sharp diamagnetic transition was observed. The inset shows the X-ray diffraction patterns, indicating a highly c-axis-oriented crystal structure normal to the substrate surfaces. S denotes the substrate peaks.Indeed, successful fabrication of Fe-clad MgB_2 tape has been reported [10]. This tape showed J_c of 1.6 x 10^4 A/cm^2 at 29.5 K and under 1 T, encouraging the practical application of MgB_2.

2) single crystals in a high vacuum condition at ~ 10^{-7} Torr by using pulsed laser deposition and postannealing techniques, which were reported in our earlier paper [14]. Typical dimensions of the samples were 10 mm in length, 10 mm in width and 0.4 μm in thickness. Fig. 1 shows the low-field magnetization at H = 4 Oe for both the zero-field-cooled (ZFC) and field-cooled (FC) states of an MgB_2 thin film. A very sharp diamagnetic transition is observed. X-ray diffraction analysis indicates that the MgB_2 thin film had a highly c-axis-oriented crystal structure and that the sample purity exceeded 99% (inset of Fig. 1). These results indicate that the MgB_2 films used in the present study are homogeneous and of very high quality. In order to measure I-V characteristics, thin films were patterned into microbridge shape with the strip dimension of 1 mm long and 65 μm wide by the standard photolithography technique, and then chemically etched in the dilute acid solution with HNO_3 (50%) and pure water (50%). To obtain good ohmic contacts (< 1 Ω), we coated Au film on the contact pad after cleaning the film surface with an Ar ion-beam milling. This patterning process didn't reduce the superconducting properties of MgB_2 thin film.

III. Results and Discussion

Fig. 2 shows the typical temperature dependence of the resistivity of MgB_2 thin film. The onset transition temperature of 39.2 K with a very sharp transition of ~ 0.15 K, determined from 90% to 10% of the normal-state resistivity, was observed. The room temperature resistivity (300 K) of 10.4 μΩ cm in the thin film is similar to that in polycrystalline MgB_2 wire [15] whereas a residual resistivity ratio (RRR = ρ_{300K}/ρ_{40K}) of 3, which is much smaller than the value observed in MgB_2 wire, is observed. This large difference of RRR value depending on various synthesis methods is still under debate [6], [17]. A very small (less than 0.5%) magnetoresistance was observed at 5 T and 40 K.

We measured the magnetization (*M-H*) hysteresis loops of a MgB_2 thin film in the field range of -5 T ≤ *H* ≤ 5 T with parallel to the c-axis by using a superconducting quantum interference device magnetometer. Fig. 3 shows the *M-H* curves of the

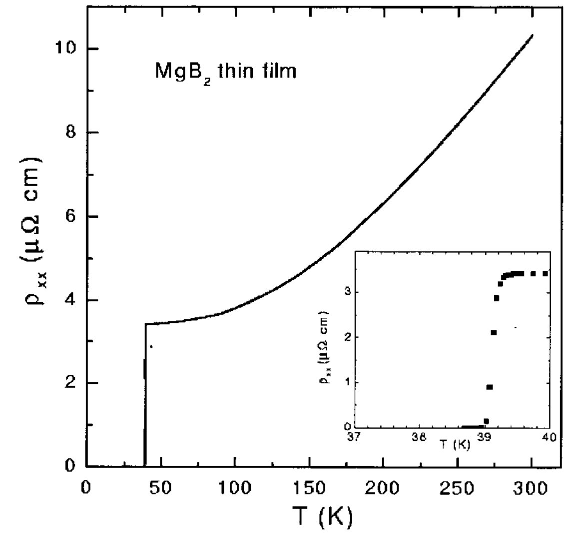

Fig. 2. Temperature dependence of resistivity for MgB_2 thin film.

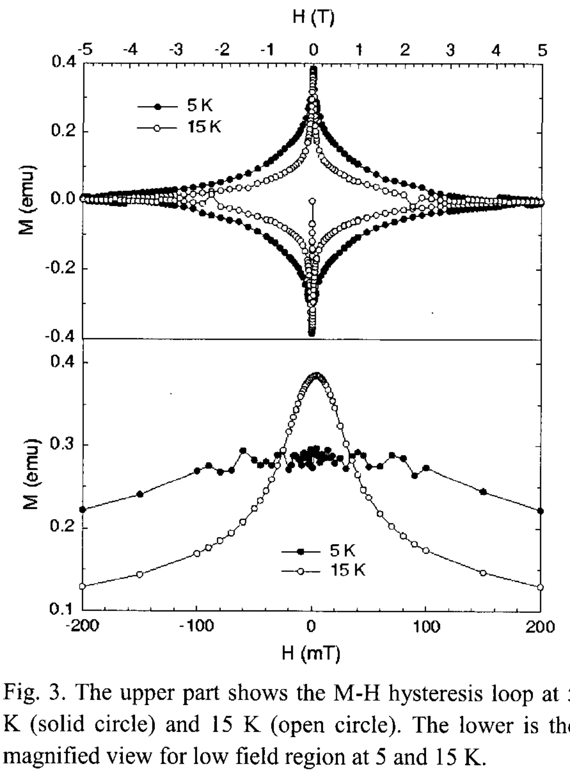

Fig. 3. The upper part shows the M-H hysteresis loop at 5 K (solid circle) and 15 K (open circle). The lower is the magnified view for low field region at 5 and 15 K.

thin film at temperatures of 5 and 15 K. The magnetization at low field decreases below $T = 10$ K with decreasing temperature (lower panel of Fig. 2),

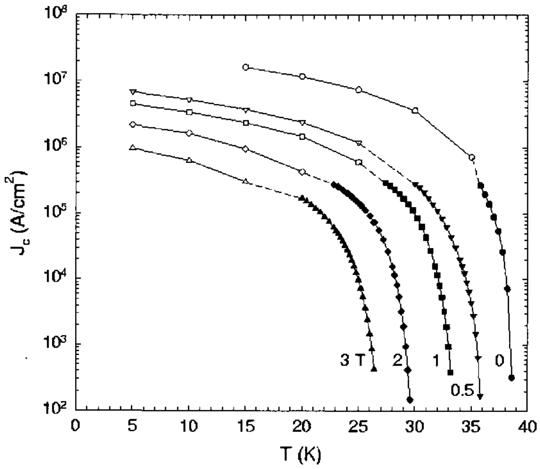

Fig. 4. The temperature dependence of critical current density of MgB_2 thin film for $H = 0 - 5$ T, extracted from the *M-H* (open symbols) and the *I-V* (solid symbols) curves, respectively. $J_c = 0.1$ MA/cm^2 is a common benchmark for practical application.

indicating the dendritic penetration of vortices. This is explained a thermo-magnetic instability in the flux dynamics [18]. Therefore, we may not apply the Bean critical state model in this temperature region.

Fig. 4 shows the J_c estimated from *M-H* loops (open symbols) and measured directly by transport method (solid symbols), as functions of temperatures and magnetic fields. The transport J_c was determined by using a voltage criterion 1 μV/mm. From the *M-H* curves, we calculated the values of J_c using Bean critical state model ($J_c = 30\Delta M/r$), where ΔM is the height of *M-H* loop. Here, we used $r = 1.784$ mm, the corresponding radius to the total area of sample size, which is calculated from $\pi r^2 = 4 \times 2.5$ mm^2. With this sample size, the J_c curves obtained from *M-H* loops and *I-V* measurements are well coincided, indicating strongly linked nature of the inter-grains on the thin film, but different from the behavior of the HTS [19].

Under self-field, the J_c was observed to be ~ 16 MA/cm^2 at 15 K and then slightly decreases to ~ 12 MA/cm^2 at 5 K. As mentioned before, since the temperature region below 15 K cannot be applied critical state model, the transport J_c at 5 K is probably higher. From the *I-V* measurements region using polycrystalline thin films, the monotonous increase of critical current density with decreasing temperature at low temperature was observed [20].

The extrapolation value of J_c at 5 K was estimated to be 40 MA/cm^2, which is the highest record for MgB_2 superconductors and is comparable to that of $YBa_2Cu_3O_7$ thin film [21] or even exceeds those of other HTS, such as Hg- and Bi-based superconductors [22], [23]. The high J_c of ~ 0.1 MA/cm^2 at 37 K in self-field suggests that MgB_2 thin film has very high potential for applications of electronic devices operating high temperature, such as microwave devices and portable SQUIDs sensors by using miniature refrigerators with low cost. At H = 5 T, the current carrying capability of 0.1 MA/cm^2 at 15 K, is also of considerable for practical application in superconducting solenoids using mechanical cryocoolers with low power consumption if we fabricate high quality MgB_2 thick films or tapes.

In order to investigate the vortex phase diagram of MgB_2 thin film, we have measured *I-V* characteristics for various magnetic fields as shown in Fig. 5. The *I-V* curves in the inset of Fig. 5 are very similar to typical behavior of $YBa_2Cu_3O_7$ superconductor [12] around vortex-glass transition temperature T_g. According to the vortex-glass theory [11], *I-V* curves show positive curvature for $T > T_g$, negative curvature for $T < T_g$, and a power-law behavior at T_g,

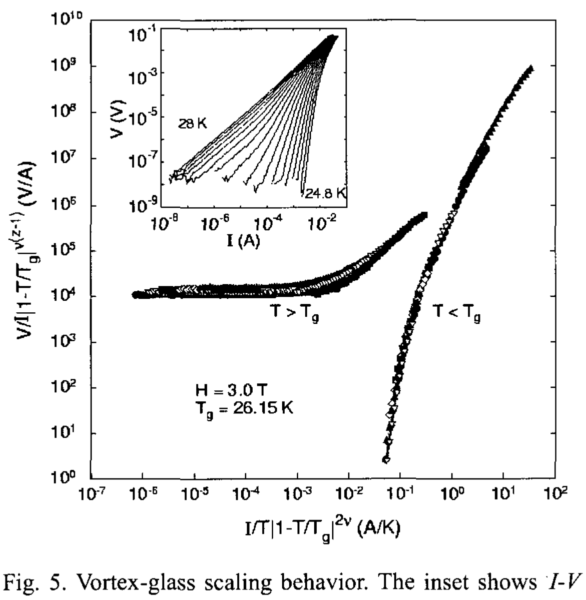

Fig. 5. Vortex-glass scaling behavior. The inset shows *I-V* characteristics at $T = 24.8 - 28$ K in 0.2 K step under $H = 3$ T.

which is in good agreement with our results with T_g = 26.15 K at H = 3 T. Furthermore, these *I-V* curves can be expressed by a universal scaling function near T_g with two common variables given by

$$V_{sc} = V / I \, | T - T_g |^{\nu(z-1)} \quad (1)$$

$$I_{sc} = I / T \, | T - T_g |^{2\nu} \quad (2)$$

All *I-V* curves collapse onto above scaling functions with static exponents of $\nu = 1.0$ and dynamic exponents of $z = 4.5$, which were in good agreement with the theoretical prediction for a three-dimensional (3D) system. This scaling behavior is well satisfied all *I-V* curves measured at other fields from 1 to 5 T. We find that the vortex-glass region of MgB_2 is wide, implying that the pinning force is very strong at low temperature. We suggest that the high current carrying capability of MgB_2 superconductor is probably originated from the 3D vortex-glass phase with strong pinning disorders and with higher charge carriers [6]. Indeed, the vortex glass phase of untwined YBCO single crystal was observed only for a highly disordered samples after proton irradiations whereas the vortex lattice melting transition was observed in pristine samples [13].

IV. Summary

We have measured J_c in MgB_2 thin film by both transport property and *M-H* hysteresis curves. We find these two data are quite well coincided into one curve for entire temperature region, indicating that the Bean's critical-state model is well consistent with this material. We observed high J_c of ~ 16 MA/cm^2 at 15 K and under zero-field, which is comparable to those of HTS. At a magnetic field of 5 T, the critical current density of ~ 0.1 MA/cm^2 was detected at 15 K, suggesting that this compound is very promising candidate the practical application at high temperature, such as a liquid-He-free superconducting magnet system and superconducting electronic devices by using mechanical or miniature cryocoolers with lower power consumption. We have suggested the 3D vortex-glass phase as a possible origin for high current carrying capability of MgB_2.

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