High Current-Carrying Capability in c-Axis-Oriented Superconducting MgB_2 Thin Films

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In high-quality c-axis-oriented MgB_2 thin films, we observed high critical current densities (J_c) of $\sim$16 MA/cm^2 at 15 K under self-fields comparable to those of cuprate high-temperature superconductors. The extrapolated value of J_c at 5 K was estimated to be $\sim$40 MA/cm^2. For a magnetic field of 5 T, a J_c of $\sim$0.1 MA/cm^2 was detected at 15 K, suggesting that this compound would be a very promising candidate for practical applications at high temperature and lower power consumption. The vortex-glass phase is considered to be a possible explanation for the observed high current-carrying capability.

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The recent discovery of the binary metallic MgB_2 superconductor [1] with a remarkably high transition temperature $T_c = 39$ K has attracted great interest in both basic scientific [2–6] and practical applications [7–14]. This new compound is expected to be useful for superconducting magnets and microelectronic devices at low cost because its transition temperature is 2–4 times higher than those of conventional metallic superconductors such as Nb_3Sn and Nb-Ti alloy. The strongly linked nature of the intergrains [7] with a high charge carrier density [6] in this material is a further indication of its possible use in technological applications. Recently, an upper critical field, $H_{c2}(0)$, of $\sim$29–39 T [8,9], which was much higher than previously reported, was observed, suggesting that MgB_2 should be of considerable use for practical application in superconducting solenoids using mechanical cryocoolers, such as a closed-cycle refrigerator. In addition to the higher T_c and H_{c2} in MgB_2, the magnitude of the critical current density is a very important factor for practical applications. For example, if a superconducting wire carries a high electric power, the size of the cryogenic system can be reduced considerably so that the system can operate with lower power consumption. Indeed, the successful fabrication of Fe-clad MgB_2 tape has been reported [10]. This tape showed a J_c of 1.6×10^4 A/cm^2 at 29.5 K under 1 T, which is encouraging for practical application of MgB_2.

In order to explain the nature of the vortex state in strong magnetic field for cuprate high-T_c superconductors (HTS), Fisher *et al.* [15] proposed the theory of vortex-glass superconductivity by considering both the pinning and the collective effects of vortex lines. According to this theory, a diverging vortex glass correlation length (ξ) near the vortex-glass transition (T_g) can be described by $\xi \sim |T - T_g|^{-\nu}$ and a correlation time scale ξ^z, where ν is a static exponent and z is a dynamic exponent; thus, I-V curves can be expressed by universal scaling functions. For HTS, experimental evidence of a vortex glass phase has been reported [16]. Moreover, a vortex-glass transition was observed in an untwinned single crystal of $YBa_2Cu_3O_7$ after inducing a sufficiently high density of pinning centers, suggesting that a vortex-glass phase may be one origin of the high J_c [17].

In this Letter, we report a high current-carrying capability in high-quality MgB_2 thin films, which was confirmed by direct current-voltage (I-V) measurements for various magnetic fields and temperatures. Furthermore, the vortex glass phase will be discussed as a possible origin of the high J_c in MgB_2 thin films.

The MgB_2 thin films were fabricated using a two-step method; the detailed process is described elsewhere [11]. Briefly, an amorphous B thin film was deposited on a $(1\bar{1}02)$ Al_2O_3 substrate at room temperature by using pulsed laser deposition. The B thin film was put into a Nb tube together with high purity Mg metals (99.9%) and the Nb tube was then sealed using an arc furnace in an Ar atmosphere. The heat treatment was carried out at 900 °C for 10–30 min in an evacuated quartz ampoule, which was sealed under high vacuum. The film thickness was 0.4 μm, which was confirmed by scanning electron microscopy. X-ray $\theta - 2\theta$ diffraction patterns indicated that the MgB_2 thin film had a highly c-axis-oriented crystal structure normal to the substrate surface; no impurity phase was observed. The ϕ-scan x-ray diffraction patterns showed randomly oriented crystal structures along the ab plane of the thin film. In order to measure the I-V characteristics, we used standard photolithography, and then chemical etching in an acid solution, HNO_3 (50%) and pure water (50%), to pattern the thin films into microbridge shapes (inset of Fig. 1) with strip dimensions of 1 mm long and 65 μm wide. To obtain good Ohmic contacts ($<1\ \Omega$), we coated the contact pads with Au films after using Ar ion-beam milling to clean the film surface. This patterning process did not degrade the superconducting properties of the MgB_2 thin films.

Figure 1 shows the typical temperature dependence of the resistivity of a MgB_2 thin film measured after patterning into a microbridge shape. An onset transition temperature of 39 K with a very sharp transition of $\sim$0.2 K, determined from the 90%-to-10% dropoff of the normal-state resistivity, was observed. The observed

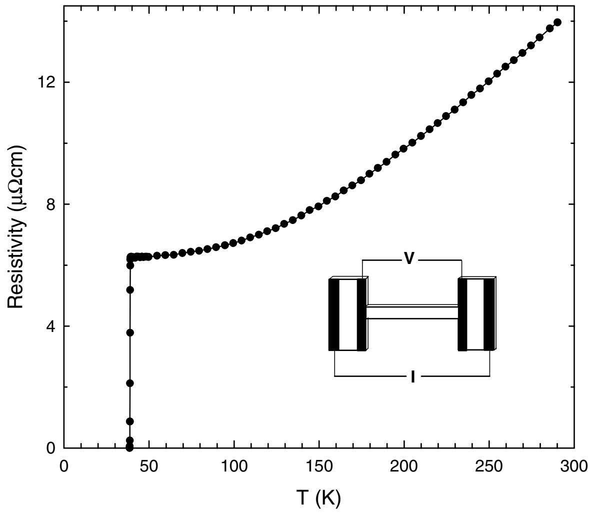

FIG. 1. Resistivity vs temperature for an MgB_2 thin film grown on an Al_2O_3 substrate by using pulsed laser deposition with postannealing. The inset shows the narrow bar pattern, 65 μm × 1 mm, of the MgB_2 thin film.

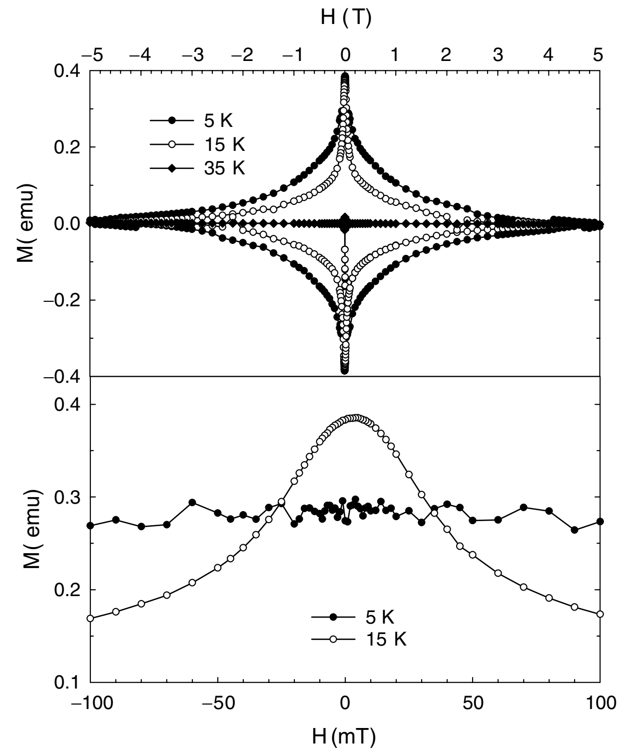

FIG. 2. Upper part shows the M-H hysteresis loop at 5 K (solid circles), 15 K (open circles), and 35 K (triangles). The lower is a magnified view of the low-field region at 5 and 15 K.

room-temperature (300 K) resistivity of 13.9 $\mu\Omega$ cm for the thin film was similar to that in a polycrystalline MgB_2 wire [12], and a residual resistivity ratio, RRR $= \rho(300\text{ K})/\rho(40\text{ K})$, of 2.3, which is much smaller than the value in the MgB_2 wire, was observed. This large difference between the RRR values depends on the synthesis method, and its cause is still under debate [6,14]. A very small (less than 0.5%) magnetoresistance was observed at 5 T and 40 K.

We used a superconducting quantum interference device magnetometer (SQUID, Quantum Design) to measure the magnetization (M-H) hysteresis loops of MgB_2 thin films in the field range of $-5 \leq H \leq 5$ T with the field parallel to the c axis. Figure 2 shows the M-H curves at temperatures of 5, 15, and 35 K. Below $T = 10$ K, the magnetization at low field decreases with decreasing temperature (lower panel of Fig. 2), indicating a dendritic penetration of vortices. This may be explained by a thermomagnetic instability in the flux dynamics [18]. Therefore, we may not apply the Bean critical state model in this temperature region.

Figure 3 shows J_c, estimated from the M-H loops (open symbols) and measured directly by using a transport method (solid symbols), as a function of temperatures for various magnetic fields. The transport J_c was determined by using a voltage criterion of 1 μV/mm. We calculated the values of J_c from the M-H curves, by using the Bean critical state model ($J_c = 30\Delta M/r$), where ΔM is the height of M-H loops. Here we used $r = 1.784$ mm, which is the radius corresponding to the total area of the sample size, and was calculated from $\pi r^2 = 4 \times 2.5$ mm^2. With this sample size, the J_c curves obtained from the M-H loops and the I-V measurements coincided, indicating the strongly linked nature of the intergrains on the thin film; this behavior is different from that of the HTS [19]. Under a self-field, the J_c was ~16 MA/cm^2 at 15 K. This value is higher than the J_c of 10 MA/cm^2 observed in polycrystalline MgB_2 films grown on (0001) Al_2O_3 and (100) MgO substrates [20]. As mentioned before, since the critical state model cannot be applied to the temperature region below 15 K, the transport J_c at 5 K

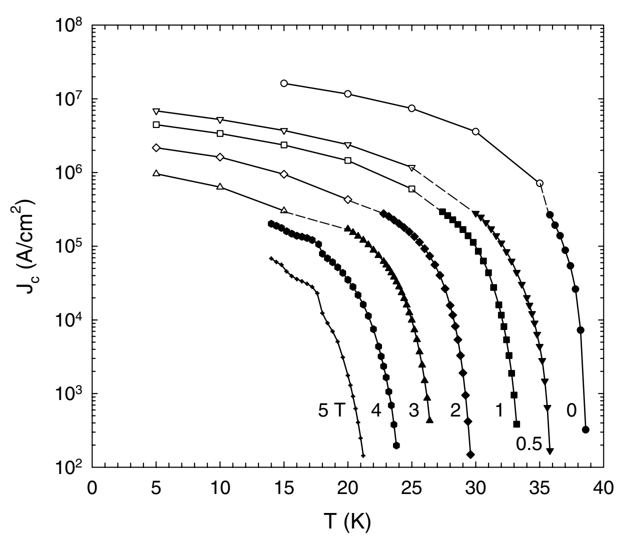

FIG. 3. Temperature dependence of the critical current density of MgB_2 thin films for $H = 0$–5 T extracted from the M-H (open symbols) and the I-V (solid symbols) curves. $J_c = 0.1$ MA/cm^2 is a common benchmark for practical applications.

is probably higher than that estimated by the Bean critical state model. From I-V measurements using polycrystalline thin film, a monotonic increase of the critical current density with decreasing temperature was observed at low temperature [20]. Based on the temperature dependence of J_c measured at 0.5 T, the extrapolated value of J_c at 5 K was estimated to be $\sim$40 MA/cm^2. This value is comparable to that of $YBa_2Cu_3O_7$ thin film [21], and even exceeds the values for other HTS, such as Hg- and Bi-based superconductors [22,23]. The high J_c of $\sim$0.1 MA/cm^2 at 37 K under a self-field suggests that MgB_2 thin films have very high potential for low-cost applications in electronic devices operating at high temperature, such as microwave devices and portable SQUIDs sensors, by using miniature refrigerators. At $H = 5$ T, the current-carrying capability of 0.1 MA/cm^2 at 15 K may be of considerable importance for practical applications in superconducting solenoids using mechanical cryocoolers with low power consumption, if we can fabricate high-quality MgB_2 thick films or tapes.

In order to investigate the vortex-phase diagram of MgB_2 thin films, we measured the I-V characteristics for various magnetic fields, as shown in Fig. 4. The I-V curves in the upper inset of Fig. 4 are very similar to those features of $YBa_2Cu_3O_7$ superconductor [16] around the vortex-glass transition temperature T_g. According to the vortex-glass theory [15], I-V curves show positive curvature for $T > T_g$, negative curvature for $T < T_g$, and a power-law behavior at T_g, which is in good agreement with our results with $T_g = 26.15$ K at $H = 3$ T. Furthermore, near T_g, these I-V curves can be described by a universal scaling function with two common variables, $V_{sc} = V/I|T - T_g|^{\nu(z-1)}$ and $I_{sc} = I/T|T - T_g|^{2\nu}$. All the I-V curves collapse onto a scaling function with a static exponent of $\nu = 1.0$ and a dynamic exponent of $z = 4.5$. These values for the exponents are in good agreement with the theoretical predictions for a three-dimensional (3D) system. This scaling behavior is also followed by the I-V curves measured at other fields from 1 to 5 T. The bottom inset of Fig. 4 shows the phase diagram in the H-T plane. The $H_{c2}(T)$ were estimated from the R-T curves when the resistivity drops to 90% of the normal-state resistivity. 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 the MgB_2 superconductor probably originates from a 3D vortex-glass phase with strong pinning disorder, and from a higher density of charge carriers [6]. Indeed, the vortex-glass phase of untwinned YBCO single crystals was observed only for high disordered samples after proton irradiation, whereas a vortex-lattice melting transition was observed in pristine samples [17].

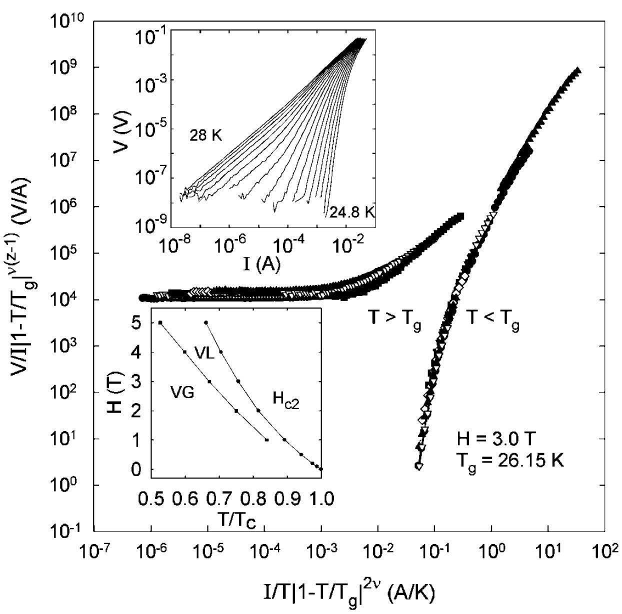

FIG. 4. Vortex-glass scaling behavior. When two variables, $V_{sc} = V/I|T - T_g|^{\nu(z-1)}$ and $I_{sc} = I/T|T - T_g|^{2\nu}$, are used, the I-V curves collapse into a scaling function near the vortex-glass phase transition temperature. The upper inset shows the I-V characteristics for $T = 24.8$–28 K in 0.2 K steps under a field of $H = 3$ T. The lower inset shows the phase diagram based on a vortex-glass (VG) to vortex-liquid (VL) transition.

In summary, we have studied J_c in MgB_2 thin films by using both the M-H hysteresis and I-V measurements. We find that these two sets of data collapse quite well into one curve over the entire temperature region, indicating the strongly linked current flow in this material. For a magnetic field of 5 T, a critical current density of $\sim$0.1 MA/cm^2 was detected at 15 K, suggesting that this compound is a very promising candidate for practical applications at high temperature, such as liquid-He-free superconducting magnet systems and superconducting electronic devices, and using mechanical or miniature cryocoolers with lower power consumption. We suggest a 3D vortex-glass phase as a possible origin for the high current-carrying capability of MgB_2.

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