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, and exceeding, those of cuprate high-temperature superconductors. The extrapolated value of $J_c$ at 5 K was estimated to be $\sim 40$ MA/cm$^2$. At 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.

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$_3$Sn and Nb-Ti alloy. The strongly linked nature of the intergrains [7] with a high charge carrier density [8] in this material is a further indication of its possible use in technological applications. Recently, an upper critical field, $H_{c2}(0)$, of $29 \sim 39$ 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 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 $1.6 \times 10^4$ 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. [1] 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 ($\xi$) near the vortex-glass transition ($T_g$) can be described by $\xi \sim |T - T_g|^{-\nu}$ and a correlation time scale $\xi^\beta$, where $\nu$ 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 [13]. Moreover, a vortex-glass transition was observed in an untwinned single crystal of YBa$_2$Cu$_3$O$_7$ 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 1 0 2) $\text{Al}_2\text{O}_3$ 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 a arc furnace in an Ar atmosphere. The heat treatment was carried out at 900 C for 10 - 30 minutes in an evacuated quartz ampoule, which was sealed under high vacuum. The film thickness was 0.4 $\mu$m, 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 $\phi$-scan x-ray diffraction patterns showed randomly oriented crystal structures along 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 $\mu$m 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 didn’t 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% drop off of
the normal-state resistivity, was observed. The observed room-temperature (300 K) resistivity of 11.9 $\mu\Omega$ cm for the thin film was similar to that in a polycrystalline MgB$_2$ wire, and a residual resistivity ratio, RRR = $\rho(300K)/\rho(40K)$, 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. 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. 3), indicating a dendritic penetration of vortices. This may be explained by a thermomagnetic instability in the flux dynamics. 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 $1 \mu V$/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 $\Delta M$ 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. Under a self field, the $J_c$ was $\sim 16$ 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$_2$O$_3$ and (100) MgO substrates. 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 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. 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$_2$Cu$_3$O$_7$ thin film, and even exceeds the values for other HTS, such as Hg- and Bi-based superconductors. The high $J_c$ of $\sim 0.1$ MA/cm$^2$ at 37 K under a self field suggests that MgB$_2$ thick films or tapes 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$_2$Cu$_3$O$_7$ superconductor around the vortex-glass transition temperature $T_g$. According to the vortex-glass theory, $I$-$V$ 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, $V_{sc} = V/I|T - T_g|^z$ 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. 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.

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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FIG. 1. Resistivity vs. temperature for an MgB$_2$ thin film grown on an Al$_2$O$_3$ substrate by using pulsed laser deposition with post annealing. 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.

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. $J_c = 0.1\ \text{MA/cm}^2$ is a common benchmark for practical applications.

FIG. 4. Vortex-glass scaling behavior. When two variables, $V_{sc} = V / |T - T_g|^{\nu(z-1)}$ and $I_{sc} = I / |T - T_g|^{2\nu}$, 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.
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