MgB$_2$ films with very high critical current densities due to strong grain boundary pinning

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MgB$_2$ superconductor has a great potential for applications because of its high $T_c$ and $B_{c2}$, exceeding those of any Nb-base superconductors at any temperature. It is now important to understand its flux pinning so as to raise high values over a wide field range. We show that nanometer-sized columnar-grain structure can produce $J_c$ exceeding $5 \times 10^6$ A/cm$^2$. The angular dependence of $J_c$ indicates that the strongest pinning occurs when the field is aligned parallel to the grain boundaries.

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Our results confirm earlier deductions that grain boundaries in MgB$_2$ act as effective pinning centers like those in Nb$_3$Sn. © 2004 American Institute of Physics. [DOI: 10.1063/1.1805195]

Magnesium diboride (MgB$_2$) superconductor$^1$ has a great potential for applications because of its high transition temperature and upper critical fields ($B_{c2}$) that can exceed those of any Nb-base superconductors at any temperature. Moreover, many groups$^2$–$^{17}$ are making films and wires of MgB$_2$. In order to realize the full potential of MgB$_2$, it is now important to understand its flux pinning so as to raise the critical current density ($J_c$) to high values over a wide field range. In this letter we show conclusively that 20–30 nm diameter columnar grains can produce $J_c$ values exceeding $5 \times 10^6$ A/cm$^2$. By studying the angular dependence of $J_c$ in films where the grains grow at a small angle to the substrate, we conclusively show that the strongest pinning occurs when the field is aligned parallel to the grain boundaries, even though $B_{c2}$ is lower for this field orientation than when parallel to the Mg and B planes. Our results confirm earlier deductions$^2$–$^4$ that grain boundaries in MgB$_2$ do not obstruct current flow as in the high-temperature cuprate superconductors, but act like those in intermetallic superconductors such as Nb$_3$Sn.

Intensive research work has been performed to fabricate MgB$_2$ thin films$^5$–$^{17}$ with high $J_c$. For example, $J_c$ values reaching $10^7$ A/cm$^2$ at 4.2 K in zero external fields are reported.$^5$–$^{13}$ However, magnetic field dependence of $J_c$ is large, and $J_c$ decreases to about 10% and 1% of self-field values in 1–3 and 4–5 T, respectively, even at low temperatures in most cases.$^5$–$^{8,14,15}$ Further understanding and improvements in flux pinning are essential to realize $J_c$ enhancements in fields both for thin films and wires.

We prepared MgB$_2$ thin films on a polished sapphire C (0001) single-crystal substrate by using electron-beam evaporation technique. We controlled the background pressure to less than $10^{-6}$ Pa and the substrate temperature to 543(±5) K. The evaporation flux ratio of Mg was set at four times as high as that of B, and the growth rate of the MgB$_2$ layer was 1 nm/s. We prepared two films with different thicknesses of MgB$_2$ layer of 0.30 and 0.15 µm. No heat treatment was performed after the deposition. Therefore, we examined their properties in the “as-grown” state. For the transport measurements, the films were patterned by dry-etching and electron cyclotron resonance etching processes. Both the width and length of the strip line were 1 mm. We then deposited 0.20-µm-thick gold layers for electrodes. We performed the dc four-probe transport measurements for the patterned specimens. We measured critical currents $I_c$ as a function of the external magnetic fields $B$ and the angle $\theta$ of the fields in liquid helium (4.2 K). Current direction was set perpendicular to the field direction and the specimen was rotated around this current axis. In this work, we define $\theta$=0° and 90° as the fields parallel and perpendicular to the film surface (hereafter referred to as the parallel field and the perpendicular field, respectively). We employed the 1 $\mu$V/cm criterion for the $I_c$ determination. We observed and analyzed the microstructure by transmission electron microscopy (TEM). We prepared cross-sectional foil specimens by using a focused-ion-beam instrument equipped with a micro-sampling system and performed the observation with an electron microscope accelerated at 200 kV.

Figure 1 shows $J_c$–$B$ relations at 4.2 K for the films with (a) 0.30-µm-thick and (b) 0.15-µm-thick MgB$_2$ layers. $J_c$–$B$ curve for $\theta=90^\circ$ stays higher than that for $\theta=0^\circ$ in the 0.30-µm-thick film. It is notable that $J_c$ exceeds $10^6$ A/cm$^2$ even in the perpendicular field of 4 T. On the contrary, $J_c$–$B$ curve for $\theta=90^\circ$ stays lower than that for $\theta=0^\circ$ in the 0.15-µm-thick film. Many research papers report that $B_{c2}$ is higher in...
though the large decrease of \( J_c \) around \( \theta = 0^\circ \) and \( \theta = 90^\circ \) correspond to the fields parallel and perpendicular to the film surface, respectively. Open and solid circles represent \( J_c \) values at \( \theta = 0^\circ \) and \( \theta = 90^\circ \), respectively. \( J_c \) values exceeding \( 5 \times 10^6 \) A/cm² in low fields could not be measured because of a thermal problem due to heat formation at the current contacts. The microstructure of the MgB₂ layer gives the origin of the peak positions in \( J_c \)–\( B \) relations. This indicates that the MgB₂ layer has two pinning mechanisms. One corresponds to the peak around \( \theta = 90^\circ \) originating in grain boundaries in the columnar microstructure. The other, corresponding to the peak at \( \theta = 0^\circ \), may originate in the surface of the MgB₂ layer, the MgB₂/substrate interface, or the layer structure of MgB₂ crystals. Figure 4 shows the explanation for these two pinning mechanisms and the two peaks in \( J_c \)–\( B \) relations. This indicates that the pinning becomes strong when the field is aligned parallel to the grain boundaries. The detailed observation of the micrographs indicates that the direction of the columnar grains is shifted several degrees from the perpendicular direction. This agrees with the results that the peak position in \( J_c \)–\( \theta \) with the columnar growth direction. The grain boundaries between these columnar grains may work as effective pinning centers and lead to the high \( J_c \) performance in the perpendicular fields.

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thickness of the MgB₂ layer increases the pinning due to the grain boundaries and makes the peak around $\theta=90^\circ$ more cusplike.

In summary, we can conclude based on our results that the grain boundaries between columnar grains work as effective pinning centers and lead to the high $J_c$ performance in the perpendicular fields.

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