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Flux Pinning in MgB_2 Film with Columnar Grains

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기둥형 결정립 구조를 지닌 MgB_2 박막에서 자속고정 현상

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Abstract

MgB_2 films grown by hybrid physical chemical vapor deposition under appropriate growth conditions commonly exhibit columnar grain structure. The grain boundaries between adjacent columnar grains have been reported to be good flux pinning centers. In this work, we measured the angular dependence of critical current density (J_c) and observed the enhanced flux pinning when an external magnetic field was aligned parallel to the columnar direction. This J_c was almost comparable to the J_c for intrinsic pinning case up to 1 T at low temperatures, indicating that grain boundary pinning is very effective. At high fields, however, J_c decreased rapidly resulting from the fact that the density of flux pinning centers provided by grain boundaries was outnumbered by the flux density.

Keywords : MgB_2 films, Grain-boundary flux pinning

I. Introduction

Flux pinning in MgB_2 superconductor is one of widely studied subjects since its discovery because MgB_2 is a potential candidate for use in electric power applications and electronic devices. Many efforts have been put forward to enhance the critical current density (J_c) and upper critical field (B_{c2}) of bulk MgB_2 mostly by doping impurities [1] or increasing electrical connectivity between grains [2]. Unlike high-temperature superconductors, grain boundaries do not obstruct current flow and furthermore they can be good flux pinning centers. In case of MgB_2 films, especially in the form of columnar growth, the role of grain boundaries as strong flux pinning centers has been clearly observed [3-5].

In this work, we studied the flux pinning exerted by grain boundaries in MgB_2 film by measuring angular dependence of J_c and resistivity (ρ). Flux pinning force

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densities, F_p=-$J_c \times B$, for magnetic fields parallel to the columnar direction were analyzed to understand the pinning mechanism by grain boundaries.

II. Experiments

MgB_2 films were grown on (0001) Al_2O_3 substrate by hybrid physical chemical vapor deposition (HPCVD). The HPCVD system consists of a vertical quartz reactor with a uniquely designed inductive heating susceptor to compensate for the low sticking coefficient of Mg. Before the film deposition, the quartz tube was first purged with high purity Ar and H_2 gas. The susceptor, along with the Al_2O_3 substrate and Mg pieces, was heated inductively to 630°C in 150 Torr of the hydrogen flow. Then B_2H_6 gas (5%) in H_2 was introduced at a flow rate of 50 sccm into the reactor to start the deposition of the MgB_2 films. In our present work, the total gas flow rate was kept at a 150 sccm and the react total pressure was 150 Torr. The structure of MgB_2 films were investigated by scanning electron microscope (SEM) and X-ray diffraction.

Thickness of a particular film used in this study was 0.5 μm and the film was patterned by using conventional photolithography and Ar-ion milling to form a bridge of 8 μm × 600 μm for J_c measurement. All the transport properties were measured by using a horizontal rotator in Physical Property Measurement System (Quantum Design).

III. Results and Discussion

XRD measurement on this film showed (0001) and (0002) peaks similar to the earlier results indicating that the film was *c*-axis oriented perpendicular to the substrate [5]. The *c*-axis lattice constant was 0.3510 nm, slightly smaller that that 0.3524 nm of bulk MgB_2. Resistive transition in an ambient field showed the onset of the superconducting transition at 39.4 K and the zero resistance at 38.9 K.

J_c was measured in magnetic fields while rotating the sample. The bias current and B was always perpendicular to each other in maximum Lorentz force configuration. Fig. 1 shows the angular dependence of J_c measured at 5 K in magnetic fields. J_c were determined by a rather high voltage criterion of 10 μV/cm considering the fact that this criterion corresponds to an actual voltage of 0.6 μV between the voltage electrodes. The angular position of 0° corresponds to external magnetic field parallel to the *ab*-plane ($B\|ab$), and that of 90° corresponds to $B\|c$. We observed two J_c peaks at 0° and 90°, and the former is due to the intrinsic and/or surface pinning and the latter is due to the flux pinning provided by grain boundaries. The values of J_c for grain-boundary pinning are comparable to those for intrinsic pinning. The effect of grain-boundary flux pinning lasts even to 3 T as shown in the logarithmic plot in the right panel of Fig. 1.

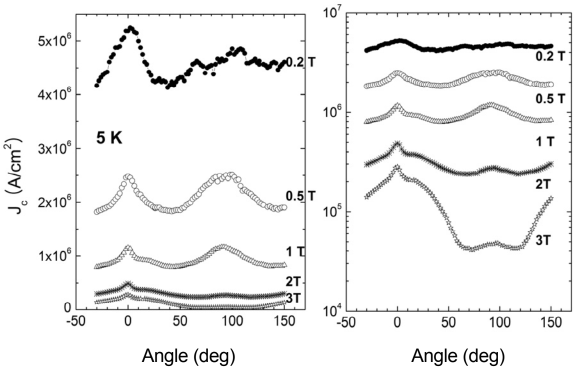

Fig. 1. Angular dependence of J_c measured at 5 K. The right panel is a re-plot in the logarithmic scale in order to clearly show the grain-boundary pinning effect in high fields.

Fig. 2 compares J_c for $B\|c$ with J_c for $B\|ab$ at various temperatures. J_c for both directions are almost the same up to a certain crossover field, after that, J_c for $B\|c$ drops rapidly with increasing B. This rapid drop of J_c above the crossover field (B_g) is due to the fact that the density of flux pinning centers provided by grain boundaries was outnumbered by the flux density. B_g was found to be decreasing with increasing T, probably resulting from the decrease of thermodynamic critical field, which is proportional to pinning energy, with T.

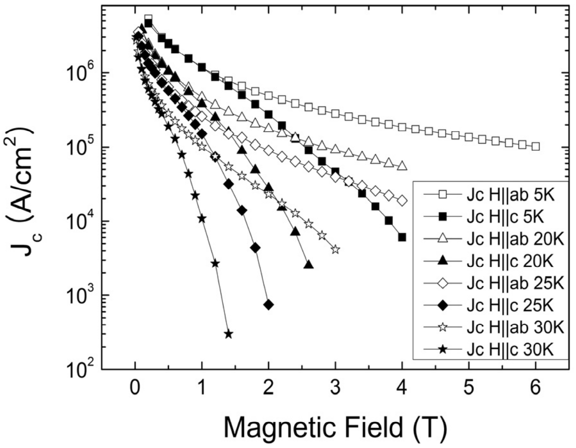

Fig. 2. Magnetic field dependence of J_c for $B||ab$ and $B||c$ at various temperatures. Two J_c's are comparable to each other up to certain fields.

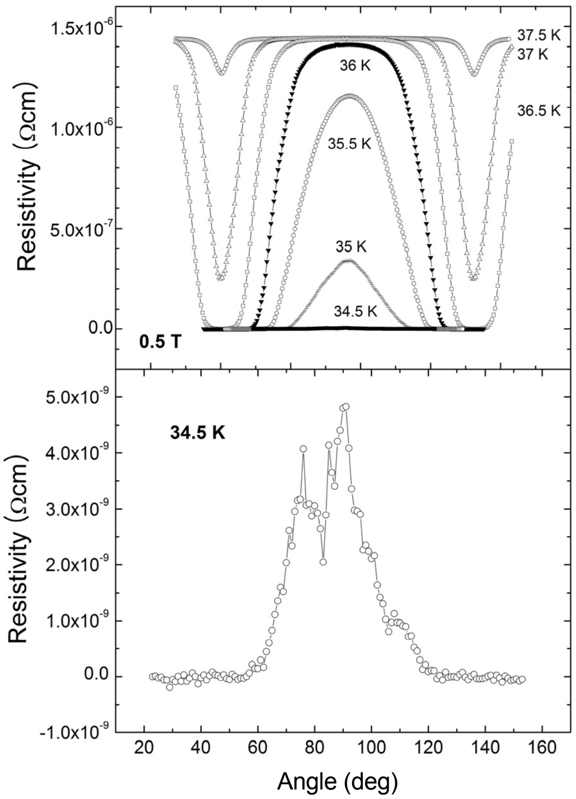

Fig. 3. Angular dependence of resistivity measured at 0.5 T. No resistive dip due to the grain-boundary pinning is observed except at 34.5 K, of which the expanded view is shown in the lower panel.

However, the angular dependence of the resistivity in magnetic fields did not show any obvious resistance dip at $B||c$. A typical angular dependence of the resistivity measured for 0.5 T at several temperatures during the superconducting transition is shown in Fig. 3. The data plotted in Fig. 3 show an angular dependence of anisotropic material with no special feature at 90°, except at 34.5 K very close to the zero resistance where a resistance dip is barely visible as shown in the lower panel of Fig. 3. This indicates that flux pinning by grain boundary is effective only when the T and B are somewhat away from the B_{c2} phase boundary. A similar behavior was observed in some samples grown by the same method [5].

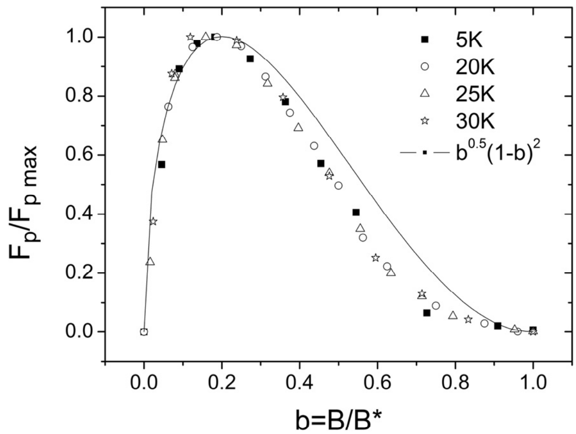

Fig. 4. Flux pinning force densities at various temperatures. The solid line is the magnetic field dependence in Eq. (1).

Flux pinning force densities, F_p=-$J_c \times B$, is a useful tool to identify the mechanism of flux pinning. The functional form of the B dependence of F_p varies with the dominant flux pinning mechanism. The most relevant formula known for representing the grain-boundary flux pinning is given as

$$F_p \propto b^{0.5}(1-b)^2 \qquad (1)$$

where b=B/B^* and B^* is the field where J_c becomes zero [6]. B^* is usually replaced by irreversible field.

Fig. 4 shows the scaling behavior of F_p as a function of B^*. F_p at different fields show good scaling behavior, however, the scaled F_p did not follow Eq. (1) for the scaling relation for flux pinning by distorted flux line lattice (FLL) by linear pins. This result implies that the flux pinning observed in this work might have a different origin than distorted FLL by grain boundaries. An alternative mechanism could be electron scattering by grain boundaries [7]. Mean free path (l) of electrons near the grain boundary can be greatly affected by the presence of grain boundary especially for electrons heading toward the boundary. The shortening of l is then related to the change in B_{c2}, i.e., change in the Ginzburg-Landau parameter (κ). This change in κ can give rise to flux pinning in the grain boundary regions.

IV. Summary

We studied the effect of grain-boundary flux pinning in MgB_2 films by measuring the angular dependence of J_c and resistivity in magnetic fields. We observed enhanced J_c for $B||c$, which is believed to be results of grain-boundary flux pinning. On the other hand, resistivity did not show any related dip for $B||c$ except where resistivity is almost zero. The flux pinning force densities at different temperature showed good scaling behavior, however, the functional dependence on reduced field did not follow the well known scaling formula for flux pinning by distorted FLL by linear pins.

Acknowledgments

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