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임계상태 모형을 이용한 MgB_2 초전도체의 비가역 자기화 기술

(Theoretical description of irreversible magnetization of MgB_2 by the critical-state model)

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I. Introduction

We measured the magnetic-field dependence of the irreversible magnetization of the binary superconductor MgB_2[1]. For the temperature region of $T < 0.9T_c$, the contribution of the bulk pinning to the magnetization overwhelms that of the surface pinning[2]. This was evident from the fact that the magnetization curves, $M(H)$, were well described by the critical-state model[3,4,5] without considering the surface pinning effect. It was also found that the $M(H)$ curves at various temperatures scaled when the field and the magnetization were normalized by the characteristic scaling factors $H^*(T)$ and $M^*(T)$, respectively. This feature suggests that the pinning mechanism determining the hysteresis in $M(H)$ is unique below $T = T_c$.

II. Experimental

Details of sample preparation are given in Ref. [6]. The magnetization curves were measured using a superconducting quantum interference device (SQUID) magnetometer (Quantum Design, MPMS-XL).

III. Results and Discussion

The irreversible magnetization can be described by various critical state models. The Bean model[3] has been commonly used to calculate the critical current density of superconducting materials. The model assumes that the slope $dh(r)/dr$ is constant and field independent, where $h(r)$ denotes the local magnetic induction inside a sample. Thus, the critical current density (or irreversible magnetization) should also be field independent, which is contrary to most experimental results.

Other critical-state models, such as the exponential and the Watson models[4,5], which take into account the field dependence of the critical current density, can be used to describe the irreversible magnetization properly. In the frame of the exponential model, the critical current density, $J_c(h(r))$, is given by

$$J_c(h(r)) = J_0\exp(-|h(r)|/H_0),$$

where J_0 and H_0 are adjustable parameters. According to Ampere's law, the field gradient inside a sample is given by $dh(r)/dr = -sgn(J)(4\pi/c)J_c(h(r))$, where $sgn(x)$ is the sign function. In cylindrical coordinates, we obtain an average magnetic induction of a sample with a radius a, $\langle h \rangle = B = H + 4\pi M = 1/(\pi a^2)\iint h(r)d\theta dr$. If the surface barrier effect[2] is ignored, the boundary condition for $h(r)$ is $h(r=a) = H$, where H is the external magnetic field.

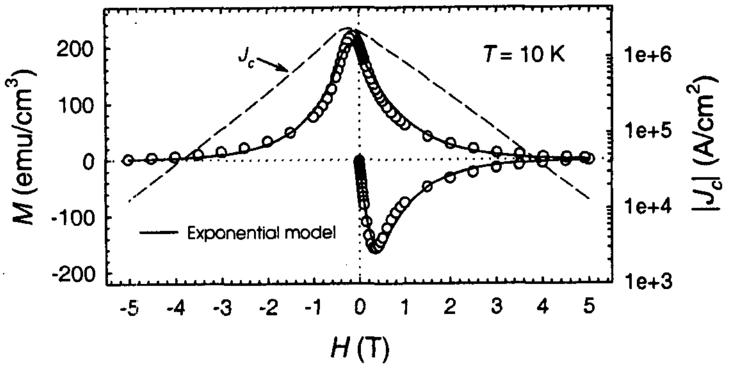

Fig. 1 Magnetization curve, $M(H)$, at T = 10 K. The solid line represents the theoretical curve for the exponential critical-state model. The dashed line denotes the average critical current density $J_c(H)$ calculated from the decreasing-field branch of the theoretical $M(H)$ curve at T = 10 K.

Figure 1 shows our attempt to fit $M(H)$ at T = 10 K using the exponential critical-state model with j_0a = 697 emu/cm^3 and h_0 = 0.93 T. For the theoretical description of the $M(H)$, we can choose an arbitrary number for a sample size a within the constraint that the multiplier j_0a is a constant. As one can see, the data are well described by the model without considering the contribution of the reversible magnetization and the surface-barrier effect[2]. This implies that, in the mixed state, the magnetization mainly comes from the contribution of the bulk-pinning. The dashed line of Fig. 1 represents the average critical current density $J_c(H)$ calculated from the decreasing-field branch of the theoretical $M(H)$ curve assuming the grain size a = 25 μm.

IV. Summary

In this work, we measured magnetization $M(H)$ of MgB_2 superconductor as a function of the external magnetic field to elucidate its pinning properties in detail. We found that the $M(H)$ curves for various temperatures can be described by the exponential critical-state model. From this analysis, we present evidence of the significant role of bulk pinning in this system even up to $T/T_c \sim 0.9$, which is contrary to the case of high-T_c cuprates.

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