Prominent bulk pinning effect in the MgB_2 superconductor

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We report the magnetic-field dependence of the irreversible magnetization of the recently discovered binary superconductor MgB_2. For the temperature region of $T<0.9T_c$, the contribution of the bulk pinning to the magnetization overwhelms that of the surface pinning. This was evident from the fact that the magnetization curves $M(H)$ were well described by the critical-state model without considering the reversible magnetization and 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_c.

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I. INTRODUCTION

In the mixed state, the magnetization of superconductors is a combination of two different contributions, M_{eq} and M_{irr}. M_{eq} is the equilibrium (or reversible) magnetization[1] and M_{irr} is the irreversible magnetization. The former is caused by the equilibrium surface current. The latter arises from the surface (Bean-Livingston) barrier effect,[2] as well as the bulk pinning due to the interaction between vortices and various defects within the superconductor. The surface barrier originates from the competition between two forces, (a) an attractive interaction between a vortex and its image vortex and (b) a repulsive interaction between a vortex and the surface-shielding current. For high-T_c cuprate superconductors, the irreversible magnetization at low temperatures is dominated by the bulk pinning. However, the role of the surface-barrier effect becomes significant as the temperature approaches toward T_c.[3]

Recently, superconductivity in a noncuprate binary compound MgB_2 was discovered by Akimitsu and co-workers[4] This material is known to be type-II superconductor with the Ginzburg-Landau parameter $\kappa \sim 26$ and $T_c \simeq 40$ K,[5] and various experimental studies[6–13] have been carried out to elucidate the fundamental properties of this superconductor.

In the mixed state, the magnetic behavior of MgB_2 has been known to resemble that of the conventional superconductors such as Nb-Ti and $NbSn_3$. Larbalestier *et al.*[8] showed that the parameter $H^{0.25}\Delta M^{0.5}$ is linear in H over a wide range of temperature as in Nb_3Sn, where the ΔM ($\propto J_c$) is the magnetic hysteresis in $M(H)$. They also reported the proportionality of the irreversible field $H_{irr}(T)$ and the upper-critical field $H_{c2}(T)$, which are usually independent in high-T_c cuprates.

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.[14] 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.

II. EXPERIMENT

A commercially available powder of MgB_2 (Alfa Aesar) [Ref. 15] was used to make a pellet. High-pressure heat treatment was performed with a 12-mm cubic multianvil press.[16,17] The pellet was put into a Au capsule in a high-pressure cell. A D-type thermocouple was inserted near the Au capsule to monitor the temperature. It took about 2 h to pressurize the cell to 3 GPa. After the pressurization, the heating power was increased linearly and then maintained constant for 2 h. The sample was sintered at a temperature of $850 \sim 950\,°C$ and then quenched to room temperature. The sample weighed about 130 mg and was about 4.5 mm in diameter and 3.3 mm in height. The magnetization curves were measured by using a superconducting quantum interference device magnetometer (Quantum Design, MPMS-XL).

III. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the zero-field-cooled magnetization measured at $H=20$ Oe. From this figure, we found that the superconducting transition tempera-

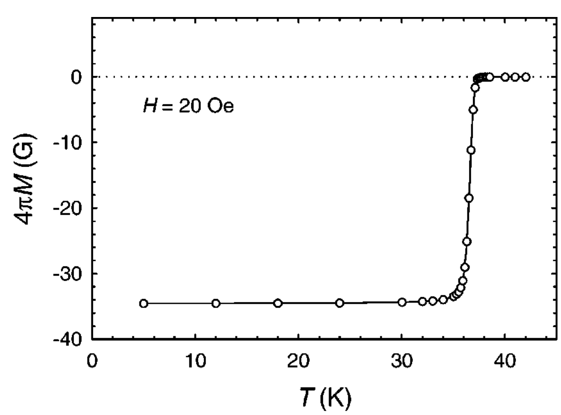

FIG. 1. Zero-field-cooled magnetization, $M(T)$, of MgB_2 for $H=20$ Oe. This curve reveals the superconducting transition temperature T_c and the transition width ΔT_c to be about 37 K and 1 K, respectively.

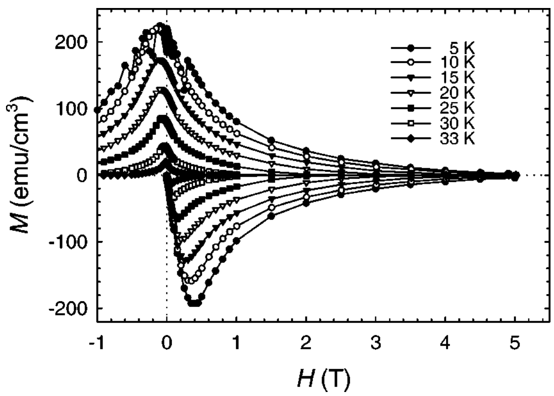

FIG. 2. Magnetization curves $M(H)$ measured in the region $5\ \mathrm{K}\leqslant T\leqslant 33\ \mathrm{K}$ and $-5\ \mathrm{T}\leqslant H\leqslant 5\ \mathrm{T}$.

ture T_c and the transition width ΔT_c were about 37 K and 1 K, respectively.[17]

Figure 2 shows the magnetization curves, $M(H)$, of MgB_2, which were measured in the temperature region of $5\ \mathrm{K}\leqslant T\leqslant 33\ \mathrm{K}$.[18] One notable feature is the symmetry in the increasing and the decreasing-field branches for $H\gtrsim 0.5$ T, i.e., $M(H^+)\simeq -M(H^-)$, where $M(H^+)$ and $M(H^-)$ are the magnetizations in the increasing and the decreasing-field branches, respectively. Such a feature can be commonly found in previous reports.[5,8,13] This means that the contribution of the equilibrium magnetization and the surface pinning is negligible compared to that of the bulk pinning. The irreversible magnetization can be described by various critical-state models. The Bean model[19] has been 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[14] and the Watson[20] models, 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 Watson model, the critical-current density, $j_c(h(r))$, is given by

$$j_c(h(r))=j_0(1+|h(r)|/h_0), \tag{1}$$

where j_0 and h_0 are adjustable parameters that depend on the material. The exponential model proposes that the critical current density has the form

$$j_c(h(r))=j_0\exp[-|h(r)|/h_0], \tag{2}$$

where j_0 and h_0 are again adjustable parameters as in the Watson model. According to Ampere's law, the field gradient inside a sample is given by

$$\frac{dh(r)}{dr}=-\operatorname{sgn}(j)\frac{4\pi}{c}j_c(h(r)), \tag{3}$$

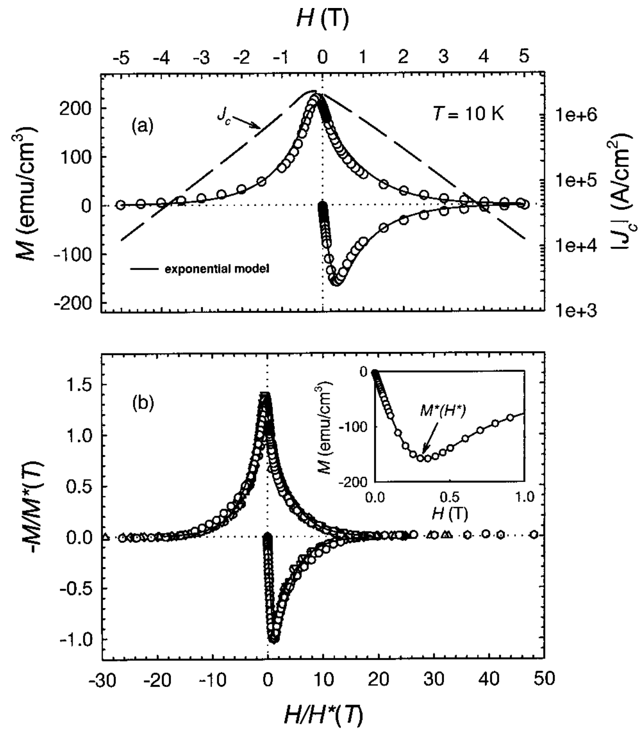

FIG. 3. (a) Magnetization curve $M(H)$ at $T=10$ K. The solid line represents the theoretical curve for the exponential critical-state model. The line denotes the absolute value of the average critical-current density $J_c(H)=\langle j_c(h(r))\rangle$ calculated from the decreasing-field branch of the theoretical magnetization curve at $T=10$ K. (b) Scaling of the magnetization curves $M(H)$ in the temperature region $5\ \mathrm{K}\leqslant T\leqslant 33\ \mathrm{K}$. The inset illustrates the definitions of M^* and H^* (see text).

where $\operatorname{sgn}(x)$ is the sign function and c is the speed of light. In cylindrical coordinates, we obtain an average magnetic induction $\langle h\rangle$ of a sample with a radius a

$$\langle h\rangle=B=H+4\pi M=\frac{1}{\pi a^2}\int_0^a\int_0^{2\pi}h(r)\,d\theta\,dr. \tag{4}$$

If the surface-barrier effect is ignored, the boundary condition for $h(r)$ is $h(r=a)=H$, where H is the external magnetic field.

Figure 3(a) shows our attempt to fit $M(H)$ at $T=10$ K by using Eq. (4) with the exponential critical-state model with $j_0a=697\ \mathrm{emu/cm^3}$ 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 critical-state model without considering the contribution of the reversible magnetization and the surface-barrier effect. As stated before, this implies that, in the mixed state in the MgB_2 superconductor, the magnetization mainly comes from the contribution of the bulk-pinning effect. A fit using the Watson model was also attempted, but was poor for all adjustments of the parameters. The dashed line of Fig. 3(a) represents the average critical current density $J_c(H)$

$=\langle j_c(h(r))\rangle$ calculated from the decreasing-field branch of the theoretical magnetization curve assuming the grain size $a=25\ \mu$m.

We note that the shapes of the $M(H)$ curves shown in Fig. 2 are remarkably similar to each other. This suggests that the vortex-pinning mechanism in MgB_2 does not change even as the temperature is varied up to near T_c. More concrete evidence for this can be found from the scaling analysis of the $M(H)$ curves. For the scaling of the $M(H)$ curves, we define two phenomenological parameters as shown in the inset of Fig. 3(b). $H^*(T)$ means the field where the absolute value of magnetization in the increasing-field branch reaches its maximum value $|M^*(T)|$. We divided the M and the H in each curve of Fig. 2 by $-M^*(T)$ and $H^*(T)$, respectively. The result is shown in Fig. 3(b). Without any exception, all the curves collapse on a single universal curve. The solid line in the figure denotes the exponential critical-state model. This result is consistent with the scaling of the pinning force, $F_p(H)\propto HJ_c$, in a temperature range of $T\geqslant 0.5T_c$ reported by Larbalestier *et al.*[8] In case of high-T_c cuprates, such scaling behavior of the $M(H)$ curves is established in a limited low-temperature region. This implies that the fundamental mechanism determining the magnetic hysteresis at low temperatures changes as the temperature is increased toward T_c. For $Bi_2Sr_2CaCu_2O_8$ (Bi-2212), while the bulk pinning is dominant at low temperatures, the contribution of the surface or geometrical barrier effects to the magnetization becomes more important as the temperature is increased.[3] Thus, universal scaling of $M(H)$ is not seen in Bi-2212.

Figure 4 shows the temperature dependence of the scaling parameters $H^*(T)$ and $M^*(T)$ used in the above analysis. The right axis for $H^*(T)$ in the figure was corrected by the demagnetization factor $D=0.42$. The value of D was obtained from the low-field susceptibility curve in Fig. 1 assuming 100% magnetic screening. It was obvious that the M^* and $H^*(T)-4\pi M^*(T)D$ scaled linearly with temperature as indicated by solid lines. The linearity in $H^*(T)-4\pi M^*(T)D$ requires a linear temperature dependence of the irreversible field H_{irr} where the magnetic hysteresis disappears. This is because the normalized hysteresis curves $M(H)$ for $T\leqslant 0.9T_c$ collapsed into a single universal curve

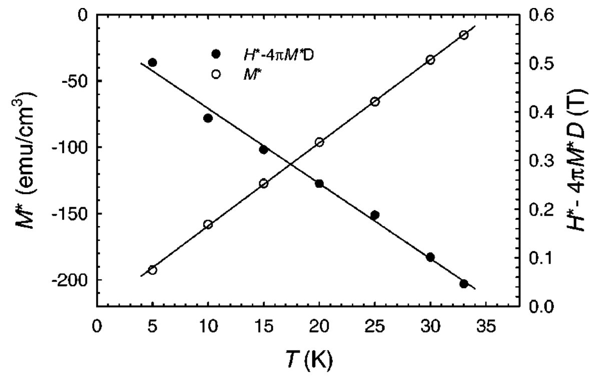

FIG. 4. Temperature dependence of phenomenological parameters M^* and $H^*-4\pi M^*D$, where D is the demagnetization factor of the sample. Solid lines represent linear least-squares fits of the data.

as we showed. In fact, a nearly linear $H_{\mathrm{irr}}(T)$ was shown from the Kramer analysis of magnetization.[8] This feature differentiates MgB_2 from other cuprate high-T_c materials with $H_{\mathrm{irr}}\sim(T_c-T)^{1.5}$.

IV. SUMMARY

In summary, we measured the magnetization curves $M(H)$ for metallic MgB_2 superconductor, which has a $T_c \simeq 37$ K, in the region 5 K$\leqslant T\leqslant$33 K and -5 T$\leqslant H \leqslant 5$ T. The magnetic hysteresis in our experimental region was well described by the exponential critical-state model, without considering the reversible magnetization and the surface-barrier effect. Also, we found that all the magnetization curves collapsed onto a single universal curve when the field and the magnetization were normalized by the characteristic scaling factors $H^*(T)$ and $M^*(T)$, respectively. These results lead us to the conclusion that the irreversible magnetization of MgB_2 is dominated by bulk pinning and that the pinning mechanism does not change even when the temperature is varied up to $T/T_c\sim 0.9$.

ACKNOWLEDGMENTS

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