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Examination of the scaling behavior of critical properties in MgB_2/SiC/Si thin films

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Abstract

Scaling behaviors of critical current densities in MgB_2 thin films are investigated with different film thickness. MgB_2 films were grown on SiC buffered Si substrate by sequential evaporation of boron and magnesium. The amount of supplied boron was controlled so as to result in MgB_2 film thickness of 50 nm or 10 nm with excess magnesium. The critical current density J_c and irreversibility field H_{irr} were estimated from magnetic field dependence of DC magnetization hystereses. Variation of J_c is analyzed against temperature at each value of constant magnetic field. For the 50 nm film J_c could scale with $[1-(T/T_c)^2]^{m'}$ with critical exponents m' from 4 to 8. However, variation of m' is interpreted as only in appearance and as due to low-field approximation assumed in this simplified scaling. More comprehensive scaling formula for reduced critical current density has been applied in wide range of temperature and field, and good fitting to our experimental data has been obtained over 10 orders of magnitude. On the other hand, for the 10nm film, experimental data of the reduced current density indicated a kink in the middle temperature and field range, and fitting with the formula was poor, inferring weak pinning. Various scaling behaviors of J_c and H_{irr} are examined in relation to film quality, pinning strength and nature of superconductivity.

Keywords: MgB_2 thin film ; critical current density ; scaling behavior ; thickness effect

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1. Introduction

Investigations of the scaling behavior of critical superconducting properties are important both from basic and application points of view, since scaling analysis is based on superconducting mechanism and also helps to predict values of practical superconducting critical parameters in various conditions.

In the absence of thermal activation of flux pinning, critical current density J_c at temperature T and magnetic field H is expressed as

$$J_c(H,T) = A\mu_0^{m-1}H_{c2}^{m-\gamma}(T)H^{\gamma-1}[1-H/H_{c2}(T)]^{\delta}, \tag{1}$$

where A is a constant, $H_{c2}(T)$ is the upper critical field, and m, γ and δ are parameters depending on the pinning mechanism[1]. This is known as the scaling law with the empirical temperature dependence of $H_{c2}(T) = H_{c2}(0)[1-(T/T_c)^2]$.

On the other hand, in the presence of thermally activated motion of fluxoid (flux creep), superconductors cannot carry non-resistive transport current outside the irreversibility line. The criterion is given by the irreversibility field $H_{irr}(T)$. Matsushita *et al.* [2] deduced an expression for $H_{irr}(T)$ appropriate for high-T_c superconductors (in which H_{irr} is much smaller than H_{c2}) as

$$H_{irr}(T) = (K/T)^p[1-(T/T_c)^2]^n, \tag{2}$$

where K is a constant determined by the electric field criterion of irreversibility, and indices p and n are

$$p = 4/(3-2\gamma),\ n = 2(m-\gamma)/(3-2\gamma)\ . \tag{3}$$

At high temperatures ($T \sim T_c$) eq. (2) further reduces to the well-known scaling relation:

$$H_{irr}(T) = H_{irr}(0)[1-(T/T_c)^2]^n, \tag{4}$$

Kitahara *et al.* [3] examined scaling law and irreversibility fields in MgB_2 superconductors in the powder form and successfully explained their experimental results according to eq. (2) with such pinning parameters of $m\sim2$, $\gamma\sim0.4$ (then $n\sim2$) and $\delta\sim2$. Investigations of the scaling behavior in MgB_2 in the form of thin film is especially interesting from view points of various pinning and thickness effects.

In our previous reports [4,5], we investigated critical properties in MgB_2 thin films of 50 and 10 nm thickness, and found that the irreversibility field scaled as eq. (4) with critical exponents n of 3 and 1.5 for 50 and 10 nm films, respectively. It was suggested that the exponent n of 3 reflected good film quality and strong flux pinning, while n of 1.5 reflected anomalous superconductivity. In this work, we further investigate the scaling behavior in the critical current density J_c for MgB_2 thin films and examine various scaling nature in H_{irr} and J_c with different film thickness.

2. Experimental

MgB_2 films studied here are the same films as in our previous reports [4,5], which were prepared by sequential evaporation of boron and magnesium on SiC-buffered Si substrate followed by in-situ annealing. AC and DC magnetizations were measured with magnetic fields perpendicular to the film using PPMS magnetometer (Quantum Design). The upper critical field H_{c2} was estimated from AC susceptibility, and the critical current density J_c was evaluated from DC magnetization hysteresis with the

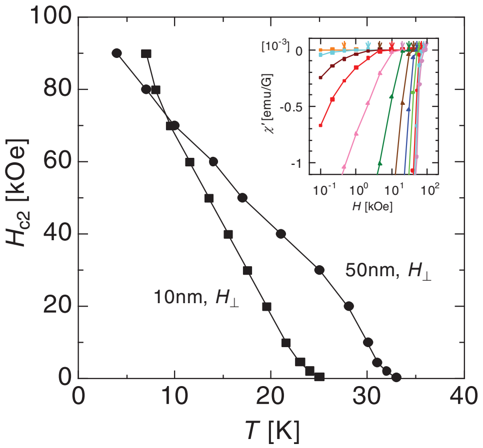

Fig. 1. Upper critical field H_{c2} as a function of temperature. Inset: AC diamagnetic susceptibility χ' for the 50 nm film as a function of magnetic field H at temperatures (from right to left) of 4,7,10,14,17,21,25,28,30,31,32,33K.

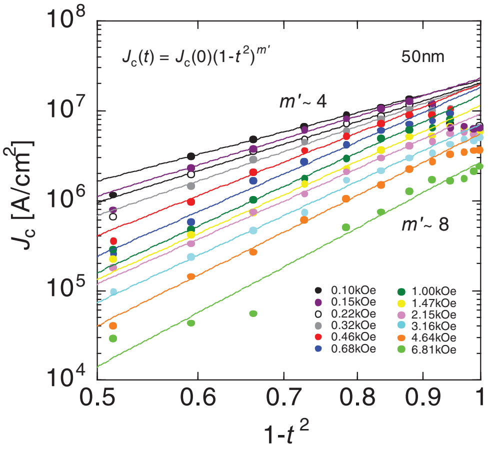

Fig. 2. Variation of J_c as a function of 1-t^2 with t=T/T_c for the 50 nm film. Solid lines indicate best linear-fits to respective data by $J_c(t) = J_c(0)(1-t^2)^{m'}$ with exponents m' from 4 to 8.

Bean critical state model: $J_c = 30\Delta M/r$, where ΔM is the height of the magnetization loop and r is the sample half-width (about 0.15 cm).

3. Results and discussion

Inset of Fig. 1 shows AC diamagnetic susceptibility χ' as a function of magnetic field H at typical temperatures for the 50 nm film. The upper critical field $H_{c2}(T)$ can be estimated from termination (indicated by arrows) of diamagnetism at a given temperature T. Thus estimated $H_{c2}(T)$ is plotted in Fig. 1 together with similarly obtained values for the 10 nm film. Both curves are in good agreement with the previously obtained H_{c2} [4,5], respectively. Apparent positive curvature in H_{c2} for the 10 nm film suggests low-dimensional superconductivity, in contrast to generally linear H_{c2} for the 50 nm film.

It is interesting how differently behaves the scaling of the critical current density J_c in these different films. Figure 2 shows variation of J_c for the 50 nm film as a function of 1-t^2 with $t = T/T_c$ at each value of constant magnetic field. The observed J_c variation may be fitted by the scaling law like

$$J_c(t) = J_c(0)(1-t^2)^{m'} \tag{5}$$

with exponents m'. Solid lines in Fig. 2 indicate best linear-fits to respective data excluding lowest and/or highest temperature region. Thus estimated m' values increase from about 4 to 8 with the applied field H. However, we consider that this variation of m' would not be intrinsic. The reason is as follows. With the empirical temperature dependence of $H_{c2}(t) = H_{c2}(0)(1-t^2)$, eq. (1) gives the scaling formula as

$$J_c(b_0,t) = J_\gamma b_0^{\gamma-1}(1-t^2)^{m-\gamma}[1-b_0/(1-t^2)]^\delta, \tag{6}$$

where, $J_\gamma = A\mu_0^{m-1}H_{c2}^{m-1}(0)$ and $b_0 = \mu_0 H/\mu_0 H_{c2}(0)$. If the applied magnetic field is small, the temperature dependent contribution from $[1-b_0/(1-t^2)]^\delta$ term can be neglected and eq. (6) reduces to eq. (5) with $m' = m-\gamma$. However, when the field value increases, $[1-b_0/(1-t^2)]^\delta$ term becomes effective and make apparent m'

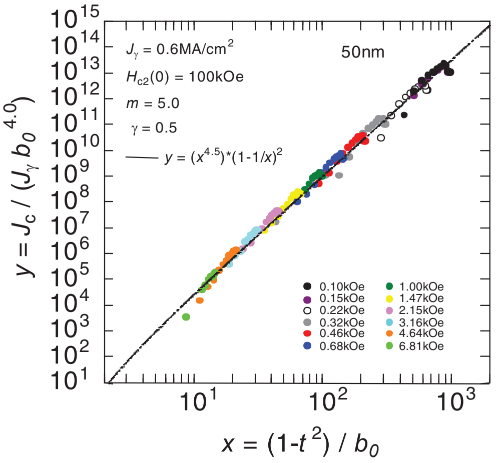

Fig. 3. Plot of reduced critical current density $y = J_c/(J_\gamma b_0^{4.0})$ in 50nm film as a function of $x = (1-t^2)/b_0$ with $b_0=H/H_{c2}(0)$.

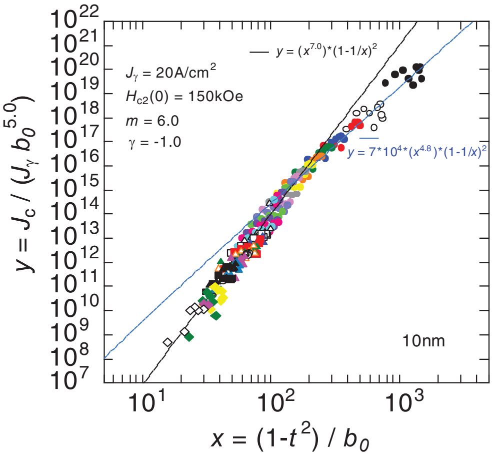

Fig. 4. Plot of reduced critical current density y in 10nm film as a function of x.

increase. Thus, the variation of m' with H is only in appearance, and such values at lower fields would reflect the intrinsic (constant) m'. From Fig. 2 we expect the intrinsic m' to be about 4.5.

Based on these considerations, we now examine applicability of the scaling equation (6) to the 50 nm MgB_2 film. In order to examine wide range of data with a single scaling formula for both temperature and magnetic field, eq. (6) is finally transformed to

$$J_c(b_0,t) / (J_\gamma b_0^{m-1}) = ((1-t^2)/b_0)^{m-\gamma}[1-b_0/(1-t^2)]^{\delta}. \tag{7}$$

It is noted that once the pinning parameters are given the right hand side of eq. (7) contains no adjustable parameter.

In the following discussion we assume $\delta = 2$ according to literatures [2,3]. The value of γ can be estimated from magnetic field dependence of J_c at constant temperature low enough to neglect the flux creep. From Fig. 3 in our previous report [4], we can regard the field dependence as $J_c(H) \sim H^{-0.5}$. In comparison with eq. (6), γ is estimated to be 0.5 and $m = m'+\gamma = 5.0$.

Putting values of the pinning parameters as $m = 5.0$, $\gamma = 0.5$ and $\delta = 2.0$, we plot in Fig. 3 experimental reduced critical current density $y = J_c / (J_\gamma b_0^{4.0})$ as a function of $x = (1-t^2)/b_0$. Here, we employed $H_{c2}(0) =$ 100 kOe according to Fig. 1. As can be seen, wide range of experimental data in temperature from 2 to 22 K and in field from 0.1 to 6.8 kOe are aligned in a single line. Either larger or smaller m than 5.0 results in gap among different sets of data (with different colors) for respective fields and deteriorate data alignment from the single line. This also supports appropriateness of the values of $m = 5.0$ and $\gamma = 0.5$.

The solid line in Fig. 3 represents eq. (7) as $y = x^{4.5}(1-1/x)^2$ and the line fits experimental data very well over 10 orders of magnitude in reduced J_c. The only adjustable parameter is the scaling factor J_γ which reflects the pinning strength but does not directly have to do with the critical current density itself, and the value of 0.6 MA/cm^2 results in the best agreement between experimental data and the scaling equation (7). It is noted that our analyses differ from generally employed scaling method in a sense that we use inverse variable $x = 1/b = (1-t^2)/b_0$ and that we explicitly treat temperature dependence of H_{c2}.

According to eq. (3) with the above parameters, however, the exponent n is expected to be 4.5 and this does not agree with our previous report [4] on the scaling behavior of H_{irr} with $n = 3$. This is a remained problem which needs further investigations.

As for the scaling behavior of J_c in the 10 nm film, agreement between experimental data and the scaling law of eq. (7) is poor. In fact, generally employed values for gamma ($0 < \gamma < 1$) cannot explain experimental J_c and if we dare to fit J_c data with eq. (7) we are forced to take $\gamma = -1.0$ as shown in Fig. 4. Although other parameters such as $H_{c2}(0) = 150$ kOe and $m = 6.0$ are fair in comparison with Fig. 1 and 2 (similar fitting is obtained for the 10 nm film), J_γ of 20 A/cm^2 is much lower than that for the 50 nm film. This infers that the pinning strength of the 10 nm film is extremely weak, and the flux creep effect is significant. In addition to these anomalies, it is recognized that experimental J_c data indicate a kink around the middle field. Dependence on x becomes weaker for lower fields and lower temperatures. In this region, the flux creep effect is less significant, and scaling behavior may be closer to the normal flux pinning similar to that in the 50 nm film. The position of the kink seems to correspond to the field values where sudden drops of J_c occurred in our previous report [5], and this may be related to dimensional crossover between 3D and 2D flux pining.

In conclusion, scaling behaviors of J_c in MgB_2 thin films are examined in comparison with the flux pinning model. The scaling behavior in the 50 nm film is well explained by the model without flux creep effect over 10 orders of magnitude in the reduced J_c, which corresponds to good film quality and sound superconductivity of the 50 nm film. On the other hand, scaling behavior in the 10 nm film is quite anomalous, and this is probably related to unconventional character of the film with very short coherence length, weak pinning and granular or low dimensional superconductivity.

Acknowledgements

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