Scaling analyses on the critical current density in MgB$_2$/SiC/Si thin film processed at higher temperature

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Abstract. Scaling analyses are performed on the critical current density $J_c$ in MgB$_2$/SiC/Si thin film processed at higher temperature, in comparison with similar films processed at lower temperature. Experimental $J_c$ data under magnetic field perpendicular to the film surface are reduced against transition temperature and critical field, and then analyzed with the comprehensive scaling formula, which turns out to fit experimental data remarkably well over 15 orders of magnitude.

1. Introduction
In our previous articles [1,2] we studied scaling behaviors in MgB$_2$ thin films, and showed that single scaling formula without flux creep effect is able to fit critical current density in 50 nm and 100 nm films for more than nine orders of magnitudes, corresponding to good film quality and sound superconductivity.

In order to further investigate applicability of the formula, we here investigate critical scaling behavior of another 50 nm MgB$_2$ thin film processed at higher temperature. We utilize experimental data of the upper critical field, critical current density and irreversibility field and compare them with the comprehensive scaling formula [1,2] on the basis of reduced critical current density as a function of reduced combination parameter of magnetic field and temperature, which is formulated as follows.

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

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

where $A$ is a constant, $H_{c2}(T)$ is the upper critical field, and $m$, $\gamma$ and $\delta$ are parameters depending on the flux pinning mechanism [3]. With the scaling parameters $J_c = A\mu_0^{1/m}H_{c2}^{-m/(\gamma+1)}(0)$ and $b_0 = \mu_0H / \mu_0H_{c2}(0)$ and empirical temperature dependence of $H_{c2}(t) = H_{c2}(0)(1-t^2)$ with $t = T/T_c$, equation (1) gives the scaling formula as:

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

which is finally transformed to:
\[ J_c(b_0, t) / (J_\gamma b_0^{m-1}) = (1 - t^2) / (b_0(1 - t^2))^\delta. \]

It should be noted that once the pinning parameters are given the right hand side of equation (3) contains no adjustable parameter.

2. Experimental

MgB\(_2\) film with 50 nm thickness studied here is the same film as in our past report [4], which was prepared by sequential evaporation of boron and magnesium on SiC-buffered Si substrate followed by in-situ annealing. In our earlier stage of investigation, we processed as-deposited films at rather higher temperature of 830°C, and later we found that lower temperature annealing at 750°C results in better quality of MgB\(_2\). Moreover, XPS analyses [5] of the film revealed that higher temperature annealing has severely degraded the crystallinity of MgB\(_2\), giving rise to BO\(_x\) species, and the film thickness (of MgB\(_2\) portion) should be regarded as 50 nm instead of 200 nm as cited in that report [4], where the comprehensive scaling analysis on \(J_c\) was not yet performed. Thus we here reanalyse our previous \(J_c\) data and examine applicability of the scaling formula in the film of different quality.

AC and DC magnetizations were measured using PPMS magnetometer (Quantum Design). The upper critical field \(H_{c2}\) was estimated from AC susceptibility measurements with magnetic fields parallel and perpendicular to the film, while the critical current density \(J_c\) was evaluated from DC magnetization hysteresis under perpendicular magnetic field with the Bean critical state model: \(J_c = 30 \Delta M / r\), where \(\Delta M\) is the height of the magnetization loop and \(r\) is the sample half-width (0.11 cm).

3. Results and discussion

Temperature dependence of the upper critical field \(H_{c2}\) is plotted in figure 1 with the same data as in the past report [4]. Least square fitting (straight line) to the perpendicular data (solid circles) gives estimation of \(H_{c2}^\perp(0) = 125\) kOe, which is higher than that of 750°C-annealed 50 nm film probably due to BO\(_x\) impurities. This value will be used later for the normalization of the applied fields, i.e. \(b_0\) parameter in equation (3).

![Figure 1](image1.png)

**Figure 1.** Upper critical field \(H_{c2}\) for 830°C-annealed 50 nm film under perpendicular (solid circles) and parallel (open circles) fields. Least square fitting (solid line) to the perpendicular data gives estimation of \(H_{c2}^\perp(0) = 125\) kOe, which is higher than 750°C-annealed 50 nm film.

![Figure 2](image2.png)

**Figure 2.** Variation of \(J_c\) as a function of \(1 - t^2\) with \(t = T / T_c\) for 830°C-annealed 50 nm film. Solid lines indicate best linear-fits to respective \(J_c\) at respective values of constant magnetic field by \(J_c(t) = J_c(0)(1 - t^2)^m\) scaling equation.
Figure 2 shows the critical current density $J_c$ in 830°C-annealed 50 nm MgB$_2$ film as a function of $1-t^2$ with $t = T/T_c$, ($T_c = 32.0$ K) at each value of constant magnetic field perpendicular to the film. Note that $J_c$ values are 4 times larger than those in ref. [4] because of the reduction in thickness estimation. The solid straight lines in the figure indicate least square fittings with the scaling equation:

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

which give the critical exponents $m'$ at respective magnetic fields.

Thus estimated $m'$ values are plotted in figure 3 as a function of the applied magnetic field $H$. As discussed previously [1,2], if the applied magnetic field is small, the temperature dependent contribution from $[1-b_0/(1-t^2)]^\delta$ term can be neglected and equation (2) reduces to equation (4) with $m' = m-\gamma$. Thus, the intrinsic value of $m'$ can be deduced from the lower field values of the exponents. Taking average of the lowest three values in figure 3, we obtain the intrinsic critical exponent in equation (4) as $m' = 4.8$.

![Figure 3](image-url)  
**Figure 3.** Critical exponent $m'$ increases with increase in the applied magnetic field. Average of the lowest three values provides the intrinsic critical exponent as $m' = 4.8$.

![Figure 4](image-url)  
**Figure 4.** Critical current density $J_c$ in 830°C-annealed 50 nm MgB$_2$ film as a function of perpendicular magnetic field $H$. The solid line indicates field dependence as $J_c(H) \sim H^{-0.8}$, which is comparable with experimental field variation.

The value of $\gamma$ can be estimated from magnetic field dependence of $J_c$ at constant temperature low enough to neglect the flux creep effect. Figure 4 shows critical current density $J_c$ in 830°C-annealed 50 nm MgB$_2$ film as a function of perpendicular magnetic field $H$. The solid line indicates the field dependence as $H^{-0.8}$ which is comparable with experimental field variation of $J_c$ at lower temperatures. Thus, we can regard the field dependence of the critical current density without flux creep as $J_c(H) \sim H^{-0.8}$. Comparing this dependence with equation (2), we obtain $\gamma - 1 = -0.8$ and thus $\gamma$ is estimated to be 0.2, which further results in $m = m' + \gamma = 5.0$.

This value of $m$ is identical with the value in 750°C-annealed 50 nm film and infers surface pinning effects as suggested before [2]. However, the value of $\gamma = 0.2$ is smaller than 0.5 in 750°C-annealed films and may indicate some effects due to BO$_x$ impurities and degradation of the film caused by higher temperature annealing. The value of $\delta$ is assumed to be 2.0 according to the literature [6,7].
This value of $\delta = 2.0$ corresponds to the presence of saturation effects in the summation problem for the total pinning strength, the assumption being always employed in our scaling analyses [1,2].

![Graph showing reduced experimental critical current density](image)

**Figure 5.** Plot of reduced experimental critical current density $y = J_c/({J_\gamma b_0}^{4.0})$ in 830°C-annealed 50 nm film as a function of $x = (1-t^2)/b_0$ with $b_0 = H/H_{c2}(0)$. The solid line represents $y = x^{4.8}(1-1/x)^2$, which fits experimental data remarkably well over 15 orders of magnitude in reduced $J_c$.

Putting values of these pinning parameters in equation (3) as $m = 5.0$, $\gamma = 0.2$ and $\delta = 2.0$, we plot in figure 5 experimental reduced critical current density $y = J_c/({J_\gamma b_0}^{4.0})$ as a function of $x = (1-t^2)/b_0$ under perpendicular magnetic field. Here, we employed $H_{c2}(0) = 125$ kOe according to figure 1. As can be seen, the wide range of experimental data in temperature from 10 to 20 K and in field from 0.1 to 40 kOe are aligned in a single line. This is a remarkable result. Either larger or smaller $m$ than 5.0 deteriorates data alignment from the single line. This also supports appropriateness of the values of $m = 5.0$ and $\gamma = 0.2$. Some scattered downward deviations from the line especially below $x = 50$ would indicate some effect of thermal flux creep which may happen at higher temperature and higher magnetic field, i.e. at smaller $x$.

The solid line in figure 5 represents equation (3) as $y = x^{4.8}(1-1/x)^2$ and the line fits experimental data very well over 15 orders of magnitude in reduced $J_c$. This is even more remarkable compared to our previous analyses in 750°C-annealed films [1,2]. On making such fit, the only adjustable parameter is the scaling factor $J_c$ which reflects the pinning strength through the factor $AH_{c2}^{m-1}(0)$ in equation (2), and the value of 20 kA/cm$^2$ results in the best agreement between experimental data and the scaling equation (3). This value of $J_c$ is one order of magnitude smaller than our 750°C-annealed 50 nm film. This may also be due to additional impurities of BO$_x$ appeared by higher temperature annealing.

Finally, we examine behavior of the irreversibility field $H_{irr}$, which is the criterion of occurrence of flux creep. At higher temperatures $H_{irr}$ follows the well-known scaling relation:
\[ H_{irr}(t) = H_{irr}(0) (1-t^2)^n \]  

(5)

where \( n = \frac{2(m-\gamma)(3-2\gamma)}{3-2\gamma} \) [2,6]. Putting values of \( m = 5.0 \) and \( \gamma = 0.2 \), we obtain \( n = 3.7 \) which seems rather closer to averaged critical exponent \( n \) in our past report (figure 4) [4].

In summary, scaling behaviors of \( J_c \) in 830°C-annealed 50 nm MgB₂ film are analyzed in comparison with 750°C-annealed MgB₂ films. Higher \( H_{c2} \) results in good fitting of reduced experimental data by the comprehensive single scaling formula over 15 orders of magnitude which is an even wider range than our previous analyses in 750°C-annealed films. Higher \( H_{c2} \) and smaller \( \gamma \) are suggested to be due to BO\( \delta \) impurities produced by higher temperature annealing. On the other hand, same value of \( m \) infers surface pinning effects in our all 50 nm and 100 nm thin films. Thus, the present work further enhances our conclusion that the theoretical scaling formula (equation (3)) is well applicable to \( J_c \) without flux creep effect and is useful to predict practical \( J_c \) values in various MgB₂ films under wide temperatures and fields.

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