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Power-law relationship between critical current density, microstructure, and the n-value in MgB2 superconductor wires

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Abstract

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Keywords

relationship, law, value, power, critical, between, current, mgb2, density, wires, superconductor, microstructure, n

Disciplines

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Power-law relationship between critical current density, microstructure, and the *n*-value in MgB_2 superconductor wires

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Abstract

Dissipation-free MgB_2 superconducting wires are valuable in terms of practical applications. Herein, we have found a strong correlation between critical current density (J_c) and the *n*-value extracted from the electric field versus current density characteristic. The power-law relationship (*m*) between the J_c and the *n*-value, $n \propto J_c^m$, represents a critical index which is strongly dependent on operating temperatures.

Keywords: magnesium diboride, critical current density, power law, *n*-value

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Very recently, further enhancement of the critical current density, J_c, and the irreversibility field, B_{irr}, has been reported for carbon doped MgB_2 wires with malic acid additive, produced by the chemical solution method [1-5]. In terms of monofilament conductor, a high J_c of 23,000 Acm^{-2} at 4.2 K and 10 T was achieved in our previous study [6]. However, an inherent problem for MgB_2 wire is still the low mass and low volume densities, which are due to its porous nature. In addition, commonly used carbon dopant, which is known to be effective for achieving a larger upper critical field, tends to aggregate at grain boundaries as a residue, due to the limit of carbon solubility in the MgB_2 structure. Thus, both porosities and residual carbon could act as major current-limiting factors, which are directly reflected in the electric field (E) − current density (J) characteristic.

The E-J characteristic is commonly known to be a crucial index for optimization of the design of superconducting applications. For example, typical values of n for "persistent magnet-grade" conductors are required to be 50-100. However, the index resistance due to low n-value, 10-20, of MgB_2 at higher operating temperature close to 25 K and 3-4 T applied magnetic field is expected to make it impossible to operate an MgB_2-based magnet in persistent mode, i.e., <0.01 ppm/hr, even if all joints are superconducting [7]. From the viewpoint of materials, a high quality sample usually shows a larger n-value, defined by the close approximation of the E-J characteristic by a curve $E \propto J^n$. This means more homogeneous microstructure causes larger n-value. Compared with high temperature superconductors [8], MgB_2 shows a sharper transition from the superconducting state to the normal state with increasing transport current. However, its voltage rise due to its low n–value cannot be negligible, even below the critical current, because it can lead to electrical and thermal dissipation. Thus, dissipation-free superconductor wires have been the primary issue for practical application. For these reasons, it is necessary to investigate the effects of carbon dopant on the n-value and microstructure. In this study, we have evaluated in detail the relationship between J_c, microstructure, and the n-value in the best performance carbon doped wire obtained through malic acid doping.

MgB_2/Nb/Monel monofilament wire with 10wt% malic acid additive and un-doped MgB_2 wire as a reference for comparison, both fabricated by Hyper Tech Research Inc., were studied in this work. Details of the experiments have been described elsewhere [1, 6]. Transport critical current up to 400 A was measured by using the standard four-probe method with a criterion of 1 μVcm^{-1}. The magnetic field was increased up to 18 T, while the temperature was varied within the range of 4.2 K to 30 K. The n-values were determined from the slope in the plot of log E versus log J in the electric field (E) range from 0.1 to 10 μVcm^{-1}, based on the power law, $E_c = E(V/V_c)^n$, Where the E_c represents the critical potential V_c in unit length. The critical temperature (T_c) was determined by AC susceptibility measurements at f = 76.97 Hz with $\mu_0 H_c$ = 50

μT, where H_c is the upper critical field. Microscopic studies were carried out using a JEOL JEM-2500SES, a Cs-corrected STEM equipped with a Gantan 776 EELS (Enfina 1000).

In order to determine the optimal sintering temperature, transport J_c values for malic acid doped wires sintered at different temperatures were collected and are shown in Figure 1. Quite interestingly, even when sintering at a temperature as low as 550^{o}C, the J_c is still as high as ~18,000 Acm^{-2} at 4.2 K and 10 T. Further enhancement of the J_c is achievable by slightly increasing the sintering temperature and decreasing the sintering time, for example, J_c was 25,000 Acm^{-2} when the sample was sintered at 600^{o}C for 4 hours. At an external magnetic field of 11.7 T, the J_c is still around 10,000 Acm^{-2}. On the other hand, the J_c of the reference un-doped wire sintered at 650^{o}C for 30 min was about an order of magnitude lower, about 2,800 Acm^{-2} at 4.2 K and 10 T. Interestingly, transport J_c values were found to be strongly dependent on the sintering temperature, which can lead to differences in the T_c. The T_c of the un-doped wire is 36 K, but T_c of all the carbon-doped wires is approximately 34 K. Corresponding to this reduction in T_c, the *a*-lattice parameter of the malic-acid doped wires was decreased from 3.0832(2) to 3.0758(2) Å. This can be attributed to volume shrinkage due to carbon substitution.

Among them, we choose the best performance wire sintered at 600^{o}C for 4 hours and temperature dependence of $J_c(B)$ is shown in Figure 2(a). We observed that the J_c normally decreased with increasing magnetic field. In addition, the slope of $J_c(B)$ became steeper with increasing operating temperature. It is noteworthy that critical current density values at 4.2 K and 20 K are still above 10^4 Acm^{-2}, even in fields up to 10 T and 5 T, respectively. The corresponding *n*-values are shown in Figure 2(b). This behaviour is similar to that of $J_c(B)$ under different operating temperatures. Here, our natural question is then why the *n*-value is crucial. It is well known that electrical and thermal properties are significantly degraded at inhomogeneous parts of a sample, thereby reducing the stability of the whole system [7, 9, 10]. In particular, the non-uniformity in the conductor can result in "hot spot formation" that leads to localized thermal quenching [11]. For Nb_3Sn, the *n*-value sharply decreases as the field approaches the upper critical field, and the critical current also decreases sharply [8, 12]. On the other hand, for $YBa_2Cu_3O_7$ (YBCO) coated conductor, the decrease in the critical current density is rather gradual, and the *n*-value also changes gradually at the same time [13]. This proves that different kinds of superconducting wires show unexpected *n*-value behaviour under magnetic fields. This is why it would be informative if we can understand behaviour of *n*-value for the MgB_2 wire under different fields and operating temperatures.

As was noted, effect of dimensional defects in MgB_2 necessary to study on the current-carrying performances, i.e., carbon doping. When carbon is doped into the MgB_2, it is believed that it substitutes for boron, stiffens the optical E_{2g} phonon mode, which is strongly linked with anisotropic σ bands, hence, lowers the transition temperature [14]. Even if carbon doped wire still shows better J_c, inhomogeneous microstructure remains rooms for degradation of n-value. Figure 3 shows a lattice distortion inside MgB_2 grain. Many dislocations can be occurred, resulting in severe crystallographic imperfections. These structural defects produce an increase in the impurity scattering rate, which thereby enhance the upper critical field and the high-field J_c. However, it simultaneously leads to lower n-value.

The power-law relationship between the J_cs and the n-values of wire evaluated over all temperature ranges is shown in Figure 4. The index m value was estimated to be 0.399, which is comparable to our previous result [14]. In the literatures, Martinez et al, Kitaguchi et al, and Li et al reported that m-indexs were estimated to be 0.72, 0.69, and 0.5, respectively [15-17]. Among these, HIPed bulk samples show larger m-value [16]. This means it depend on microstructure even if m-index does not vary much. It is noteworthy that higher J_c values can be attributed to larger n-values. From our results, the quantitative n-value of current MgB_2 wire is demonstrated to need further improvement, especially for persistent magnet-mode.

In summary, the correlation between J_c and the n-value in MgB_2 superconducting wires was evaluated under different operating temperatures. From the E-J characteristics, we found that J_c is proportional to the n-value, which is strongly dependent on the operating temperature. Large n-values > 30 are expected to make it possible to operate an MgB_2-based magnet in persistent mode at 20 K.

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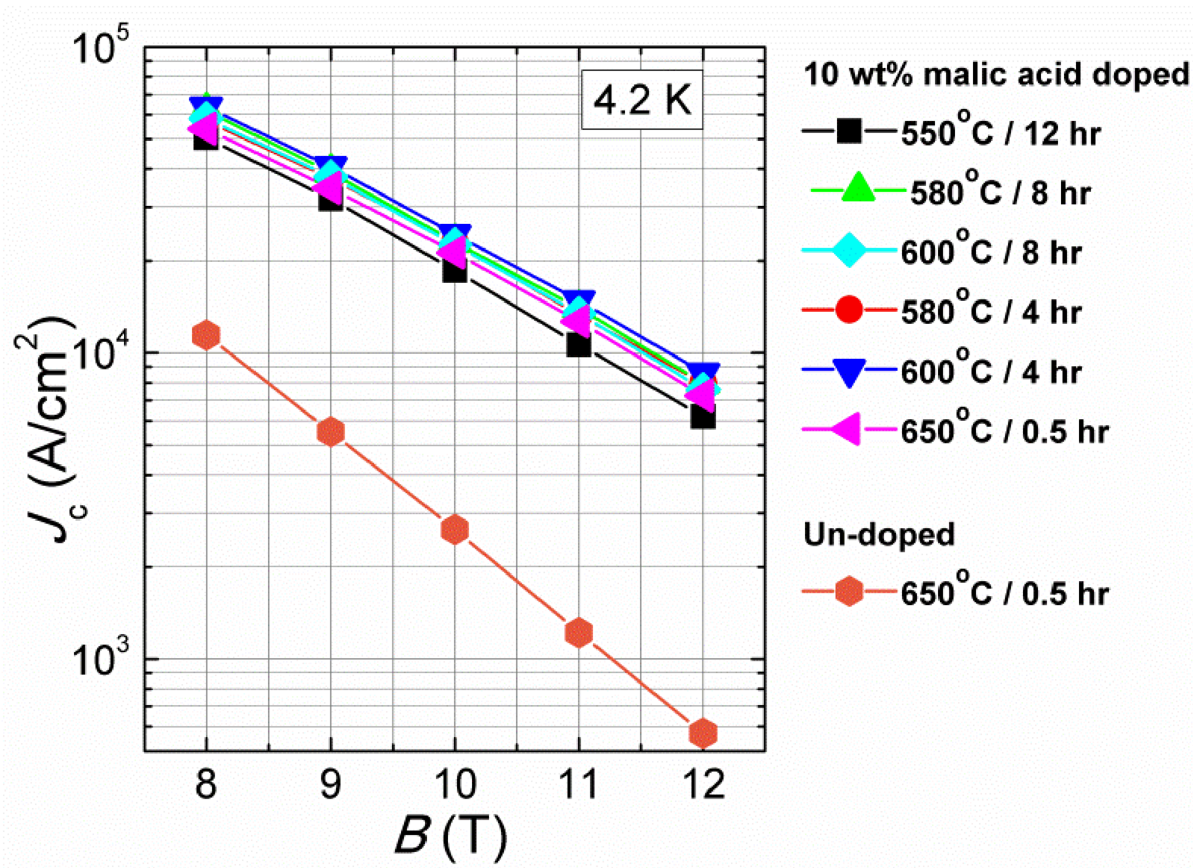
Figure Captions

Fig. 1. Magnetic field dependence of the transport J_c for malic acid-doped MgB_2 wires with different sintering temperatures.

Fig. 2. (a) Magnetic field dependence of the transport J_c, and (b) magnetic field dependence of the *n*-value at 4.2, 10, 14, 20, 25, and 30 K for malic acid-doped MgB_2 wires.

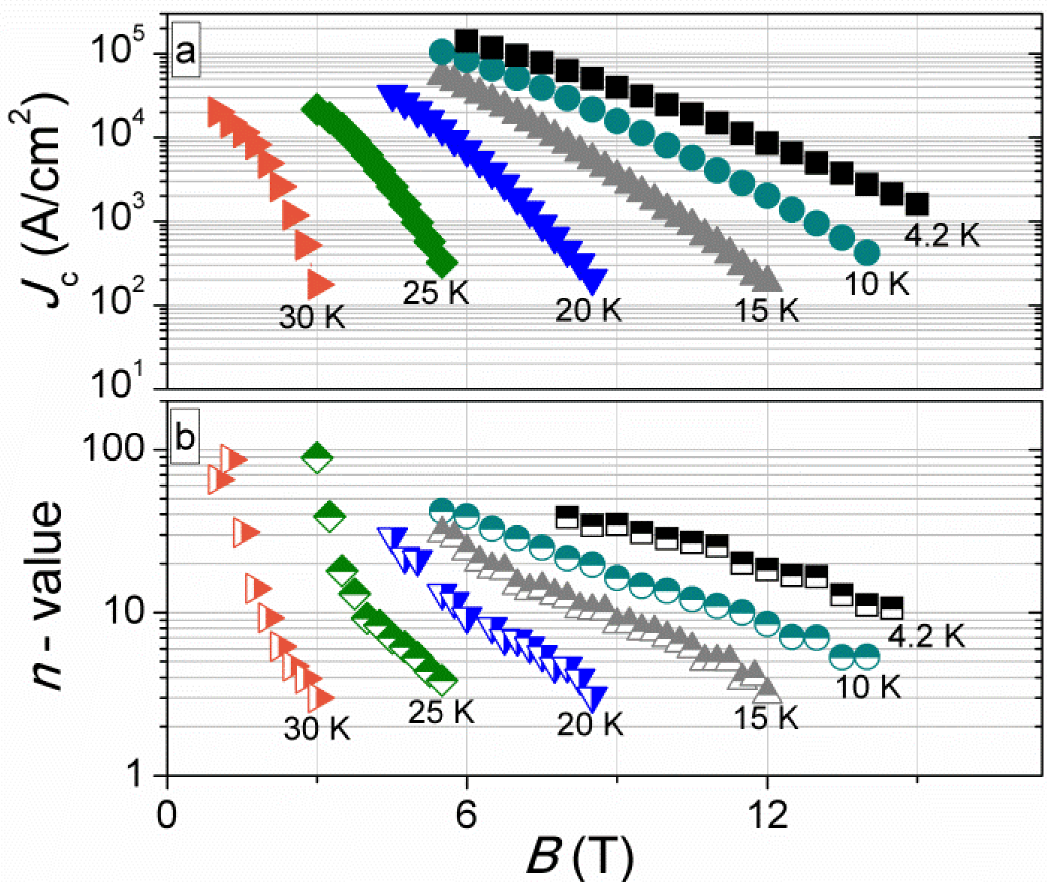
Fig. 3. Lattice distortion inside carbon doped MgB_2

Fig. 4. Correlation between the J_c and the *n*-value for malic acid-doped MgB_2 wire in the operating temperature range of 4.2 to 30 K.



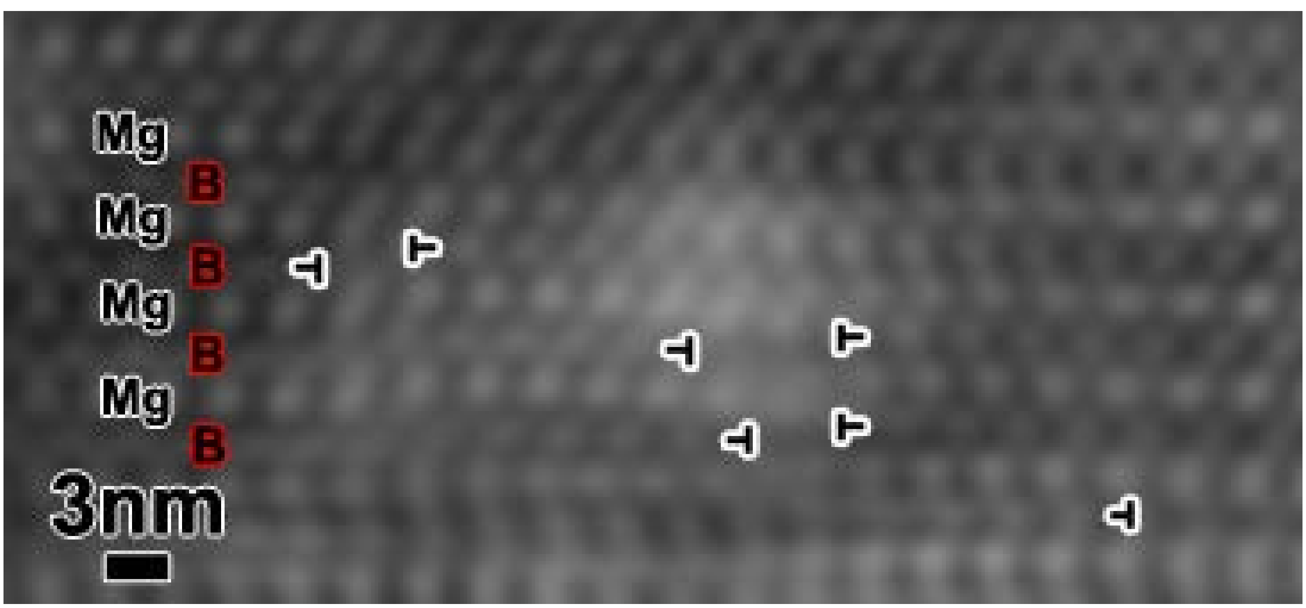
4.2 K
10 wt% malic acid doped
550°C / 12 hr
580°C / 8 hr
600°C / 8 hr
580°C / 4 hr
600°C / 4 hr
650°C / 0.5 hr
Un-doped
650°C / 0.5 hr
J_c (A/cm^2)
10^5
10^4
10^3
8
9
10
11
12
B (T)

Fig. 1



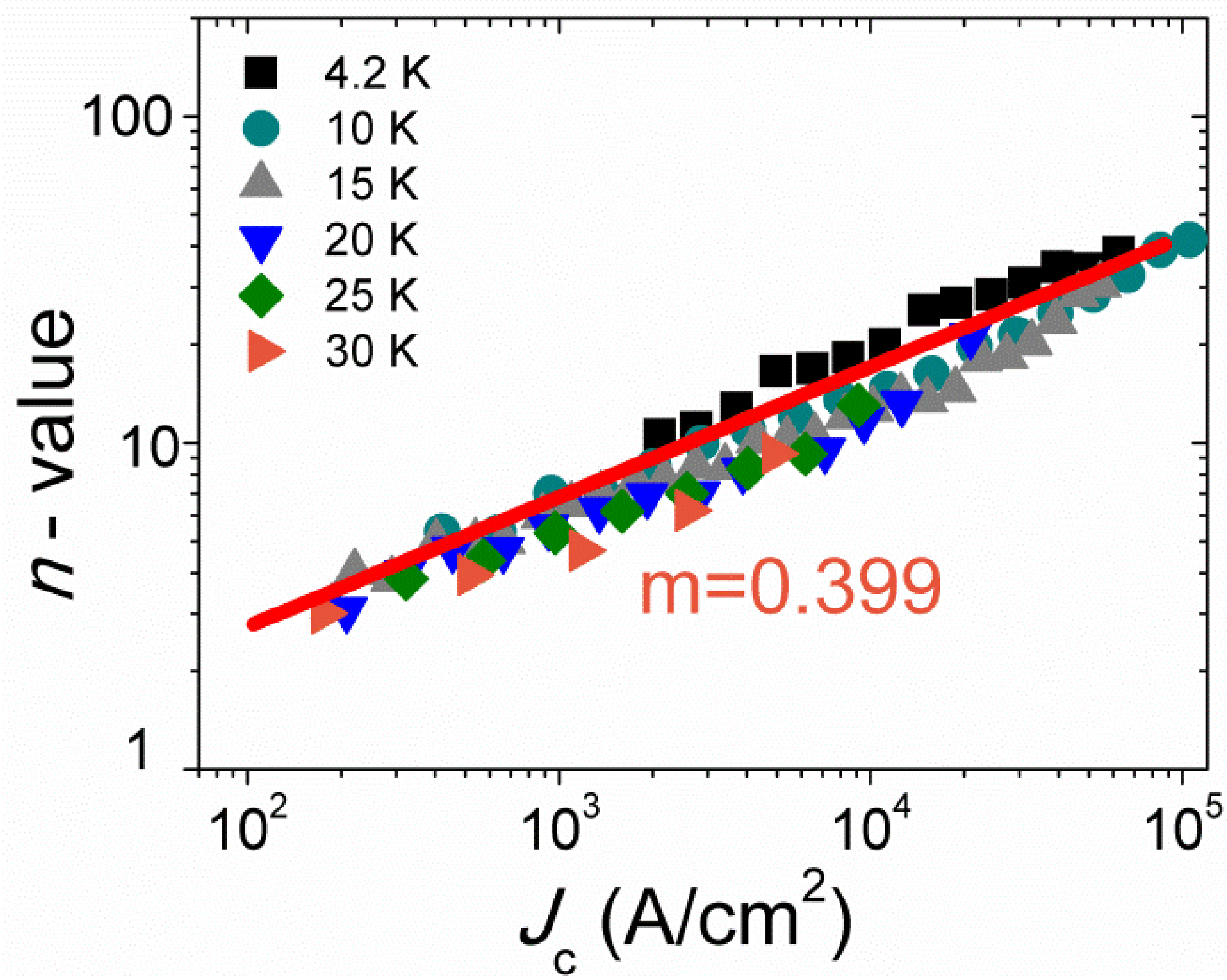
a
b
J_c (A/cm^2)
10^5
10^4
10^3
10^2
10^1
4.2 K
10 K
15 K
20 K
25 K
30 K
n - value
100
10
1
0
6
12
B (T)

Fig. 2



Mg
B
Mg
B
Mg
B
Mg
B
3nm

Fig. 3



4.2 K
10 K
15 K
20 K
25 K
30 K
m=0.399
n - value
100
10
1
10^2
10^3
10^4
10^5
J_c (A/cm^2)

Fig. 4