Effect of sample size on the magnetic critical current density in nano-SiC doped MgB_2 superconductors

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The effect of sample size on the critical current density and the flux pinning of pure and SiC doped MgB_2 bulk samples has been investigated. At high fields a systematic degradation of magnetic J_c and H_{irr} was observed as the sample size decreased. However, J_c remarkably increased on decreasing the sample volume at low magnetic fields below 1 T. The SiC doped samples show less sample size effect than the pure samples, indicating a larger n factor and therefore a stronger pinning effect due to SiC doping. H_{irr} was observed to decrease as a logarithmic function of the sample volume, and the zero field J_c can be fitted as an exponential decay function.

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The recent discovery of MgB_2 superconductors[1] has attracted remarkable attention. It shows great potential for applications due to its relatively high transition temperature. Improving the critical current density (J_c) is one of the most important issues so far as applications are concerned. One of the best J_c field performances has been reported recently for nano-SiC doped MgB_2 bulk and wires.[2,3] Results show that SiC doped MgB_2 superconductors are one of the best candidates for high-field applications.

In contrast to the direct transport J_c measurements used for tapes and wires, for bulk samples one has to calculate the magnetic J_c from the dc magnetization using the Bean model. In our recent work we have shown that the magnetic J_c strongly depends on the sample size.[4] In contrast to the high-T_c superconductor materials[5] it was observed that in pure MgB_2 bulk samples H_{irr} decreased as the sample volume decreased. Due to the dependence of J_c on sample size, for a reliable comparison of J_c values derived from magnetic measurements, sample size has to be carefully taken into account.

Some explanations have been presented to explain this behavior. Jin *et al.* suggested a linear dependence of the activation energy on the J_c and gave an explanation for the J_c dependence on the sample size.[6] They proposed that in a cylindrical MgB_2 sample, vortices are remarkably rigid in small samples up to 1 mm long, while they behave as individual segments for longer samples. Horvat *et al.* qualitatively explain this phenomenon by considering the different coupling between the grains at different length scales.[4] Very recently Qin *et al.* established a model to explain this effect. Based on this model, the magnetic J_c depends on sample size as $J_c \propto R^{1/n}$ where R is the radius of a cylindrical sample and n is the n factor characterizing the E-J curve $E = E_c(J/J_c)^n$.[7] They proposed that the low-n factor at high magnetic fields is the reason for the significant sample size effect for pure MgB_2 superconductors.

As the nano-SiC doped sample exhibited much stronger flux pinning than the pure MgB_2, we intend to investigate the size effect in the strong pinning samples and compare them with pure MgB_2 samples. A detailed study with the aim to further understand the sample size effect in both pure and doped MgB_2 superconductor is presented in this paper.

Two groups of polycrystalline MgB_2 and MgB_2+10% SiC samples were synthesized from high-purity Mg and B and nano-SiC powders using the high isostatic pressure (HIP) method. The sample preparation details have been explained elsewhere.[8] The magnetization was measured over a temperature range of 5 K to 30 K using a physical properties measurement system (PPMS, Quantum Design) in a time-varying magnetic field of sweep rate 50 Oe/s and amplitude 9 T. Bar-shaped samples were cut and dry polished from each pellet for magnetic measurements. The shiny polished surface was golden and black for the pure and doped samples, respectively. The sample volume was decreased about 75% through sawing and dry polishing after each measurement. To avoid any geometrical effect on the results, each dimension is reduced by a factor of about 0.35% (i.e., the ratio of a:b:c remains constant) before each subsequent measurement.

The sample information is presented in Table I. The magnetic measurements were performed by applying the magnetic field parallel to the longest sample axis. The magnetic J_c was calculated from the height ΔM of the magnetization loop (M-H) using the Bean model, where $J_c = 20\Delta M/[a/(1-a/3b)]$, where a and b are the dimensions of the sample perpendicular to the direction of the applied magnetic field with $a<b$. J_c versus magnetic field was measured up to 8.5 T for all the samples at 5 K, 10 K, 20 K, and 30 K. T_c was determined to be 38.6 K and 37.05 K for the pure and doped samples, respectively. A small bar shaped sample of the same size as sample 4 was directly cut from the same batch and given a J_c measurement. No significant difference was found between the results for this sample and for sample 4, indicating that the repeated polishing and measurements had no effect on the samples.

The field dependence of J_c for SiC doped and undoped MgB_2 samples at 5 K, 20 K, and 30 K for samples of different sizes are presented in Figs. 1(a) and 1(b), respectively. It can be clearly seen that in both doped and undoped samples the J_c field performance strongly depends on the sample size. At high fields, J_c significantly decreased as a function

TABLE I. The dimensions of samples prepared for magnetic measurements. Each dimension was reduced by about 35% before each subsequent measurement. The magnetic field was applied parallel to the c axis

	Undoped				Doped			
Sample	a (mm)	b (mm)	c (mm)	V (mm^3)	a (mm)	b (mm)	c (mm)	V (mm^3)
1	1.07	3.27	7.15	25.01	1.12	2.98	6.95	23.195
2	0.7	2.12	4.65	6.9	0.698	2.116	4.616	6.817
3	0.456	1.34	2.92	1.78	0.448	1.342	2.902	1.745
4	0.29	0.85	1.87	0.46	0.295	0.847	1.805	0.451

of the magnetic field as the sample size decreased. On the other hand, the low-field J_c increased as the sample size decreased in both pure and doped samples. These changes in either low fields or in high fields are stronger in the lower-temperature regime.

Flux jumping was observed in both pure and doped samples but flux jumps occurred at higher fields for bigger samples. Flux jumping was also found to be less serious in the doped samples. For sample 1 flux jumping was observed up to 3.9 T for the doped sample, but in the pure sample flux jumping can be seen even at 5 T. Flux jumping also occurred in the pure samples 1 and 2 at 20 K, but no flux jumping was observed in the doped samples at 20 K.

The ratio of J_{c1}/J_{c4} for samples 1 and 4 between 5 T and 8.5 T for both pure and doped samples at 5 K are presented in Fig. 2. For both samples the larger the sample, the higher the J_{c1}/J_{c4} ratio. However, the sample size dependence is much more pronounced in the undoped sample. At 6.5 T and 5 K J_{c4} is lower than J_{c1} by a factor of 1.8 for the doped samples. However, under the same conditions, J_{c4} is more than one order of magnitude lower than J_{c1} in the pure samples. The J_c field dependence of the doped samples at low magnetic fields and 20 K are shown in the inset of Fig. 2. As we can see, the zero-field J_c increases as the sample size decreases. However, the differences between the J_c values of all the samples are reduced by increasing the magnetic field. The J_c field dependence curve of sample 1 crosses over the J_c curves of the smaller samples at a magnetic field of about 1 T. The same behavior was also found in the pure samples.

The dependence of the irreversibility field H_{irr} on the volume of pure and doped samples at 20 K is shown in a semilogarithmic plot in Fig. 3. H_{irr} was determined from J_c-H curves using the criterion of 100 A/cm^2. Some points for the pure samples were extracted from our previous work.[4] As we can see, H_{irr} decreases logarithmically as the sample volume decreases. The irreversibility field H_{irr} versus the sample volume is plotted in the inset with linear scaling, showing a gradual saturation behavior as the sample volume increases. Almost the same trend was found at other temperatures as well.

Figure 4 shows the dependence of the zero-field critical current (J_{c0}) on the sample volume of pure and doped samples at 20 K and 30 K. Some points for pure samples

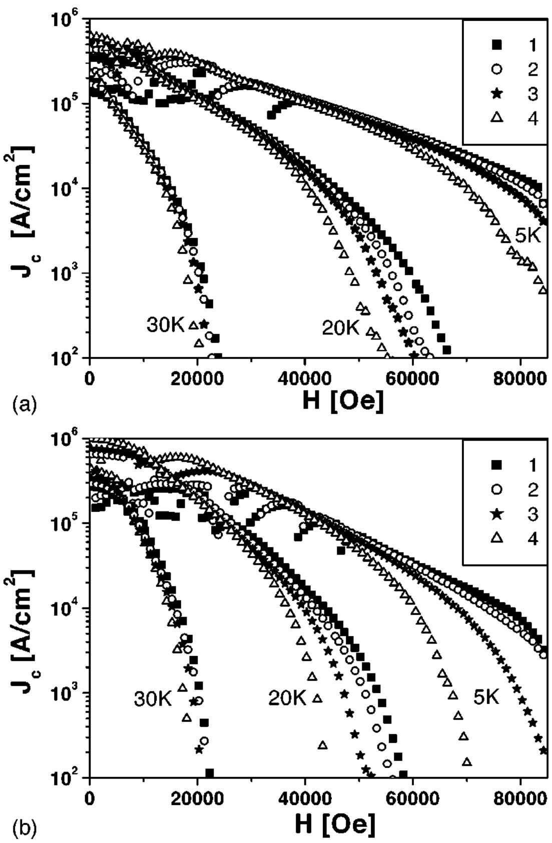

FIG. 1. (a) Magnetic J_c field dependence of the MgB_2 +10%SiC samples of different sizes (Table I) at 5 K, 20 K, and 30 K. (b) Magnetic J_c field dependence of the pure MgB_2 samples of different sizes (Table I) at 5 K, 20 K, and 30 K.

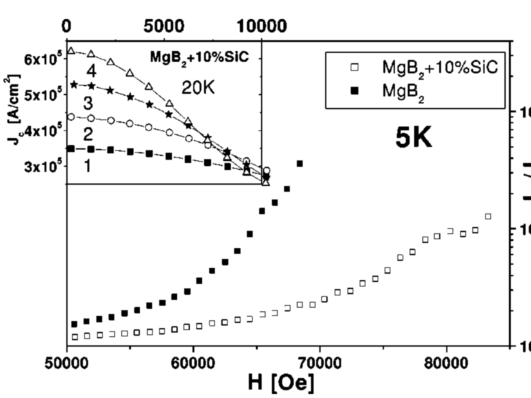

FIG. 2. The ratio of J_{c1}/J_{c4} between 5 T and 8.5 T for both pure and doped samples at 5 K. The J_c field dependence of doped sample at low magnetic fields at 20 K is shown in the inset.

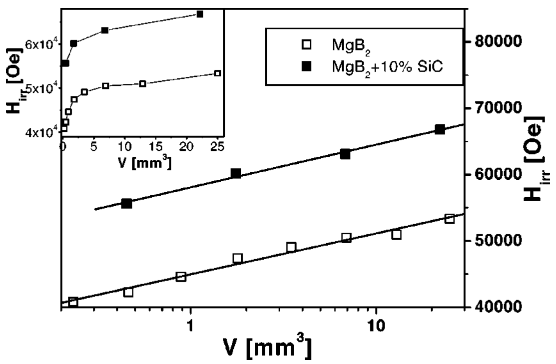

FIG. 3. The dependence of H_{irr} samples on the sample volume of pure and doped MgB_2 at 20 K in a semilogarithmic plot. H_{irr} versus the volume with linear scaling is shown in the inset.

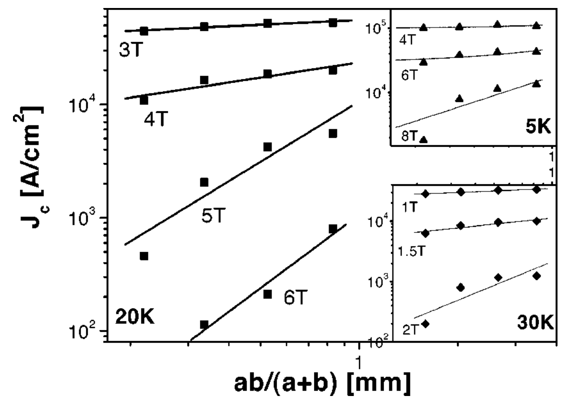

FIG. 5. The sample size dependence of J_c for doped MgB_2 samples at 20 K. The same dependence is plotted in the insets for 5 K and 30 K. The solid lines are linear fits to the data.

were extracted from our previous work.[4] All J_{c0} values were normalized to the J_{c0} value of the biggest sample. Over all temperature ranges the smaller samples had a higher J_{c0}. For pure samples the normalized J_{c0} increases slightly as the sample volume decreases down to $7\,\mathrm{mm}^3$, followed by a faster increase for smaller sample volumes. J_{c0} can also be very well scaled for both 20 K and 30 K with the same curve. However, for doped samples, J_{c0} increases more gradually than for the pure samples as the sample size decreases.

Moreover, the J_{c0} values for 20 K and 30 K cannot be scaled using the same curve. The difference between the normalized J_{c0} values for 20 K and 30 K is increased by decreasing the volume. The lower the temperature, the faster J_{c0} increases. The absolute value of J_{c0} versus the sample volume for pure and doped samples at 20 K is plotted on a logarithmic scale in the inset to Fig. 4. The curves can be fitted as an exponential decay function as is shown in the figure (lines).

Based on the Qin *et al.* method we have plotted $\ln(J_c)$ versus $\ln[ab/(a+b)]$ for the doped samples at 20 K and at 3 T, 4 T, 5 T, and 6 T in Fig. 5. Similar curves at 5 K and 30 K for different magnetic fields are presented in the insets of this figure. The solid lines are the best linear fittings between $\ln(J_c)$ and $\ln[ab/(a+b)]$. The inverses of the slopes give the n factors. Calculated n factors for the SiC doped samples are shown in Fig. 6 at 5 K, 20 K, and 30 K. The n factors of pure samples extracted from our recent work[7] are also included as open squares and open triangles for 5 K and 20 K, respectively. The solid lines are just guides to the eye.

As the n factor is the exponent characterizing the E-j curve $E=E_c(j/j_c)^n$, a large n factor will lead to a sharp E-j curve. On the other hand, the n factor can be calculated as $n=U_0/kT$,[7] where U_0 is the energy scale for the current density dependent activation energy $U(j)=U_0\ln(j_c/j)$ with k the Boltzmann constant. Therefore a large n indicates a stronger pinning effect. Moreover, the dependence of the current density on the sample size has been derived to be $j \propto R^{1/n}$, indicating that a large n will give rise to less sample size dependence. It can be seen from Fig. 6 that the n factors of the doped sample are much higher than those of the pure samples, indicating that strong pinning centers have been introduced into the MgB_2 samples by means of SiC doping. Figure 6 also explains the observed lesser sample size effect in the SiC doped samples shown in Figs. 1–3.

In conclusion we have studied the sample size effect in

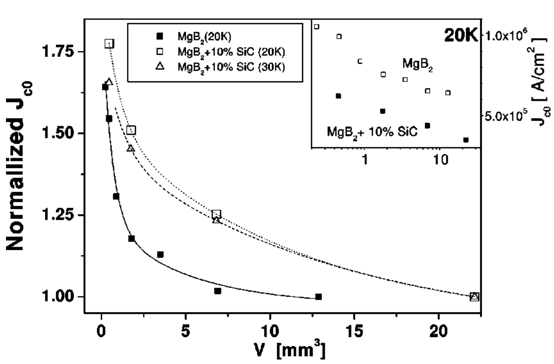

FIG. 4. The dependence of the zero-field J_c (J_{c0}) on the sample volume of pure and doped samples at 20 K and 30 K. In the inset the dependence of J_{c0} on the volume at 20 K is plotted on a logarithmic scale.

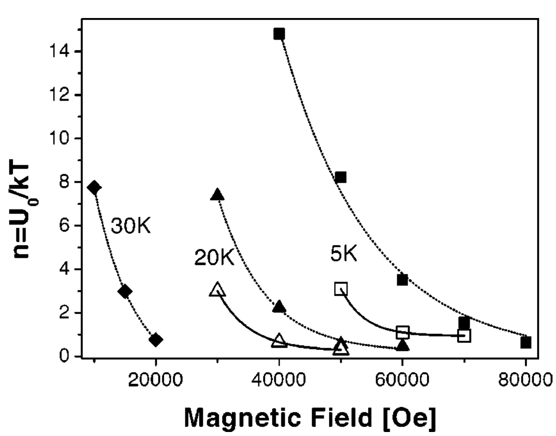

FIG. 6. The n factor versus applied magnetic field for the doped MgB_2 samples at 5 K, 20 K, and 30 K (solid symbols). The n factor of pure samples extracted from our previous work are also included (open symbols). The solid lines are only guides to the eye.

pure and SiC doped MgB_2 samples and derived the n factors for both samples. The doped samples show a larger n factor and less sample size dependence, indicating a stronger pinning effect by SiC doping in MgB_2 samples. The irreversibility field H_{irr} was found to increase with increasing sample volume as a logarithmic function. The zero-field J_c decreased with decreasing sample volume as an exponential decay function.

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