Enhancement of the critical current density and flux pinning of MgB2 superconductor by nanoparticle SiC doping

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Doping of MgB₂ by nano-SiC and its potential for the improvement of flux pinning were studied for MgB₂₋ₓ(SiC)ₓ/2 with x=0, 0.2, and 0.3 and for 10 wt% nano-SiC-doped MgB₂ samples. Cosubstitution of B by Si and C counterbalanced the effects of single-element doping, decreasing Tc by only 1.5 K, introducing intragran pinning centers effective at high fields and temperatures, and significantly enhancing Jc and Hirr. Compared to the undoped sample, Jc for the 10 wt% doped sample increased by a factor of 32 at 5 K and 8 T, 42 at 20 K and 5 T, and 14 at 30 K and 2 T. At 20 K and 2 T, the Jc for the doped sample was 2.4×10⁵ A/cm², which is comparable to Jc values for the best Ag/Bi-2223 tapes. At 20 K and 4 T, Jc was twice as high as for the best MgB₂ thick films and an order of magnitude higher than for the best Fe/MgB₂ tapes. The magnetic Jc is consistent with the transport Jc, which remains at 20 000 A/cm² even at 10 K and 5 T for the doped sample, an order of magnitude higher than the undoped one. Because of such high performance, it is anticipated that the future MgB₂ conductors will be made using a formula of MgB₃SiₓCₓ instead of pure MgB₂.

The critical temperature ($T_c$) was obtained as the onset of the diamagnetic transition in the magnetic ac susceptibility measurements. The transport $J_c$ was measured with the four-probe method using a pulsed current source.

Figure 1 shows x-ray diffraction (XRD) patterns for the SiC doped and nondoped samples. The XRD pattern for the nondoped sample (sample 1) reveals about 5% MgO, beside MgB$_2$ as the main phase. Samples 2 and 3 consist of MgB$_2$ as the main phase, with Mg$_2$Si as the major impurity phase (crosses in Fig. 1). The estimated fraction of Mg$_2$Si was 10%. The energy dispersive spectroscopy (EDS) analysis results showed that the Mg:Si ratio was identical over the entire sample area, indicating a homogeneous phase distribution.

Figure 2 shows magnetic $J_c(H)$ curves for the SiC-doped MgB$_2$ samples at 5 K, 20 K, and 30 K, for different doping levels. It is noted that all the $J_c(H)$ curves for doped samples show a crossover with the nondoped samples at higher fields. Although SiC doping caused a slight reduction of $J_c$ in low fields, it is much larger than for the nondoped samples in high fields for all the measured temperatures. Compared to the nondoped sample, $J_c$ for the 10 wt % doped sample increased by a factor of 32 at 5 K and 8 T, 23 at 15 K and 6 T, 42 at 20 K and 5 T, and 14 at 30 K and 2 T. This is the best $J_c(H)$ performance ever reported for MgB$_2$ in any form. It is noted that the $J_c(H)$ curves for the nondoped sample showed a rapid drop in high fields and a plateau near $H_{irr}$. Earlier, we ascribed this phenomenon to the grains de-

**FIG. 1.** XRD patterns for the nondoped and SiC-doped samples.

**FIG. 2.** The magnetic $J_c$ dependence at 5, 20, and 30 K for samples 1, 2, 3, and 4, shown by solid, dashed, and dotted lines, and crosses, respectively.

coupling at higher fields, as a consequence of impurities at the grain boundaries. In contrast, none of the SiC-doped samples show this phenomenon, as either the substitutions or the induced nano-inclusions are incorporated into the grains.

Figure 3 shows a comparison of magnetic $J_c(H)$ for a 10 wt % SiC-doped sample at 20 K with data reported in literature. $J_c$ for this sample exhibits a better field performance and higher values of $J_c$ in high field than any other element doped samples or nondoped wires. Our SiC-doped MgB$_2$ is even better than the thin-film MgB$_2$ (Fig. 3), which had exhibited the strongest reported flux pinning and the highest $J_c$ in high fields to date. At 20 K, the best $J_c$ for the 10 wt % SiC-doped sample was $10^5$ A/cm$^2$ at 3 T, which exceeds the $J_c$ values of state-of-the-art Ag/Bi-2223 tapes. At 20 K and 4 T, $J_c$ was $36 000$ A/cm$^2$, which is twice as high as for the best MgB$_2$ thin films and an order of magnitude higher than for the state-of-the-art Fe/MgB$_2$ tapes.

**FIG. 3.** A comparison of magnetic $J_c(H)$ at 20 K for the 10 wt % SiC-doped sample (sample 4) and for samples that were: Ti doped (see Ref. 4), Y$_2$O$_3$ (see Ref. 5) doped, thin film with strong pinning (see Ref. 2) and Fe/MgB$_2$ tape (see Ref. 9). Inset: temperature dependence of the irreversibility field for SiC-doped MgB$_2$ with different SiC content (triangles and squares) and for previously prepared nondoped MgB$_2$ (round symbols).

The transport temperature dependence of $H_{irr}$ for nano-SiC-doped MgB$_2$, as well as for the pellets and tapes prepared previously (round symbols), is shown in the inset to Fig. 3. Apparently, $H_{irr}$ for $x=0$ overlaps with $H_{irr}$ for the previous samples, even though the latter had significantly smaller values of $J_c$. Doping with SiC significantly improved $H_{irr}$. For example, $H_{irr}$ for the SiC-doped samples reached 7.3 T at 20 K, compared to 5.7 T for the nondoped one. This is consistent with improvement of the field dependence of $J_c$ with the doping. Because $H_{irr}$ for the nondoped control sample ($x=0$) is the same as for the previously prepared samples, the improvement of $J_c(H)$ definitely occurred because of the improvement of flux pinning by the doping and not because of improved sintering of MgB$_2$.

Figure 4 shows the transport $J_c(H)$ values for the undoped and 10 wt % SiC-doped MgB$_2$ wires (samples 5 and 6) at 5 K, 10 K, and 20 K. It is evident that the transport $J_c$ results for both the undoped and doped wires are in excellent agreement with the magnetic $J_c$. It is also clear that the enhancement in transport $J_c$ due to SiC doping is consistent with the magnetic $J_c$. The transport $J_c$ for the 10 wt % SiC-doped MgB$_2$/Fe reached 660 A at 5 K and 4.5 T ($J_c$ at 0 T overlaps with $J_c$ at 5 K, 10 K, and 20 K for samples 1, 2, 3, and 4, shown by solid, dashed, and dotted lines, and crosses, respectively.)
Persed additives are responsible for the enhanced flux pinning when SiC reacts with liquid Mg and amorphous B at the sintering temperatures. The nanoparticles of SiC will act as nucleation sites to form MgB$_2$ and other nonsuperconducting phases which can be included within the grains as inclusions. Thus, the reaction-induced products are highly dispersed in the bulk matrix.

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