Abstract

Processing methods are described for the development of magnesium diboride wire using the chemical vapor deposition (CVD) to produce long lengths of suitably doped starting boron fiber. It is found that titanium can be co-deposited with the boron to make long lengths of doped fiber that contain both TiB and TiB$_2$. When this fiber is reacted in Mg vapor to transform boron into MgB$_2$, the resulting conductor has a superconducting critical current density of about $5 \times 10^6$ A/cm$^2$ at 5 K and self field. The critical current density at 25 K and 1 Tesla is 10,000 A/cm$^2$. Using optical methods to define grain boundaries and energy dispersive X-rays to determine Ti and Mg concentration, these samples show a fine dispersion of Ti throughout the grains and no conspicuous precipitation of TiB$_2$ on the MgB$_2$ grain boundaries. This is to be contrasted with the precipitation of TiB$_2$ on MgB$_2$ grain boundaries observed for samples prepared by solid state reaction of Ti, Mg, and B powders. Introducing Ti impurities into the B during the CVD deposition of the B gives a distribution of TiB$_2$ in the resulting MgB$_2$ different
from solid state reaction of powders.
74.25.Bt, 74.25.Fy, 74.25.Ha
I. INTRODUCTION

The discovery\(^1\) of superconductivity in \(MgB_2\) at 39.2 K opens some very interesting opportunities for practical applications of this material as a conductor in power applications.\(^2\) Typically, the operating temperature of these conductors would be at about half the superconducting transition temperature, \(T_c\), or about 20 K where closed cycle refrigerators are quite efficient. Early studies of the temperature and magnetic field dependence of the superconducting critical current density, \(J_c\),\(^3\) indicated that grain boundaries in this material would carry very substantial supercurrents, \(5 \times 10^5 A/cm^2\), in conductors prepared in a variety of ways.\(^4,5\) In addition, a very early attempt to explore the use of powder-in-tube methods by Jin and co-workers\(^6\) showed that practical conductors are feasible.

On the fundamental side, the measurement of an isotope\(^7\) effect with \(\alpha = 0.26\) where \(T_c \sim M^{-\alpha}\) and \(M\) is the isotopic mass of the boron atom indicated that phonons play a major role in the superconducting interaction in \(MgB_2\). For clean samples, resistivity measurements at 40 K indicated that \(\rho \sim 1.0 \mu \text{ohm} - \text{cm}\) which, combined with the calculated Fermi velocity,\(^8\) \(v_F \sim 4.7 \times 10^6 \text{ m/s}\), gives a mean-free-path, \(\ell \sim 60 \text{ nm}\). From the measured upper critical field, \(H_{c2} 16 T\),\(^9\), the coherence distance of a clean sample can be determined from \(H_{c2} = \Phi_o/[2\pi \xi_o^2]\) to be \(\xi_o \sim 5 \text{ nm}\). Here, \(\Phi_o\) is the flux quantum. With \(\ell\) substantially greater than \(\xi_o\), these materials are in the clean limit. Several groups\(^4,5\) found \(J_c\) values in the range of 500,000 \(A/cm^2\) in self field at 5 K, but these values fell below 1,000 \(A/cm^2\) at 1 T at 5 K. Broadly speaking, the irreversibility field, \(H_{irr}\) was roughly half of \(H_{c2}\).

The primary drawback for this material appeared to be the relatively low values of the upper critical field, \(H_{c2} = 16 T\),\(^9\) and the resulting rapid drop in \(J_c\) with field. The most straightforward way to raise \(H_{c2}\) is to shorten the mean-free-path, \(\ell\), which in turn shortens the coherence distance, \(\xi = \sqrt{\xi_o \ell}\). Thus \(H_{c2} = \Phi_o/[2\pi \xi^2]\) would rise with decreasing \(\ell\). The introduction of point defects is an effective way to raise \(H_{c2}\). In pure \(MgB_2\), the volume pinning force seems to decrease as \([1 - H/H_{irr}]^2\) indicating that grain boundary pinning dominates.\(^4\) Hence, reducing the grain size should help. Alternatively, the strength of the
pinning and $J_c$, can be increased by introducing precipitates. Typical dimensions might be an array of pinning sites with a characteristic dimension of the coherence distance, 1–5 nm, and a spacing between pinning centers about 5 times larger.

Doping of $MgB_2$ has proven to be difficult because relatively few impurities go into the lattice in solid solution. Early reports by Slusky and co-workers\textsuperscript{10} show that $Al$ added by reacting powders in a solid state reaction substitute for $Mg$ in the $MgB_2$ lattice. There is a smooth change in lattice parameter and smooth decrease in $T_c$ for $Mg_{1-y}Al_yB_2$ for $y$ out to 0.10 and then a two phase region is entered. At $y = 0.1$, $T_c$ is still about 33 $K$ and thus still relatively high.

For $Ti$ doping by solid state reaction of powders, it appears that relatively little $Ti$ is incorporated in the $MgB_2$ grains. Work by Zhao and coworkers\textsuperscript{11} showed that $Ti$ appears as very thin layers of $TiB_2$ precipitates on the $MgB_2$ grain boundaries. Samples were made via solid state reaction by grinding the $Ti$, $Mg$, and $B$ powders, pressing pellets, and heat treating. Microstructural analysis seemed to indicate that $TiB_2$ may act as a sintering agent leading to higher density, very fine $MgB_2$ grain-size of about 10 nm, and excellent grain-to-grain coupling. Some high resolution transmission electron microscopy evidence points to the thickness of some of these grain boundary layers being as low as one $TiB_2$ unit cell.\textsuperscript{11} Because the $Ti$ does not enter the unit cell, there is relatively little diminution in $T_c$ and very substantial increases in the critical current density, $J_c$. Optimum doping was in the range of a $Mg/Ti$ ratio of about 0.1. One of the more important outcomes of this work was the observation that the $Ti$ seems to refine the grain structure to a grain size of about 10 nm.

For carbon doping, rather large amounts of carbon can replace boron in the structure. Takenobu and co-workers\textsuperscript{12} found that carbon substitutes for boron in $MgB_2\_x\_x$, out to $x \sim 0.06$ as indicated by a smooth decrease in a-axis lattice parameter from 0.3085 nm at $x = 0$ to 0.3070 nm at $x = 0.06$ while $T_c$ drops from 38.2 $K$ to about 34.8 $K$. There was relatively little change in the c-axis dimension. Here, samples were made by mixing powders of the elements and firing at 900$^\circ$C for 2 $h$. At higher $x$-values, they found that the
(110) X-ray peak of $MgB_2$ broadens indicating two phases.$^{12}$ Bharathi and co-workers,$^{13}$ by contrast, found that reacting under high pressure $Ar$, permitted the extension of carbon content to $x = 0.5$. They find a relatively smooth depression of $T_c$ from 39 K at $x = 0$ to about 26 K at $x = 0.5$. Using a somewhat different procedure, we have found that reacting $B_4C$ with $Mg$ vapor at $950^\circ C$ for 2 h gives a material with $T_c \sim 17$ K. In other work, the change in lattice constant and $T_c$ with carbon content also has been reported to be somewhat less than these values.$^{14}$

For Si doping, a solid state reaction of $Mg$ and amorphous $B$ powder with nano-size $Si$ particles show substantial $Mg_2Si$ lines in the X-ray data and relatively little diminution in the transition temperature to about 36 K.$^{15}$ This seems to imply that very little Si seems to enter the $MgB_2$ structure. In an alternate preparation method, Cooley and co-workers$^{16}$ have shown $Mg$ can be reacted with $SiB_6$ at temperatures as low as 500$^\circ C$ to give $Mg_2Si$ precipitates in a $MgB_2$ matrix with $T_c = 37$ K. These preliminary experiments seem to indicate that the enhancements in flux pinning arise from $Mg_2Si$ precipitates rather than $Si$ substitution into the $MgB_2$ lattice.

The purpose of this review is to summarize progress in attempts to make $MgB_2$ conductors using a CVD method for depositing the starting boron material. There is a well established commercial scale method to make boron fiber in kilometer lengths for use in high strength composites. The primary goal of this work is to find ways to make doped boron fiber that will permit the preparation of long lengths of high performance $MgB_2$ conductor. Tasks include 1) the development of processing methods to convert pure boron fiber to $MgB_2$, 2) the development of methods to dope the starting boron fiber with point defects that will raise the upper critical field, $H_{c2}$, 3) the development of boron fibers that will produce nano-scale precipitates in the $MgB_2$, and 4) the development of methods to handle the brittle character of the superconductor.

Chemical vapor deposition of the starting boron is a particularly attractive route to materials preparation because the impurity atoms can possibly be introduced with atomic scale dispersion. Initial experiments have focussed on titanium-doping to produce small
$TiB_2$ precipitate pinning centers with the next step to be the introduction of carbon point
defects to shorten the electronic mean free path.

In a typical deposition process for boron fibers, a conducting filament such as tungsten
or a carbon coated commercial silicon carbide fiber is introduced into a long glass chamber
through a $Hg$ seal at a rate of a few $cm/s$. A flowing stream of $BCl_3$ and hydrogen gas move
through the full length of the chamber. The fiber is heated electrically to temperatures in
the $1100–1300°C$ range, and the boron is deposited in the hot zone. If a suitable carrier gas
can be mixed with this gas stream, then impurity atoms such as $Ti$ or $C$ can be co-deposited
with the boron to form filaments that can subsequently converted to impurity doped-$MgB_2$.
Critical current densities were measured via magnetization as reported earlier.$^3$

II. CONVERSION OF PURE B-FIBER TO MAGNESIUM DIBORIDE

Soon after the discovery of superconductivity$^1$ in $MgB_2$, small wire segments of commercial
boron fiber were converted to $MgB_2$. These wire segments were only a few $cm$ long and
rather fragile, but they showed exceptionally low resistivity of 0.4 $\mu$ohm $– cm$ at 40 $K$ and
a sharp superconducting transition at 39.2 $K$. In a subsequent series of upper critical field
measurements,$^9$$^{17}$ $H_{c2}vsT$ curves indicated an extrapolation to $H_{c2}(T = 0)$ of about 16 $T$.
Critical current densities, $J_c$ for a 100 $\mu$m diameter pure boron fiber reacted in $Mg$ vapor
at $900°C$ for 2 $h$ are shown for both 5 $K$ and 25 $K$ in Fig. 1. At 5 $K$, $J_c \sim 5 \times 10^5$ $A/cm^2$
in self field, and $J_c$ is about 1000 $A/cm^2$ at 2.5 $T$. At 25 $K$, $J_c \sim 2 \times 10^5 A/cm^2$ in self field,
and $J_c$ is about 1000 $A/cm^2$ at 1.4 $T$. Also shown on Fig. 1 are data for a sample made by
depositing 25 $\mu$m of pure boron on a carbon substrate. The 5 $K$ data are the open circles
and the 25 $K$ data are the solid triangles. Within the reproducibility of the experiments,
the 100 $\mu$m pure boron fibers give the same $J_c$ values as samples made from 25 $\mu$m of pure
B on a C substrate within the accuracy of the measurement. For all samples, the reaction
is carried out at a single temperature, and the time can then be adjusted to optimize $J_c$ if
that is desired.
A series of measurements were undertaken to determine the lowest temperatures where these boron fibers would transform to $MgB_2$ at a high rate. A sample reacted at $800^\circ C$ for 2 $h$, as shown in Fig. 2, shows a $Mg$ region only part way across the boron fiber in the relatively light area near the edge of the filament. A more detailed analysis shows that this is a uniform wall of a high boron compound, $MgB_x$, progressing across the fiber. Energy dispersive spectra in the scanning electron microscope indicate that this phase has $x$ near 6 or 7. Because this phase is not the study of this work, further analysis was not undertaken. For this time and temperature, essentially no $MgB_4$ or $MgB_2$ forms. The white core of the filament is $W_2B_5$.

By contrast, if a similar pure boron fiber is heated in $Mg$ vapor at $875^\circ C$ for 2$h$, the fiber transforms to $MgB_2$ nearly everywhere as shown in Fig. 3. The darker gray areas are small regions of $MgB_4$ as shown by the EDS line scan along the line shown, where the circle with a cross is the starting point of the scan. The large dip in $Mg$ count rate is the $W_2B_5$ core and the 30 percent dip in count rate to the left of the core illustrates the decrease in $Mg$ density going from $MgB_2$ to $MgB_4$. Also visible in the micrograph are several faults along the edge of the fiber and a large void near the right end of the portion of the $W_2B_5$ core. The filament is not completely flat, so that the $W_2B_5$ core does not show along the entire length of the filament for this particular depth of polish. These flaws are typical in $MgB_2$ filaments prepared from commercial pure $B$ fibers. In Fig. 4, an electron micrograph is shown in end view for the long time limit where a 100 $\mu m$ diameter fiber that has been reacted in $Mg$ vapor at $950^\circ C$ for 78 $h$. The white core of $W_2B_5$ in the center is measured here to be 16.7 $\mu m$ in diameter and the starting 100 $\mu m$ boron fiber has grown to about 135 $\mu m$ diameter as $Mg$ is added. There is a small patch of $MgB_4$ in the upper left quadrant, and there the void pattern is very typical of all the samples grown.
III. TITANIUM DOPING

In the early experiments with CVD doping of B with Ti, the material was deposited on either a W substrate or a C coated substrate, and a preliminary report of this work has been presented.\textsuperscript{18} Most of the experiments reported here, however, were done by simultaneously depositing B and a few percent Ti on a continuous 75 µm diameter silicon carbide filament coated with several micrometers of glassy carbon (commercially available as SCS-9A). Deposition was accomplished in a reactor similar to that used for commercial boron filament production.\textsuperscript{19} The substrate filament was drawn through the reactor at 100 mm/s; the filament in the reactor was resistively heated to peak temperatures of approximately 1100°C. The reactant gas was predominantly a stoichiometric mixture of hydrogen and boron trichloride at atmospheric pressure. Titanium dopant was added by bubbling the hydrogen component through titanium tetrachloride held at 0°C. The resulting partial pressure of titanium tetrachloride was approximately $2 \times 10^{-3}$ bar. The doped boron-coated substrate was spooled continuously upon emerging from the reactor. An X-ray powder diffraction study of the resulting fibers before Mg reaction indicates comparable amounts of TiB and TiB$_2$ as well as a small amount of B$_{10}$C. Subsequent reaction with Mg vapor produced MgB$_2$ filaments with precipitated TiB$_2$. The intensity of the X-ray lines indicates less TiB in the reacted fiber than in the unreacted fiber.

A series of samples were prepared in which B and Ti were co-deposited on the carbon surface with thicknesses of 4 µm, 6 µm and 10 µm. After reaction in Mg vapor at both 950°C for 2 h and at 1100°C for 30 min, the conversion of B to MgB$_2$ was complete.\textsuperscript{18} An extensive study of the Ti distribution was undertaken with EDS in a SEM where the beam size was approximately 1 micrometer. Generally, the Ti/Mg ratio was in the neighborhood of 9% in the bulk of the material. This is illustrated in Fig. 5 where a sample with 6 µm of B $\sim$ 9% Ti is deposited on a carbon coated substrate. There are two regions of the sample, however, that are consistently high Ti. This is near the C substrate and near the outer surface. Reaction kinetics indicate that the deposition of Ti compared to B is
higher at lower temperatures. Hence, as the fiber moves through the deposition zone, the $Ti$ deposition will be faster than that of boron during the initial warm-up on entrance to the hottest regions and during the cool-down as the fiber exits the hottest regions. Another specimen illustrated in Fig. 6 shows a 4 $\mu m$ thick layer of $B \sim 9\% Ti$. Here, there are two rather distinct regions of $Ti$ content. In most of the boron layer, the $Ti$ content is about 9%, but sometimes there are bright lacy regions where the $Ti$ content is about 30%. By studying polished regions of the $MgB_2$ with polarized light, the grain structure is readily apparent. If a particular region of the sample is studied both with polarized light and with SEM with EDS area maps, the $Ti$ is found to be spread throughout the grains. The grain boundaries are not seen to be high in $Ti$ on these area maps. This result differs from the beautiful decoration of $MgB_2$ grain boundaries with $TiB_2$ seen for samples made from powders in solid state reactions.\textsuperscript{11} Titanium doping using CVD methods gives a dispersion of $TiB_2$ in $MgB_2$ that is different from that seen for solid state reaction of powders.

**IV. CRITICAL CURRENT DENSITIES**

The addition of $Ti$ greatly enhances the $J_c$ values if the level of $Ti$ doping is properly adjusted. As reported previously, anything approaching a $Ti/Mg$ ratio of 1 is far too much $Ti$.\textsuperscript{18} The volume fraction of superconductor is reduced by half, and the value of $T_c$ drops to about 20 K. In accord with earlier findings,\textsuperscript{9} a $Ti/Mg$ ratio in the neighborhood of 0.09 greatly enhances both $J_c$ and $H_{irr}$ while depressing $T_c$ only a few degrees. At 5 K and self field, $J_c$ increases from about $4 \times 10^5$ A/cm$^2$ for pure $MgB_2$ to about $2 \times 10^6$ A/cm$^2$ for the 9% $Ti$ sample. With increasing magnetic field, $J_c$ crosses 10,000 A/cm$^2$ at 5 T with 9% $Ti$ as compared to 1.4 T for the pure $MgB_2$ sample as shown by the solid triangles in Fig. 7. At 25 K, the 9%$Ti$ sample crosses 10,000 A/cm$^2$ at about 1.3 T compared with the pure $MgB_2$ sample which crosses 10,000 A/cm$^2$ at 0.9 T.

In addition to simply adding $Ti$ to the boron fibers, there is a great deal of optimization that can yet be done. When the starting $B_{0.91}Ti_{0.09}$ fibers are prepared, there is a large
amount of both TiB and TiB\textsubscript{2} in the boron. During the reaction to form MgB\textsubscript{2}, some of the TiB is converted to TiB\textsubscript{2}, and there may be some migration of C from the substrate into the sample. Much more needs to be learned about both of these processes. An optimization of $J_c$ at 25 K with $B_{0.91}T_{i0.09}$\textsuperscript{18} shows that a reaction time of 30 min is best for a reaction temperature of 1100°C and a reaction time of 2 h is best for a reaction temperature of 950°C. An optimization for $J_c$ values at 5 K, shown in Fig. 8, indicates that 30 min at 1100°C gives the highest $J_c$ values.

V. THICKNESS DEPENDENCE

For pure B fibers deposited on a 15 μm W core, a series of B fibers having diameters ranging from 100 μm to 300 μm were fully reacted in Mg vapor at 950°C for times ranging from 2 h to 48 h. In all cases, the reaction to form MgB\textsubscript{2} increases the fiber diameter by about 35%. At 5 K and self field, the $J_c$ values range from 700,000 A/cm\textsuperscript{2} to 300,000 A/cm\textsuperscript{2} and have a magnetic field dependence similar to those shown in Fig. 1. At 25 K, the data of Fig. 9 indicate that $J_c(H)$ nearly is independent of diameter. To the accuracy and reproducibility of the measurement, all of these fiber diameters have the same $J_c$ vs H plots.

For the B9%Ti deposited on a carbon coated substrate, samples having a thickness of 4 μm, 6 μm, and 10 μm have been studied. We expected a difference in $J_c$ among these samples caused by different amounts of C impurity or caused by a different distribution of TiB or TiB\textsubscript{2} during the Ti and B deposition on the C substrate. These are relatively small effects as shown on Fig. 10. These data were taken for samples reacted at 1100°C for 15 min. A reaction time less than the 30 min for optimum $J_c$ was intended to limit possible diffusion of C from the substrate. In broad terms, the 5 K $J_c$ data are about $3 \times 10^6$ A/cm\textsuperscript{2} at low field and the $J_c$ data cross the 10,000 A/cm\textsuperscript{2} line at about 4 T. There is not a large thickness dependence of $J_c$, but at high fields, the thicker samples seem to show a higher $J_c$ values. At low fields, the thinner samples seem to show the higher $J_c$ values. Similar data
have been reported elsewhere.\textsuperscript{18} There is lots of room for improvement by optimizing the $Ti$ content, the reaction temperatures, and the reaction times.

\section*{VI. CONCLUSIONS}

Co-deposition of boron along with the desired impurities offers a distinctive method of doping. When these doped fibers are converted to $MgB_2$ by heating in $Mg$ vapor, the resulting $TiB_2$ is distributed relatively uniformly within the grains. This distribution is quite different from $MgB_2$ samples prepared by solid state diffusion of mixed powders. Critical current densities of 2 to 5 million $A/cm^2$ are obtained at 5 $K$ and self field. Critical current densities of 10,000 $A/cm^2$ are obtained at 25 $K$ and 1.4 $T$.

A number of important variables are still not well understood. Improvement is needed in the control of the distribution of $TiB_2$, and a more thorough study of carbon doping needs to be undertaken so that a quantitative contrast can be developed between the effects of $C$ substitution in the lattice with the effects of $TiB_2$ precipitates. Although there is a fairly wide sweet spot for the reaction of doped $B$ fibers to form doped $MgB_2$, there is lots of room for improvement. The performance of the conductor can yet be optimized with respect to $Ti$ content and carbon content as well as the time and temperature of $Mg$ reaction.

\section*{VII. ACKNOWLEDGMENTS}

Work is supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Science, through the Ames Laboratory under Contract No. W-7405-Eng-82.
REFERENCES

1 J. Nagamatsu, N. Nakagawa, T. Muranaka, Y Zenitani, and J. Akimitsu, Nature 410 (2001) 63.

2 Paul M. Grant MRS Symposium Proceedings, 689 (2002) 3.

3 D. K. Finnemore, J. E. Ostenson, S. L. Bud’ko, G. Lapertot, P. C. Canfield, Phys. Rev. B 86 (2001) 2420.

4 D. C. Larbalestier, M. Rikel, L. D. Cooley, A. A. Polyanskii, J. Y. Jinang, S. Putnaik, X. Y. Cai, D. M. Feldmann, A. Gurevich, A. A. Squitier, M. T. Naus, C. B. Eom, E. E. Hellstrom, R. J. Cava, K. A. Regan, N. Rogado, M. A. Hayward, T. He, J. S. Slusky, K. Iaumaru, M. Haas, Nature 410 (2001) 186.

5 Y. Bugoslavsky, G. K. Perkins, X. Qi, L. F. Cohen, and A. D. Caplin, Nature 410 (2001) 563.

6 S. Jin, H. Mavoori, and R. B. vanDover, Nature, 411 (2001) 563.

7 S. L. Bud’ko, G. Lapertot, C. Petrovic, C. E. Cunningham, N. E. Anderson, and P. C. Canfield, Phys. Rev. Lett. 86, (2001) 1877.

8 J. Kortus, I. I. Mazin, K. D. Belashchenko, V. P. Antropov, and L. L. Boyer, Phys. Rev. Lett. 86 (2001) 4656.

9 S. L. Bud’ko, C. Petrovic, G. Lapertot, C. E. Cunningham, P. C. Canfield, M - H, Jung, and A. H. Lacerda, Phys. Rev. B, 63 (2001) 220503(R).

10 J. S. Slusky, N. Rogado, M. A. Hayward, P. Khalifah, T. He, K. Inumaru, S. Loureire, M. K. Haas, H. W. Zandbergen, and R. J. Cava, Nature, 410 2001 343.

11 Y. Zhao, Y. Feng, C. H. Cheng, L. Zhou, Y. Wu, T. Machi, Y Fudamoto, N. Koshizuka, and M. Murakami, Appl. Phys. Lett. 79, 1154 (2001); Y. Zhao, D. X. Huang, Y. Feng, C. H. Cheng, T. Machi, N. Koshizuka, and M. Murakami, Appl. Phys. Lett. 80 (2002) 1640.
12. T. Takenobu, T. Ito, D. H. Chi, K. Prassides, and Y. Iwasa, Phys. Rev. 64 (2001) 134513.

13. A. Bharathi, S. K. Balaselvi, S. Kalavathi, G. L. N. Reddy, V. S. Sastry, Y. Haribaran, and T. S. Radfakrishnan, Physica C 370 (2002) 211.

14. M. Paranthaman, J. R. Thompson, and D. K. Christen, Physica C 355 (2001) 1.

15. X. L. Wang, S. H. Zhou, M. J. Qin, P. R. Monroe, S. Soltanian, H. K. Liu, and S. X. Dou, LANL Cond. Mat./0208349

16. L. D. Cooley, V. Braccini, J. Waters, P. Hellenbrand, B. Senkowicz, J. Y. Jiang, P. J. Lee, E. E. Hellstrom, and D. C. Larbalestier, (private communication)

17. P. C. Canfield, D. K. Finnemore, S. L. Bud’ko, J. E. Ostenson, G. LaFerrot, C. E. Cunningham, and C. Petrovic, Phys. Rev. Lett. 86 (2001) 2423.

18. N. E. Anderson, W. E. Straszheim, S. L. Bud’ko, P. C. Canfield, and D. K. Finnemore, Physica C, Submitted.

19. R. J. Suplinskas and J. V. Marzik, ”Boron and Silicon Carbide Filaments”, in Handbook of Reinforcements for Plastics, J. V. Milewski and H. S. Katz, ed., Van Nostrand Reinhold, New York, (1987).
FIGURES

FIG. 1. Comparison of $J_c$ values for pure $MgB_2$ made from 100 $\mu m$ boron fibers with a $W_2B_5$ core and 25 $\mu m$ of pure boron on a carbon substrate at both 5 $K$ and 25 $K$.

FIG. 2. Micrograph and EDS line scan showing the initial diffusion of $Mg$ into a 100 $\mu m$ diameter boron fiber. The white core is $W_2B_5$.

FIG. 3. Typical section of a $MgB_2$ filament that is fully reacted. The white area in the center is a portion of the $W_2B_5$ core. The darker gray areas are $MgB_4$ as indicated by the 30% drop in EDS scan intensity.

FIG. 4. Typical end view of a $MgB_2$ filament prepared from a 100 $\mu m$ diameter pure $B$ fiber. The dark gray area in the upper left quadrant is $MgB_4$ and void area is typical.

FIG. 5. A section of 4 $\mu m$ thick layer of $B9%Ti$ deposited on a $C$ substrate and reacted at 1100$^\circ C$ for 15 min. The light and dark regions reflect a change in Ti/Mg ratio. High Ti near the $MgB_2$ inner and outer surfaces is typical.

FIG. 6. A section of a 4$\mu m$ thick layer of $B9%Ti$ deposited on a $C$ substrate in which the $Ti$ is high in the outer half and about 50% as high in the inner half.

FIG. 7. Comparison of the $J_c$ data for a sample made from 25 $\mu m$ of pure boron on a carbon substrate with a sample made from 10 $\mu m$ of $B_{0.91}Ti_{0.09}$ on a carbon substrate at both 5 $K$ and 25 $K$. Both $J_c$ and $H_{c2}$ are increased substantially by adding a few percent $Ti$.

FIG. 8. Optimization of $J_c$ vs time at 1100$^\circ C$ and 9$%Ti$.

FIG. 9. $J_c$ data for various wire diameters for pure $B$ fiber at 25 $K$.

FIG. 10. $J_c$ data for various thicknesses of $B_{0.91}C_{0.09}$ at 5 $K$. 

14
This figure "fig1rbw.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig2a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig3a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig4.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig5a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig6a.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig7bw.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig8rbw.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig9bw.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1
This figure "fig10rbw.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0302242v1