Summary of Nano-SiC doped MgB_2

--Breakthrough in development of superconducting magnesium diboride wires through nano-scale doping

Contact Details: Professor S.X. Dou,
Institute for Superconducting and Electronic Materials
University of Wollongong, Wollongong, NSW 2522 Australia
Tel: 61-2-4221 4558, Fax: 61-2-4221 5731
e-mail: shi_dou@uow.edu.au
Website: www.uow.edu.au/eng/research/ISEM

EXECUTUVE SUMMARY

The researchers at the Institute for Superconducting and Electronic Materials (ISEM) in the University of Wollongong have made a breakthrough in the fabrication of wires from the newly discovered superconductor magnesium diboride (MgB_2) by using nano-scale silicon carbide doping. They have achieved a world record high critical current density in superconducting MgB_2 wires. A record high upper critical field of 37 Tesla has been achieved for nano-particle SiC doped MgB_2. The critical current density in magnetic fields for the nano-particle doped MgB_2 increased by more than an order of magnitude, compared to the best results reported in the literature. This is one of the most important advances since the discovery of superconductivity in this material and will have an important impact on the development of technological superconductors. Our team has used this discovery to develop superconductor wires which can carry one million Amperes per square centimeter at 20K. They clearly demonstrate the great potential of this emerging superconductor for various practical applications, such as magnets for magnetic resonance imaging (MRI), power cables, motors, energy storage systems, generators, magnetic separators, transformers, etc. Widespread applications of this invention will lead to enormous energy savings and environmental benefits. This achievement has been verified by leading groups at the National High Magnetic Field Laboratory in Florida, the University of Geneva, Los Alamos National Laboratory, the National Institute of Materials Science in Japan, the University of Wisconsin and Ohio State University. A PCT patent has been filed for the protection of the invention. Because of the significant enhancement in critical current density that can be achieved by nano-scale SiC doping, it is evident that in the future MgB_2 wires for large-scale applications will not be competitive without SiC doping. Thus, our patent position is very strong and commercially valuable for all the above applications.

The high performance of nano-doped MgB_2 opens a technical window to a range of electric power applications previously believed to be only accessible to the high temperature superconductor (HTS) materials. With a T_c of 39K, MgB_2 holds promise of being particularly suitable for applications such as MRI, which presently use coils of metallic low temperature superconductor (LTS) wires operating in liquid helium at 4 K. Increases in the temperature of operation of MRI to 20 K or higher using MgB_2 wires, would open up a whole new product line for the superconductor industry. This leads us to the conclusion that MgB_2, which is less expensive than Nb_3Sn but has an H_{c2} higher than NbTi, will lead to cost-effective products. Our invention has put an Australian research team at the forefront of this field.

A typical example of a significant application of this invention is MRI, which represents the most significant superconductor market, amounting to several billion dollars. MRI machines are currently built using conventional niobium titanium superconductors and must be cooled with very expensive liquid helium. Our industry partners Alphatech International Ltd and Hyper Tech Inc

have formed a consortium to explore the commercial potential for development of magnet applications. Hyper Tech has transferred this invention to the production of long wires, which can be used to make magnet coils for MRI. The new technology developed by our group could make it possible for MRI to operate at higher temperatures and higher magnetic field. This means that the next generation MRI machines made from nano-particle doped MgB_2 superconductors will be much more powerful and much smaller than the current ones. The new technology could also slash the cost of MRI substantially.

In summary, we have demonstrated that the critical current density, irreversibility field and flux pinning properties of MgB_2 can be significantly improved by a readily achievable and economically viable chemical doping with SiC, paving the way for MgB_2 to replace the current market leader, Nb-Ti, and high temperature superconductors in many applications such as MRI.

TECHNICAL DATA

The exceptional properties of SiC as a dopant have been systematically studied by our group over the past two years. We have found that chemical doping with nano-particle SiC into MgB_2 can significantly enhance J_c in high fields with only slight reductions in T_c up to a doping level as high as 30% of B. In fact we obtained the highest J_c values in magnetic fields at 20K ever reported for MgB_2 wires and bulk. Compared to the un-doped sample, the J_c for the 10wt% SiC doped sample increased by a factor of 32 at 5K and 8T, 42 at 20K and 5T, and 14 at 30K and 2T, respectively, as shown in Figure 1. At 20K, which is considered to be a benchmark operating temperature for MgB_2, the best J_c for the doped sample achieved $2.4\times10^5 A/cm^2$ at 2T which is an order of magnitude higher than the J_c values of state-of-the-art Fe/MgB_2 tapes. The H_{irr} for the doped sample is as high as 15T at 5K and 7.3T at 20K. Because of this high performance it is anticipated that in the future "MgB_2" conductors will be made using the formula $MgB_xSi_yC_z$ instead of simple MgB_2. This finding paves the way for this new compound to replace the current market leaders NbTi and HTS in many applications, as the chemical doping is a readily achievable, highly reproducible and economically viable process to introduce effective flux pinning.

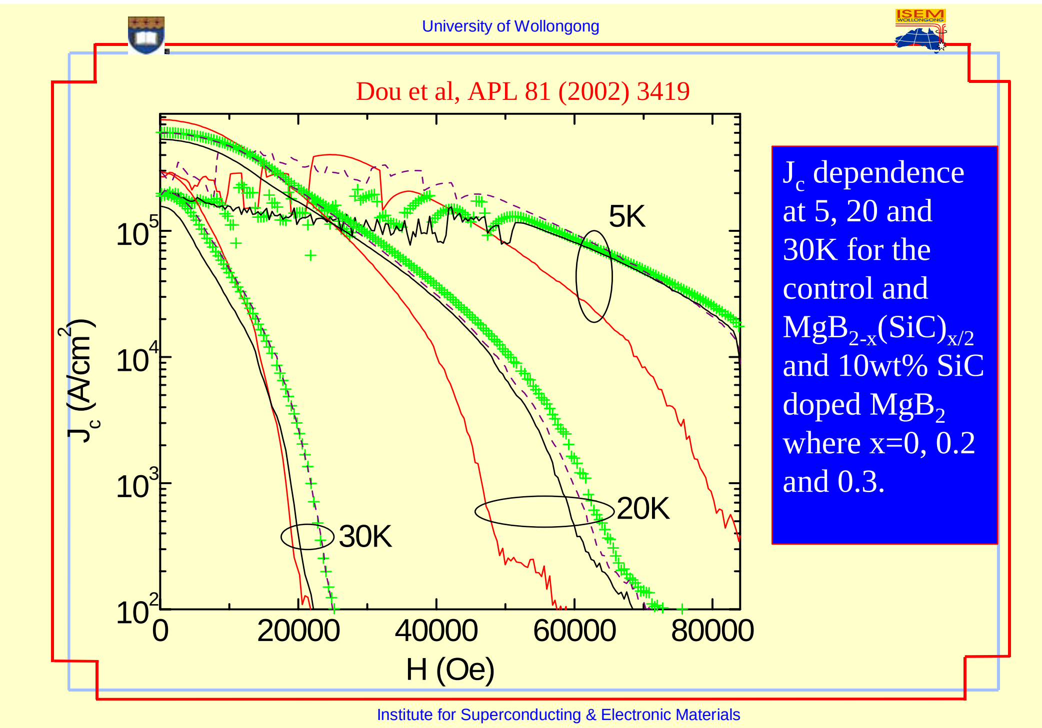


Figure 1. Comparison of critical current density of the nano-SiC doped MgB_2 with an un-doped sample (Dou et al., Appl. Phys Lett. 81 (2002) 3419).

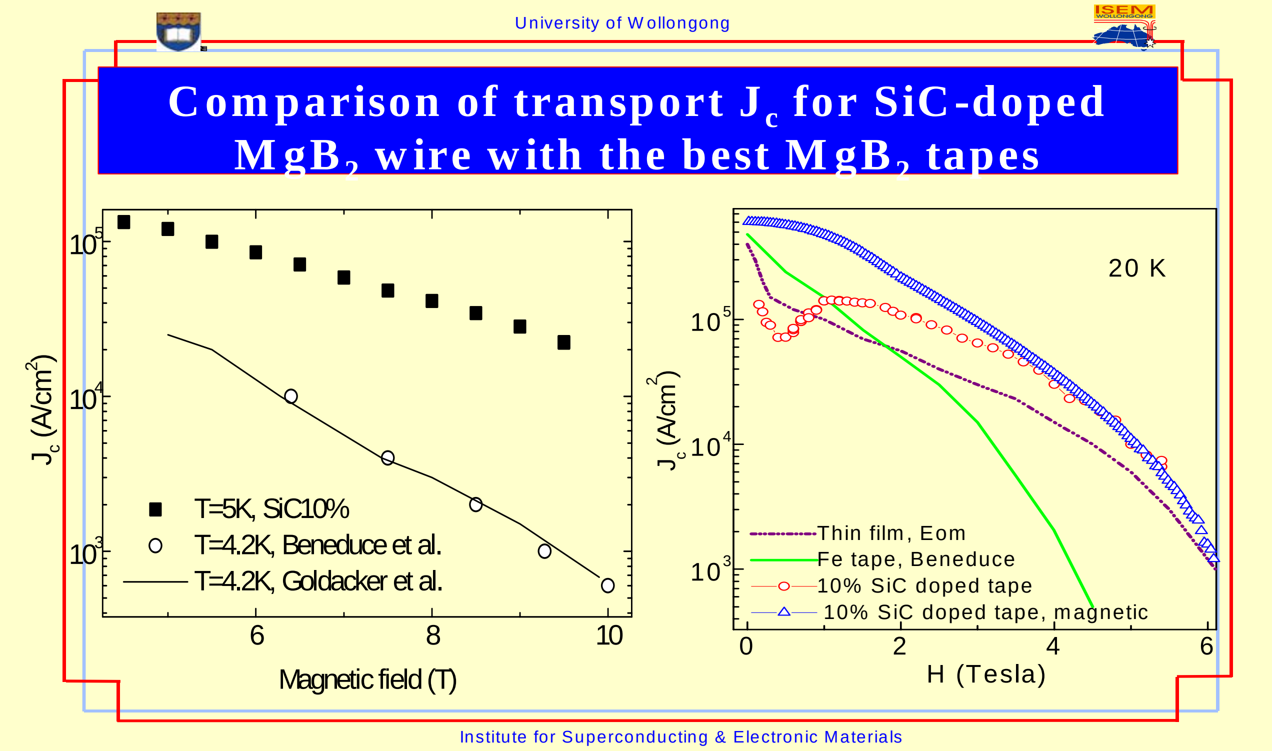


Figure 2. Comparison of the critical current density of nano-SiC doped magnesium diboride superconducting wire (S.X.. Dou et al., Appl. Phys. Lett. 81 (2002) 3419) with the state-of-the-art performance of un-doped wires at 4K (R. Flükiger et al., Physica C 385 (2002) 286 and W. Goldaker, Supercond. Sci. Technol. 14 (2001) 787) (a) and 20K (b, including the best critical current density of a strongly pinned thin film reported by the Wisconsin Group, Eom et al., Nature 411 (2001) 558).

Figure 2 shows the transport $J_c(H)$ values for un-doped and 10wt% SiC doped MgB_2 wires at 5K and 20K. It is evident that the transport J_c results for both the un-doped and doped wires are in excellent agreement with the magnetic J_c. The figure also shows a comparison of the transport $J_c(H)$ for 10 wt% SiC doped MgB_2/Fe wire with the best thin film and Fe-sheathed MgB_2 tape at 5K and 20K reported previously. We see that the J_c for the 10wt% SiC doped wire is more than an order of magnitude higher than the best transport J_c reported in Fe-MgB_2 tape at 5K and 8T and 20K and 4T respectively. It is even comparable to the strongly pinned thin film (magnetic J_c for the thin film) at 20K. This is the best transport J_c – H performance ever reported for MgB_2 in any form. The transport I_c for the 10wt% SiC doped MgB_2/Fe reached 660A at 5K and 4.5T (J_c = 133,000A/cm^2) and 540A at 20K and 2T (J_c = 108,000A/cm^2).

Figure 3 compares the irreversibility fields (H_{irr}) of various samples. Doping with SiC significantly improved H_{irr}, which is double that of the clean limit sample.

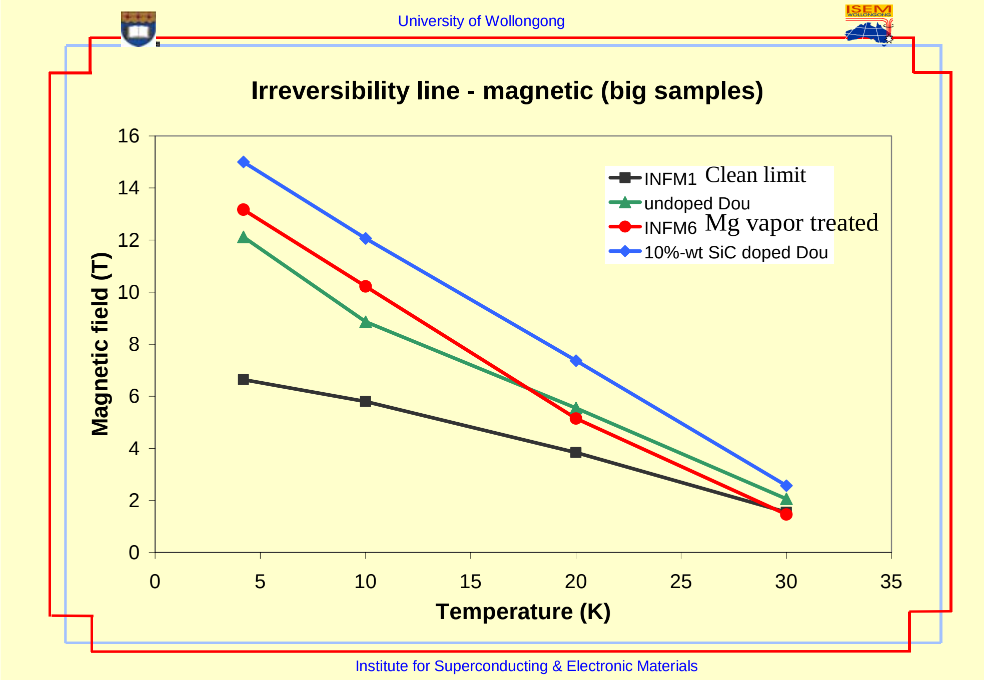
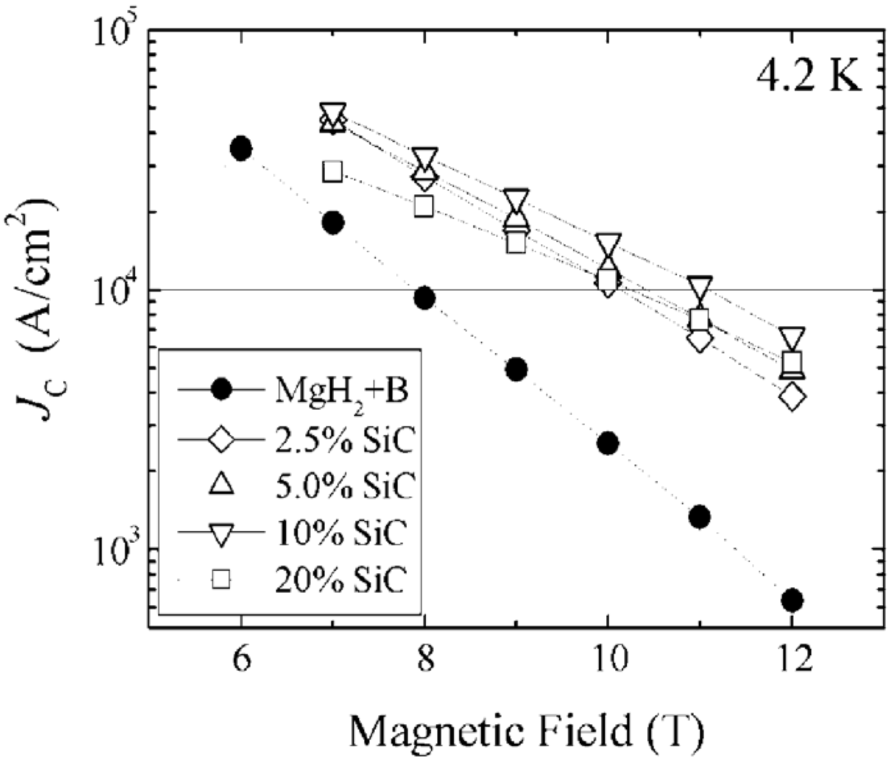


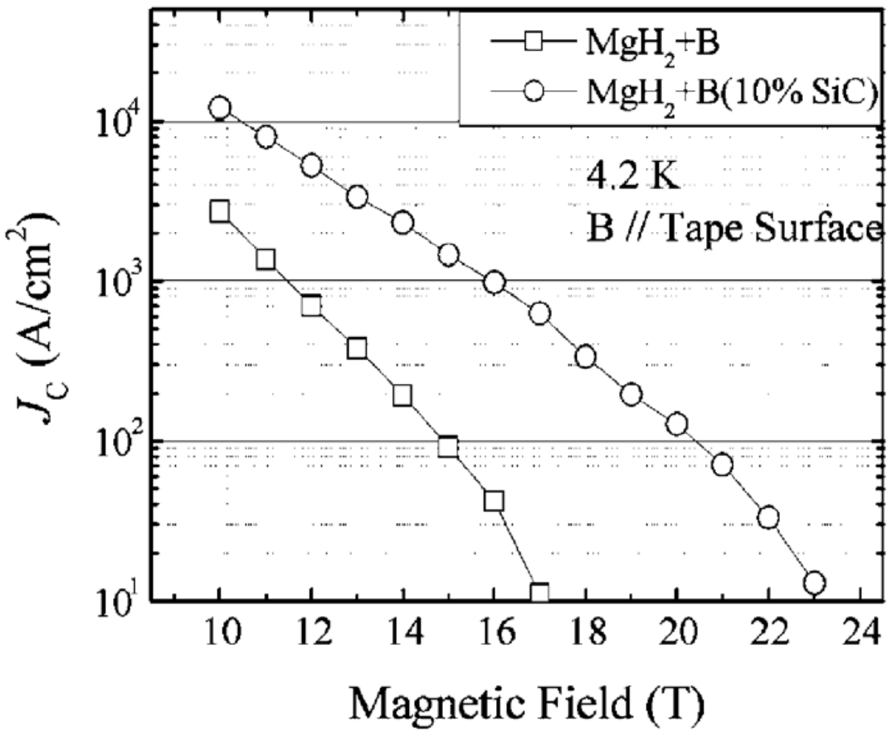
Figure 3. The irreversibility field, H_{irr} vs. temperature for the nano-SiC doped MgB_2, compared to the undoped, Mg-vapor treated and clean limit MgB_2 which were measured by the Wisconsin Group (Dou et al., J Appl. Phys., in press)

CONTROL SYSTEMS OR REVIEWS

The significant enhancement of J_c, H_{irr} and H_{c2} by nano-SiC doping has been confirmed by a number of leading groups around the world in the last two years. Matsumoto et al. have confirmed the effect of SiC doping in improving J_c, as well as substantially increasing H_{irr}. In his particular case, J_c was increased by an order of magnitude and H_{irr} went from about 17 T to about 23 T. The anomalous increase in H_{c2} and J_c is attributable to the unique feature of two-gap superconductivity in MgB_2, which forms the core innovation of this invention. Figure 4 shows a comparison of the J_c-H behaviour of the SiC doped MgB_2 wire with un-doped wires reported by the group at the National Institute for Materials Science in Japan. Figure 5 shows a comparison of SiC doped MgB_2 with a control sample—clean limit MgB_2. The J_c values for the SiC doped wires are higher than for the clean limit wire by two orders of magnitude. At 20K, the 10wt% SiC doped sample achieved $10^5 A/cm^2$ at 3T, comparable to that of state-of-the-art Ag/Bi-2223 tapes and an order of magnitude higher than recent state-of-the-art Fe/MgB_2 tapes. These results significantly strengthen the position of MgB_2 as a competitor for both low and high temperature superconductors.



(a)



(b)

Figure 4. (a) The critical current density versus magnetic field of in-situ processed MgB_2 tape in comparison with SiC doped MgB_2 tape with different SiC doping level (A. Matsumoto et al. Supercond. Sci. Technol. 16 (2003) 926). (b) The J_c-H curves in high magnetic fields of SiC doped and non-doped MgB2 tapes (A. Matsumoto et al. Supercond. Sci. Technol. 16 (2003) 926, National Institute for Materials Science).

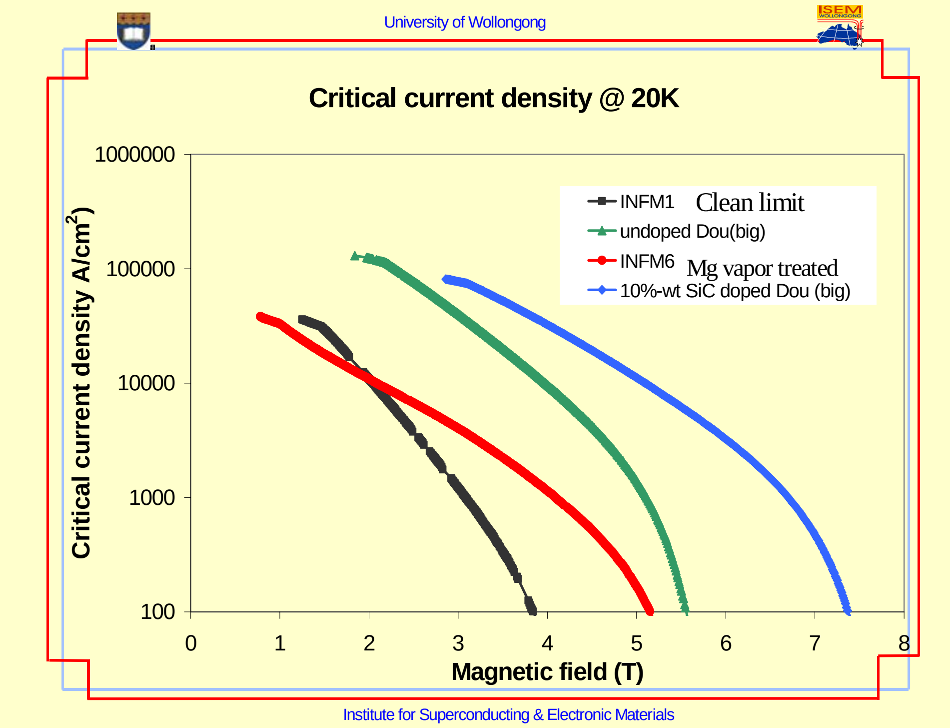


Figure 5. Confirmation of SiC doping effect on J_c-H performance by the Wisconsin Group. The critical current density for the nano-SiC doped MgB_2 wire is more than an order of magnitude higher in magnetic fields, compared to the clean limit and un-doped MgB_2 measured by V. Baccini et al. at Wisconsin University.

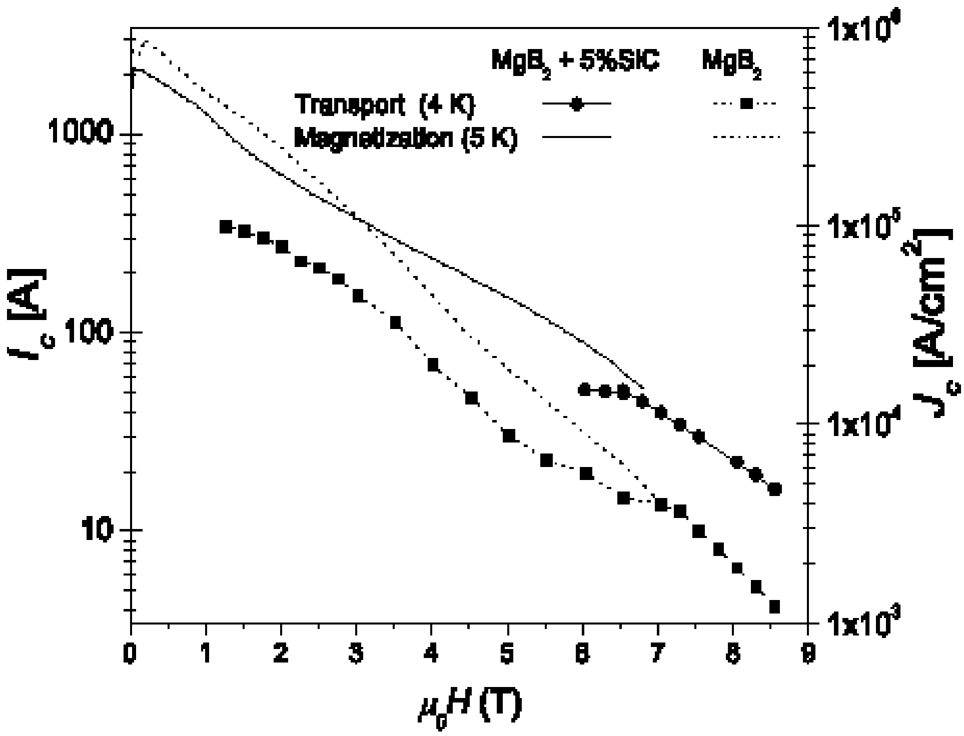


Figure 6. Confirmation of the effect of SiC doping on MgB_2 by A. Serquis et al. at Los Alamos National Laboratory (Cond-mat/0404052). Critical current I_c (left axis) and critical current density J_c (right axis) versus magnetic field at 4K for a 1-layer SiC doped MgB_2 coil compared to a 6-layer coil made from non-doped MgB_2.

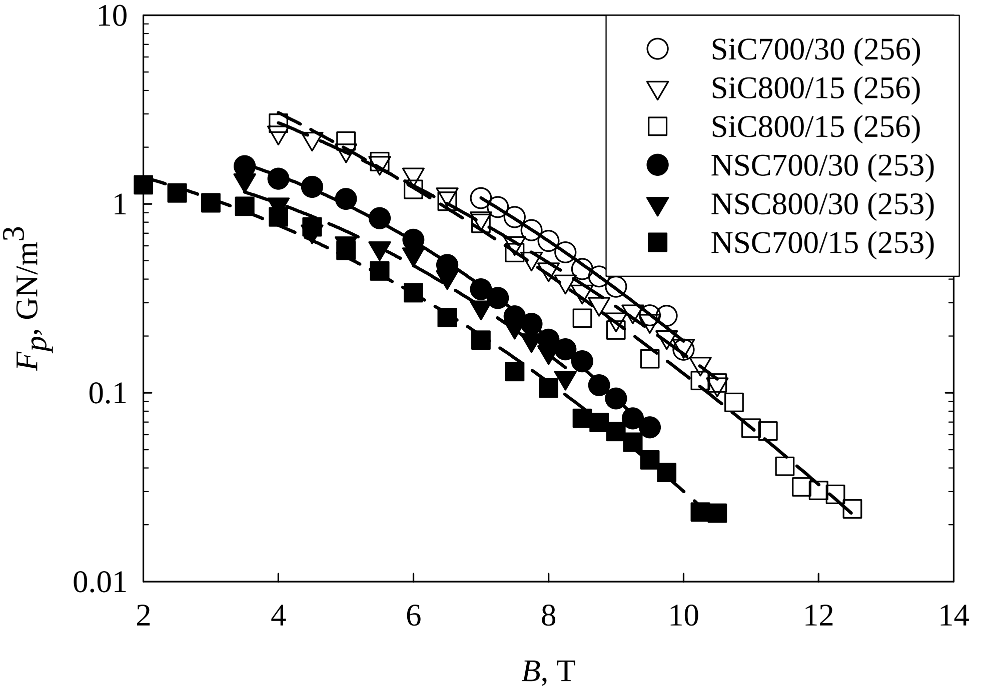


Figure 7. Pinning force density (from transport J_c) vs B at 4.2 K for MgB_2 wires, with and without SiC doping (SiC/NSC), reported by M Sumption et al. (Ohio State University).

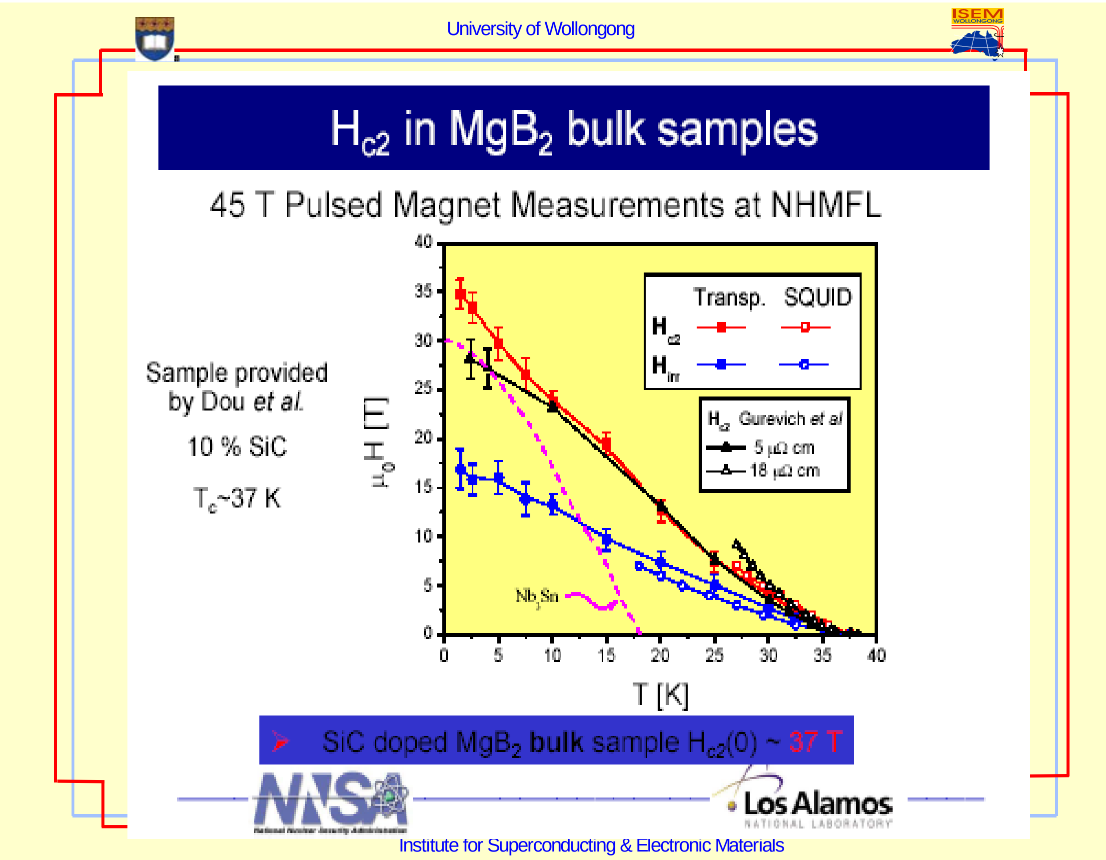


Figure 8. A record high upper critical field of 37 Tesla for a nano-SiC doped magnesium diboride bulk sample made by S.X Dou's team at UoW, measured by A. Serquis et al. of Los Alamos National Laboratory at the High Magnetic Field Laboratory at Florida State University (Presented at MRS Fall meeting in Boston, Dec 2003).

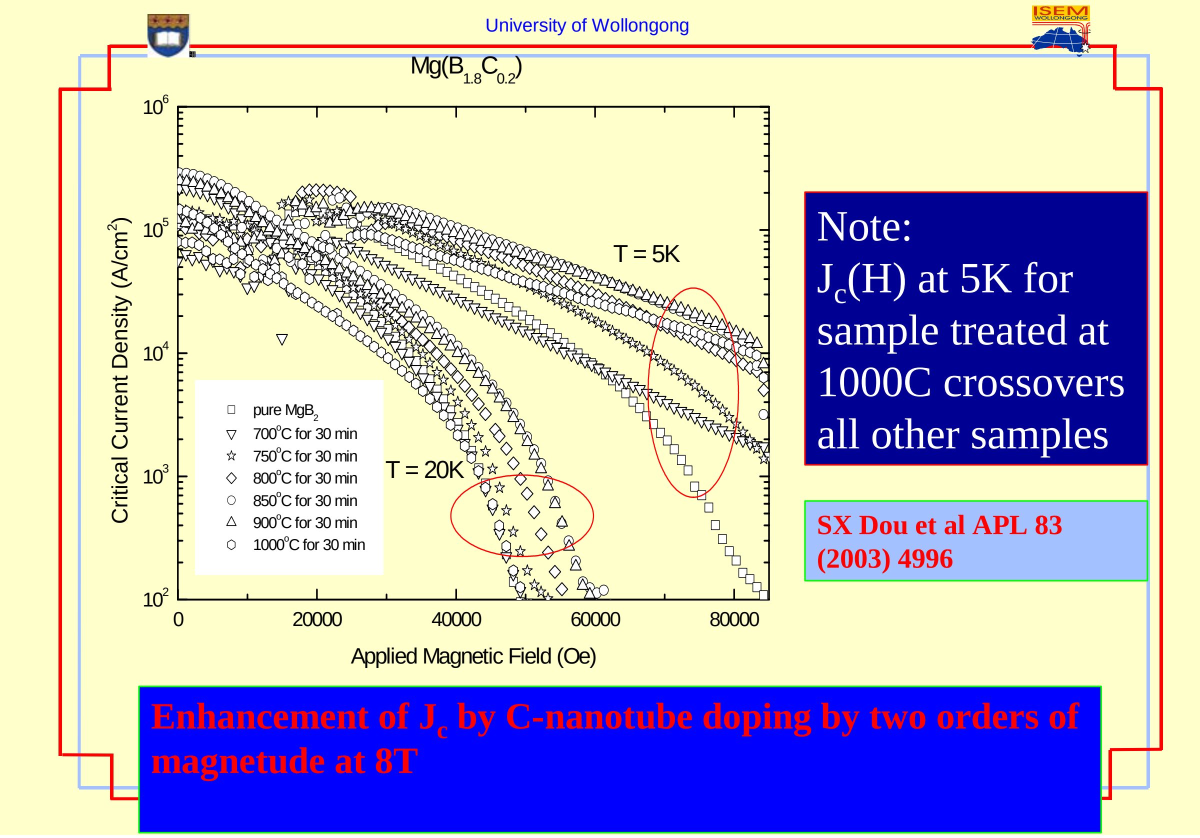


Figure 9. Comparison of J_c for the carbon nano-tube doped MgB_2 with undoped one. (Dou et al, Appl. Phys. Lett. 83 (2003) 4996)

Details of the technical data and mechanisms for the enhancement of J_c-H performance can be found in the selected papers relevant to this breakthrough as listed below.

S.X. Dou, S. Soltanian, J. Horvat, X.L. Wang, S.H. Zhou, M. Ionescu, H.K. Liu, P. Munroe and M. Tomsic, "Enhancement of the critical current density and flux pinning of MgB_2 superconductor by nanoparticle SiC doping", *App. Phys. Lett.* **81,** 3419-3421 (2002).

S.X. Dou, A.V. Pan, S. Zhou, M. Ionescu, H.K. Liu and P.R. Munroe "Substitution-induced pinning in MgB_2 superconductor doped with SiC nano-particles", *Supercond. Sci. Technol.* **15**, 1587-1591 (2002).

S.X. Dou, A.V. Pan, S. Zhou, M. Ionescu, X.L. Wang, J. Horvat, H.K. Liu and P.R. Munroe "Superconductivity, critical current density, and flux pinning in $MgB_{2-x}(SiC)_{x/2}$ superconductor after SiC nanoparticle doping" *J. Appl. Phys.* **94, 3,** 1850-1856 (2003)

S.X. Dou, W.K. Yeoh, J. Horvat, and M. Ionescu, "Effect of carbon nanotube doping on critical current density of MgB_2 superconductor", *Appl. Phys. Lett.* **83,** 4996-4998 (2003)

S.X. Dou, J. Horvat, S. Soltanian, X.L. Wang, M.J. Qin, S.H. Zhou, H.K. Liu and P.G. Munroe, "Transport critical current density in Fe-sheathed nano-SiC doped MgB_2 Wires" *IEEE Trans. On Appl. Supercond.* **13, 2** 3199-3202 (2003)

Contributors and collaborators

The members of superconductivity group at ISEM have made substantial contributions to the success of this breakthrough.. Research staff includes Drs J. Horvat, M. Ionescu, Prof. H.K. Liu, Drs A.

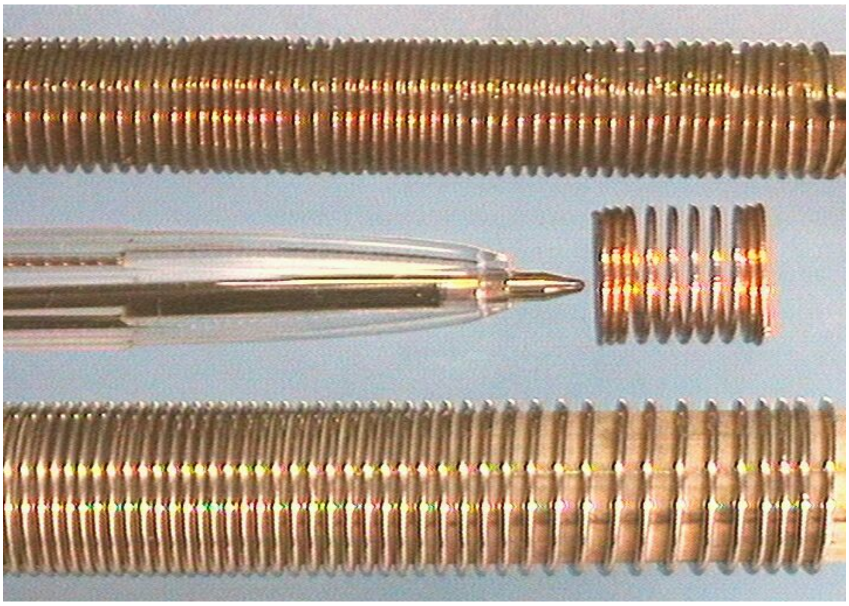
Pan, M.J. Qin, T. Silver and X.L. Wang. Postgraduate students include S. Keshavarzi, A. Li, M. Roussel, S. Soltanian, S.H. Zhou, W.K. Yeoh, Y.Q. Wen and Y Zhao. A collaborative team at Ohio State University headed by Prof E.W. Collings and Dr M. Sumption, the Applied Superconductivity Centre at Wisconsin headed by Prof D. Larbalestier, Dr. R. Klies at Brookhaven Laboratory, Dr. Serquis at Los Alamos Laboratory, and Dr S. Li at Nanyang Technological University have also contributed to the research work. This work has been supported by an ARC Discovery project grant and a Linkage grant for the last two years, and support will continue for another three years.

Our industry partner, a local company, Alphatech International headed by Mr. R. Neal, has contributed financial support to the ARC linkage project. Alphatech has been awarded a contract to build the main magnets for the Australian Synchrotron Project in Melbourne. Alphatech is very keen to explore the new generation MRI made using MgB_2 coils. MRI is an important facility for medical diagnosis and represents the single most significant market in superconductors.

Another partner, Hyper Tech Research (HTR) headed by the manager, Mr. Michael Tomsic, is presently developing MgB_2 wires for several applications -- MRI coils, [illegible]D, an inductor and a transformer (for the U.S. Navy), and a cryogenic motor (for NASA). HTR has signed a three-year agreement with UoW for the improvement of MgB_2 superconductors within the current ARC Linkage project. HTR has also attracted interest from numerous companies: three MRI companies, one company interested in the development of transformers and fault current limiters, and companies interested in military applications.

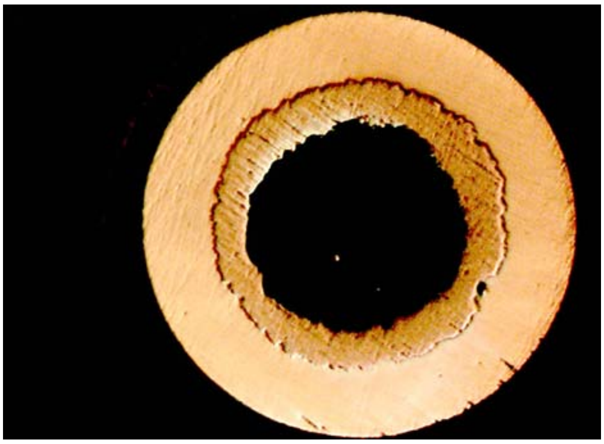
A local company, Australian Superconductors Ltd at Wollongong has been involved with the research program for the last ten years, laying the foundation for the success in our research with both HTS and MgB_2.

ILLUSTRATIVE MATERIALS



Superconducting coils made from copper-clad MgB_2 wire.

MgB_2 coil fabricated by our industry partner HTR using the wind and reaction technique.



Cross-section of 1.0 mm diameter all Cu sheathed MgB_2 wire.

SEM micrograph of the transverse section of a copper-clad 19-filament MgB_2 wire . The diameter ofthe wire was 1 mm.