Role of Carbon in Enhancing the Performance of MgB$_2$ superconductor

V.P.S. Awana$^{1,2,*}$, Arpita Vajpayee$^1$, Monika Mudgel$^1$, Rajeev Rawat$^3$, Somobrata Acharya$^2$, H. Kishan$^1$, E. Takayama-Muromachi$^4$, A. V. Narlikar$^3$ and I. Felner$^5$

$^1$ National Physical Laboratory, Dr K.S. Krishnan Road, New Delhi-110012, India
$^2$ ICYS centre National Institute for Material Science (NIMS), Tsukuba, Ibaraki 305-0044, Japan
$^3$ UGC-DAE Consortium for Scientific Research, University Campus, Khandwa Road, Indore-452017, MP, India
$^4$ Advanced nano-materials Laboratory, National Institute for Material Science (NIMS), Tsukuba, Ibaraki 305-0044, Japan
$^5$ Racah Institute of Physics, the Hebrew University, Jerusalem, 91904, Israel

Abstract

The enhancement of the critical current density ($J_c(H)$) of carbon and $nano$-SiC doped MgB$_2$ is presented and compared. The upper critical field ($H_{c2}$) being determined from resistivity under magnetic field experiments is though improved for both C substitution and $nano$-SiC addition the same is more pronounced for the former. In MgB$_{2-x}$C$_x$ carbon is substituted for boron that induces disorder in the boron network and acts as internal pinning centres. The optimal $J_c(H)$ values are obtained for $x = 0.1$ sample. In case of $nano$-SiC doped in MgB$_2$, the $J_c(H)$ improves more profoundly and two simultaneous mechanisms seems responsible to this enhancement. Highly reactive $nano$-SiC releases free carbon atom, which gets easily incorporated into the MgB$_2$ lattice to act as intrinsic pinning centres. Further enhancement is observed for higher $nano$-SiC concentrations, where the un-reacted components serve as additional extrinsic pinning centres.

PACS: 74.25.Ha Magnetic properties, 74.70.Ad Metals; Alloys and binary compounds (including A15, MgB$_2$ etc.)
Key Words: MgB$_2$ superconductor, nano-particle doping, Flux pinning, Critical current density

* Corresponding Author: e-mail: awana@mail.nplindia.ernet.in
1. Introduction

Recently, there have been several reports describing high performance *nano* (n) - particle doped MgB$_2$ superconductor where the *n*-SiC/*n*-diamond/*n*-carbon-tubes/*n*-carbon have yielded high dividends [1-5]. One wonders if the enhanced flux pinning is indeed solely due to these small size (< 10 nm) additives or whether carbon plays any additional important role.

Soon after the discovery of superconductivity in MgB$_2$ at $T_c$ nearly 40 K [6], its various interesting physical properties were found to be intimately linked with: (a) the unexpected transparency of its grain-boundaries [7,8] to passage of electric current, and (b) to the existence of unusual two-band structure [9]. Because of its higher $T_c$, MgB$_2$ clearly holds a distinct advantage over most other superconductors in that it can conveniently function at a relatively higher temperature of, say 20K, easily produced using a conventional close cycle cooling system. Although the $T_c$ of high temperature superconductors (HTS) is much higher, i.e., around 90-130 K, their small coherence length $\xi$ (around 0.3 nm to 2.0 nm), large anisotropy and ceramic nature have posed formidable problems for conductor development for practical applications. It is nearly impossible to optimally pin the flux vortices in HTS via foreign additives because of very small $\xi$. On the other hand, the relatively larger $\xi$ of MgB$_2$ (about 5-10 nm) allows optimum pinning by *n*-particles for enhancement of the $J_c(H)$ performance. Although this effect has been studied for a variety of different *nano*-particle additives, e.g., *n*-Dy$_2$O$_3$ [10], *n*-SiO$_2$ [11], *n*-carbon [2,4], *n*-tubes of carbon [3] and *n*-diamond [5], the best performance yet seen, is with nanosized carbon derivatives. In fact it might be interesting to inter-compare the high field critical current ($J_c(H)$) behaviour resulting from carbon, when substituted for boron (MgB$_{2-x}$C$_x$) with that when it (or its derivatives) are introduced as additive. We found here, that in the MgB$_{2-x}$C$_x$ system, though $T_c$ decreases with $x$, the high field $J_c(H)$, when measured at lower temperatures, is markedly higher for low $x$ values. For MgB$_2$+ *n*-SiC the $T_c$ decreased slightly but the $J_c(H)$ goes on improving more profoundly till 7 %wt addition. We thus conclude that the enhancement in $J_c(H)$ is a result of two parameters: the existence of pinning centres due to addition of *n*-SiC and, simultaneously, the presence of disorder.
in boron networks caused by carbon substitution. Our present results demonstrate the importance of disorder originated from carbon substitution.

2. Experimental details

Our polycrystalline MgB$_2$-$n$SiC ($n=0, 5\%, 7\% \& 10\%$) and MgB$_{2-x}$C$_x$ ($x=0, 0.04, 0.08, 0.10 \& 0.20$) samples were synthesized by solid-state reaction route with ingredients of Mg, B, $n$-SiC and C powders. The Mg powder used is from *Reidel-de-Haen* of 99% purity, insoluble in HCl and with Fe impurity of less than 0.05%. Amorphous B powder used is from *Fluka* (of 95-97% purity). The $n$-SiC powder is from Aldrich with average particle size (APS) of 5-12 nm. For synthesising the samples, the stoichiometric amounts were ground thoroughly, palletized, and put in a quartz tube inserted at 850 °C (heating rate 425 °C per hour) under a flow of argon at ambient pressure. This temperature was held for 2.5 hours, and subsequently cooled under Ar, to room temperature over a timeframe of 6 hours. The x-ray diffraction pattern of the compound was recorded by using CuK$_\alpha$ radiation. *Jeol*-200KV transmission electron microscope was used for bright/dark field images. The magnetization measurements were carried out using *Quantum Design* MPMS-XL magnetometer.

3. Results and discussion

Fig. 1 depicts the X-ray diffraction (XRD) patterns of some of the studied MgB$_{2-x}$C$_x$ and $n$-SiC added MgB$_2$ samples and the lattice parameters are listed in Table 1. The pristine MgB$_2$ compound carries a small amount of un-reacted MgO (marked as #). In MgB$_{2-x}$C$_x$, the single phase is retained up to $x=0.2$. When $n$-SiC is added to MgB$_2$, the phase purity is maintained up 3-wt%. For 5-wt% (assigned as $n$-SiC5) the SiC derivative viz. Mg$_2$Si lines are clearly seen in the XRD spectrum (marked by *). Lattice parameters are given in Table 1. For MgB$_{2-x}$C$_x$ system thought the a-lattice parameter decreases, the c increases slightly with increasing $x$ up to $x=0.2$. The same is true for $n$-SiC added samples except that some un-reacted lines are seen above 5-wt% addition. This is consistent with previous reported data on MgB$_{2-x}$C$_x$ [12]. This indicates clearly that in both cases carbon enters to
the matrix. The nano $n$-SiC reacts with Mg (leaving free silicon or Mg$_2$Si) and release highly reactive free C which can be easily incorporated into the lattice of MgB$_2$ and substitute into the B sites [13]. For higher $n$-SiC concentrations, the unbroken $n$-SiC still acts as additional pinning centres. The inset in Fig. 1 shows the presence of nano particles in bright field TEM image with average particle size of around 10 nm.

The zero-field-cooled (ZFC) and field-cooled (FC) magnetic susceptibility curves of the MgB$_{2-x}$C$_x$ and $n$-SiC added MgB$_2$ samples are shown in Fig. 2. The $T_c$ values for all the studied samples are given in Table 1. The ZFC branch of pristine MgB$_2$ exhibits a sharp diamagnetic superconducting transition ($T_c$) at 38.5 K, whereas the FC signal is very small due to intrinsic pinning. Intrinsic pinning in MgB$_2$ due to various nano-structural defects was highlighted by us very recently [14] and is not discussed here. For MgB$_{2-x}$C$_x$ system, the $T_c$ values of 34.5 and 32 K for with $x = 0.10$ and 0.20 are obtained, which are in agreement with the previous reports [12]. For $n$-SiC added MgB$_2$ materials the $T_c$ obtained for 5-wt % is 36 K and 35 K for 10wt% $n$-SiC added sample. The relatively constant $T_c$ in $n$-SiC added MgB$_2$ samples for 5 wt% up to 10 wt% indicates that at higher concentrations, only a fraction of C presumably substitutes for boron in MgB$_2$, which would justify the marginal decrease in $T_c$. The rest of $n$-SiC is available in the matrix and serves as pinning centres.

Fig. 3 depicts the $J_c(H)$ results for $n$-SiC added MgB$_2$ samples at 10 and 20 K up to relatively high fields of 70 kOe. The critical current is deduced from the $M(H)$ plots by invoking Bean’s critical state model. As inferred from this figure and Table 1, $J_c(H)$ performance of MgB$_2+7$ wt% $n$-SiC sample is the optimum one at both temperatures and its value at 10 K under 70 kOe field is an order of magnitude higher than the pristine MgB$_2$. To see the irreversibility field ($H_{irr}$), the extended $M(H)$ plots at 10 K of these samples are shown in the inset of Fig. 3. As may be seen, for pristine MgB$_2$, the $H_{irr}$ is close to 70 kOe and it is significantly enhanced for $n$-SiC added samples. Note the higher $H_{irr}$ for the 7 wt% $n$-SiC added sample and the relatively smaller loop for the 10 wt% sample, which indicates that the 7 wt% $n$-SiC is optimum concentration MgB$_2$ performance. The "curl" like curve exhibited in Figs. 3 and 4, are due to flux jumps which are observed at low applied fields, only for higher $J_c(H)$ samples and very low heat
capacity. The flux jumps phenomenon was already commented very recently by some of us in an earlier report [15].

The $J_c(H)$ results for MgB$_{2-x}$C$_x$ samples along with pristine MgB$_2$ are shown in Fig. 4. The low field region ($< 40$ KOe), $J_c(H)$ of pristine MgB$_2$ is higher than that of MgB$_{2-x}$C$_x$: $x = 0.10$ and $0.20$ samples. However as field increases further, the $J_c(H)$ performance of C doped samples is better than that of pure MgB$_2$. The sample with $x = 0.10$ (i.e. the 5at% C at B site in MgB$_2$) has the best characteristics. Its $J_c$ at 10 K and 70 kOe, is higher than for both $x = 0$ and $x = 0.20$ samples, in spite of the reduction in $T_c$ by 4 K (Table 1). Comparatively, the $J_c(H)$ performance of MgB$_2$ + $n$-SiC (Fig.3) is superior than that of MgB$_{2-x}$C$_x$ (Fig.4).

To confirm the improved flux pinning behaviour through carbon doping, the field dependence of normalized flux pinning force ($F_p / F_{p, max}$) is shown in fig. 5 & fig. 6 at 20 K. The relationship between flux pinning force and critical current density could be described by [16, 17].

$$F_p = \mu_0 J_c(H) H$$

(1)

Where $\mu_0$ is the magnetic permeability in vacuum. It is clear from these figures that the pinning forces are much higher than the pure MgB$_2$ above 1.5 Tesla for both C and SiC doped samples, indicating enhanced flux pinning force in high fields. It can be seen in fig. 5 that for the 7-wt% $n$-SiC doped sample the peak is much broader than those of other three samples, indicating that the pinning strength in the higher field region has improved. The same behaviour is shown by MgB$_{2-x}$C$_x$: $x = 0.10$ sample. The Broadness of the $F_p / F_{p, max}$ versus $H$ plot is comparatively more for MgB$_2$ + $n$-SiC (Fig.5) than that of C doped (Fig.6) samples. This indicates that higher field flux pinning is more effective in $n$-SiC doped samples than in MgB$_{2-x}$C$_x$.

Resistance variation with temperature of Pure, SiC 7-wt% and C ($x=0.10$ in MgB$_{2-x}$C$_x$) added MgB$_2$ samples are shown in fig.7. From this figure we see that the room temperature resistance value is increased as we doped C & SiC in MgB$_2$. The residual resistivity ratio (RRR = $R_{T280K}$/$R_{Tonset}$) values for these samples are obtained as 3.15, 1.73 & 1.53 respectively. It indicates towards the increased disorder in doped samples in comparison to pure one. Transition temperature ($T_c$) decreases in both SiC added and C substituted
sample as compared to pure MgB\(_2\) because of carbon substitution at boron site, which is confirmed by decrease in lattice parameter ‘\(a\)’. Exact values of \(T_c(R=0)\) and lattice parameters are tabulated in Table 1.

Transition zone of Resistance vs Temperature plots at varying field values is shown for Pure, SiC 7\% and C (\(x=0.10\) in MgB\(_{2-x}\)C\(_x\)) added MgB\(_2\) samples in Fig. 8. Transition width is more or less same in all the samples. With the help of this graph we found out the upper critical field values and the variation of upper critical field with temperature for SiC 7\%, C (\(x=0.08\) & 0.10 in MgB\(_{2-x}\)C\(_x\)) and pure MgB\(_2\) sample is shown in fig. 9. This figure depicts that there is an increment in \(H_{c2}\) values by both the dopants because of carbon substitution [18]. Increase in \(H_{c2}\) is accompanied by a rise in resistivity. Relative increase in \(H_{c2}\) is more for MgB\(_{2-x}\)C\(_x\) than that of pure and \(n\)-SiC doped samples at all temperature. It reveals that carbon substitutes at Boron site in MgB\(_2\) lattice more prominently in case of Mg\(_{1-x}\)B\(_{2-x}\)C\(_x\) as compared to \(n\)-SiC added samples. This is indicated by steep decrease in \(a\) parameter (XRD results) and \(T_c\) of Mg\(_{1-x}\)B\(_{2-x}\)C\(_x\) samples. On the other side in MgB\(_2\)+\(n\)-SiC series of samples, some free Carbon being available from broken \(n\)-SiC also substitutes at Boron site but in less effective manner than in Mg\(_{1-x}\)B\(_{2-x}\)C\(_x\), resulting in a relatively smaller decrease in \(a\) parameter and \(T_c\). It seems that only a portion of broken \(n\)-SiC goes to the grain boundary and/or within the MgB\(_2\) grains as \textit{nano}-inclusions and remaining unbroken \(n\)-SiC and Mg\(_2\)Si particles act as extrinsic pinning centres in the composite system. This results in better \(J_c(H)\) performance for MgB\(_2\)+\(n\)-SiC samples than that of Mg\(_{1-x}\)B\(_{2-x}\)C\(_x\). Summarily though the upper critical field values are higher for Mg\(_{1-x}\)B\(_{2-x}\)C\(_x\), the \(J_c(H)\) performance is better for MgB\(_2\)+\(n\)-SiC series of samples. This is primarily due to the dual role of added \(n\)-SiC, first as an extrinsic \textit{nano}-pinning agent and secondly its broken free Carbon which substitutes at B-site in MgB\(_2\) lattice and acts separately as intrinsic pinning disorder in the system. Both these effects improve the performance more dramatically than as for Mg\(_{1-x}\)B\(_{2-x}\)C\(_x\). Lattice parameters, critical temperatures (\(T_c\)) and critical current density (\(J_c\)) values are tabulated in Table 1.

For quantitative comparison, the \(J_c(H)\) (50 KOe, 10 K) values for all the studied MgB\(_{2-x}\)C\(_x\) and \(n\)-SiC added MgB\(_2\) samples are given in Table 1. It appears that the \(J_c(H)\) values obtained for MgB\(_2\)+\(n\)-SiC (Fig. 3), are much higher than that of the substituted MgB\(_{2-x}\)C\(_x\) samples. In the later case, the enhancement of \(J_c(H)\) is entirely due to the
disorder in $\sigma$ band [9,12] via carbon substitution at boron site, as there are no additives serving as *nano*-pins. On the other hand, in the MgB$_2$ + $n$-SiC system the higher $J_\text{c}(H)$ arises from additives which serve as pinning centres. So in principle the $J_\text{c}(H)$ of MgB$_2$ can be enhanced by two mechanisms: (1) by partial substitution (of about 5%) of boron by carbon as occurs in MgB$_{2-x}$C$_x$ and (2) by un-reacted nano-particles which serve as pinning centres. In this way we may understand why $n$-SiC, $n$-Diamond, $n$-Carbon-tubes and $n$-Carbon additions to MgB$_2$ yielded higher dividends than other additives of non-carbon *nano*-derivatives [1-5, 13, 19, 20]. In MgB$_{2-x}$C$_x$ as well as in low concentrations of $n$-SiC added materials the C substitution for B induces disorder in lattice sites and thereby contributes to additional flux pinning and substantiates and hence enhances the MgB$_2$ performance. Further increase of $J_\text{c}(H)$ occurs for high concentrations of $n$-SiC where the remaining unbroken *nano*-particles though in lesser concentration are still present within the MgB$_2$ grains.

Worth mentioning is the fact that breaking of doped *nano*-Carbon derivatives and ensuing substitution at B site in MgB$_2$ depends upon both nature of dopant and the heat treatment [13, 19-21]. For example, the $n$-SiC is more susceptible to react than $n$-Diamond [13, 19-21] at common MgB$_2$ synthesis temperatures.

### 4. Summary and Conclusion

To sum up, we have provided clear evidence that two mechanisms are responsible for the enhancement of $J_\text{c}(H)$ in carbon doped MgB$_2$. A nontrivial contribution to flux pinning originates from the disorder created in $\sigma$ band superconducting condensate, particularly in the boron networks, serving as weakly superconducting pins. Beside that, un-reacted *nano*-particles introduced as additives serve as normal pin centres. Both components are responsible for the enhancement in $J_\text{c}(H)$ of MgB$_2$ formed with *nano*-carbon derivatives as additives.
Acknowledgement

This research is partly supported by the Israeli Ministry of Science under the mutual India (DST) - Israel (MST) grant. One of us (VPSA) thanks ICYS centre Director Prof. H. Bando for his current visit to NIMS Japan. AVN would like to thank Indian National Science Academy, New Delhi for the Senior Scientist position. Arpita Vajpayee and Monika Mudgel would like to thank the CSIR for the award of JRF to pursue their Ph. D degree. Authors from the NPL thank their director Professor Vikram Kumar for encouragement.

Table 1: The $a$, $c$ lattice parameters, $T_c$ and $J_c$ (50 KOe, 10K) for studied MgB$_2$-$n$SiC and MgB$_{2-x}$C$_x$ samples

| Sample                        | $a$ (Å)    | $c$ (Å)    | $T_c^{dia}$ (K) | $T_c(R=0)$ | $J_c$ (A/cm$^2$) (50 KOe/10K) |
|-------------------------------|-----------|-----------|-----------------|------------|-------------------------------|
| MgB$_2$                       | 3.0817(8) | 3.5230(8) | 38.5            | 38.2       | 5.40 x 10$^3$                |
| MgB$_{1.96}$C$_{0.04}$        | 3.0793(7) | 3.5280(8) | 37              | -          | 1.27 x 10$^4$                |
| MgB$_{1.92}$C$_{0.08}$        | 3.0754(16)| 3.5275(16)| 36              | 34         | 1.10 x 10$^4$                |
| MgB$_{1.90}$C$_{0.10}$        | 3.0742(24)| 3.5287(24)| 34.5            | 32.5       | 1.30 x 10$^4$                |
| MgB$_{1.80}$C$_{0.20}$        | 3.0678(20)| 3.5336(21)| 32              | 29.5       | 7.3 x 10$^3$                 |
| MgB$_2$+SiC5at%               | 3.0762(5) | 3.5289(8) | 36              | 35.5       | 1.4 x 10$^4$                 |
| MgB$_2$+SiC7at%               | 3.0772(9) | 3.5297(6) | 36              | 35         | 4.15 x 10$^4$                |
| MgB$_2$+SiC10at%              | 3.0759(8) | 3.5292(9) | 35              | 34.5       | 3.07 x 10$^4$                |
References

1. S.X. Dou, S. Soltanian, J. Horvat, X.L. Wang, S.H. Zhou, M. Ionescu, H.K. Liu, P. Munroe and M. Tomsic, Applied Physics Letters 81, 3419 (2002).

2. W.K. Yeoh, J.H. Kim, J. Horvat, X. Xu, M.J. Qin, S.X. Dou, C.H. Jiang, T. Nakane, H. Kumakura, and P. Monroe, Superconductor Science and Technology 19, 596 (2006)

3. P. Kovác, I. Husek, V. Skákalova, J. Meyer, E. Dobrocka, M Hirscher and S Roth, Superconductor Science and Technology 20, 105 (2007)

4. B.J. Senkowicz, J.E. Giencke, S. Patnaik, C.B. Eom, E.E. Hellstrom and D.C. Larbalestier, Applied Physics letters 86, 202502 (2005)

5. C. H Cheng, H. Zhang, Y. Zhao, Y. Feng, X. F. Rui, P. Munroe, H. M. Zeng, N. Koshizuka and M. Murakami, Superconductor Science and Technology 16, 1182 (2003)

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

7. D.C. Larbalestier et al., Nature (London) 410, 186 (2001).

8. S. B. Samanta, H. Narayan, A. Gupta, A. V. Narlikar, T. Muranaka, and J. Akimitsu Physical Review B 65, 092510 (2002).

9. H. J. Choi, D. Roundy, H. Sun, M.L. Cohen, and S.G. Louie, Nature (London) 418, 758 (2002).

10. S.K. Chen, M. Wei, and J.L. MacManus-Driscoll, Applied Physics letters 88, 192512 (2006)

11. A. Matsumoto, H. Kumakura, H. Kitaguchi, and H. Hatakeyama, Superconductor Science and Technology 16, 926 (2003)

12. R. A. Ribeiro, S. L. Bud’ko, C. Petrovic and P. C. Canfield, Physica C 384, 227 (2003).

13. S.X. Dou, O. Scherbakova, W.K. Yeoh, J.H. Kim, S. Soltanian, X.L. Wang, C. Senatore, R. Fulkiger, M. Dhalle, O. Husnjak, and E. Babic, Phys. Rev. Lett. 98, 097002 (2007).

14. V.P.S. Awana et al, submitted for publication (2007).

15. I. Felner, V.P.S. Awana, Monika Mudgel, and H. Kishan, J. Appl. Phys. 101, 09G101 (2007).
16. E. Martinez, P. Mikheenko, M. Martinez-lopez, A. Millan, A. Bevan and J.S. Abell, *Phys. Rev. B* **75**, 134515 (2007)

17. T.M. Shen, G. Li, C.H. Cheng and Y. Zhao, *Supercond. Sci. and Tech.* **19**, 1219 (2006)

18. R.H.T. Wilke, S. L. Bud’ko, P.C. Canfield, D.K. Finnemore, R.J. Suplinskas and S.T. Hannahs *Phys. Rev. Lett.* **92**, 217003 (2004).

19. S.X. Dou, W.K. Yeoh, O. Shcherbakova, D. Wexler, Y. Li. Zhong, M. Ren, P. Munroe, S.K. Chen, K.S. Tan, B.A. Glowacki and J.L. MacManus-Driscoll, Adv. Mater. **18**, 758 (2006).

20. C H Cheng, Y Yang, P Munroe and Y Zhao, Superconductor Science and Technology **20**, 296 (2007).

21. Arpita Vajpayee, Hannu Huhtinen, V.P.S. Awana, Anurag Gupta, Rajeev Rawat, N.P. Lalla, Hari Kishan, R. Laiho, I. Felner and A.V. Narlikar, Superconductor Science and Technology **21**, S1-S5(2007).
Figure Captions:

Fig. 1: X-ray diffraction patterns at room temperature of various MgB$_2$-$n$SiC and MgB$_{2-x}$C$_x$ samples. The MgO impurity is marked as # and Si derivatives with *. The inset shows the TEM image with scale bar of 100 nm, for MgB$_2$+7wt% $n$-SiC sample, highlighting the presence of nano-particles in the matrix.

Fig. 2: Low field (10 Oe) magnetic susceptibility ($\chi$) versus Temperature ($T$) plots for various MgB$_2$-$n$SiC and MgB$_{2-x}$C$_x$ samples.

Fig. 3: $J_c(H)$ plots at 10 and 20 K for MgB$_2$-$n$SiC samples, the inset shows the extended $M(H)$ plots of the same to mark the $H_{irr}$.

Fig. 4: $J_c(H)$ plots at 10 and 20 K for MgB$_{2-x}$C$_x$ samples; the notation C4, C8, C10 and C20, does mean x = 0.04, 0.08, 0.10 and 0.20 respectively.

Fig. 5: Reduced flux pinning force ($F_p/F_{p,max}$) variation with magnetic field for SiC doped samples at 20 K.

Fig. 6: Reduced flux pinning force ($F_p/F_{p,max}$) variation with magnetic field for MgB$_{2-x}$C$_x$ samples at 20K; the notation C4, C8, C10 and C20, does mean x = 0.04, 0.08, 0.10 and 0.20 respectively.

Fig. 7: Resistance vs Temp. Plots for MgB$_{2-x}$C$_x$, x=0.10, MgB$_2$+nSiC7% and Pure MgB$_2$ samples.

Fig. 8: Transition zone of resistance vs Temperature Plots under different magnetic fields up to 8 Tesla for MgB$_{2-x}$C$_x$, x=0.10, MgB$_2$+nSiC7% and Pure MgB$_2$ samples.

Fig. 9: Upper critical Field ($H_{c2}$) vs Normalized temperature Plots for MgB$_{2-x}$C$_x$, x=0.10 & x=0.08, MgB$_2$+nSiC7% and Pure MgB$_2$ samples.
Fig. 1 Awana et al.

![X-ray diffraction pattern](image1)

- $I$ (arb. units)
- $2(\Theta)$ Degrees
- $\text{MgB}_2 + n\text{-SiC}5$
- $\text{MgB}_2 + n\text{-SiC}2$
- $\text{MgB}_{1.8}C_{0.2}$
- $\text{MgB}_{1.9}C_{0.1}$
- $\text{MgB}_{1.1}$

Fig. 2 Awana et al.

![Magnetic susceptibility plot](image2)

- $\chi$ (emu/g)
- $T$ (K)
- $\text{MgB}_2$
- $\text{MgB}_{1.0}C_{0.1}$
- $\text{MgB}_{1.8}C_{0.2}$
- $\text{MgB}_{1.9}C_{0.1}$
- $\text{MgB}_2 + n\text{SiC}5$
- $\text{MgB}_2 + n\text{SiC}10$
Fig. 3 Awana et al,
Fig. 4 Awana et al,
Fig. 5 Awana et al,

![Graph showing data for pure SiC and SiC with different dopants.](image)

\[ T = 20 \text{ K} \]

Fig. 6 Awana et al,

![Graph showing data for pure C and C with different dopants.](image)

\[ T = 20 \text{ K} \]
Fig. 7 Awana et al,

![Graph showing resistance (R) vs. temperature (T) for different samples.]

Fig. 8 Awana et al

![Graph showing resistance (R) vs. temperature (T) for different samples.]
Fig. 9 Awana et al

![Graph showing the relationship between $H_{c2}$ (Tesla) and $T/T_c$ for different compositions of MgB$_2$ and MgB$_2$ + SiC 7% materials. The graph includes four different types of materials: MgB$_{2-x}$C$_x$, x=0.10, MgB$_2$ + SiC 7%, Pure MgB$_2$, and MgB$_{2-x}$C$_x$, x=0.08. Each material is represented by a different symbol and line style on the graph.](image-url)