Enhanced Flux Pinning Performance of Bulk MgB₂ via Immersion of Synthetic Motor Oil

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Abstract
The present investigation focuses on the incorporation of synthetic motor oil as an inexpensive, rich carbon source in bulk MgB₂ superconductor and its effect on superconducting and flux pinning properties. A set of three MgB₂ bulk samples were prepared from commercial high-purity powders of Mg metal and amorphous B powder utilizing a conventional in situ solid-state reaction process. Before sintering, the MgB₂ samples were immersed in used and new synthetic motor oil for a standby time of 30 min and sintered in pure Ar atmosphere at 775 °C for 3 h. X-ray powder diffractometer (XRD) analysis confirmed that single-phase formation of MgB₂ with a small shift in X-ray diffraction peaks especially at (110) towards the peak position due to the effect of carbon substitution into the boron sites in lattice for samples immersed in new and used synthetic oil. The magnetization measurements indicated the T_c (onset) value to somewhat decrease to 37.5 K as a result of carbon doping. Microstructural observations with scanning electron microscopy (SEM) suggested that fine nano-sized MgB₂ grains improved self-field critical current density around 3.8 × 10⁵ A/cm² at 20 K for all samples studied. Further, the high-field critical current density (J_c) was improved especially for the sample immersed in used synthetic motor oil with the value of 2.7 × 10⁴ A/cm², 6 × 10³ A/cm² at 20 K, and at 3 T and 4 T, which is higher as compared to pure-MgB₂ sample. In essence, the results signify that the bulk MgB₂ samples immersed with used synthetic motor oil would improve the bulk performance at high magnetic fields indicating to be a viable option for industrial applications.

Keywords Bulk MgB₂ · Synthetic motor oil · X-ray diffraction · Critical current density · Flux pinning

1 Introduction

In January 2001, the discovery of a superconducting phenomenon with the transition temperature of 39 K in MgB₂ compound had ignited a renaissance of interest in solid-state physics community as it had proposed a simple, binary intermetallic superconductor with a groundbreaking superconducting transition temperature recorded for non-60-based compounds and non-oxides [1]. MgB₂ exhibits a wide range of attractive features including small anisotropy, large coherence length, simple crystal structure, transparent grain boundaries, and easy processing allowing it to be a desirable candidate for numerous industrial and commercial applications [2, 3]. The essential application areas of bulk MgB₂ are NMR devices, MRI systems, particle accelerators, maglev transport technology, wind turbine generators, etc. [4, 5]. However, additional enhancement of flux pinning and critical current density (J_c) is significant for material compatibility at high-field applications as MgB₂ superconducting material consists of weak flux pinning and poor grain connectivity which would further lead to a sharp fall in critical current density at higher magnetic fields around 20 K [6, 7]. In particular, doping and chemical addition with C or C-based compounds in MgB₂ contributed towards the improvement of critical current density performance due to amelioration of intra-band scattering and grain connectivity as well as the induction of extra pinning centers [8]. In fact, numerous groups in the past had investigated the simultaneous enhancement of J_c in MgB₂ by introducing carbon-containing dopants where Yang et al. showed that polymer doping in MgB₂ enhanced both irreversibility field and critical current density at high-field region due to the parameters of percolation threshold and anisotropy; whereas improved effects of J_c were much weaker at high temperature ranges due to effect of less reduction of anisotropy at similar temperature [9]. De Silva et al. noted that graphene doping
in MgB$_2$ notably enhanced the superconducting properties under a small reduction of $T_c$; further, improved flux-flow activation energy, low resistivity, and high critical fields were observed for the optimal doped bulk and flux pinning mechanism referred to spatial fluctuation in transition temperature for graphene doped MgB$_2$ sample [10]. Dou et al. conveyed that nano-SiC doping in MgB$_2$ crucially improved $H_{irr}$ and $J_c$ while decreasing $T_c$ by 1.5 K as intragrain pinning centers were introduced at high temperatures and fields [11]. Kim et al. presented that carbohydrate doping with the usage of malic acid in MgB$_2$ bulks showed numerous advantages such as prevention of expensive nano-additives, enablement of homogenous mixing of precursor powders, and an exceptional improvement in $H_{c2}$, $H_{irr}$, and $J_c$ when differentiated from pure MgB$_2$ sample; in fact, MgB$_2$ + 30 wt % C$_6$H$_{12}$O$_5$ bulk sample’s $J_c$ tremendously increased by a factor of 21 under 5 K and 8 T with the absence of degradation of self-field $J_c$ [12]. Also, Kim et al. inferred that doping effect of two types of multi-wall carbon nanotubes (CNTs) showed a slight decrease in $T_c$ as the sintering temperature increased and $T_c$ values for long CNT doped bulk samples showed an increase. The following result explains that small aspect ratio enabled stronger reactivity between short CNT and MgB$_2$ where carbon C from short CNT substituted for boron B. The short CNT samples which were sintered at high temperature ranges of 900 °C and 1000 °C showed that magnificent $J_c$ value of 10$^4$ A/cm$^2$ within the fields up to 8 T at 5 K. Strong flux pinning centers were formed due to substitution of C into MgB$_2$ lattice along with the inclusion of nano-sized MgO particles [13]. Qin et al. suggested that hydrocarbon doping in MgB$_2$ samples via citric acid showed gradual decrease in anisotropy of upper critical field with an aberration of experimental data from grain boundary pinning theory with a reduction of increasing doping level as temperature approaches $T_c$ [14]. Yamamoto et al. indicated that B$_4$C doping in MgB$_2$ bulks effected substantial improvement in $J_c$ especially under high magnetic fields at 5 K due to strengthened flux pinning properties at grain boundaries due to carbon substitution with a decrease of $a$-axis length and $T_c$ with deterioration of crystallinity [15]. Moreover, carbon would be substituted at boron (B) sites in the MgB$_2$ lattice that further increases impurity scattering between $\pi$ and $\sigma$ bands resulting in improved upper critical field ($B_{c2}$) [16]. Nevertheless, a uniform distribution in the matrix tends to be a drawback if the dopants presented above were incorporated. In order to overcome this issue, researchers had introduced carbon-encapsulated boron for a batch production of MgB$_2$ samples and proved to be successful. In contrast, carbon-encapsulated boron powder was considered to be expensive making the entire fabrication process costly and was not a preferable option for a commercial production of bulk MgB$_2$ super-magnets [7]. Due to the following reasons, “synthetic motor oil” was utilized because it was considered to be a rich source of carbon since it could be easily accessed at a relatively cheaper price and was suggested to be a viable alternative towards low cost processing for industrial approach; as a matter of fact, synthetic motor oil produces a high tolerance towards aging and heat as it poses high oxidative and high thermal stability. Consequently, it was pivotal to study the effects of used and new synthetic motor oil towards the flux pinning and superconducting properties of bulk MgB$_2$ samples at a high field to be compared with a reference sample without incorporation of synthetic motor oil.

In this present investigation, a set of three MgB$_2$ samples were prepared where two samples were immersed in used and new synthetic motor oil, while third sample was a reference sample without any exposure to synthetic motor oil addition. The following samples were characterized utilizing X-ray powder diffractometer (XRD) and superconducting quantum inference device (SQUID) magnetometer to report superconducting transition temperature ($T_c$) and critical current density ($J_c$); in essence, it was observed that flux pinning performance was enhanced especially in high magnetic fields at 20 K via an immersion of used synthetic motor oil.

2 Materials and Methods

First of all, the bulk polycrystalline MgB$_2$ samples were synthesized by utilizing conventional in situ solid-state reaction methodology. High purity commercial powders of Mg metal of 99.9%, 200 meshes from Furuuchi Chemical Corporation, and nano-sized amorphous B powder of 98.5% purity, 200 nm from Pavezyum Advanced Chemicals, Turkey, were utilized to produce a set of three bulk MgB$_2$ samples; additionally, the following powders were mixed with a stoichiometric ratio of Mg:B = 1:2. Note that the starting powders were thoroughly ground in a glove box setting under the conditions of argon atmosphere. Then, the powder mixture was compressed into pellets with the dimension of 10 mm in diameter and 5 mm in thickness via usage of uniaxial press under the load of 20 kN. The pellet samples were distinguished into three separate specimens where (i) u-MgB$_2$ was noted as a MgB$_2$ sample immersed in used synthetic motor oil for a standby time of 30 min; (ii) n-MgB$_2$ was referred as a MgB$_2$ sample submerged in new synthetic motor oil for a standby time of 30 min; (iii) pure-MgB$_2$ was a reference pellet sample of without any synthetic motor oil addition. Note that the following pellets were instantly wrapped with tantalum foils [17] and were put through heat treatment under argon atmosphere in a tube furnace. All of the samples were heated at a temperature of 775 °C for 5 h and kept constant for a period of 3 h with flow of Ar gas. Then, the samples were cooled under the room temperature at a rate of 100 °C/h.
Secondly, SQUID magnetometer (Quantum Design MPMS5) was used to characterize and evaluate the superconducting properties of the samples such as $J_c$ and $T_c$. The specimens from bulk MgB$_2$ samples were cut with the dimensions of $1.5 \times 1.5 \times 0.5$ mm$^3$ to acquire the measurements of critical temperature ($T_c$) in addition to magnetization hysteresis loops ($M$-$H$ loops) within an applied magnetic field range of $-1$ to $+5$ T at 20 K. The extended Bean critical state formula was applied to estimate the critical current density as given below

$$J_c = 20\Delta m/[l^2d(w-l/3)]$$  \hspace{1cm} (1)

where $d$ is the sample thickness, $l$ and $w$ are cross-sectional dimensions, $w \geq l$, and $\Delta m$ difference of magnetic moments on the descending and ascending field branches of $M$-$H$ loop \cite{18}. Furthermore, X-ray powder diffractometer (RINT2200) was employed to identify constituent phases of the samples at a high resolution and field emission scanning electron microscope (FE-SEM) (JEOL/JSM-7610F) for studying the microstructural features.

### 3 Results and Discussion

XRD of the bulks reveal the complete single-phase formation of MgB$_2$, with scarce MgO impurity that is generally observed in this system due to the high oxidizing nature of Mg (see Fig. 1, left). The close study of (110) diffraction peaks enabled to determine a slight shift in the peak position usually a sign of carbon substitution into the lattice (see Fig. 1, right). Further, the (002) peak was noted to be the same observed in all samples.

Lattice parameter calculations using Bragg’s law (see Table 1) revealed that the value of “a” decreased from pure-MgB$_2$ to n-MgB$_2$ and then to u-MgB$_2$, while the value of “c” remained almost constant for all samples.

| Sample     | c (Å) | a (Å) | c/a | $\Delta(c/a)$ × 7.5 | $x \times 10^{-2}$ |
|------------|-------|-------|-----|---------------------|--------------------|
| pure-MgB$_2$ | 3.525 | 3.085 | 1.1432 | -                  | -                  |
| n-MgB$_2$   | 3.525 | 3.084 | 1.1431 | $\sim$0.00075       | $\sim$7.5           |
| u-MgB$_2$   | 3.525 | 3.083 | 1.1430 | $\sim$0.0015        | $\sim$15            |

This points out to carbon-boron substitutions in the boron honey comb (in ab-plane) layer without disturbing the interlayer interactions \cite{19}. The $c/a$ calculations are used to estimate the carbon substitution using Eq. (2) \cite{20}. Our calculations show that u-MgB$_2$ has highest $\Delta(c/a)$ value which corresponds to $x=0.0015$ in MgB$_{2-x}$C$_x$ or 0.075% carbon doped into the MgB$_2$ lattice.

$$x = \Delta(c/a) \times 7.5$$ \hspace{1cm} (2)

While the likes of [NMgB$_2$] showed only 0.0325% of carbon doping. This is expected as the used oil has experience more heating cycles during the course of its uses and then results in breakdown of compound into a number of different chemicals species such as aldehydes, ketones, and carboxylic acids which are carbon-based.

Critical transition temperatures ($T_c$) of pure-MgB$_2$ bulks were around 38.1 K, and the transition width is less than 0.5 K indicating a sharp superconducting transition (see Fig. 2). $T_{c,\text{onset}}$ of u-MgB$_2$ seem to be slightly lower than pure-MgB$_2$, around 37.5 K which is to be expected from carbon substitution as suggested from earlier reports on carbon encapsulated boron powder for MgB$_2$ fabrication \cite{22,30} (see Fig. 2).

Various studies also show that the $T_c$ depreciates in proportion with amount of carbon doped, for instance, 4 and 5% of nano-carbon substitution has dropped the $T_c$ to 34.68

![Fig. 1 X-ray diffractograms of pure-MgB$_2$, n-MgB$_2$, and u-MgB$_2$ bulks revealing the complete MgB$_2$ phase formation](image-url)
and 34.35 K, respectively [21]. In general, the depreciation is proportional to carbon doping amount [22]. Critical current densities of MgB$_2$ bulks have shown to be improved via carbon doping in several instances such as using carbon nanotubes (2.5–10 at.%) where they found $J_c$ increase up to $5 \times 10^4$ A/cm$^2$ at 5 T and 5 K, similarly for 10% SiC-doped sample showed $J_c$ of $3.6 \times 10^4$ A/cm$^2$ at 4 T (20 K), and 3% GO-doped samples showed $J_c$ of $0.5 \times 10^4$ A/cm$^2$ at 4 T (20 K) [23–25]. On similar note, the incorporation of carbon into MgB$_2$ via suspending the bulks in synthetic oil was attempted. To our surprise, the carbon substitution took place as confirmed by XRD results, and this resulted in improved high-field critical current density especially over magnetic fields of 3 T and 4 T as shown in Fig. 3. However, it was observed that critical current density was slightly improved in n-MgB$_2$ as compared to u-MgB$_2$ (see Fig. 3). To understand high-field critical current densities, the $J_c$ estimated at self-field, 2 T, 3 T, and 4 T for three samples are summarized inset of Fig. 3. It is clear that the critical current density remained constant for all samples in self-field and u-MgB$_2$ showed a clear increase in $J_c$ at 2 T, 3 T, and 4 T (see inset of Fig. 3). At 20 K, the $J_c$ value for u-MgB$_2$ at 2 T, 3 T, and 4 T was around $9.2 \times 10^4$, $2.7 \times 10^4$, and $6 \times 10^3$ A/cm$^2$ which were all above the values for pure-MgB$_2$ and n-MgB$_2$ bulk.

Fig. 2 Normalized susceptibility vs temperature plots for pure-MgB$_2$, n-MgB$_2$, and u-MgB$_2$ bulks showing sharp superconducting transitions

Fig. 3 Logarithmic dependence of critical current densities against magnetic field for pure-MgB$_2$, n-MgB$_2$, and u-MgB$_2$ bulks. Inset present the critical current density values for self-field, 2 T, 3 T, and 4 T at 20 K

Fig. 4 Low (top) and high (bottom) magnification FE-SEM micrographs of fractured surface of bulk MgB$_2$ samples. pure-MgB$_2$ (left), n-MgB$_2$ (middle), and u-MgB$_2$ (right). It can be lucidly indicated that higher magnification showing the nano-sized grains ranged from 50 to 300 nm which are responsible for high self-field $J_c$. 
This suggests that the enough carbon substitution has taken place in u-MgB$_2$ resulted in high-field flux pinning, while this effect is not clearly visible in n-MgB$_2$ probably due to insufficient carbon doping. Similar behavior has been observed in n-SiC doping as well as nano-carbon doping where the $J_c$ value at low fields is high in undoped bulks rather than doped ones [26]. The self-field $J_c$ values of pure-MgB$_2$, n-MgB$_2$, and u-MgB$_2$ are around $3.8 \times 10^5$ A/cm$^2$. The enhancement of $J_c$ at high fields indicates the pinning from carbon substitution. Various studies have already elucidated that carbon substitution can enhance upper critical fields which is especially due to its nature of flux pinning that specifically acts at high fields. On the other hand, this self-field $J_c$ of pure-MgB$_2$, n-MgB$_2$, and u-MgB$_2$ is much higher than some of the previously reported results [27]. This is due to amorphous nano boron precursor that was used. The nano boron precursor results in nano-sized MgB$_2$ grains in the final bulk leading to high grain boundary pinning which acts specifically at low fields [7].

Microstructural images are obtained using FE-SEM to understand the grain structure and morphology. Figure 4 presents the low and high magnification SEM images for the pure-MgB$_2$, n-MgB$_2$, and u-MgB$_2$ bulks. It is clear that MgB$_2$ matrix comprises of several voids in numerous sizes and shapes (see Fig. 4, top), as highlighted in previous reports [27]. Much higher magnification reveals that the grain size is ranged from 50 to 300 nm as a consequence of using nano boron precursor (see Fig. 4, bottom). One can note the nature of similar grain size in three bulks due to utilization of same nano-boron and same sintering condition. Such fine grains mean that the matrix has more grain boundaries that are low-field pinning centers thereby enhancing the low-field flux pinning and subsequently high self-field $J_c$. As a result, we had attained similar critical current density values at self-field which was presented in set of Fig. 3.

Consequently, in order to comprehend more on critical current ($J_c$) performance at 20 K of MgB$_2$ samples immersed

### Table 2  Summary of sintering conditions and critical current density ($J_c$) of MgB$_2$ samples

| S. No | Material/particle size | Sintering temperature (°C) | Sintering time (h) | $J_c$ at 20 K (self-field) | $J_c$ at 20 K (1 T) | Ref |
|-------|------------------------|-----------------------------|--------------------|---------------------------|---------------------|-----|
| 1     | MgB$_2$ Mg: 200 meshes B: 300 meshes | 775 °C Solid-state sintering | 3 h | 181 kA/cm$^2$ | 67 kA/cm$^2$ | [27] |
| 2     | MgB$_2$ Mg: 200 meshes B: 300 meshes | 1050 and 1150 °C Spark plasma sintering | 20 min | 210 kA/cm$^2$ | 56 kA/cm$^2$ | [28] |
| 3     | MgB$_2$+4wt% Ag Mg: 200 meshes B: 300 meshes | 775 °C Solid-state sintering | 3 h | 290 kA/cm$^2$ | 112 kA/cm$^2$ | [29] |
| 4     | MgB$_2$ Mg: 200 meshes B: 2.8wt% carbon coated | 775 °C Solid-state sintering | 3 h | 375 kA/cm$^2$ | 220 kA/cm$^2$ | [30] |
| 5     | MgB$_2$ Mg: 325 meshes B: <250 nm | 1000 °C Dip 300 min. in SE oil followed by 1000 °C | 15 min | 53 kA/cm$^2$ | (at 15 K) | [31] |
| 6     | MgB$_2$ Mg: 200 meshes B: 300 meshes and 15 min ultrasonic | 775 °C Solid-state sintering | 3 h | 280 kA/cm$^2$ | 140 kA/cm$^2$ | [32] |
| 7     | MgB$_2$ Mg: 200 meshes B: sub-micron | 775 °C Solid-state sintering | 1 h | 270 kA/cm$^2$ | 30 kA/cm$^2$ | [33] |
| 8     | MgB$_2$ Commercial powder | 1,000 °C Solid-state sintering | 1 h | 39.8 kA/cm$^2$ | | [34] |
| 9     | MgB$_2$ ABCR GmbH as the starting powders | 950 °C Spark plasma sintering | 45 min | 360 kA/cm$^2$ | 250 kA/cm$^2$ | [35] |
| 10    | MgB$_2$+2wt% carbon nanotubes Mg: 99% pure B: 95% pure | 650 °C | 1 h | 32 kA/cm$^2$ | 8 kA/cm$^2$ | [36] |
| 11    | MgB$_2$ Mg: 200 meshes B: 200 nm | 775 °C Dip 30 min in used oil | 3 h | 355 kA/cm$^2$ | 215 kA/cm$^2$ | [present work] |
in used synthetic motor oil, the data has been compared with literature with samples produced utilizing carbon-coated boron, addition of carbon nanotubes, nano-boron, ultrasonicated boron, silver, and various sintering conditions as more details are highlighted in Table 2. It is intriguing to note that critical current density attained at 20 K and 1 T is close to the reported value of carbon-coated boron powder that was utilized to fabricate bulk MgB$_2$ samples, and the value indicated to be less than the samples produced utilizing carbon nanotubes or ultrasonicated boron. Furthermore, high critical current performance was slightly higher when compared to samples produced without oil immersion or samples immersed in new synthetic motor oil (see Fig. 3, inset). Additionally, a similar $J_c$ behavior at 25 K was also observed in optimal 4.0 wt% C$_2$H$_6$O$_3$ added MgB$_2$ sample that was produced by two-step solid-state reaction method [37]. This is indeed a simple trial attempting to utilize the optimum sintering condition combined with used synthetic motor oil to reduce the cost of fabrication of bulk superconducting materials and improvement of high-field performance.

To clearly show the influence of carbon based flux pinning. The flux pinning diagrams were plotted based on the Dew-Hughes general expression [38]

$$f_p = A(h/\gamma)^n(l - h)^m$$

(3)

where $f_p$ is normalized flux pinning force, $f_p = F_p/F_{p,max}$, and $h$ is reduced magnetic field, $h = H/H_{irr}$, where the irreversibility field, $H_{irr}$, was determined as the field, where $J_c$ in the $J_c(H)$ dependence fell down to 100 A/cm$^2$, a standard practice in our works. The $f_p(h)$ dependence was analyzed at 20 K and plotted for all the bulks (see Fig. 5). In general, the dominant pinning mechanism in MgB$_2$ bulk materials is from grain boundaries with a peak position ($f_p = 1$) at lying at $h = 0.19–0.2$ as observed for the pure-MgB$_2$ specimen. When magnified, it can be seen that the peak of flux pinning diagrams has shifted towards higher values (see inset figure in Fig. 5) for the u-MgB$_2$ as compared to pure-MgB$_2$ bulk. The peak position of u-MgB$_2$ is around 0.23, which points out to slight increase flux pinning contribution from carbon substitution, which is similar to bulk MgB$_2$ produced utilizing the carbon encapsulated boron powders [22].

Surprisingly, the peak position for n-MgB$_2$ was located at 0.2 indicating a dominant grain boundary pinning, which is most likely due to insufficient carbon doping. However, the pinning behavior at $h > 0.5$ for u-MgB$_2$ and n-MgB$_2$ have shifted towards right indicating the high-field pinning showing the signs of flux pinning from carbon-substitution. These results are in accordance with some previous reports [39]. Optimization of bulk MgB$_2$ material with dipping in synthetic motor oil before sintering in long duration would further improve the performance of material, which would be considered to be the next task, as it would serve to be useful for day to life applications.

### 4 Conclusions

To summarize, high purity single-phase bulk MgB$_2$ samples were successfully fabricated and was able to dope carbon into the lattice via suspending the pellets in synthetic oil before sintering. A slight shift in XRD peaks was observed especially in (110) peak which points out to 0.55 and 0.89% carbon substitution into the lattice when suspended in new and used synthetic oil. Also, the (002) peak position had remained unchanged for all samples. Simultaneously, a slight drop in $T_{c,onset}$ up to 37.5 K was observed as expected from carbon substitution. This substitution resulted in high-field $J_c$ improvement, especially in field region of $H > 2$ T. The $J_c$ value reached for u-MgB$_2$ at 2 T, 3 T, and 4 T was around $9.2 \times 10^4$, $2.7 \times 10^4$, and $6 \times 10^3$ A/cm$^2$, which is higher than undoped bulk. Further, the self-field $J_c$ is also huge due to the nano-boron precursor which resulted in fine nano-sized MgB$_2$ grains as confirmed by FE-SEM. Finally, the flux pinning diagrams indicated that dominant pinning comes from grain boundaries, but there was also a considerable effect from increased electron impurity scattering caused by carbon substitution. The present results suggest that the bulk MgB$_2$ material performance can be further improved by optimizing the used synthetic motor oil for longer time duration, as it will serve to be useful for low cost and high performance superconducting super-magnet production for several day-to-life applications.

![Fig. 5 Flux pinning diagrams of pure-MgB$_2$, n-MgB$_2$, and u-MgB$_2$ bulks, indicating the shift in peak position due to carbon substitution](Image)
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References

1. Nagamatsu, J., Nakagawa, N., Muranaka, T., Zenitani, Y., Akimitsu, J.: Nature 410, 63 (2001)
2. Glowacki, B.A., Majaros, M., Vickers, M., Evets, J.E., Shi, Y., McDougall, I.: Supercond. Sci. Tech. 14, 193 (2001)
3. Larbalestier, D.C., Cooley, L.D., Rikel, M.O., Polyanskii, A.A., Jiang, J., Patnaik, S., Cai, X.Y., Feldmann, D.M., Gurevich, A., Squitieri, A.A., Naus, M.T., Eom, C.B., Hellstrom, E.E., Cava, R.J., Regan, K.A., Rogado, N., Hayward, M.A., He, T., Slusky, J.S., Khalifah, P., Inumaru, K., Haas, M.: Nature 410, 186 (2001)
4. Zhao, Y.: Appl. Phys. Lett. 79, 1154 (2001)
5. Muralidhar, M., Murakami, M.: J. Supercond. Nov. Suppl. 31, 2677 (2018)
6. Batalu, D., Aldica, G., Burdusel, M., Badica, P.: Key. Eng. Mat. 638, 357 (2015)
7. Muralidhar, M., Higuchi, M., Kitamoto, K., Koblischka, M., Jirsa, M., Murakami, M.: IEEE. T. Appl. Supercon. 28, 1 (2018)
8. Giunchi, G., Ripamonti, G., Cavallin, T., Bassani, E.: Cryogenics 46, 237 (2006)
9. Yang, Y., Wang, L., Sun, H.H., Cheng, C.H., Zhao, Y.: J. Phys. Chem. Solids. 72, 593 (2011)
10. De Silva, K.S.B., Xu, X., Gambhir, S., Wang, X.L., Li, W.X., Wallace, G.G., Scripta, S.X.: Mater. 65, 634 (2011)
11. Dou, S.X., Soltanian, S., Horvat, J., Wang, X.L., Zhou, S.H., Ionescu, M., Liu, H.K.: J. Appl. Phys. 81, 3419 (2002)
12. Kim, J.H., Zhou, S., Hosssain, M.S.A., Pan, A.V., Dou, S.X.: J. Appl. Phys. 89, 142505–142511 (2006)
13. Kim, J.H., Yeoh, W.K., Qin, M.J., Xu, X., Dou, S.X.: J. Appl. Phys. 100, 013908–013911 (2005)
14. Qin, J.J., Yang, Y., Wang, L., Sun, H.H., Liu, Y.T., Ke, C., Cheng, C.H., Zhao, Y.: J. Supercond. Nov. Suppl. 35, 415 (2022)
15. Yamamoto, A., Shimoyama, J., Ueda, S., Iwayama, I., Horii, S., Kisho, K.: Supercond. Sci. Tech. 18, 1323 (2005)
16. Gao, Z., Wang, D., Zhang, X., Ma, Y., Awaji, S., Nishijima, G., Watanabe, K., Flukiger, R.: Supercond. Sci. Tech. 23, 043024 (2010)
17. Serquis, A., Liao, X.Z., Zhu, Y.T., Coulter, J.Y., Huang, J.Y., Willis, J.O., Peterson, D.E., Mueller, F.M.: J. Appl. Phys. 92, 351 (2002)
18. Bean, C.P.: Phys. Rev. Lett. 8, 250 (1962)
19. Takenobu, T., Ito, T., Chi, D.H., Prassides, K., Iwasa, Y.: Phys. Rev. B. 64, 134513 (2001)
20. Avdeen, M., Jorgensen, J.D., Ribeiro, R.A., Bud’ko, S.L., Canfield, P.C.: Physica C. 387, 301 (2003)
21. Mudgel, M., Awana, V.P.S., Khishan, J., Bhalia, G.L.: Solid. State. Commun. 146, 330 (2008)
22. Sai Srikanth, A., Muralidhar, M., Sunsanee, P., Jirsa, M., Nakai, N., Oka, T., Murakami, M.: Adv. Eng. Mater. 22, 2000478 (2020)
23. Serquis, A., Serrano, G., Moreno, S.M., Civale, L., Maiorov, B., Balakirev, F., Jaime, M.: Supercond. Sci. Tech. 20, L12 (2007)
24. Dou, S.X., Soltanian, S., Horvat, J., Wang, X.L., Zhou, S.H., Ionescu, M., Liu, H.K.: Appl. Phys. Lett. 81, 3419 (2002)
25. Sudesh, Kumar, N., Das, S., Bernhard, C., Varma, G.D.: Supercond. Sci. Tech. 26, 095008 (2013)
26. Awana, V.P.S., Vajpayee, A., Mudgel, M., Rawat, R., Acharya, S., Kishan, H., Takayama-Muromachi, E., Narlikar, A.V., Felner, I.: Physica C. 467, 67 (2007)
27. Muralidhar, M., Inoue, K., Koblischka, M.R., Tomita, M., Murakami, M.: J. Alloy. Compd. 608, 102 (2014)
28. Noudem, J.G., Aburras, M., Bernstein, P., Chaud, X., Muralidhar, M., Murakami, M.: J. Appl. Phys. 116, 163916 (2014)
29. Muralidhar, M., Inoue, K., Koblischka, M., Murakami, A., Murakami, M.: Adv. Eng. Mater. 17, 831 (2015)
30. Muralidhar, M., Higuchi, M., Jirsa, M., Diko, P., Kokal, I., Murakami, M.: IEEE. T. Appl. Supercon. 27, 6201104 (2017)
31. Taylan Koparan, E., Savaskan, B., Yaman, E.: Physica C. 527, 36 (2016)
32. Sai Srikanth, A., Muralidhar, M., Jirsa, M., Sakai, N., Murakami, M.: J. Supercond. Nov. Magn. 34, 1297 (2021)
33. Muralidhar, M., Kenta, N., Koblischka, M., Murakami, M.: Phys. Status. Solidi. A. 212, 2141 (2015)
34. Hapipi, N.M., Chen, S.K., Shaari, A.H., Kechik, M.M.A., Lim, K.P., Tan, K.B., Lee, O.J., Sai Srikanth, A., Muralidhar, M.: J. Mater. Sci. Mater. 33, 11257 (2022)
35. Kaya, N., Cavdar, S., Ozturk, O., Yildirim, G., Koralay, H.: J. Mater. Sci. Mater. 33, 3786 (2022)
36. Zhang, J.Y., Zhang, Y.F., Lou, Z.W., Zhang, P.H., Li, C.Y., Yuan, J.W., Peng, L., Ma, Y.X., Noudem, J.G., Izumi, M.: Supercond. Sci. Tech. 34, 0455011 (2021)
37. Cakir, B., Koparan, E.T., Savaskan, B.: J. Mater. Sci. Mater. 32, 20317 (2021)
38. Dew Hughes, D., Philos. Mag. 30, 293 (1974)
39. Ghorbani, S.R., Farshidnia, G., Wang, X.L., Dou, S.X.: Supercond. Sci. Tech. 27, 125003 (2014)

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