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Keywords

jc, surface, pinning, silicone, oil, field, doped, effects, mgb2, bulks, wires, temperature, annealing

Disciplines

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The Effects of Annealing Temperature on the in-field J_c and Surface Pinning in Silicone Oil Doped MgB_2 Bulks and Wires

M. S. A. Hossain, A. Motaman, Ö. Çiçek, H. Ağıl, E. Ertekin, A. Gencer, , X. L. Wang, S. X. Dou

Abstract— The effects of sintering temperature on the lattice parameters, full width at half maximum (FWHM), strain, critical temperature (T_c), critical current density (J_c), irreversibility field (H_{irr}), upper critical field (H_{c2}), and resistivity (ρ) of 10 wt % silicone oil doped MgB_2 bulk and wire samples are investigated in state of the art by this article. The a-lattice parameter of the silicone oil doped samples which were sintered at different temperatures was drastically reduced from 3.0864 Å to 3.0745 Å, compared to the un-doped samples, which indicates the substitution of the carbon (C) into the boron sites. It was found that sintered samples at the low temperature of 600 °C shows more enhancement in lattice distortion, more C-substitution, lower T_c , larger lattice strain, higher impurity scattering, and much more enhancement in both J_c and H_{c2} , compared to those sintered samples at high temperatures. The flux pinning mechanism has been analyzed based on the extended normalized pinning force density $f_p = F_p/F_{p,max}$ scaled with $b = B/B_{max}$. Results show that surface pinning is the dominant pinning mechanism for the doped sample sintered at the low temperature of 600 °C, while point pinning is dominant for the un-doped sample. The MgB_2 wire was also fabricated by using of this cheap doping and found that both J_c and n-factor increased which proves this silicone oil doping can be a good candidate for industrial application.

Index Terms—

I. INTRODUCTION

MgB_2 superconductor is a promising material for power applications, because of its high critical temperature (T_c) than Nb-Ti and Nb_3Sn and a larger superconducting coherence length than the high temperature superconductors (HTS) [1]. MgB_2 is classified in two-gap superconductor, and it shows less weak-link and anisotropic effects [2, 3] compared to the HTS compounds. Due to the higher T_c of 39 K and the lower fabrication cost, MgB_2 has been regarded as a promising candidate for practical applications, such as a cryogen-free

magnetic resonance imaging (MRI) magnet which can operate at temperatures above 20 K [4]. Unfortunately, due to 8weak flux pinning, the critical current density (J_c) of un-doped MgB_2 drops quickly with increasing magnetic field at high temperatures. A significant enhancement in the J_c and flux pinning in MgB_2 has already been achieved through chemical doping, especially when the dopants are on the nanoscale. For example, additions of nano-SiC [5-7], nano-Si [9], nano-C powders [10, 11], carbon nano-tubes (CNTs) [12], and carbohydrates (CH) [13] have all been found to be very effective in improving the field dependence of J_c in MgB_2 . However, all these chemicals are solid materials, which can cause resulted MgB_2 to have an agglomeration problem when they are blended together and this phenomenon leads to further limitation on improvements of the MgB_2 performance. Wang et al. reported that by adding a liquid additive, silicone oil, into the MgB_2 , the J_c - H properties can be significantly enhanced [14]. The advantage of the liquid silicone oil is that the mixing with Mg and B of either Si or C released from the decomposition of silicone oil takes place on the atomic scale and is more homogeneous than when solid nano powders are used. This homogeneity of mixing is very crucial in determination of the flux pinning ability for MgB_2 made by the *in-situ* reaction method. It was found that MgB_2 doped with 10 wt% silicone oil exhibits the largest J_c in-field enhancement among a variety of samples sintered at the fixed temperature of 780 °C [14]. However, heat-treatment effects on the flux pinning performance have not yet been reported for silicone oil-doped MgB_2 . In this work, we report a systematic study of the sintering temperature effect on the MgB_2 lattice parameters, C substitution levels, T_c , J_c , upper critical field (H_{c2}), and irreversibility field (H_{irr}) in 10 wt% silicone oil doped MgB_2 bulk samples as well as detailed study on the transport J_c in 10 wt% silicon oil doped MgB_2 monofilamentary wire. It was figured out that low sintering temperatures can result in a large enhancement of the magnet and transport J_c in-field performance in the silicone oil doped MgB_2 . The possible flux pinning mechanism will also be discussed.

II. EXPERIMENTAL

Amorphous boron (B) powders, Mg powders, and commercial high temperature silicone oil from Sigma Aldrich have been used as starting materials for this work. B and Mg powders in chemical stoichiometry were thoroughly mixed

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with diluted silicone oil. The amount of silicone oil added was 10 wt %. Pellets 13 mm in diameter and 2 mm in thickness were made under uniaxial pressure. Three samples were then sealed in an iron tube and sintered in-situ in a tube furnace at 600 °C for 4 hrs, and for 780 and 900 °C for 30 min, respectively. A high purity argon gas flow was maintained throughout the *in-situ* sintering process to avoid oxidation. Three un-doped MgB₂ samples (650, 800 and 900 °C for 30 min) were also prepared under the same conditions to serve as reference samples. The information from X-ray diffraction (XRD) on the crystal structures, such as the lattice parameters and the lattice strain, was refined by using the Rietveld refinement method. T_c was defined as the onset temperature at which the diamagnetic property was observed. The resistivity and magnetization were measured at 5 and 20 K using a Physical Properties Measurement System (PPMS, Quantum Design) in magnetic fields up to 8.5 T. The magnetic J_c was derived from the width of the magnetization loop using Bean's model. The H_{c2} and H_{irr} for all the samples were defined as $H_{c2} = 0.9R(T_c)$ and $H_{irr} = 0.1R(T_c)$ from the resistance (R) versus temperature (T) curve. For wire sample; 10 wt% silicon oil doped MgB₂ wire and one MgB₂ pure wire as a reference with 37% filling factor for both pure and doped wires were fabricated based on the powder in tube process with iron as an outer sheath. All manufactured wires were then covered by zirconium foil and sintered at 650 and 900 °C in Ar atmosphere. The transport J_c was measured at 4.2 and 20 k by using the 400 A power supply and four probes method with a criterion of $1\mu Vcm^{-1}$.

III. RESULTS AND DISCUSSIONS

Fig. 1 shows the XRD patterns of all the samples produced at different sintering temperatures. It can be observed that both the un-doped and the silicone oil doped MgB₂ samples sintered within the range of 600-900 °C contain well developed MgB₂ phase with a small amount of MgO. Silicone oil doped MgB₂ sintered at 600 °C for 4 hrs clearly shows peaks from the Mg₂Si phase. However, the amount of Mg₂Si phase was significantly reduced for the samples sintered at higher temperatures, and it almost disappeared for samples sintered at 900 °C. The decomposition mechanism of commercial silicone oil has been well described in our previous report [14].

Table.1 shows the a -axis lattice parameter as a function of sintering temperature for both the un-doped and the silicone oil doped samples. It can be seen that the a -axis lattice parameter decreases from 3.086 to 3.076 Å for the pure and 10 wt % silicone oil doped samples, respectively. The c -axis lattice parameter is almost constant (inset) for both un-doped and doped samples sintered at different temperatures. The significant reduction in the a -axis lattice parameter indicates that carbon substitutes into the B sites in the crystal lattice.

Table.1 also shows the calculated c/a ratios of un-doped samples sintered at different temperatures. The silicone oil doped MgB₂ also shows a similar trend, suggesting that C substitution for B occurred in the silicone oil added samples. According to the method proposed by Avdeev *et al.* [15], the level of C substitution, x , in Mg (B_{1-x}C_x)₂, can be easily estimated using the formula $x = 7.5 \times \Delta(c/a)$, where $\Delta(c/a)$ is

the change in c/a when compared to an un-doped sample. We found that the actual amount of C (x) in the silicone doped samples increased from 0.004 to 0.023 as the sintering temperature increased from 600 to 900 °C, as shown in table. 1. This result indicates that C substitution can take place even at the low sintering temperature of 600 °C. This is one of the advantages of using the silicone oil as a C source, since low temperature heat-treatment processing can introduce strong grain boundary pinning, as well as C substitution effects at the same time.

The lattice strain vs. sintering temperature for both silicone oil doped and un-doped samples is shown in table.1. The strain decreases with increasing sintering temperature. This is probably related to the C-substitution and to defects within the grains, as mentioned above. In another word, the improvement of crystallinity due to grain growth may reduce defects within grains for samples sintered at high temperatures. As a result, there is a strong correlation between strain and T_c . The sample sintered at 600 °C shows a relatively higher strain value, ~0.57%, than other samples. This also indicates that various trapped defects within MgB₂ grains might act as flux pinning centers.

Among the various XRD peaks, the full width at half maximum (FWHM) of the (110) peak is related to the *in-plane* crystallinity. According to Williamson-Hall, the strain and grain size can both affect the FWHM value [16]. So far as strain is concerned, there are actually two types of strain in samples, micro-strain and macro-strain. The micro-strain varies from one grain to another one in the microscopic scale, resulting in non-uniformity, which produces peak broadening. On the other hand, macro-strain is uniform, and its uniform effects can produce peak shifting. The former is due to the contribution of defects inside grains as well as the MgB₂ grain size which varies from small grain to large grain due to sintering temperature, and the latter is due to the substitution of elements such as C into B sites [17]. Analysis of the FWHM can provide considerable information on the crystallite size and on the micro-strain in the lattice that is presented in the specimen. Table.1 also shows the T_c and the FWHM of the (110) peak vs. sintering temperature. The FWHM decreases as the sintering temperature increases in both un-doped and silicone oil doped samples. According to Scherrer's formula, the FWHM value is inversely proportional to grain size. The values of the FWHM for the doped samples are greater than for the un-doped samples. This means that the grain sizes in the doped samples are smaller than in the un-doped samples, regardless of sintering temperature.

On the other hand, T_c shows an opposite trend to the FWHM, as shown in table.1. The increase in T_c indicates better crystallinity or less crystal defects in the samples sintered at high temperatures than those sintered at low temperatures. Improvement on crystallinity should also be accompanied by better grain connectivity of the MgB₂ grains. On the other hand, the significant suppression of crystallinity for silicone oil doped MgB₂ sintered at 600 °C likely originates from disorder in the crystal lattice due to the C substitution.

Table.1 illustrates the measured ρ values, RRR (ρ_{300K} / ρ_{40K}), and active cross-sectional area fraction (A_f) for silicone oil doped MgB₂ samples with different sintering temperatures.

it was observed that ρ at 300 K decreases with increasing sintering temperature. This is related to the better crystallinity of MgB_2 phase that arises from additional grain growth, as mentioned above. Specifically, the relatively lower ρ near 300 K may be related to higher sample density and better inter-granular connectivity. On the other hand, the resistivity values near the transition temperatures are due to the intra-granular defects, since the phonon contribution to the electron scattering decreases when the temperature decreases. The defects inside grains may also affect the ρ at 40 K [18]. These observations can be further supported by the $\Delta\rho$ and RRR behavior. It is well known that relatively high values of the RRR indicate good quality of samples. The connection factor, A_f , was also evaluated using the Rowell analysis [18]. As shown in the Table 1, the values of A_f increase from 0.137 to 0.327 as the sintering temperature increases from 600 to 900 °C.

Fig. 2 shows the magnetic J_c of the un-doped and the silicone oil added MgB_2 samples as a function of sintering temperature. It can be seen that the J_c values of the un-doped sample sintered at 650 °C and 900 °C for 30 minutes are higher than those of the silicone oil doped samples in the low magnetic field region at both 5 and 20 K. As field increased, the J_c values at 20 K for the doped samples sintered at 900 °C were much higher than those for the un-doped samples at fields greater than 3 T. This is the indication of flux pinning strength enhancement in the silicone oil doped samples. At the same time, the J_c values of the doped samples are strongly dependent on the sintering temperature. The J_c values at 5 K for the doped samples sintered at 600 °C are higher than for those sintered at 900 °C up to a field of 8.7 T. However, at 20 K, the sample sintered at 900 °C shows higher J_c values than the 600 °C sample for fields above 1 T. The J_c values of the samples sintered at 600 °C and 900 °C were approximately 1.2×10^4 A/cm² at 5 K and 8 T. At 5 K and 5T the J_c value for the 600 °C sample was 9×10^4 A/cm², but 5×10^4 A/cm² for the 900 °C sample. These J_c values for the silicone oil doped MgB_2 are as high as the best J_c values obtained in MgB_2 samples doped with solid nano-SiC. This indicates that the liquid additive, silicone oil, is a cheap and convenient alternative dopant to replace solid nano-SiC powders.

The temperature dependency of H_{c2} and H_{irr} for the un-doped and silicone oil added MgB_2 samples is shown in Fig. 3. The values of dH_{c2}/dT and dH_{irr}/dT for the silicone oil added MgB_2 samples increase more quickly than un-doped MgB_2 samples. Furthermore, these values are almost independent of sintering temperature. It is well known that an enhancement of H_{c2} indicates that both intra-band and inter-band scattering are enhanced and it is due to C substitution into the B sites. It should be noted that the sample sintered at 600 °C shows almost the same H_{irr} value as that sintered at 900 °C, suggesting that a low sintering temperature is more effective in enhancing the flux pinning, due to active C substitution and a high density of grain boundaries. However, using high resolution transmission electron microscopy is needed for further study on the grain sizes and crystal defects. The presence of Mg_2Si impurity phase is also responsible for the peak broadening, as the Mg_2Si is believed to act as a grain refiner in silicone oil doped MgB_2 at lower sintering temperatures [19]. Therefore, the enhanced flux pinning, H_{c2} ,

H_{irr} , and J_c - H observed in our silicone oil added MgB_2 that was sintered at 600 °C are likely due to the C-doping effect and inclusions of Mg_2Si .

Plots of normalized pinning force density $f_p = F_p/F_{p,max}$ against reduced field are shown in Fig.7. The equation $f_p(b) = Ab^p(1-b)^q$ is usually employed as a single pinning function, where p and q are parameters describing the particular type of pinning, and b is the reduced field, with $b = B/B_{irr}$ [20]. In this model, $p = 1/2$ and $q = 2$ describe surface pinning, while $p = 1$ and $q = 2$ describes point pinning, as predicted by Kramer [21]. The best fit of the curves (solid curves in Fig. 4(a)) are obtained with $p = 0.8 - 1.2$ and $q = 2.9 - 3.4$ for all samples at $T = 20$ K. These two values obtained do not allow us to infer the real dominant pinning mechanism from this scaling behavior.

For obtaining a deeper insight into the pinning mechanism, the extended normalized pinning force density $f_p = F_p/F_{p,max}$, plotted against $b = B/B_{max}$ instead of $b = B/B_{irr}$, was examined, where B_{max} is the magnetic field at the maximum of F_p [22]. The scaling of f_p - b is often analyzed in terms of normal point pinning, $f(b) = (9/4)b(1-b/3)^2$ and surface pinning, $f(b) = (25/16)b^{0.5}(1-b/5)^2$, which has been inferred by Higuchi *et al.* [22]. The fitting results are shown by the solid curves in Fig. 4(b). In low magnetic fields, the experimental data are in good agreement with the point pinning mechanism for all samples. At normalized magnetic fields higher than b_{max} , flux pinning is dominated by surface pinning for the doped sample sintered at 600 °C, while point pinning is dominant for the un-doped sample. For the doped sample sintered at 900 °C, the experimental data are located between the theoretical curves for surface pinning and point pinning. Therefore, flux pinning is determined by both point pinning and surface pinning for this sample. These results are in good agreement with the fact that the grain sizes of the doped MgB_2 sintered at 600 °C are much smaller than for the sample sintered at 900 °C. This means that the grain boundary density and its contribution to flux pinning are dominant in the samples sintered at low temperature.

Fig.5 shows the transport J_c of doped and un-doped MgB_2 wire at different high applied fields. It has to be noted that the transport J_c measurements cannot be done at low field due to the limitation of current flow (250 A) into the probe, therefore high field results can be seen in Fig.5. Doping of silicone oil causes a gradual shift of the curve J_c versus B towards higher values. At 600 °C, the value of $B(10^4)$ [where the field at which J_c reaches to 10^4 A/cm²] was enhanced from 7.5 to 9.1 T, or by 1.6 T. The transport J_c values of the sintered sample at 600°C is higher than sintered sample at 900°C because of defects originated from higher strain and carbon substitution at low sintering temperature as evidenced by table 1, therefore, low sintering temperature is more beneficial for grain boundary pinning due to an increase in density of grain boundaries.

In view of MRI or low field NMR applications, the exponential n factor plays an important role. It is known that at 4.2 K and low fields, n of MgB_2 wires can reach very high values. However, the strong decrease of n with field is a limiting factor when envisaging applications at higher fields. As shown in Fig. 6, the silicone oil doped wire leads to a

considerable increase of the n factor. The data set is not complete yet, but it can be seen that the increase of n after doping at 650 °C is around 33%. For example, the field at which n takes the value 30 is higher in silicone doped wires, the average enhancement being estimated to ~ 1 T at 20K and ~ 2 T at 4.2 K. This argument is of industrial importance. Although n is an empirical factor which depends on a variety of effects which are not all well defined, it reflects in a certain way the homogeneity of a filament. The present enhancement of n can thus be interpreted as an improved homogeneity of the silicone oil doped filament (this is also confirmed by the analysis of the electrical resistivity presented in table 1).

In summary, we have found that the sintering temperature has a significant effect on the flux pinning enhancement in MgB₂ doped with a liquid additive, silicone oil. The low sintering temperature of 600 °C can lead to a reduction of the lattice parameters and RRR values, resulting in a significant enhancement of H_{c2} , H_{irr} , and both magnetic and transport J_c - H . Surface pinning is the dominant pinning mechanism for the doped sample sintered at 600 °C, while point pinning is dominant for the un-doped sample. Enhancement of n -value shows better homogeneity in sample sintered at 600 °C.

REFERENCES

- [1] J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani and J. Akimitsu, 2001 *Nature* **410** 63.
- [2] D. C. Larbalestier, L. D. Cooley, M. O. Rikel, A. A. Polyanskii, J. Jiang, S. Patnaik, X. Y. Cai, D. M. Feldmann, A. Gurevich, A. A. Squitieri, 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, P. Khalifah, K. Inumaru and M. Haas, 2001 *Nature* **410** 186.
- [3] M. Kambara, B. N. Hari, E. S. Sadki, J. R. Cooper, H. Minami, D. A. Cardwell, A. M. Campbell and I. H. Inoue, 2001 *Supercond. Sci. Technol.* **14** L5-7.
- [4] Y. Iwasa, D. C. Larbalestier, M. Okada, R. Penco, M. D. Sumption and X. Xi, 2006 *IEEE Tans. Appl. Supercond.* **16** 1457.
- [5] S. X. Dou, S. Soltanian, J. Horvat, X. L. Wang, S. H. Zhou, M. Ionescu, H. K. Liu, P. Munroe and M. Tomsic, 2002 *Appl. Phys. Lett.* **81** 3419.
- [6] H. Kumakura, H. Kitaguchi, A. Matsumoto and H. Hatakeyama, 2004 *Appl. Phys. Lett.* **84** 3669.
- [7] M. D. Sumption, M. Bhatia, M. Rindfleisch, M. Tomsic, S. Soltanian, S. X. Dou and E. W. Collings, *Appl. Phys. Lett.* **86** 092507.
- [8] X. L. Wang, S. H. Zhou, M. J. Qin, P. R. Munroe, S. Soltanian, H. K. Liu and S. X. Dou, 2003 *Physica C* **385** 461.
- [9] X. L. Wang, S. Soltanian, M. James, M. J. Qin, J. Horvat, Q. W. Yao, H. K. Liu and S. X. Dou, 2004 *Physica C* **408-410** 63.
- [10] R. H. T. Wilke, S. L. Bud'ko, P. C. Canfield, D. K. Finnemore, R. J. Suplinskas and S. T. Hannahs, 2004 *Phys. Rev. Lett.* **92** 217003.
- [11] 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. Munroe, 2006 *Supercond. Sci. Technol.* **19** 596.
- [12] J. H. Kim, W. K. Yeoh, M. J. Qin, X. Xu, S. X. Dou, P. Munroe, H. Kumakura, T. Nakane and C. H. Jiang, 2006 *Appl. Phys. Lett.* **89** 122510.
- [13] J. H. Kim, S. H. Zhou, M. S. A. Hossain, A. V. Pan and S. X. Dou, 2006 *Appl. Phys. Lett.* **89** 142505.
- [14] X. L. Wang, Z. X. Cheng and S. X. Dou, 2007 *Appl. Phys. Lett.* **90** 042501.
- [15] M. Avdeev, J. D. Jorgensen, R. A. Ribeiro, S. L. Bud'ko and P. C. Canfield, 2003 *Physica C* **387** 301.
- [16] G. K. Williamson and W. H. Hall, 1953 *Acta Metall.* **1** 22.
- [17] S. M. Kazakov, R. Puzniak, K. Rogacki, A. V. Mironov, N. D. Zhigadlo, J. Jun, Ch Soltmann, B. Batlogg and J. Karpinski, 2005 *Phys. Rev. B* **71** 024533.
- [18] J. M. Rowell, 2003 *Supercond. Sci. Technol.* **16** R17.
- [19] S. Soltanian, X. L. Wang, J. Horvat, S. X. Dou, M. D. Sumption, M. Bhatia, E. W. Collings, P. Munroe and M. Tomsic, 2005 *Supercond. Sci. Technol.* **18** 658.
- [20] D. Dew-Hughes, 1974 *Phil. Mag.* **30** 293.
- [21] E. J. Kramer, 1974 *J. Appl. Phys.* **44** 1360.
- [22] T. Higuchi, S. I. Yoo and M. Murakami, 1999 *Phys. Rev. B* **59** 1514.

Table caption:

Table 1. The resistivity at 40 K and 300 K, $\Delta\rho = \rho_{300\text{ K}} - \rho_{40\text{ K}}$, the RRR, the connectivity factor A_f of 10 wt % silicone oil doped MgB_2 as well as all crystallography data resulting from different sintering temperatures.

Figure captions:

Fig.1. XRD patterns for the un-doped MgB_2 sintered at 650 °C and 900 °C and the silicone oil doped MgB_2 samples sintered at 600 and 900 °C.

Fig.2. The magnetic field dependence of J_c at 5 and 20 K for un-doped MgB_2 sintered at 650 °C and 900 °C and silicone oil doped MgB_2 sintered at 600 and 900 °C .

Fig.3. H_{c2} and H_{irr} vs. normalized temperature for un-doped and silicone oil doped MgB_2 .

Fig.4. Magnetic field dependence of the reduced pinning force $f(b)$ at 20 K: (a) $b = B/B_{irr}$ and (b) $b = B/B_{max}$ for un-doped MgB_2 sintered at 650 °C and silicone oil doped MgB_2 samples sintered at 600 and 900 °C. Solid curves are fittings to models.

Fig. 5. The transport critical current density at 4.2 and 20 K as a function of sintering temperature. Un-doped MgB_2 wire is also shown as a reference.

Fig.6. The n-value at 4.2 and 20 K as a function of sintering temperature.

Table 1.

Samples	Sintering conditions	$\rho_{300\text{ K}}$ ($\mu\Omega\text{cm}$)	$\rho_{40\text{ K}}$ ($\mu\Omega\text{cm}$)	$\Delta\rho$ ($\mu\Omega\text{.cm}$)	RRR	A_f	a(°A)	c/a	Strain %	FWHM	T_c
MgB_2 + 10% Silicone oil	600°C x 4 hour	150.34	97.31	53.03	1.54	0.137	3.078	1.1434	0.575	0.676	35.2
MgB_2 + 10% Silicone oil	780°C x 30min	128.56	87.67	40.89	1.47	0.178	3.075	1.1465	0.475	0.6	36.2
MgB_2 + 10% Silicone oil	900°C x 30min	65.85	43.56	22.29	1.51	0.327	3.077	1.1444	0.44	0.55	36.35
MgB_2 un-doped	650°C x 30min	77.3	41.8	35.5	1.85	0.211	3.086	1.143	0.56	0.56	36.67
MgB_2 un-doped	800°C x 30min	56.4	27.3	29.1	2.06	0.252	3.085	1.1432	0.375	0.475	37.5
MgB_2 un-doped	900°C x 30min	53.4	24.8	28.6	2.46	0.261	3.084	1.1415	0.36	0.44	38.3

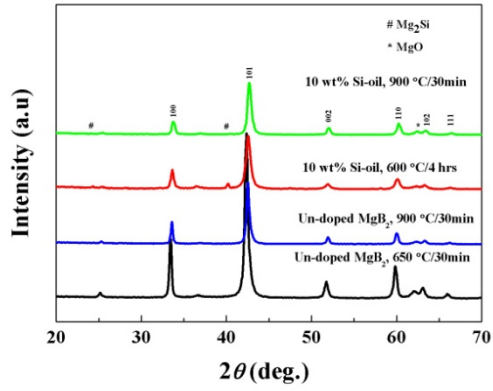


Fig. 1.

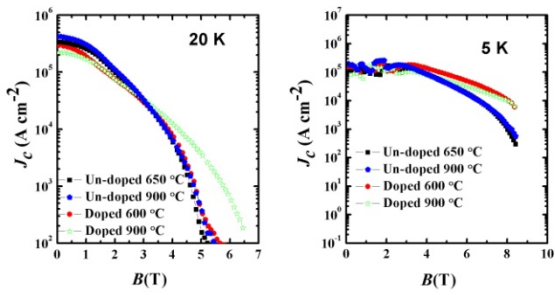


Fig. 2.

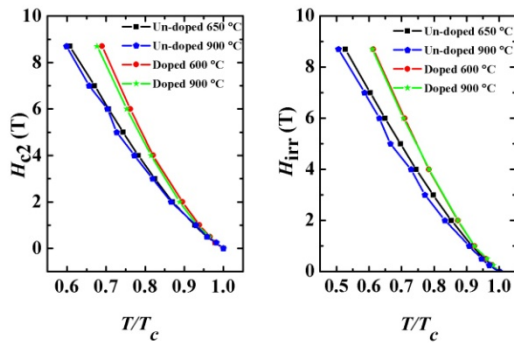


Fig. 3.

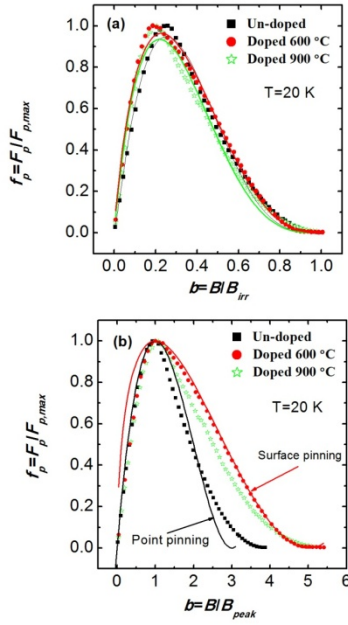


Fig. 4.

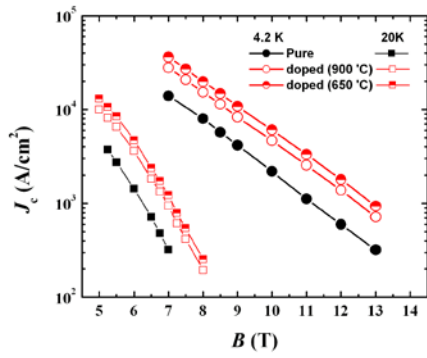


Fig. 5.

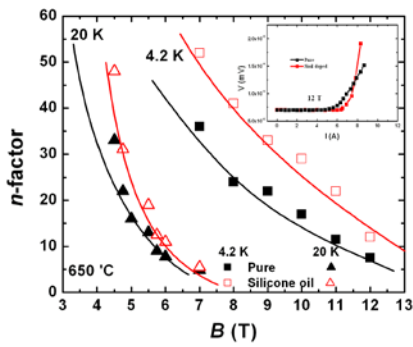


Fig. 6.