Enhancement of critical current density in helium ion irradiated Ba(Fe, Co) $_{2}\text{As}_{2}$ thin films

Nazir, M., Xu, Z., Peng, N. H., Akhtar, N. A., Papakonstantinou, P., Webb, R. P., Ma, Y., & Zheng, D. (2020). Enhancement of critical current density in helium ion irradiated Ba(Fe, Co) $_{2}\text{As}_{2}$ thin films. *Superconductor Science and Technology*, 33(7), [075012]. <https://doi.org/10.1088/1361-6668/ab8ffd>

[Link to publication record in Ulster University Research Portal](#)

Published in:
Superconductor Science and Technology

Publication Status:
Published (in print/issue): 31/07/2020

DOI:
<https://doi.org/10.1088/1361-6668/ab8ffd>

Document Version
Author Accepted version

General rights

Copyright for the publications made accessible via Ulster University's Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Ulster University's institutional repository that provides access to Ulster's research outputs. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact pure-support@ulster.ac.uk.

**Enhancement of Critical Current Density in Helium Ion irradiated
Ba(Fe, Co)₂As₂ Thin Films**

Mudassar Nazir^{1,5}, Zhongtang Xu², N. H. Peng³, Naheed Akhtar^{1,5},
P. Papakonstantinou⁴, R. P. Webb³, Yanwei Ma^{2,5}, and Dongning Zheng^{1,5,6}

¹*Beijing National Laboratory for Condensed Matter Physics, Institute of Physics,
Chinese Academy of Sciences, Beijing 100190, China*

²*Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190,
China*

³*Surrey Ion Beam Centre, University of Surrey, Guildford GU2 7XH, Surrey, UK*

⁴*Nanotechnology and Integrated Bioengineering Centre, Engineering Research
Institute, School of Engineering, Ulster University, Newtownabbey, BT37 0QB, UK*

⁵*University of Chinese Academy of Sciences, Beijing 100049, China*

⁶*Songshan Lake Materials Laboratory, Dongguan, Guangdong 523808, China*

Abstract

The effect of 600 keV He⁺ ion irradiation on the temperature and magnetic field dependence of the critical current density J_C in high quality BaFe_{1.84}Co_{0.16}As₂ (Co-doped Ba122 type) thin films is investigated. The films are prepared by pulsed-laser-deposition (PLD) on CaF₂ (001) substrates. The irradiation dosages are varied in between 1×10^{13} to 1×10^{16} cm⁻². Upon irradiation, the superconducting transition temperature T_C drops slightly from 23 K for the unirradiated sample to about 20 K for the sample with the highest irradiation level. The J_C values of the thin film samples are calculated by using the Bean critical state model. The results showed that J_C could be enhanced substantially. The maximum J_C value at 4.5 K temperature is enhanced up to 2.4 MAcm⁻² under 1 T field. The analysis of pinning force dependence on magnetic field shows that the pinning behavior is not changed in the irradiated samples, suggesting more pinning centers of similar nature to those of presented in the unirradiated samples are introduced by the irradiation process. The results indicate that the irradiation of light element ions He⁺ with relatively low energy could increase the critical current density in iron based superconductors.

INTRODUCTION

Iron based superconductors (IBSs) have been investigated extensively in the past more than ten years because of their potential for high field superconducting magnet applications due to high transition temperature T_C [1–4], large upper critical field B_{c2} (over 100 T) and small anisotropy [5-8]. Among the IBSs, the 122 type material AeFe_2As_2 (Ae = Alkaline earth metals such as Ba, Ca, Sr) have attracted much attention and are regarded as the promising candidates for future practical applications. Many efforts have been devoted to increase the critical current density J_C in this type of material and significant progress has been made [9-11]. For instance, superconducting Ba122 tapes with J_C up to 0.15 MAcm^{-2} at 4.2 K and 10 T [12] have been reported and a demonstrating pancake coil wound using the seven-filamentary tape has been made [13]. The Co-doped Ba122 type epitaxial thin films with J_C larger than 1 MAcm^{-2} on different substrates by means of pulsed-laser-deposition (PLD) have also been reported [9, 14, 15]. Despite of these achievements, it is believed that further improvement in J_C is required to meet the requirement for practical applications [16]. To conduct high critical current in a superconductor, the vortices need to be pinned. The flux pinning centers (FPCs), which could be various types of defects presented in a superconductor, can reduce the vortex motion due to interactions between pinning centers and vortices. The nature and density of the pinning centers determine the magnitude and field dependence of critical current density.

By introducing artificial pinning centers (APCs) in type II superconductors, the critical current properties could be improved. Different methods have been used to introduce defects in given materials. For instance, addition of non-superconducting secondary phases, and formation of superlattices have been proposed for IBSs [10, 11, 17]. Furthermore, irradiation technology has been successfully applied to obtain optimized critical current properties by creating different types of defects. Irradiation by using different kinds of particles such as protons, heavy ions, electrons, α particles and neutrons has been reported for IBSs in the literature [18-23]. Enhancement of critical current density after fast neutron irradiation has been observed [19].

Irradiation effect of 3 MeV protons on superconducting properties has also been studied for IBS single crystal and thin film samples, showing an overall increase in J_C at high field and low temperature, unchanged upper critical field and small suppression of transition temperature [20, 21]. The irradiation of 200 MeV heavy Au ions has enhanced critical current density due to the creation of columnar disorders [22]. Enhancement of J_C with small suppression of T_C in high energy 2.6 GeV uranium irradiation has been investigated [23]. In most of these reported experiments, high energy ions or particles are used for irradiation.

In this paper we report experimental results of He^+ ion irradiation for high quality $\text{BaFe}_{1.84}\text{Co}_{0.16}\text{As}_2$ thin films grown on CaF_2 wafers by pulsed laser deposition (PLD) technique. We studied low energy 600 keV He^+ ions irradiation effect on superconducting properties. A potential application of IBSs is for constructing high field magnets which could be used in future areas such as high energy particle accelerators and next generation fusion reactors [24-28]. In fusion reaction, large amount of He^+ ions with hundreds kilo-electron volts energy are produced. Thus, the study of He^+ ion irradiation effects is of great interest. Based on our experimental results, we conclude that relatively low energy radiations may efficiently change the superconducting properties of these thin films. It indicates that the critical current density may be enhanced at low He^+ dosage level $1 \times 10^{13} \text{ cm}^{-2}$ with slight suppression of T_C . The flux pinning force data suggest similar nature of pinning present in unirradiated and irradiated superconducting thin film samples.

EXPERIMENTAL DETAILS

$\text{BaFe}_{1.84}\text{Co}_{0.16}\text{As}_2$ thin films were prepared at 825 °C on CaF_2 (001) wafers by pulsed laser deposition (PLD) process [15]. Energy density of the laser was set about 1.4 Jcm^{-2} with a repetition rate of 9 Hz. Target of nominal composition $\text{BaFe}_{1.84}\text{Co}_{0.16}\text{As}_2$ with $T_C = 24.5 \text{ K}$ was made by the solid state reaction method and was mounted 40 mm away from the substrate. A KrF excimer laser of wavelength $\lambda = 248 \text{ nm}$ was utilized to grow thin films. The base pressure of the deposition chamber

was better than 10^{-7} torr. Temperature was decreased to room temperature at a rate of $10^{\circ}\text{C}/\text{min}$ after deposition of thin films. Several thin film samples of dimensions 5×10 mm were grown under the nominally same conditions. Film thickness was determined around 150 nm by X-ray reflectivity. The samples were cut into three pieces of size around 5×3 mm very carefully with a diamond pen. The films were irradiated with 600 keV He^{+} ions on High Voltage Engineering Europe (HVEE) 2 MV implanter at Surrey Ion Beam Centre at room temperature. Focused He^{+} ion beam was scanned over a three inch aperture defined area at a fluence rate about 5×10^{12} He^{+} ions per second. The sample names are given as IRR_1, IRR_2, IRR_4, IRR_5 and IRR_6 for different dosages 1×10^{16} , 5×10^{15} , 5×10^{14} , 1×10^{14} and 5×10^{13} cm^{-2} respectively. The samples were characterized by x-ray diffraction (XRD) before and after irradiation. Transport (resistive transition) measurements were performed in a Quantum Design Physical Property Measurement System (PPMS) by a four-probe technique. Four wires were directly connected to thin films using silver paste. For current leads, silver paste was put on both of sample edges to ensure uniform current distribution. Magnetic hysteresis measurements were carried out in the temperature range 4.5 to 20 K and fields up to 9 T in a Vibrating Sample Magnetometer (VSM) installed on the PPMS. The field was applied perpendicular to the thin film plane.

RESULTS AND DISCUSSION

X-ray diffraction (XRD) measurements for pristine and irradiated samples are presented in figures 1(a) and 1(b).

Figure 1. (a) X-ray diffraction patterns for the pristine and irradiated BaFe_{1.84}Co_{0.16}As₂ thin films. (b) Peaks of the (004) reflection before and after irradiation.

The results clearly show that the films are c-axis oriented, with only (00*l*) peaks are observed. Moreover, the data hardly show changes in peak position and width after irradiation. Thus, there is no change in the lattice parameter after irradiation, as reported previously in proton irradiated Co doped 122 single crystal samples [20].

Resistive transition curves obtained at zero applied magnetic field for samples with different irradiation levels are shown in figure 2(a).

Figure 2. (a) Resistive transition curves for different irradiation dosages at zero field for all given thin films. (b-c) Superconducting transition temperature and resistivity as a function of He^+ ion dosage are drawn. Resistivity is determined as $\rho = R A/L$, where A is the film cross-sectional area equal to width multiplied by thickness and L is the length between voltage probes.

The superconducting transition temperatures are defined at mid point between 10% and 90% of normal state resistance for all samples. Critical temperature and resistivity as a function of irradiation dosage are drawn in figures 2(b) and 2(c). The results show moderate change in the transition temperature as well as resistivity after irradiation. Furthermore, the resistivity transition curves did not show any upturn behavior at low temperature after irradiation that indicates the defects produced in IBSs act as non-magnetic scattering centers to the pair breaking [20]. Suppression of T_c is consistent with high energy proton irradiated Co doped Ba122 single crystal

samples presented in literature [20]. Additionally, we also performed resistive transition measurements in different magnetic fields for the all samples, and determined the upper critical field B_{c2} from the transition curves. Little change in the upper critical field has been seen after irradiation at low dosage levels.

To analyze the critical current and flux pinning properties, we have measured magnetization as a function of magnetic field applied perpendicular to the film surface under different temperatures, the results are presented in the inset of figures 3(a)-(f) from where the critical current density J_C is estimated. The formula for J_C is based on the Bean critical state model [29] as given below for rectangular shape thin film samples

$$J_C (A m^{-2}) = \frac{\Delta M}{w(1-w/3l)} , \quad (1)$$

where $\Delta M (=M_{-ve} - M_{+ve})$ is the difference in magnetization during increasing and decreasing field. The parameters l and w are length and width of rectangular shape film samples that should be calculated in meter ($l > w$). The critical current density as a function of magnetic field is computed according to the magnetic hysteresis data and drawn in the main panel of figures 3(a)-(f)

Figure 3. (a)-(f) Magnetic field dependence of critical current density J_C at different temperatures for unirradiated and irradiated samples, respectively. Inset shows magnetic hysteresis loops at different temperatures from where J_C is calculated by using the Bean state model given in equation 1.

for pristine and irradiated samples, respectively. In figure 4(a), we plot the graph to show the tendency of current density as a function of ion irradiation dosages for different magnetic fields $H = 1, 3, 5, 7, 9$ T at low temperature 4.5 K. Also, in figure 4(b), we show the temperature dependence of J_C measured at 1 T for all the six samples.

Results show that the J_C value is changed for different irradiated samples and J_C could be increased by He^+ ion irradiation. The general tendency of the data appears to show that J_C is peaked at irradiation dosage around 10^{13} - 10^{14} cm^{-2} . The highest J_C value is obtained for the sample IRR_6 with dosage level 5×10^{13} cm^{-2} . Compared to

the unirradiated sample, J_C is increased by a factor around 5. Upon further increasing dosage to 10^{15} - 10^{16} cm^{-2} , the J_C is decreased. We note that the J_C of the sample IRR_5 appears to be anomalous, smaller than that of the adjacent two samples. It is not clear why this anomaly is presented. Nonetheless, the general tendency is clear. Even for this sample, the J_C value is higher than the unirradiated sample.

Figure 4. (a) J_C as a function of irradiation dosage rates for field $H = 1, 3, 5, 7, 9$ T at fixed temperature 4.5 K, (b) J_C as a function of temperature at low field 1 T for given samples are plotted.

We also plot J_C as a function of temperature at 1T field for unirradiated and irradiated samples. The J_C values keep larger than 2×10^5 Acm⁻² from 4.5 to 15 K temperature under 1 T field as seen in figure 4(b). Again, clear increase in J_C is observed and the IRR_6 sample shows the highest J_C in this temperature range.

The effect of irradiation on flux pinning and critical current properties on iron based superconductors, including Co doped 122 phase materials, has been studied by a number of groups [18-23]. Most of these studies were carried on single crystal samples, and the irradiation particles include heavy ions, fast neutron and proton. The results show that 200 MeV Au ion could produce columnar defects and increase J_C up to 4 MAcm⁻² at 5 K [22], while the effect of neutron and 3 MeV proton irradiation is less clear for flux pinning and critical current properties [19, 21]. We note that in all these reported studies the irradiation dosage is in ranges higher than we used here. The increased magnitude of J_C in our case is similar to those reported in [21, 22, 30].

The J_C value approaches to 2.4 MAcm^{-2} at 1 T field for the IRR_6 sample in our study.

The 600 keV ion energy is sufficient to create disorders in such type of IBS thin films as previously illustrated in [31] with 200 keV proton irradiations. We also performed simulation using the SRIM program on irradiation effect to estimate defect density. The results show that a single 600 keV He^+ ion irradiated in the 150 nm thick $\text{BaFe}_{1.84}\text{Co}_{0.16}\text{As}_2$ film can produce, on average, 0.677, 1.18, 0.107 and 1.34 vacancies for Ba, Fe, Co and As sites, respectively.

In order to get more insight into the effect of irradiation on flux pinning properties of our samples, we calculate pinning force and analyze its field dependence. Theoretically, the critical current density could be found by the equalization of the Lorentz force and pinning force $F_L = F_p$, where F_p is taken as summation of all the elementary pinning forces from each of the individual flux lines. Although the elementary pinning force of a single flux line can be calculated from the variation of its free energy due to the interactions of normal core and screening current with the defects presented in superconductors, the summation calculation is far more difficult because the details of vortex configuration and nature of pinning centers are difficult to know. Nevertheless, it has been found that quiet often the pinning force data experimentally measured at different temperatures could be scaled on a single curve in practice, as first reported by Fietz and Webb [32]. It has been further shown that the scaling behavior can be described in many cases by the expression,

$$f(b) = AB_{c2}^n b^p (1 - b)^q \quad (2)$$

Where A relates to the material microstructure and Ginzburg-Landau parameter and b is the normalized magnetic field B/B_{c2} . Although theoretical analysis have given the values of n , p and q for different types of pinning centers [33-35] equation 2 is mostly used in a phenomenological way to analyze pinning force data in experiments. In case of high temperature superconducting cuprates, MgB_2 and iron based superconductors, it is often found that the scaling can be observed with magnetic field normalized to the irreversible field B_{irr} which could be much lower than B_{c2} .

We study the scaling analysis of pinning forces engaged in our Co-doped Ba122

superconducting thin films. The scaling behavior may tell us about the pinning nature. To understand the pinning mechanism we draw the graph between normalized volume pinning forces $f_p = F_p/F_{pmax}$ and reduced magnetic field $b = B/B_{irr}$, where $F_p = J_c B$, F_{pmax} is the maximum value of the pinning force density, and B_{irr} is the irreversible magnetic field that is estimated from Kramer's plot [36] by analyzing linear behavior of $J_c^{0.5} B^{0.25}$ as a function of field as shown in figures 5(a)-(f) for all samples.

Figure 5. (a)-(f). Kramer plots: $J_c^{0.5} B^{0.25}$ versus field graphs for all given samples at different temperatures. The linear extrapolation of red solid lines gives the estimation of irreversibility fields B_{irr} .

The linear extrapolation of high field data (as indicated by the red solid lines) to the intercept field of zero pinning force determines B_{irr} . This method is reasonable to find the irreversible field for high upper critical field superconductors [11, 12, 37]. It should be noted that the linear extrapolation in Kramer plot could lead to underestimated or overestimated value of B_{irr} if the actual pinning force curves do not follow the case of $p = 0.5$ and $q = 2$ [38]. We think the extrapolation shown in figure 5 represents reasonable approximation. With the obtained B_{irr} , we could show the normalized pinning force data as a function of normalized field $b = B/B_{irr}$, as

illustrated in figures 6(a)-(f). The results appear to suggest that, for each sample, the scaling behavior is observed. The related best fitting parameters are obtained for all given samples and are presented in figures 6(a)-(f) and table 1. The scaling behavior and the approximately similar p and q values for all samples imply that the J_C for each thin film is restricted by a similar mechanism.

Figure 6. (a)-(f) Normalization of the pinning forces f_p as a function of reduced field b at different temperatures (4.5, 7.5, 10, 12.5, 15 and 17.5 K). The data scaled on a single curve represented by red solid line using equation 2 with best fitting parameters for the pristine and all given irradiated thin films.

Table 1. Flux pinning parameters for different irradiation influences.

Samples	Influences (cm^{-2})	p	q	A
UNIRR	0	0.72	2.36	5.22
IRR_6	5×10^{13}	0.65	2.22	4.71
IRR_5	1×10^{14}	0.67	2.24	5.03
IRR_4	5×10^{14}	0.73	2.37	5.70
IRR_2	5×10^{15}	0.74	2.38	5.38
IRR_1	1×10^{16}	0.66	2.23	4.70

It has been suggested that if the dominant pinning mechanism is due to planar defects like grain boundaries, it could be $p = 0.5$ and $q = 2$, and for point like defects, it could

be $p = 1$ and $q = 2$ [33-35]. In the literature, different models have been used to fit experimental pinning force data of Co doped 122 phase IBS thin films [11, 12, 37], suggesting the actual pinning mechanism varies for samples made in different groups. The data presented here show that for the all samples p falls near to 0.5, while q in between 2 and 2.5, indicating similar pinning mechanism in these samples. Additionally, the p and q values and flux pinning forces curves in figure 6 are more close to those due to planar defects, thus we suggest that similar nature of planar defect pinning presented after irradiation.

CONCLUSION

We have presented experimental results about the irradiation effect of 600 keV He^+ ions on the superconducting properties of $\text{BaFe}_{1.84}\text{Co}_{0.16}\text{As}_2$ thin films grown on CaF_2 (001) substrates. We found that the critical temperature T_C changes slightly from 23 K for the unirradiated sample to about 20 K for the sample with the highest irradiation level. The J_C value is raised to 2.4 MAcm^{-2} at 1 T field and 4.5 K temperature for a sample with irradiation dose $5 \times 10^{13} \text{ cm}^{-2}$. Moreover, the scaling behavior of the flux pinning force data revealed that the nature of pinning centers is similar after irradiation in all samples. Our results suggest that low energy 600 keV He^+ ion could improve the flux pinning and critical current properties in Co doped Ba122 type thin films.

ACKNOWLEDGEMENTS

We would like to thank Y. Z. Zhang for his help to conduct magnetization measurements. This work is partially supported by the Chinese Academy of Sciences (Grant Nos. XDB25000000, 182111KYSB20160014, QYZDJ-SSW-JSC026), National Natural Science Foundation of China (Grant Nos. 51861135311, U1832213 and 51607174), the National Key R&D Program of China (Grant No. 2018YFA0704200).

REFERENCES

- [1] Kamihara Y, Watanabe T, Hirano M, Hosono H 2008 *J. Am. Chem. Soc.* **130** 3296
- [2] Chen X H, Wu T, Wu G, Liu R H, Chen H, Fang D F 2008 *Nature* **453** 761
- [3] Katase T, Hiramatsu H, Matias V, Sheehan C, Ishimaru Y, Kamiya T, Tanabe K, Hosono H 2011 *Appl. Phys. Lett.* **98** 242510
- [4] Rotter M, Vogt M, Johrendt D 2008 *Phys. Rev. Lett.* **101** 107006
- [5] Hunte F, Jaroszynski J, Gurevich A, Larbalestier D C, Jin R, Sefat A S, McGuire M A, Sales B C, Christen D K, Mandrus D 2008 *Nature* **453** 903
- [6] Yamamoto A, Jaroszynski J, Tarantini C, Balicas L, Jiang J, Gurevich A, Larbalestier D C, Jin R, Sefat A S, McGuire M A, Sales B C, Christen D K, Mandrus D 2009 *Appl. Phys. Lett.* **94** 062511
- [7] Jiao L, Zhang J L, Balakirev F F, Chen G F, Luo J L, Wang N L, Yuan H Q 2011 *PCS* **72** 423
- [8] Gao Z, Ma Y, Yao C, Zhang X, Wang C, Wang D, Awaji S, Watanabe K 2012 *Sci. Rep.* **2** 998
- [9] Hänisch J, Iida K, Hühne R, Tarantini C 2019 *Supercond. Sci. Technol.* **32** 093001
- [10] Lee J, Jiang J, Kametani F, Oh M J, Weiss J D, Collantes Y, Seo S, Yoon S, Tarantini C, Jo Y J, Hellstrom E E, Lee S 2017 *Supercond. Sci. Technol.* **30** 085006
- [11] Xu Z, Zhang Q, Fan F, Gu L, Ma Y 2019 *Supercond. Sci. Technol.* **32** 125014
- [12] Huang H, Yao C, Dong C, Zhang X, Wang D, Cheng Z, Li J, Awaji S, Wen H, Ma Y 2017 *Supercond. Sci. Technol.* **31** 015017
- [13] Wang D, Zhang Z, Zhang X, Jiang D, Dong C, Huang H, Chen W, Xu Q, Ma Y 2019 *Supercond. Sci. Technol.* **32** 04LT01
- [14] Tarantini C, Kametani F, Lee S, Jiang J, Weiss J D, Jaroszynski J, Hellstrom E E, Eom C B, Larbalestier D C 2014 *Sci. Rep.* **4** 7305
- [15] Yuan P, Xu Z, Wang D, Zhang M, Li J, Ma Y 2016 *Supercond. Sci. Technol.* **30** 025001
- [16] Yao C, Ma Y 2019 *Supercond. Sci. Technol.* **32** 023002
- [17] Lee S, Tarantini C, Gao P, Jiang J, Weiss J D, Kametani F, Folkman C M, Zhang

- Y, Pan X Q, Hellstrom E E, Larbalestier D C, Eom C B 2013 *Nat. Mater.* **12** 392
- [18] Eisterer M 2017 *Supercond. Sci. Technol.* **31** 013001
- [19] Mishev V, Nakajima M, Eisaki H, Eisterer M 2016 *Sci. Rep.* **6** 27783
- [20] Nakajima Y, Taen T, Tsuchiya Y, Tamegai T, Kitamura H, Murakami T 2010 *Phys. Rev. B* **82** 220504
- [21] Maierov B, Katase T, Usov I O, Weigand M, Civale L, Hiramatsu H, Hosono H 2012 *Phys. Rev. B* **86** 094513
- [22] Nakajima Y, Tsuchiya Y, Taen T, Tamegai T, Okayasu S, Sasase M 2009 *Phys. Rev. B* **80** 012510
- [23] Yagyuda H, Nakajima Y, Tamegai T, Kanai Y, Kambara T 2011 *Physica C: Superconductivity and its Applications* **471** 790
- [24] Uglietti D 2019 *Supercond. Sci. Technol.* **32** 053001
- [25] Sorbom B N, Ball J, Palmer T R, Mangiarotti F J, Sierchio J M, Bonoli P, Kasten C, Sutherland D A, Barnard H S, Haakonsen C B, Goh J, Sung C, Whyte D G 2015 *Fusion Eng. Des.* **100** 378
- [26] Shimoyama J 2014 *Supercond. Sci. Technol.* **27** 044002
- [27] Pallecchi I, Eisterer M, Malagoli A, Putti M 2015 *Supercond. Sci. Technol.* **28** 114005
- [28] Liu S, Lin K, Yao C, Zhang X, Dong C, Wang D, Awaji S, Kumakura H, Ma Y 2017 *Supercond. Sci. Technol.* **30** 115007
- [29] Bean C P 1962 *Phys. Rev. Lett.* **8** 250
- [30] Taen T, Nakajima Y, Tamegai T, Kitamura H 2012 *Phys. Rev. B* **86** 094527
- [31] Schilling M, Baumgartner A, Gorshunov B, Zhukova E, Dravin V, Mitsen K, Efremov D, Dolgov O, Iida K, Dressel M, Zapf S 2015 *Phys. Rev. B* **93** 174515
- [32] Fietz W A, Webb W 1969 *Phys. Rev.* **178** 657
- [33] Dew-Hughes D 1974 *Philos. Mag.* **30** 293
- [34] Dew-Hughes D 1987 *Phil. Mag.* **55** 459
- [35] Kramer E J 1973 *J. Appl. Phys.* **44** 1360
- [36] 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 2001 *Nature* **410** 186

[37] Tarantini C, Lee S, Zhang Y, Jiang J, Bark C W, Weiss J D, Polyanskii A, Nelson C T, Jang H W, Folkman C M, Baek S H, Pan X Q, Gurevich A, Hellstrom E E, Eom C B, Larbalestier D C 2010 *Appl. Phys. Lett.* **96** 142510

[38] Eisterer M 2008 *Phys. Rev. B* **77** 144524