Upper critical magnetic field of $LnO_{0.5}F_{0.5}BiS_2$ ($Ln = La, Nd$) superconductors at ambient and high pressure

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Abstract

The upper critical fields $H_{c2}$ of polycrystalline samples of $LnO_{0.5}F_{0.5}BiS_2$ ($Ln = La, Nd$) at ambient pressure (tetragonal structure) and high pressure (HP) (monoclinic structure) have been investigated via electrical resistivity measurements at various magnetic fields up to 8.5 T. The $H_{c2}(T)$ curves for all the samples show an uncharacteristic concave upward curvature at temperatures below $T_c$, which cannot be described by the conventional one-band Werthamer–Helfand–Hohenberg theory. For the LaO$_{0.5}F_{0.5}BiS_2$ sample under HP, as temperature is decreased, the upper critical field $H_{onset}$, estimated from the onset of the superconducting transitions, increases slowly between 4.9 and 5.8 T compared with the slope of $H_{onset}(T)$ below 4.9 T and above 5.8 T. This anomalous behavior reveals a remarkable similarity in superconductivity between LaO$_{0.5}F_{0.5}BiS_2$ samples measured under HP and synthesized under HP, although the crystal structures of the two samples were reported to be different. A reasonable explanation is that local atomic environment, which can be tuned by applying external pressure, is essential to the enhancement of $T_c$ for BiS$_2$-based superconductors. On the other hand, such anomalous behavior is very subtle in the case of NdO$_{0.5}F_{0.5}BiS_2$ under HP, suggesting that the anisotropy of the upper critical field in the $ab$-plane and the possible lattice deformation induced by external pressure is weak. This explains why the pressure-induced enhancement of $T_c$ for NdO$_{0.5}F_{0.5}BiS_2$ is not as large as that for LaO$_{0.5}F_{0.5}BiS_2$.

Keywords: high magnetic field, phase transition, high pressure, BiS$_2$-based superconductor

(Some figures may appear in colour only in the online journal)

1. Introduction

Measurements of the upper critical field, $H_{c2}$, can provide insight into the pair-breaking mechanisms present in superconducting materials and also aid in estimating other characteristics of superconductors such as coherence length and anisotropy. Since the discovery of the cuprates, a large number of high-$T_c$ superconductors have been studied, thus fundamentally challenging the validity of the existing Bardeen–Cooper–Schrieffer theory of conventional superconductivity. The recently discovered BiS$_2$-based superconducting materials, which exhibit a layered crystal structure similar to the high-$T_c$ cuprates and iron-based superconductors, provide another opportunity to investigate and develop a better understanding of superconductivity in these materials [1–6]. However, current studies on the
BiS$_2$-based compounds are only at an early stage and some important questions remain regarding crystal structure, superconductivity, and their interrelation [7–10].

One of the more striking phenomena displayed by many BiS$_2$-based superconductors, such as LnO$_{1−x}$F$_x$BiS$_2$ (Ln = La, Ce, Pr, Nd, Yb), La$_{1−y}$Sm$_y$O$_{0.5}$F$_{0.5}$BiS$_2$, Eu$_2$Bi$_2$S$_4$F$_6$, EuBiS$_3$F, SrF$_2$BiS$_2$, LaO$_{0.5}$F$_{0.5}$BiS$_2$, and Sr$_{0.5}$La$_{0.5}$F$_2$BiS$_2$ is the rather abrupt enhancement of superconductivity from a low-$T_c$ phase to a high-$T_c$ phase with the application of a moderate amount of pressure on the order of a few GPa [11–18]. X-ray diffraction experiments reveal that LaO$_{0.5}$F$_{0.5}$BiS$_2$ and EuBiS$_3$F undergo a structural phase transition from tetragonal (P4/nmm) to monoclinic (P2$_1$/m) [15, 19], which is believed to be related to the sudden increase in $T_c$. In addition to the remarkable difference in $T_c$, there are other essential differences in normal state properties between the low-$T_c$ (SC1) and high-$T_c$ (SC2) phases. In particular, the normal state electrical resistivity of LaO$_{0.5}$F$_{0.5}$BiS$_2$ in the SC2 phase is significantly smaller than that in the SC1 phase and NdO$_{0.5}$F$_{0.5}$BiS$_2$ shows metallic-like behavior in the SC2 phase instead of semiconducting-like behavior as in the SC1 phase [12, 13].

In this paper, we report the evolution of superconductivity under external magnetic fields up to 8.5 T for polycrystalline samples of LnO$_{0.5}$F$_{0.5}$BiS$_2$ (Ln = La, Nd) in both the SC1 and SC2 phases. For all samples, the temperature dependence of $H_{c2}$ shows a concave upward curvature with decreasing temperature, which cannot be described by the one-band Ginzburg–Landau theory. The effects of external pressure and chemical composition on superconductivity with increasing external magnetic field for the four samples studied are presented. The anomalous behavior of the temperature dependence of $H_{c2}$, which was observed in the high-pressure (HP) superconducting phase of LaO$_{0.5}$F$_{0.5}$BiS$_2$ and NdO$_{0.5}$F$_{0.5}$BiS$_2$ at ~5 T and ~3 T, respectively, will be described, and a comparison of the superconductivity observed in samples of LaO$_{0.5}$F$_{0.5}$BiS$_2$ in the HP phase (SC2) and the superconductivity observed in the high-pressure synthesized samples of LaO$_{0.5}$F$_{0.5}$BiS$_2$ which are measured at ambient pressure, will be discussed. We believe the results will be useful in understanding (1) whether the BiS$_2$-based superconductors are conventional or unconventional and (2) how the difference in crystal structure and local atomic environment of the BiS$_2$-based compounds affects superconductivity. This study also provides a plausible explanation for why the pressure-induced enhancements of $T_c$ for LnO$_{0.5}$F$_{0.5}$BiS$_2$ (Ln = La–Nd) decrease with heavier Ln. In the following discussion, as-grown samples measured at ambient pressure and under HP will be abbreviated as AG and HPAG, respectively. In addition, samples that were synthesized and studied by Mizuguchi et al [20], which were grown under high-pressure and high-temperature conditions, shall be abbreviated as HPT.

2. Experimental details

As-grown polycrystalline samples of LnO$_{0.5}$F$_{0.5}$BiS$_2$ (Ln = La, Nd) were synthesized and annealed at ~800 °C in sealed quartz tubes as described elsewhere [4, 6]. The AG and HPAG samples of the same chemical composition came from the same pellet to ensure both samples have the same physical properties at ambient pressure. Hydrostatic pressure was generated by using a clamped piston-cylinder cell in which a 1:1 by volume mixture of n-pentane and isoamyl alcohol was used as the pressure-transmitting medium. The pressures applied to the samples were estimated by measuring the $T_c$ of a high purity (>99.99%) Sn disk inside the sample chamber of the cell and comparing the measured values with the well-determined $T_c(P)$ of high purity Sn [21]. The resistivity measurements of the AG LaO$_{0.5}$F$_{0.5}$BiS$_2$ sample at magnetic fields up to 1 T were performed by using a Quantum Design Physical Property Measurement System Dynacool using a standard four-wire technique from 5 to 1.8 K. Electrical resistivity measurements at temperatures down to 60 mK on the HPAG LaO$_{0.5}$F$_{0.5}$BiS$_2$ sample and the AG and HPAG NdO$_{0.5}$F$_{0.5}$BiS$_2$ samples were performed with an Oxford Instruments Kelvinvix 3He–4He dilution refrigerator in magnetic fields ranging from 0 to 8.5 T. Previous studies have shown that the pressure-induced phase transition for LaO$_{0.5}$F$_{0.5}$BiS$_2$ and NdO$_{0.5}$F$_{0.5}$BiS$_2$ occurs at around 0.8 and 1.9 GPa, respectively, followed by a gradual decrease in $T_c$ in both compounds with additional pressure [12, 13, 19]. The HPAG samples were measured under an applied pressure of ~2.3 GPa to ensure that the SC2 phase was fully realized in the HPAG samples.

3. Results and discussion

Electrical resistivity $\rho$ versus temperature $T$ superconducting transition curves at various magnetic fields up to 8.5 T in temperature ranges extending down to 60 mK for LaO$_{0.5}$F$_{0.5}$BiS$_2$ (AG and HPAG) and NdO$_{0.5}$F$_{0.5}$BiS$_2$ (AG and HPAG) are displayed in figures 1(a)–(d), respectively. The normal state $\rho$ increases slightly with increasing magnetic field for all four samples, revealing a positive magnetoresistance. Superconductivity for all the samples is suppressed by the external magnetic field, as evinced by the shift of the superconducting transition curves to lower temperature with increasing magnetic field. If we define $T_c$ as the temperature at which $\rho$ falls to 50% of its normal state value, the $T_c$ values for LaO$_{0.5}$F$_{0.5}$BiS$_2$ and NdO$_{0.5}$F$_{0.5}$BiS$_2$ at 2.3 GPa are 8.28 K and 6.31 K, respectively, and the $T_c$ values for the corresponding AG samples are 2.92 and 4.54 K in zero magnetic field. The large difference in $T_c$ between the AG and HPAG samples of the same compound and the sharp superconducting transition at zero magnetic field reveals that the AG samples are in the SC1 phase and the HPAG samples are in the SC2 phase.

As shown in figure 1, superconducting transitions for all the samples are quite broad in high magnetic fields. It has been reported that anisotropy in single-crystalline samples of BiS$_2$-based superconductors is quite large [22–24]. For example, the upper critical field parallel to the ab-plane ($H_{c2}^{ab}$) for single-crystalline samples of $\sim$30% substituted Nd(O, F)BiS$_2$ is estimated to be ~ 42 T, whereas the upper critical field parallel to the c-axis ($H_{c2}^{c}$) for the same
compound is only about 1.3 T \([22]\). In other words, the superconducting state of grains whose \(c\)-axis is parallel to the applied magnetic field is more rapidly suppressed by applying high magnetic fields than the state of grains whose \(ab\)-plane is parallel to the applied magnetic field \([20]\). In figure 2, we plotted the \(T\) dependence of the upper critical field in terms of the characteristic fields \(H_{\text{c}1}\) and \(H_{\text{c}2}\) evaluated at 10% and 90% of the normal state \(\rho\) at the onset of the superconducting transition. It should be noted that modeling of the \(H_{\text{c}1}\) and \(H_{\text{c}2}\) curves is very difficult due to the contributions of superconductivity from different directions. However, the significant difference between \(H_{\text{c}1}\) and \(H_{\text{c}2}\) is expected to be related to the large anisotropy of the upper critical field; \(H_{\text{c}1}\) is expected to be close to the upper critical field for grains whose \(ab\)-plane is parallel to \(H\) \([20]\).

Application of an external magnetic field may destroy the Cooper pairs via the pair-breaking interaction between the magnetic field and/or the momenta of the electrons (electromagnetic interaction) and the spins of the electrons (Zeeman interaction). With increasing \(H\), superconductivity is suppressed more rapidly for the AG samples compared to the corresponding HPAG samples with the same chemical composition. Superconductivity in AG LaO\(_{0.5}\)F\(_{0.5}\)BiS\(_2\) cannot be observed above 1.9 K when \(H\) reaches 1 T (shown in figure 1(a)). As can be seen in figure 2(a), despite the difference in \(T_c\) in zero magnetic field, the \(H_{\text{c}1}\) increases more rapidly for HPAG NdO\(_{0.5}\)F\(_{0.5}\)BiS\(_2\) with decreasing temperature compared to the \(H_{\text{c}1}\) for HPAG LaO\(_{0.5}\)F\(_{0.5}\)BiS\(_2\). However, \(H_{\text{c}2}(T)\) curves are very similar for the two AG sample shown in the inset of figure 2(b).

In the conventional one-band Ginzburg–Landau picture, the upper critical field increases linearly with decreasing \(T\) near \(T_c\) and then saturates to a finite value in the 0 K limit. A linear-like temperature dependence of \(H_{\text{c}2}\) has been observed down to 2 K in the AG LaO\(_{0.5}\)F\(_{0.5}\)BiS\(_2\) \([25]\). However, in this study, the \(T\) dependence of \(H_{\text{c}1}\) and \(H_{\text{c}2}\) for AG NdO\(_{0.5}\)F\(_{0.5}\)BiS\(_2\) shows an uncharacteristic upward curvature with decreasing \(T\) below 2 K, which is remarkably different from the one-band Werthamer–Helfand–Hohenberg (WHH) model (shown in figure 2(b)). Similar behavior was also reported for AG samples of LaO\(_{1−x}\)F\(_x\)BiS\(_2\) \((x = 0.1−0.3)\) and BiO\(_x\)S\(_1\) \([26, 27]\). In the present work, we also adopted the dirty two-band model introduced in \([28, \text{equation (19)}]\), which treats both interband scattering and paramagnetic effects as negligible. The corresponding estimated value of \(H_{\text{c}2}(0)\) for AG NdO\(_{0.5}\)F\(_{0.5}\)BiS\(_2\) is 9.1 T, which is significantly higher than the \(H_{\text{c}2}(0)\) reported earlier (2.3 T) by using the WHH equation \([25]\). It should be mentioned that although the two-band model provides a better overall fit compared with the one-band WHH model, the difference between the experimental data and the fitting is still significant at low temperatures as shown in figure 2(b). On the
other hand, previous experimental and theoretical studies have not reached an agreement of whether the newly discovered BiS$_2$-based superconductors are conventional or unconventional. The poor description of the $T_c$ data is possibly a result of unconventional superconductivity.

For the HPAG LaO$_{0.5}$F$_{0.5}$BiS$_2$ sample, the increase of $H_{99%}$ with decreasing $T$ slows down somewhat when the external magnetic field reaches $\sim 3$ T (indicated by the black arrow in figure 2(a)). This anomalous behavior is more remarkable in the evolution of $T_{c}$ onset, which is defined as the $T$ at which $\rho$ attains its maximum value, in various external magnetic fields. As shown in figure 3(a), $T_{c}$ onset is significantly suppressed with a slight increase in $H$ at around 5 T. The temperature dependence of $H_{\text{onset}}$ for HPAG LaO$_{0.5}$F$_{0.5}$BiS$_2$ (shown in figure 4) is remarkably similar to that observed in the HPT sample of LaO$_{0.5}$F$_{0.5}$BiS$_2$ which was synthesized at a pressure of 2 GPa and temperature of 700 °C [20]. Possible anisotropy of the superconducting state within the BiS$_2$ plane, which may be induced by lattice distortion or residual strain along the superconducting layers in the HP and high-temperature condition, is considered to be the origin of the anomalous behavior observed in $H_{\text{onset}}(T)$. The vertical ticks represent the onset of superconducting transition ($T_{c}$ onset) and the dashed lines are guides to the eye. The orange curves indicate the directions of field increasing and the magnetic field applied for each curve can be found in figure 1 with the same symbol.

For the AG LaO$_{0.5}$F$_{0.5}$BiS$_2$ sample, the increase of $H_{99%}$ and $H_{95%}$ for AG NdO$_{0.5}$F$_{0.5}$BiS$_2$. The dashed and solid lines are fits to the $H_{99%}(T)$ of the one-band WHH equation and the two-band model, respectively. The inset shows $H_{99%}$ and $H_{95%}$ values (circular and rhombic symbols, respectively) for the AG LaO$_{0.5}$F$_{0.5}$BiS$_2$ (open symbols) and NdO$_{0.5}$F$_{0.5}$BiS$_2$ (filled symbols) from 0 to 0.20 T.

The poor description of the $H_{99%}$ data is possibly a result of unconventional superconductivity.
structure and superconductivity of the BiS$_2$-based compounds can be largely affected by a change in the crystal structures [5, 7, 29–33]. Anisotropic superconducting states within the $ab$-plane could be induced when the degeneracy of Bi-$6p_z$ and Bi-$6p_y$ orbital is lifted [20]. Our results indicate that the anisotropy of the upper critical field in the $ab$-plane of HPAG NdO$_{0.5}$F$_{0.5}$BiS$_2$ is not as large as that of HPAG LaO$_{0.5}$F$_{0.5}$BiS$_2$, and hence, based on the discussion above, suggests that the pressure-induced lattice deformation at 2.3 GPa in NdO$_{0.5}$F$_{0.5}$BiS$_2$ is not as significant compared with that in LaO$_{0.5}$F$_{0.5}$BiS$_2$. This also explains why the pressure-induced enhancement of the superconducting critical temperature $\Delta T_c$ in NdO$_{0.5}$F$_{0.5}$BiS$_2$ is only $\sim 2.5$ K, which is much lower than the $\Delta T_c$ value of LaO$_{0.5}$F$_{0.5}$BiS$_2$ ($\sim 7.2$ K).

Previous studies have revealed that it is possible to significantly increase $T_c$ in the $Ln$(O, F)BiS$_2$ ($Ln = La$ - Nd) superconductors by applying HP or by annealing/synthesizing the samples under HP [12, 13, 18, 19, 34]. Although the crystal structure of HPT samples is reported to be the same as the structure of AG samples at low pressure and is different from the monoclinic structure of the same compounds under HP [34–36], $T_c$ values of HPT samples and the corresponding (same chemical composition) HPAG samples in SC2 phase are very close. The enhancement of $T_c$ for these compounds under pressure is considered to be related to the structural phase transition; [19] however, there is no conclusive agreement regarding the enhancement of superconductivity in samples that are annealed or synthesized under pressure [7, 35–38]. The $T_c$ value of HPAG LaO$_{0.5}$F$_{0.5}$BiS$_2$ plotted in figure 3 is lower than the reported $T_c$ value of the HPT LaO$_{0.5}$F$_{0.5}$BiS$_2$. This discrepancy can be attributed to the fact that the measurement of electrical resistivity on the HPAG sample of LaO$_{0.5}$F$_{0.5}$BiS$_2$ was performed at 2.3 GPa, well into the SC2 phase, where a gradual suppression of $T_c$ occurs with increasing pressure. Nevertheless, the values of $dH_{\text{onset}}/dT$ are nearly the same at each of the three different stages in the evolution of $H_{\text{onset}}(T)$ as shown in figure 4. Our results raise the question of why superconductivity for the same compounds in this system, enhanced by the two different methods, is so similar. A thorough investigation of this problem may yield information that will help identify the essential parameters that determine $T_c$ in the BiS$_2$-based superconductors.

One possible explanation for the enhanced superconductivity observed in the HPT samples of LnO$_{0.5}$F$_{0.5}$BiS$_2$ ($Ln = La$ – Nd) is the presence of trace amounts of the monoclinic structure at ambient pressure; however, it has been observed that the pressure dependence of $T_c$ for the HPAG samples is completely reversible, suggesting that it is unlikely for the monoclinic phase to survive in returning from HP to atmospheric pressure [12, 13, 18]. In addition, no additional curvatures in the $T$ dependence of the resistivity, magnetic susceptibility, or specific heat due to the appearance of superconductivity from an additional superconducting phase have been reported yet. It has also been suggested that the enhanced superconductivity in the HPT samples may result from additional effects that HP annealing may have on the local crystal structure including the shorter in-plane Bi–S distances and higher symmetry in the $ab$-plane reported for the Ce(O, F)BiS$_2$ compound as well as the uniaxial strain along the $c$-axis that was observed in HPT samples of LaO$_{0.5}$F$_{0.5}$BiS$_2$ and PrO$_{0.5}$F$_{0.5}$BiS$_2$ [35–38].

The pressure-induced phase transition observed in LaO$_{0.5}$F$_{0.5}$BiS$_2$ was reported to involve sliding between the two neighboring BiS$_2$ layers along the $a$-axis, resulting in a slight increase of the angle between the $ab$ and $bc$ planes ($\beta$) from 90° at ambient pressure to 94° at $\sim 1$ GPa [19]. The in-plane structure of the BiS$_2$ layers, which is considered to be essential for the superconductivity, as well as the in-plane structure of the La(O, F) blocking layers, are nearly the same after the phase transition. Considering the results obtained in this study, it seems that local distortions or changes in the local atomic environment, as caused by the application of pressure but also quenched via HP annealing, are probably critical in affecting superconductivity, perhaps even more than the structural phase transition itself. However, further investigations of the crystal structure of the AG, HPAG, and HPT are still needed for direct evidence of changes in local structure. Very recently, it was reported that “in-plane chemical pressure” is closely related to $T_c$ in the BiS$_2$-based superconductors [32]. The in-plane chemical pressure is defined as the ratio of the expected bond distance between a Bi ion and its in-plane neighboring ions of S (or Se) to the experimental bond distance estimated by Rietveld refinements. The expected bond distance can be determined by using the ionic radii of Bi and S (or Se). Although the validity of such a relationship needs to be further confirmed, the results also emphasize the importance of local structure to superconductivity in BiS$_2$-based compounds.

**Figure 4.** (a) The $H_{\text{onset}}$–$T$ phase diagrams for HPAG and HPT LaO$_{0.5}$F$_{0.5}$BiS$_2$ as well as HPAG NdO$_{0.5}$F$_{0.5}$BiS$_2$. The data for HPT LaO$_{0.5}$F$_{0.5}$BiS$_2$ are taken from [20]. The anomalous behavior for each curve is indicated by the corresponding arrow.
4. Summary

To summarize, we performed electrical resistivity measurements on polycrystalline samples of LaO$_{0.5}$F$_{0.5}$BiS$_2$ ($Ln = La$, Nd) in both the SC1 and SC2 phases under external magnetic fields up to 8.5 T and at temperatures down to 60 mK. Significant concave upward curvatures in the $H_c(T)$ curves were observed and cannot be described by conventional one-band WHH theory. In addition, the $T$ dependence of $H_{\text{onset}}$ for HPAG LaO$_{0.5}$F$_{0.5}$BiS$_2$ shows anomalous behavior at around 5 T, revealing remarkable similarity to the superconductivity observed the HPT samples of LaO$_{0.5}$F$_{0.5}$BiS$_2$. If no high-pressure monoclinic phase exists in HPT LaO$_{0.5}$F$_{0.5}$BiS$_2$, the importance of the monoclinic phase would be diminished, suggesting the possibility of a greater importance in the role that local atomic environment plays in affecting superconductivity in the BiS$_2$-based compounds, though further investigations of atomic positions are still needed. In the case of HPAG NdO$_{0.5}$F$_{0.5}$BiS$_2$, the anomalous behavior in $H_{\text{onset}}(T)$ is very subtle, probably due to a mild pressure-induced deformation in crystal structure, which is probably responsible for the relatively slight increase in $T_c$ compared to the remarkable enhancement of $T_c$ in LaO$_{0.5}$F$_{0.5}$BiS$_2$.

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References

[1] Mizuguchi Y, Fujihsa H, Gotoh Y, Suzuki K, Usui H, Kuroki K, Demura S, Takano Y, Izawa H and Miura N 2012 Phys. Rev. B 86 220510
[2] Demura S et al 2013 J. Phys. Soc. Japan 82 033708
[3] Mizuguchi Y, Demura S, Deguchi K, Takano Y, Fujihsa H, Gotoh Y, Izawa H and Miura N 2012 J. Phys. Soc. Japan 81 114725
[4] Yazici D, Huang K, White B D, Chang A H, Friedman A J and Maple M B 2013 Phil. Mag. 93 673
[5] Fang Y, Yazici D, White B D and Maple M B 2015 Phys. Rev. B 91 064510
[6] Yazici D, Huang K, White B D, Jean I, Burnett V W, Friedman A J, Larm I K, Nallaiyan M, Spagna S and Maple M B 2013 Phys. Rev. B 87 174512
[7] Fang Y, Wolowiec C T, Yazici D and Maple M B 2015 Nov. Supercond. Mater. 1 79–94
[8] Kuroki K 2014 JPSJ News Comments 11 02
[9] Mizuguchi Y 2015 J. Phys. Chem. Solids 84 34
[10] Yazici D, Jeon I, White B D and Maple M B 2015 Physica C 514 218
[11] Kogegawa H, Tomita Y, Tou H, Izawa H, Mizuguchi Y, Miura O, Demura S, Deguchi K and Takano Y 2012 J. Phys. Soc. Japan 81 103702
[12] Wolowiec C T, White B D, Jeon I, Yazici D, Huang K and Maple M B 2013 J. Phys.: Condens. Matter 25 422201
[13] Wolowiec C T, Yazici D, White B D, Huang K and Maple M B 2013 Phys. Rev. B 88 064503
[14] Jha R, Tiwari B and Awana V P S 2014 J. Phys. Soc. Japan 83 063707
[15] Guo C Y et al 2015 Phys. Rev. B 91 214512
[16] Fujioka M, Tanaka M, Denholme S J, Yamaki T, Takeya H, Yamaguchi Y and Takano Y 2014 Europhys. Lett. 108 47007
[17] Luo Y K, Zhai H F, Zhang P, Xu Z A, Cao G H and Thompson J D 2014 Phys. Rev. B 90 220510
[18] Fang Y, Yazici D, White B D and Maple M B 2015 Phys. Rev. B 92 094507
[19] Tomita T et al 2014 J. Phys. Soc. Japan 83 063704
[20] Mizuguchi Y, Miyake A, Akiba K, Tokunaga M, Kajitani J and Miura N 2014 Phys. Rev. B 89 174515
[21] Smith T F, Chu C W and Maple M B 1969 Cryogenics 9 53
[22] Nagao M, Demura S, Deguchi K, Miura A, Watauchi S, Takei T, Takano Y, Kumada N and Tanaka I 2013 J. Phys. Soc. Japan 82 113701
[23] Miura A, Nagao M, Takei T, Watauchi S, Mizuguchi Y, Takano Y, Tanaka I and Kumada N 2014 Cryst. Growth Des. 15 39
[24] Nagao M, Miura A, Demura S, Deguchi K, Watauchi S, Takei T, Takano Y, Kumada N and Tanaka I 2014 Solid State Commun. 178 33
[25] Jha R, Kumar A, Kumar Singh S and Awana V P S 2013 J. Appl. Phys. 113 056102
[26] Higashinaka R, Miyazaki R, Mizuguchi Y, Miura O and Aoki Y 2014 J. Phys. Soc. Japan 83 5004
[27] Biswas P K, Amato A, Baines C, Khasanov R, Luetkens H, Lei H, Petrovic C and Morenzoni E 2013 Phys. Rev. B 88 224515
[28] Gurevich A 2007 Physica C 456 160
[29] Suzuki K, Usui H and Kuroki K 2013 Phys. Proc. 45 21
[30] Yildirim T 2013 Phys. Rev. B 87 020506
[31] Kajitani J, Omachi A, Hiroi T, Miura O and Mizuguchi Y 2014 Physica C 504 33
[32] Mizuguchi Y, Miura A, Kajitani J, Hiroi T, Miura O, Tadanaga K, Kumada N, Magome E, Moriyoshi C and Kuroiwa Y 2015 Sci. Rep. 5 14968
[33] Jeon I, Yazici D, White B D, Friedman A J and Maple M B 2014 Phys. Rev. B 90 054510
[34] Deguchi K et al 2013 Europhys. Lett. 101 17004
[35] Kajitani J, Hiroi T, Omachi A, Miura O and Mizuguchi Y 2015 J. Supercond. Nov. Magn. 28 1129
[36] Kajitani J, Deguchi K, Omachi A, Hiroi T, Takano Y, Kadowaki H, Miura O and Mizuguchi Y 2014 Solid State Commun. 181 1
[37] Kajitani J, Deguchi K, Hiroi T, Omachi A, Demura S, Takano Y, Miura O and Mizuguchi Y 2014 J. Phys. Soc. Japan 83 065002
[38] Paris E, Joseph B, Iadecola A, Sugimoto T, Olivi L, Demura S, Mizuguchi Y, Takano Y, Mizokawa T and Saini N I L 2014 J. Phys.: Condens. Matter 26 435701