Superconductivity with Topological Non-trivial Surface States in NbC

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Abstract

Quantum materials with non-trivial band topology and bulk superconductivity are considered superior materials to realize topological superconductivity. In this regard, we report detailed density functional theory (DFT) calculations and Z2 invariants for the NbC superconductor, exhibiting its band structure to be topologically non-trivial. Bulk superconductivity at 8.9 K is confirmed through DC magnetization measurements under field cooled (FC) and zero field cooled (ZFC) protocols. This superconductivity is found to be of type II nature as revealed by isothermal M-H measurements, and thus the Ginzburg–Landau parameter is calculated. A large intermediate state is evident from the phase diagram, showing NbC to be a strong type-II superconductor. Compared with earlier reports on superconducting NbC, a non-monotonic relationship of critical temperature with lattice parameters is seen. In conclusion, NbC is a type-II around 10 K superconductor with topological non-trivial surface states.

Keywords Topological superconductivity · Dirac semimetal · Density functional theory · Superconductivity · X-ray diffraction

1 Introduction

Condensed matter scientists are always keen to discover new materials and explore their novel physical properties [1, 2]. In this regard, materials with topologically non-trivial band structures have proved to be a rich exploring field for condensed matter physicists [1, 2]. These materials show a variety of properties, such as high magneto-resistance (MR) [3, 4], high surface conductivity [5], and Terahertz (THz) generation [6, 7]. Coming to the superconducting properties, these topological materials with a non-trivial band structure form a new class of materials, named topological superconductors (TSc) [2]. TSc have a superconducting gap in the bulk and topologically non-trivial states at the surface [8–10]. This unique feature of TSc makes them the most promising candidates to host the Majorana fermions [9]. Majorana fermions are the anti-particle of themselves, which follow the Dirac relativistic equation. The existence of Majorana fermions qualifies the TSc to be the essential quantum material for fault-tolerant quantum computing [11]. It is thus essential to search for materials that show topological superconductivity in bulk form.

Topological superconductivity in bulk material can be induced either by doping suitable elements in topological material [12–16] or by applying pressure [17, 18]. Apart from these methods, some Dirac type-II semimetals show superconductivity in their intrinsic form [19, 20]. Dirac semimetals (DSM) have a Dirac point at which bands are four-fold degenerate. DSM is categorized as type-I DSM and type-II DSM based on the nature of their Dirac point. The Dirac point in type-I DSM is point-like, while in the case of Type-II DSM, it is tilted at some angle [21]. Recently, some transition metal carbides (TMCs), viz., TaC [22, 23] and NbC [23, 24] are found to have DSM-like band structures along with bulk superconductivity. The superconductivity of these materials was observed a long time ago and is summarized in a combined report on the superconductivity of TMCs [25], but their topologically non-trivial character was not explored. Other TMCs, such as VC [26] and CrC [26], are also predicted to have non-trivial band topology along with bulk superconductivity, but experimental confirmation...
of their non-trivial topological behavior is yet to be realized. Among these TMCs, the NbC and TaC show superconductivity in the range of 8 to 11 K [22–24, 27–29]. Most of the superconductivity reports of these materials are based on polycrystalline samples, as it is challenging to grow their single crystals. The superconducting critical temperature \( T_c \) of polycrystalline NbC varies with the lattice parameter [28] due to variation in the stoichiometry of carbon [30, 31]. The non-trivial band topology in NbC was recently predicted theoretically through DFT calculations [23, 24]. In a recent report on single crystalline NbC being synthesized using Co as flux [24], the angle-resolved photoelectron spectroscopy (ARPES) measurements showed a clear Fermi surface nesting origin of non-trivial band topology in NbC.

In this work, we synthesize a polycrystalline sample of NbC in a single step at a relatively higher temperature (1350 °C) from our previous report on NbC [28]. The polycrystalline sample has a single phase and shows type-II superconductivity at below 9 K. Band structure calculations are also performed by using DFT at the same path as suggested in ref. [24]. It is found that NbC possesses the non-trivial band topology along with 8.9 K superconductivity. However, it has been proved in ref. [28] that \( T_c \) and lattice parameters strongly depend on synthesis temperature and increase as the synthesis temperature increases. But, in this report, it does not follow the same trend. Surprisingly, lattice parameters are increased from optimum value as the synthesis temperature increases from that previously reported. However, the \( T_c \) is decreased and showing a non-monotonic relationship with lattice parameters and synthesis temperature. This particular ambiguity is highlighted in this article, along with an in-depth analysis of band structure and projected DOS (density of states) in the 12 × 12 × 12 matrix including calculation of Z2 invariants. Our results, along with [23, 24], unambiguously prove that NbC is a 10 K superconductor [28, 30, 31] with a non-trivial band topology.

2 Experimental

A polycrystalline sample of NbC is prepared in a single step by following the solid-state reaction route as suggested in ref. [28], but at a slightly elevated temperature. High-purity (>4 N) powders of Nb and amorphous carbon were taken into the stoichiometric ratio. These powders were mixed and ground thoroughly by using an agate mortar pestle in an argon-filled glove box. This homogenous mixture was then palletized and vacuum encapsulated at a pressure of 5 × 10^{-5} mbar. This vacuum encapsulated sample was then placed into an automated PID controlled Muffle furnace and heated to 1350 °C at a rate of 120 °C/h. This sample is kept at this elevated temperature for a period of 48 h. After this, the sample is allowed to cool normally to room temperature.

The PXRD pattern of synthesized polycrystalline NbC powder was recorded using th Rigaku MiniFlex II tabletop X-ray diffractometer equipped with CuKα radiation of 1.5418-Å wavelength. Rietveld refinement of the PXRD pattern was performed using FullProof software, and the Unit cell of NbC was drawn using VESTA software. Band structure calculations were performed under DFT protocols using Quantum ESPRESSO (QE) software in QuantumVITAS [33, 34], whose optimized path is considered from the ARPES study in ref. [24]. Moreover, in order to calculate the Z2 invariants of the NbC, WANNIER90 is used in which Wannierization of Bloch wave function is implemented [35]. In this regard, the MLWFs (maximally localized Wannier function) are considered, which is used to verify the band structure that is generated through the first-principle method. Based on the MLWFs, we obtain an effective tight-binding (TB) model for the system NbC. This TB model is further processed and implemented in WannierTools [36] on a 4 × 4 × 4 K-mesh, which samples the whole Brillouin zone. Wannier charge centers are further calculated of which evolution in Brillouin zone planes indicated the states of the Z2 invariant. Magnetization measurements were carried out on the Quantum Design Physical Property Measurement System (PPMS).

3 Results and Discussion

Figure 1 shows the Rietveld refined PXRD pattern of synthesized polycrystalline powder of NbC, confirming the single phase of the material, as no impurity peak is observed in the PXRD. The synthesized NbC sample has a cubic structure.
with F m – 3 m space group symmetry. The Rietveld refined PXRD pattern shows that all observed peaks are well fitted under F m – 3 m space group symmetry. The goodness-of-fit \( x^2 \) is found to be 2.85, which is in an acceptable range. The constituent elements, Nb and C, occupy (0, 0, 0) and (0, 0, 0.5) atomic positions in the lattice. Lattice parameters obtained from Rietveld refinement are \( a = b = c = 4.4739(8) \) Å and \( \alpha = \beta = \gamma = 90 \). The obtained lattice parameters are slightly higher than as reported in our previous report \[28\]. It was observed earlier \[28\] that lattice parameters depend on the temperature at which the sample is prepared, and the same increases with the processing temperature. Here, the obtained results are consistent with this fact as the sample is prepared at a higher temperature than that reported in ref. \[28\]. The variation in lattice parameters in NbC results is due to the change in the stoichiometry of carbon \[30, 31\]. It has been suggested in previous reports that the lattice parameter of NbC increases as the carbon content increases. For exact stoichiometric NbC, lattice parameters are observed to be 4.4704 Å, and all previous reports are based on carbon-deficient NbC, for which the lattice parameter lies between 4.4281 and 4.4704 Å (for NbC) \[30\]. Here, the lattice parameter is greater than that observed for exact stoichiometric NbC. It suggests that the synthesized NbC sample has a C/Nb ratio greater than 1. The XRD pattern cannot determine the exact carbon content in the synthesized NbC sample as carbon is a lighter element. All empirical formulas that are reported to calculate the stoichiometry of carbon in NbC work only from 0.7 to 0.96 molar ratio of C with respect to Nb. It is challenging to predict how much carbon content is there in the sample, but the enhancement of lattice parameters from NbC suggests that carbon has a higher molar ratio with respect to Nb in the presently synthesized NbC polycrystalline sample.

Figure 2 shows FC and ZFC measurements of presently synthesized NbC polycrystalline sample in a magnetic field of 8 Oe. These results show a clear diamagnetic transition in both FC and ZFC measurements at 8.9 K. This diamagnetic transition signifies the presence of bulk superconductivity in synthesized NbC. The superconducting volume fraction is around 31% in ZFC measurements which is quite good for polycrystalline sample. It signifies that the sample is crystallized in a single phase. This ZFC signal starts to saturate near 6 K, showing the transition width to be around 3 K. The observed superconducting transition is lesser than the optimum value, i.e., 11.5 K. The reason behind this lower \( T_c \) is the stoichiometry of carbon which eventually changes

![Figure 2](image-url)

(a) FC and ZFC measurements of the 1350 °C synthesized NbC sample at 8 Oe; inset shows variation in \( T_c \) with lattice parameters at different processing temperatures. (b) Isothermal M-H plots of 1350 °C synthesized NbC samples at 2 K, 4 K, 6 K, 8 K, and 10 K; inset shows the same at 2 K. (c) Isothermal M-H plots of the 1350 °C synthesized polycrystalline NbC sample at 2 K, 4 K, and 6 K in the low magnetic field region; inset shows the exercise done to calculate the lower critical field \( H_{c1} \). (d) Phase diagram showing the superconducting, intermediate and normal state of the synthesized NbC polycrystalline sample.
the lattice parameter. From the previous reports, it is well established that $T_c$ in NbC strongly depends on carbon stoichiometry and lattice parameters [28, 30]. Our previous report also showed the same where it is concluded that the lattice parameters change with the synthesis temperature, and accordingly, $T_c$ also changes [28]. Maximum $T_c$ was achieved in the sample prepared at 1250 °C. However, the sample is synthesized here at an even higher temperature of 1350 °C. The growth temperature increases the lattice parameter from the perfectly stoichiometric NbC. It signifies that carbon content is higher than that for Nb. So, it can be said that both carbon-deficient and carbon-rich NbC phases have lower $T_c$ than the optimum value, which is indirectly influenced by the lattice parameters. In the inset of Fig. 2a, the dependence of superconducting transitions of NbC samples on their lattice parameters is highlighted. The critical temperature for NbC samples synthesized at a lower temperature is taken from ref. [28]. It shows that the optimum $T_c$ is obtained at 1250 °C with the exact stoichiometric composition of NbC, and if the processing temperature is further increased, it results in a decrement in $T_c$ due to increment in carbon content as seen for present NbC, being synthesized at 1350 °C. It shows that $T_c$ has a non-monotonic relationship with the lattice parameter in NbC. Lattice parameters and $T_c$ of NbC samples synthesized at 1350 °C and at lower temperatures in ref. [28] are summarized in Table 1.

Table 1: Variation in $T_c$ and possible phase formation due to change in lattice constant by changing the synthesis temperature

| Synthesis temperature | Lattice parameter (Å) | $T_c$ (K) |
|-----------------------|-----------------------|-----------|
| 1150 °C               | 4.468 (2)             | 9.09      |
| 1200 °C               | 4.469 (3)             | 11.0      |
| 1250 °C               | 4.470 (2)             | 11.5      |
| 1350 °C               | 4.474 (4)             | 8.9       |

Figure 2b shows isothermal M-H plots of synthesized NbC samples at 2 K, 4 K, 6 K, 8 K, and 10 K. These plots start with linear variation in magnetization with respect to the applied field, showing the Meissner state. Then after a critical field, it deviates from this linearity and enters into a mixed state. For this, first, the low magnetic field M-H data is linearly fitted. The slope of this linear fit is used to determine $M_0$, and then this $M_0$ is subtracted from each isotherm. This difference ($M - M_0$) is represented as $\Delta M$, and this change is plotted against the applied field. A baseline is drawn for $\Delta M = 0$, and $H_{c1}$ is the point at which $\Delta M$ deviates from this zero baseline. This exercise is shown in the inset of Fig. 2c. The values of $H_{c1}$ are found to be 81 Oe, 69 Oe, and 60 Oe at 2 K, 4 K, and 6 K, respectively. There is a big difference between the values of $H_{c1}$ and $H_{c2}$ at 2 K. It signifies that mixed states persist for approx. 22 kOe and the synthesized NbC sample is a strong type-II superconductor.

The values of $H_{c1}$ and $H_{c2}$ at different temperatures, viz., 2 K, 4 K, 6 K, and 8 K, are used to plot the phase diagram of the synthesized NbC polycrystalline sample, as shown in Fig. 2d. This phase diagram is clearly showing the superconducting state, intermediate state, and normal state of NbC. This phase diagram is plotted by fitting the values of $H_{c1}$ and $H_{c2}$ with the following equations:

$$H_{c1}(T) = H_{c1}(0)\left|1 - T^2/T_c^2\right| \& H_{c2}(T) = H_{c2}(0)\left|1 - T^2/T_c^2\right|$$

The values of $H_{c1}$ and $H_{c2}$ are well fitted with their model equations which are the standard behavior for superconductors. The phase diagram is plotted by taking the $XYY$-axis as the difference between the values of $H_{c1}$ and $H_{c2}$ is quite large. The left- and right-hand side axis are showing the values of $H_{c1}$ and $H_{c2}$, respectively. A relatively large intermediate state can be clearly seen in the phase diagram of NbC, which confirms it to be a strong type-II superconductor.

The values of $H_{c1}$ and $H_{c2}$ are used to determine the mean critical field ($H_c$) at 2 K by using $H_c = (H_{c1} * H_{c2})^{1/2}$. The values of $H_{c1}$ and $H_{c2}$ at 2 K are 81 Oe and 23 kOe, respectively. Using these values, $H_c$ is found to be 1.36 kOe. It means that the critical field will be used to determine the value of the upper critical field at absolute zero $H_{c2}(0)$. $H_{c2}(0)$ is calculated by using the Ginzburg Landau equation (G-L equation), which is given by
Here, in the above equation, \( t = T/T_c \), known as reduced temperature. \( T \) is the temperature at which the upper critical field is taken, i.e., 2 K, and \( T_c \) is the critical temperature, taken to be 8.9 K as observed in FC and ZFC measurements, giving a reduced temperature of 0.225. So, by using these values, \( H_{c2}(0) \) is found to be 25.42 kOe. The nature of superconductivity, whether type I or type II, can be determined by calculating the G-L kappa (\( \kappa \)) parameter. The \( \kappa \) parameter can be calculated by following the relation \( H_{c2}(0) = \kappa^* (2)^{1/2} \cdot H_c \). The value of the \( \kappa \) parameter is found to be 13.21. This value is much above the threshold value for type-I superconductivity, suggesting that the synthesized NbC sample is a strong type-II superconductor, supporting the wide opened M-H plots in Fig. 2b as well.

Other critical parameters of superconductivity, such as coherence length \( \xi(0) \), can be calculated using the formula

\[
H_{c2}(0) = \frac{\Phi_0}{2\pi \xi(0)^2}
\]

where \( \Phi_0 \), a constant term, is known as flux quanta. The value of this constant term is \( 2.0678 \times 10^{-15} \) Wb. From the above equation, the value of \( \xi(0) \) is found to be 1.29 Å. Penetration depth \( \lambda(0) \) can be calculated by using the relation \( \kappa = \lambda(0)/\xi(0) \), and it is found to be 17.04 Å.

Further, to determine the projected DOS and possible topological non-triviality of the band structure of the synthesized NbC polycrystalline sample, the DFT calculations are performed by using software QuantumVITAS which depends on Quantum ESPRESSO. The CIF (crystallographic information framework/file) produced through Rietveld refinement is used to calculate the band structure. DFT calculations are performed by considering both with and without spin–orbit coupling using the crystal parameters from the grown NbC. The \( k \)-path which is taken to calculate band structure is as follows:

\[
W \rightarrow L \rightarrow K \rightarrow \Gamma \rightarrow X
\]

This particular \( k \)-path is considered from ref. [24]. The calculation is realized in Quantum ESPRESSO with Perdew-Burke-Ernzerhof (PBE) exchange–correlation functional [33, 34]. The calculated band structure and the projected DOS with and without SOC are shown in Fig. 3a, b respectively. The Fermi level is marked as zero energy. It is clear from the projected DOS plots that bands near the Fermi level are generated due to the hybridization of 2p orbitals of Carbon and 4d orbitals of Nb. The d orbitals of Nb dominate in these bands. Finite DOS present near the Fermi level reveals the metallic nature of the synthesized NbC polycrystalline sample too. The splitting of p and d orbitals bands is observed with the inclusion of SOC, as shown in Fig. 3b. This particular splitting confirms the presence of effective

![Fig 3](image-url)
SOC in the NbC. The calculated band structure is shown in the right-hand side image of Fig. 3a, b.

Most of the bands are shown to cross the Fermi level, which confirms the metallic nature of the synthesized polycrystalline NbC sample. A Dirac cone–like structure can be visualized at the Γ point in the Brillouin zone. The enlarged view of bands near this point is shown in Fig. 3c. A similar Dirac cone–like band structure is observed near this Γ, which is encircled in Fig. 3a. This Dirac cone–like structure is found to be tilted at some angle, and bands observed at the Γ point are six-fold degenerate. The band structure with inclusion of SOC is shown in Fig. 3b. It has been observed that after the inclusion of SOC, the six-fold degenerate bands observed at Γ point in without SOC plots become four-fold degenerate. It can be seen in Fig. 3c, which contains an enlarged view of the band structure too around Γ point with and without SOC. It suggests that the degeneracy of bands is lifted when SOC is included. The Dirac cone–like structure encircled in Fig. 3a also split into several bands when SOC is included. It can be seen in the inset of Fig. 3b, which shows that all bands become gapped when SOC is included. These results are in good agreement with the previous theoretical calculations made on this compound [23, 24]. It suggests that SOC is effective in NbC samples. All the bands are found to be split at and around the Γ point, when SOC is included, and are observed near the Fermi level, suggesting that the synthesized NbC sample has a topologically non-trivial band structure. The tilted Dirac cone–like structure observed near the Γ point suggests that the NbC sample is a Dirac type-II semimetal. The DFT results are in direct accordance with the ARPES measurements given in a recent report on this compound [24].

The first-principle calculation of the band structure shows that the NbC system respects the time-reversal symmetry (TRS) since each band splits into two when SOC is included, as shown in Fig. 3a, b. Moreover, the Chern number is not a good quantity to characterize the topology as it turns out to be zero for TRS systems, while the Z2 invariants are found

**Fig. 4** The evolution of Wannier charge centers in the six planes of in Brillouin zone. The Z2 invariants are (a) k₁ = 0.0, k₂–k₃ plane: Z₂ = 1. (b) k₁ = 0.5, k₂–k₃ plane: Z₂ = 1. (c) k₂ = 0.0, k₁–k₃ plane: Z₂ = 0. (d) k₂ = 0.5, k₁–k₃ plane: Z₂ = 1. (e) k₃ = 0.0, k₁–k₂ plane: Z₂ = 0. (f) k₃ = 0.5, k₁–k₂ plane: Z₂ = 1.
to be more appropriate for TRS systems [37]. We follow
the Soulyanov-Vanderbilt [37] method of Wannier charge
centers (WCC) that are calculated from MLWFs. These
WCC are basically evolved in 6 Brillouin zone planes,
which are resembled through $K_1$, $K_2$, $K_3 = 0$ and $K_1$, $K_2$, $K_3 = 0.5$. Based on these planes, the presence of Wilson’s
loop is determined in order to figure out the topology in the
system. It can be understood through the literature [37] that
an even number of the crossing of WCC implies a topologi-
cally trivial state ($z_2 = 0$), whereas an odd number of cross-
ings indicate the presence of a topologically non-trivial state ($z_2 = 1$). The Z2 topological invariants for these six planes
in NbC (Fig. 4) are found to be.

(i) $k_1 = 0.0$, $k_2$–$k_3$ plane: $Z_2 = 1$
(ii) $k_1 = 0.5$, $k_2$–$k_3$ plane: $Z_2 = 1$
(iii) $k_2 = 0.0$, $k_1$–$k_3$ plane: $Z_2 = 0$
(iv) $k_2 = 0.5$, $k_1$–$k_3$ plane: $Z_2 = 1$
(v) $k_3 = 0.0$, $k_1$–$k_2$ plane: $Z_2 = 0$
(vi) $k_3 = 0.5$, $k_1$–$k_2$ plane: $Z_2 = 1$

The topological Z2 index is represented as $(\theta_0; \theta_1 \theta_2 \theta_3)$. The last three Z2 numbers are the weak index, whereas
the first one is the strong index. The strong index has some
redundancy [37] as we can see that for the first pair of the
plane (i) and (ii), the $\theta_0 = 0$ indicates topologically trivial,
state but for the other two pairs of planes, it is $\theta_0 = 1$, which
indicates a topologically non-trivial state. Here, the weak
index has no redundancy, and it is $\theta_0 = 111$. Thus, the weak
index indicates that NbC has non-trivial topological states,
and it can be surely sorted that at least, a weak topology is
present in NbC. Moreover, it is essential to highlight here
that the Wannier charge calculation does not converge due to
the presence of nodal points in the NbC system when imple-
mented in WannierTools as confirmed through the output file
of the tool. The presence of nodal points also confirms that
the NbC has a non-trivial topology. Thus, the DFT calcula-
tions, along with the Z2 invariants and nodal points, the non-
trivial band topology in NbC, and tunable superconductivity
with the elevated temperature have been confirmed.

4 Conclusion

Summarily, we have synthesized a polycrystalline sample
of NbC in a single step at a higher temperature than previ-
ously reported. A non-monotonic relationship is observed in
$T_c$ with lattice parameters and synthesis temperature. FC
and ZFC plots confirm bulk superconductivity at 8.9 K. The
nature of superconductivity is found to be of strong type II
through M-H plots and phase diagrams. Simultaneously, the
DFT calculations show that bands at high symmetry points
do split when SOC is included which is also confirmed by
calculating the Z2 invariant for the same. It suggests that
NbC has a topologically non-trivial band structure. This
result, along with observed superconductivity at around
8.9 K, suggests that NbC is a potential candidate to explore
topological superconductivity.

Acknowledgements The authors would like to thank Director NPL for
his keen interest and encouragement. The authors thank Mr. Krishna
Kandpal for vacuum encapsulation of the sample. M.M. Sharma and
N.K. Karn would like to thank CSIR for the research fellowship. N.K.
Karn, M.M. Sharma, and Prince Sharma are also thankful to AcSIR
for the Ph.D. registration.

Funding Prince Sharma would like to thank UGC for his fellowship
support.

References

1. Hasan, M.Z., Kane, C.L.: Rev. Mod. Phys. 82, 3045 (2010)
2. Qi, X.L., Zhang, S.C.: Rev. Mod. Phys. 83, 1057 (2011)
3. Sultana, R., Neha, P., Goyal, R., Patnaik, S., Awana, V.P.S.: J.
Magnet Magn. Mater. 428, 213 (2017)
4. Sharma, D., Kumar, Y., Kumar, P., Nagpal, V., Patnaik, S.,
Awana, V.P.S.: Solid State Commun. 323, 114097 (2021)
5. Moore, J.E.: Nature 464, 194 (2010)
6. Sharma, P., Kumar, M., Awana, V.P.S.: J. Mater. Sci. Mater.
Electron. 31, 7959 (2020)
7. Sharma, P., Sharma, M.M., Kumar, M., Awana, V.P.S.: Solid
State Commun. 319, 114005 (2020)
8. Sato, M., Ando, Y.: Reports Prog. Phys. 80, 076501 (2017)
9. Leijnse M., Flensberg, K.: Semicond. Sci. Technol. 27, 124003 (2012)
10. BEENAKKER C.W.J.: Annu. Rev. Condens. Matter Phys. 4, 113 (2013)
11. Das Sarma, S., Freedman, M., Nayak, C.: NPj Quantum Inf. 4,
15001 (2015)
12. Hor, Y.S., Williams, A.J., Checkelsky, J.G., Roushan, P., Seo, J.,
Xu, Q., Zandbergen, H.W., Yazdani, A., Ong, N.P., Cava, R.J.: Phys.
Rev. Lett. 104, 057001 (2010)
13. Shruti, V., Maurya, K., Neha, P., Srivastava, P., Patnaik, S.: Phys.
Rev. B - Condens. Matter Mater. Phys. 92, 020506 (2015)
14. Sharma, M.M., Rani, P., Sang, L., Wang, X.L., Awana, V.P.S.: J.
Supercond. Nov. Magn. 33, 565 (2020)
15. Sharma, M.M., Sang, L., Rani, P., Wang, X.L., Awana, V.P.S.: J.
Supercond. Nov. Magn. 33, 1243 (2020)
16. Chi, H., Liu, W., Sun, K., Su, X., Wang, G., Lošt’Ák, P., Kucek,
V., Drašar, C., Uher, C.: Phys. Rev. B - Condens. Matter Mater.
Phys. 88, (2013)
17. Zhang, J.L., Zhang, S.J., Weng, H.M., Zhang, W., Yang, L.X.,
Liu, Q.Q., Feng, S.M., Wang, X.C., Yu, R.C., Cao, L.Z., Wang,
L., Yang, W.G., Liu, H.Z., Zhao, W.Y., Zhang, S.C., Dai, X., Fang,
Z., Jin, C.Q., Yang, W.G., Yu, X.H., Zhu, J.L., Zhao, Y.S.: J.
Phys. Condens. Matter 25, 362204 (2013)
18. Qi, Y., Naumov, P.G., Ali, M.N., Rajamathi, C.R., Schnelle, W.,
Barkalov, O., Hanfland, M., Wu, S.C., Shekhar, C., Sun, Y., Süß,
V., Schmidt, M., Schwarz, U., Pippel, E., Werner, P., Hillebrand,
R., Förster, T., Kampert, E., Parkin, S., Cava, R.J., Felser, C., Yan,
B., Medvedev, S.A.: Nat. Commun. 7, 11038 (2016)
