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Structural, surface morphology and magneto-transport properties of self flux grown Eu doped Bi$_2$Se$_3$ single crystal

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Abstract

Here, we report the effect of europium (Eu) doping in Bi$_2$Se$_3$ topological insulator (TI) by using different characterization techniques viz. X-ray diffraction (XRD), scanning electron microscopy (SEM) coupled with energy dispersive x-ray analysis (EDXA) and magneto-transport measurements. Good quality Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) single crystal is grown by the self flux method through the solid state reaction route. Single crystal XRD pattern displayed the high crystalline quality of the Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample along (00l) alignment whereas; the powder XRD confirmed the rhombohedral crystal structure without any impurity phases. SEM images exhibited a layered slab like structure stacked one over the other whereas; EDXA measurements confirmed the chemical composition of Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample. Further, the EDXA mapping showed the homogeneous distribution of Bi, Se and Eu elements. Temperature dependent electrical resistivity curves revealed a metallic behaviour both in the presence and absence of applied magnetic field. Magneto-transport measurements showed a decrease in the magneto-resistance (MR) value of the Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample (~32% at 5 K) in comparison to the pure Bi$_2$Se$_3$ sample (~80% at 5 K). For, Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample, a complex crossover between WL and WAL phenomenon was observed at lower applied magnetic fields, whereas the same was absent in case of the pristine one. Further, HLN (Hi kami Larkin Nagaoka) fitted magneto-conductivity (MC) analysis revealed a competing weak anti localization (WAL) and weak localization (WL) behaviour. Summarily, in the present work we study the structural, surface morphology and magneto-transport properties of as grown Eu$_{0.1}$Bi$_{1.9}$Se$_3$ single crystals.

Introduction

The discovery of topological insulators (TIs), a new phase of quantum matter have surprised and fascinated physicists for about a decade [1–5]. In fact, it’s extraordinary electronic properties along with a wide range of potential applications including the development of futuristic quantum computers is now among the hottest topics in physics research. In particular, TIs are characterized by a gapped bulk state and gapless surface/edge states which are further protected by time reversal symmetry (TRS) and have spin momentum locking property i.e., the conducting surface states of TIs are robust against time reversal invariant perturbations [1–11]. The existence of a topologically protected gapless surface state along with a single Dirac cone at the $\Gamma$ point of the Brillouin zone is the most prominent property of a TI. Recent theoretical as well as experimental studies suggest that the breaking of TRS in TIs by magnetic doping opens up a gap in the spectrum of the surface states and hence generate massive surface carriers [12–14]. As reported, the bulk of a magnetically doped TI exhibits a long-range magnetic order both in the metallic and insulating phases through Van Vleck mechanism. Conversely, on the surface, such a long-range magnetic order can also be formed independent of the bulk magnetic ordering via the Ruderman–Kittel–Kasuya–Yosida (RKKY) exchange mechanism [12–16, 17, 18]. Consequently, doping three dimensional (3D) TIs (Bi$_2$Te$_3$, Bi$_2$Se$_3$, Sb$_2$Te$_3$) with transition metal elements (Cr, Fe, Mn, V, etc) leads to...
the breaking of TRS and can bring about a long range ferromagnetic order either through Van Vleck/RKKY mechanism. Moreover, it has been shown that magnetic doping results into the realization of a variety of exotic topological properties such as the topological magneto-electric effect, quantum anomalous Hall (QAH) effect, imaging magnetic monopoles, and the Faraday and Kerr effects [12–25]. Accordingly, the magnetically doped TIs have received considerable attention and acts as one of the most exciting research area due to their striking topological phenomena (as mentioned above) arising from the breaking of TRS. Furthermore, an intrinsic TI shows the signatures of weak anti-localization (WAL) effect which is observed in the absence of any magnetic scattering. On the other hand, the electronic transport response of a magnetically doped TI exhibits a weak localization (WL) effect due to the surface gap opening induced by TRS breaking. There already exist some published reports on magnetically (Mn, Ni, Fe, Cr, V and Co) doped TIs, which focus on describing the effects of magnetic impurities, or discussing typical ferromagnetism on Dirac like conducting surface states in various TIs viz. Bi2Se3, Bi2Te3 and Sb2Te3 [18, 26–44]. Till date, a very few reports have discussed on the magneto transport behaviour of Eu doped Bi2Se3 thin films [45, 46]. To the best of our knowledge, there has been no reports on the detailed physical property characterization of bulk Eu doped Bi2Se3 single crystals. Also, crystal growth itself is a very challenging task, as it depends upon the physical properties viz., melting point, volatile nature, solubility in water etc, of the materials under consideration. Furthermore, obtaining a high quality, reproducible single crystal along with interesting properties is the need of the hour. Keeping in view the importance of magnetically doped TIs, we report the structural, surface morphology and magneto-transport properties of Eu doped Bi2Se3 (Eu0.1Bi1.9Se3) single crystal grown by the facile self flux method. As mentioned above, a magnetic dopant should destroy the topological surface robustness owing to the breaking of TRS, so we compare the results obtained for Eu doped Bi2Se3 (Eu0.1Bi1.9Se3) single crystal with the pure Bi2Se3 single crystal results.

**Experimental details**

Single crystals of Eu0.1Bi1.9Se3 were grown using the standard flux free (self flux) method via the solid state reaction route. High purity (99.99%, Alfa Aesar) bismuth (Bi), selenium (Se) and europium (Eu) were taken as the starting materials. Stoichiometric mixture (~1 gram) of the starting materials were taken and sealed in an evacuated quartz tube (10−3 Torr) as mentioned in our previously reported literature [44, 47]. Briefly, the sealed quartz tube containing the rectangular pellet was kept inside an automated tube furnace and heated to 950 °C for 7.5 h (120 °C h−1). The ampoule was kept at the same temperature (950 °C) for 24 h and then slowly cooled (2 °C h−1) to 650 °C. Further, a hold time of 48 h was maintained at 650 °C, followed by switching off the furnace to cool down naturally to room temperature. The detailed heat treatment diagram is displayed in figure 1. The as grown Eu0.1Bi1.9Se3 sample (~1 cm) was taken out by breaking the quartz tube and mechanically cleaved for further characterizations.

The phase identification and crystalline nature of as grown Eu0.1Bi1.9Se3 sample was carried out by employing Rigaku Miniflex II, Desktop x-ray Diffractometer (XRD) with Cu-Kα radiation (λ = 1.5418 Å). Scanning electron microscopy (SEM) coupled with energy dispersive x-ray analysis (EDXA) measurements were
carried out using ZEISS-EVO MA-10 scanning electron microscope. The magneto-transport properties were measured using the Cryogenic System with fields up to 5 Tesla and temperature down to 2 K. The magnetoconductivity of Bi$_2$Se$_3$ and Eu$_{0.1}$Bi$_{1.9}$Se$_3$ TIs is understood on the basis of HLN (Hikami-Larkin-Nagaoka) equation.

**Results and discussion**

The most straightforward and primary characterization technique for structural determination is the XRD. In order to identify the crystallinity, phase purity, crystal structure and lattice parameters, room temperature single crystal and powder XRD pattern were obtained for as grown Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample as shown in figures 2(a), (b). Both (single crystal and powder) the XRD patterns were recorded using the Rigaku Miniflex-II, desktop XRD with Cu - K$_\alpha$ radiation ($\lambda = 1.5418$ Å). The single crystal XRD pattern was taken on the silvery surface of mechanically cleaved Eu$_{0.1}$Bi$_{1.9}$Se$_3$ crystal (~4 mm), whereas for powder XRD patterns several small crystals were thoroughly ground into powder form with the help of agate mortar and pestle.

Figure 2(a) depicts the single crystal XRD pattern obtained for Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) samples in the angular range of $2\theta_{\text{min}} = 10^\circ$ and $2\theta_{\text{max}} = 80^\circ$. The on surface XRD patterns exhibited well defined as well as
sharp diffraction peaks, indicating good crystalline nature of the as synthesized Eu_{0.1}Bi_{1.9}Se_{3} sample (figure 2(a)). Apparently, the XRD pattern clearly shows that the synthesized Eu_{0.1}Bi_{1.9}Se_{3} sample is single crystalline in nature and oriented in c-axis, similar to the pure Bi_{2}Se_{3} sample.

Figure 3. (a) SEM images taken on freshly cleaved Eu_{0.1}Bi_{1.9}Se_{3} single crystal (b)–(e) EDAX mapping of Eu_{0.1}Bi_{1.9}Se_{3} single crystal.
Figure 2(b) shows the powder XRD pattern obtained for as grown Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) sample in the angular range of 2θ$_{\text{min}} = 10^\circ$ and 2θ$_{\text{max}} = 80^\circ$. Rietveld refinement of the obtained raw powder XRD (PXRD) data was performed with the help of FullProf Suite ToolBar software. The Rietveld refinement of the PXRD data confirmed that the Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) sample crystallized in rhombohedral crystal structure with R$3\bar{m}$ (D5) space group similar to the parent compound (Bi$_2$Se$_3$). The refined lattice parameters obtained are $a = b = 4.146(3)$ Å and $c = 28.670(4)$ Å. Clearly, the values of the refined lattice parameters obtained for Eu doped sample are close to that of the pristine one [45]. Furthermore, figure 2(b) shows the respective crystallographic planes (Miller indices) and confirms that the studied Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample exhibited a single phase without any impurities within the XRD limits.

To understand the surface topography and chemical stoichiometry/elemental analysis of as synthesized Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample, we collected the SEM and EDXA data, respectively as shown in figures 3(a)–(e). The SEM images of as grown Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample were taken on freshly cleaved silvery single crystal surfaces. Figure 3(a) clearly shows that the studied Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample exhibits a slab like layered structure stacked one over the other, similar to the pristine (Bi$_2$Se$_3$) sample. The EDXA data as displayed in figure 3(b) confirmed that the as grown Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample is pure (uncontaminated from impurities like carbon/oxygen) and composed of atomic constituents Eu, Bi and Se respectively. The quantitative weight% values of the atomic constituents (Eu, Bi and Se) were found to be near to stoichiometric, i.e., close to Eu$_{0.1}$Bi$_{1.9}$Se$_3$ (inset of figure 3(b)) with a small loss of selenium which may have occurred during the preparation of the sample. As mentioned in the introduction, that crystal growth is itself a very challenging task, so a perfect crystal cannot be achieved, i.e., some elemental loss do occur during synthesis process. Here, we can say that Eu is substituted at Bi site and not in the elemental loss do occur during synthesis process. Here, we can say that Eu is substituted at Bi site and not in the

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\rho = \frac{\text{R}}{\text{D}}
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where $\rho$ is the resistivity, $\text{R}$ is the resistance and $\text{D}$ is the diameter of the sample. The measured electrical resistivity for Eu doped Bi$_2$Se$_3$ single crystals as a function of temperature from 5 K to 295 K for both pristine and Eu doped Bi$_2$Se$_3$ samples is shown in figure 4(a). The resistivity as well as conductivity behaviour of pure and Eu doped Bi$_2$Se$_3$ crystals is in agreement with our previously reported literature [44]. Furthermore, we can say that doping Bi$_2$Se$_3$ with magnetic (Eu and Co) impurities results into lesser conductivity due to the breaking of TRS. The Boltzmann conductivity analysis for heavily 3d metal doped topological insulators is proposed theoretically [13, 14]. We could not perform the Boltzmann conductivity analysis as our lightly doped Eu$_{0.1}$Bi$_{1.9}$Se$_3$ crystal is yet highly metallic. Instead the HLN analysis of the pure and Eu doped Bi$_2$Se$_3$ is provided in next sections.

Figures 4(b), (c) depicts the temperature dependence of electrical resistivity ($\rho$) for freshly cleaved Eu$_{0.1}$Bi$_{1.9}$Se$_3$ and Bi$_2$Se$_3$ single crystals measured under varying applied magnetic fields viz., 0, 1, 3 and 5 Tesla. The values of resistivity for both pure and Eu doped Bi$_2$Se$_3$ crystals under different applied magnetic fields are observed to increase with increase in temperature from 5 K to 75 K. Similar to the parent compound (Bi$_2$Se$_3$), the $\rho$(T)$H$ curves for the as grown Eu$_{0.1}$Bi$_{1.9}$Se$_3$ crystal exhibits a metallic behaviour. However, the values of resistivity for the pure crystal are much more in comparison to the Eu doped Bi$_2$Se$_3$ crystals. To further investigate the relative impact of magnetic field on resistivity for both pure and Eu doped Bi$_2$Se$_3$ crystals, we show the isothermal magneto-resistance (MR) behaviour at varying temperatures (5, 10, 20, 50 and 100 K) as discussed in next section.

In particular, the MR is important for technological applications and is defined as the change in the resistivity of the material with applied magnetic fields i.e., $\text{MR} = \{[\rho(\text{H}) - \rho(0)]/\rho(0)\} \times 100$, where $\rho$ is the applied perpendicular magnetic field, $\rho(\text{H})$ and $\rho(0)$ are the resistivity with and without applied magnetic field respectively. Figures 5(a), (b) displays the perpendicular magnetic field induced MR% for both pure (Bi$_2$Se$_3$) and Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) single crystals measured at varying temperatures (5 to 100 K) and fields up to $\pm$5 Tesla. Magneto-transport measurement schematic diagram is given in our own previous work on Co added Bi$_2$Se$_3$ TI [44].

MR% is observed to decrease with increase in temperature from 5 to 100 K, for both pure (Bi$_2$Se$_3$) and Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) single crystals [figures 5(a), (b)]. Table 1 displays the magnetic field dependent MR values at different temperatures for pure (Bi$_2$Se$_3$) and Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) single crystals. Pure Bi$_2$Se$_3$,
Figure 4. (a) Temperature dependent electrical resistivity under zero applied magnetic field for Eu0.1Bi1.9Se3 and Bi2Se3 single crystal. Inset shows the temperature dependent normalized conductivity curves for both Eu0.1Bi1.9Se3 and Bi2Se3 single crystal. Temperature dependent electrical resistivity under different applied magnetic field for (b) Eu0.1Bi1.9Se3 and (c) Bi2Se3 single crystal.
exhibits a MR of $\sim 80\%$ at the lowest temperature i.e., 5 K and only $\sim 30\%$ at 100 K (table 1). On the other hand, for Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) crystal, the MR at 5 K is 32%; whereas the same decreases to 22% at 100 K (table 1). We can say that the MR reduces by half in case of the Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample in comparison to the Bi$_2$Se$_3$, which confirms the fact that the TRS is affected by the Eu doping. Above 100 K, the MR becomes negligible for both pristine and doped samples. Further, it is clear from figures 5(a) and (b) that though in case of Bi$_2$Se$_3$, the
MR is all positive, in case of Eu$_{0.1}$Bi$_{1.9}$Se$_3$, the same is —ve at lower fields. Particularly, at lower applied magnetic fields of $H \leq \pm 0.2$ Tesla, the magneto-transport data of Eu$_{0.1}$Bi$_{1.9}$Se$_3$ exhibits crossover of WL (—ve) and WAL (+ve) behaviour with the change of temperature. This suggests a qualitatively different MR mechanism in Eu$_{0.1}$Bi$_{1.9}$Se$_3$ sample at different temperature, which is absent in case of the pure Bi$_2$Se$_3$ sample. As reported, that due to the TRS breaking gap opened at the Dirac point of the topologically surface states, magnetically doped TIs will undergo a WAL to WL crossover [49]. M. Liu et al showed that when a TI is magnetically doped it gets transformed into a topologically trivial dilute magnetic semiconductor (DMS) [27]. Also, it has been proposed that the incorporation of magnetic impurities results into the increased disorder in the films causing localization in the electronic states (WL), which is strongly related to the field induced magnetization [29]. However, in our case the Eu$_{0.1}$Bi$_{1.9}$Se$_3$ single crystal exhibits complex crossover behaviour at lower applied magnetic fields. Briefly, at 5 K WL dominates, which changes to WAL at 10 K, re enters to WL state at 20 and 50 K respectively, and finally drives back to WAL state at 100 K. Indeed, the competition between WL and WAL behaviour suggests that the fact that Eu doping into Bi$_2$Se$_3$ has affected the TRS. The possible reason behind the occurrence of such complex crossover phenomenon is still unknown. However, to know the actual underlying mechanism behind the complex crossover of the localization behaviour, we need further studies viz., the magneto - transport measurements can be performed at various Eu concentrations and temperatures.

Furthermore, we fit the MC data to the 2D WAL model, i.e., Hikami Larkin Nagaoka (HLN) which is represented as [50]:

$$\Delta \sigma (H) = \sigma (H) - \sigma (0) = -\frac{e^2}{\pi h} \left[ \ln \left( \frac{B_p}{H} \right) - \Psi \left( 1 + \frac{B_p}{H} \right) \right]$$

Where, $\Delta \sigma (H)$ represents the change of magneto-conductivity, $\alpha$ is a coefficient signifying the overall strength of the WAL, $e$ denotes the electronic charge, $h$ represents the Planck’s constant, $\Psi$ is the digamma function, $H$ is the applied perpendicular magnetic field, $B_p = \frac{h}{keff l_p}$ is the characteristic magnetic field and $l_p$ is the phase coherence length. The value of $\alpha$ is positive for WL and negative for WAL. Also, a large negative value can be caused by WAL in the bulk and two decoupled surface states, each contributing with $\alpha = -0.5$. The experimentally fitted value of $\alpha$ varies widely, due to the problems arising from differentiating the bulk and surface contributions clearly. As reported, $\alpha$ may lie between $-0.4$ and $-1.1$, for single surface state, two surface states, or intermixing between the surface and bulk states [51, 52].

We first applied the HLN formula to the MC curves of Eu doped (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) sample measured at different temperatures. The HLN fitting becomes challenging at low temperature (5 K) and lower fields (below say 1 Tesla) in particular for the studied Eu$_{0.1}$Bi$_{1.9}$Se$_3$ crystal, primarily due to the competition between WAL and WL and hence extraction of $\alpha$ value becomes difficult. Keeping this in view we tried to fit the magneto-conductivity (MC) data in available applied field range of $\pm 2$ Tesla and 10 K. This is to avoid both low temperature and low field regions to get rid of competing WL and WAL being present in case of Eu$_{0.1}$Bi$_{1.9}$Se$_3$ crystal. Figure 6 shows the MC curves for both pure (Bi$_2$Se$_3$) and Eu doped Bi$_2$Se$_3$ (Eu$_{0.1}$Bi$_{1.9}$Se$_3$) single crystals at 10 K with fields up to $\pm 2$ Tesla. Both pure and doped sample, exhibits $\alpha$ value as $-0.998$ and $-1$ respectively, signifying WAL clearly dominating
the MC data with a negligible WL component. The value of phase coherence length \(l_c\), obtained for pure and doped sample is 11.61 and 14.75 nm respectively. Interestingly in both cases (pure and Eu doped Bi\(_2\)Se\(_3\)) the \(\alpha\) and \(l_c\) values are within the range of surface states dominated conduction.

**Conclusion**

We successfully grew good quality Eu doped Bi\(_2\)Se\(_3\) (Eu\(_{0.1}\)Bi\(_{1.9}\)Se\(_3\)) single crystals which exhibited sharp reflections along 00 l alignment, indicating good crystalline quality. SEM images confirmed the surface topography and composition of as grown Eu doped Bi\(_2\)Se\(_3\) (Eu\(_{0.1}\)Bi\(_{1.9}\)Se\(_3\)) single crystals. EDXA mapping showed a homogeneous distribution revealing the close chemical stoichiometry of the synthesized (Eu\(_{0.1}\)Bi\(_{1.9}\)Se\(_3\)) sample. We observed a decrease in the MR value when the pristine Bi\(_2\)Se\(_3\) is doped with Eu viz., from \(\sim 80\%\) for pure Bi\(_2\)Se\(_3\) to \(\sim 32\%\) for Eu\(_{0.1}\)Bi\(_{1.9}\)Se\(_3\) at 5 K. Though the magneto-transport studies at lower applied magnetic field (H \(\leq 0.2\) Tesla) at 5 K revealed a complex crossover between WL and WAL, at relative higher fields of \(\pm 2\) Tesla and temperature 10 K, the WAL is seen to be dominating.

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**References**

[1] Hasan M Z and Kane C L 2010 Rev. Mod. Phys. 82 3045
[2] Kane C L and Mele E J 2005 Phys. Rev. Lett. 95 146802
[3] Bernevig B A, Hughes T L and Zhang S C 2006 Science 314 1757
[4] Moore J E 2010 Nature 464 194
[5] Ando Y and Phys. J 2013 Soc. Jpn. 82 102001
[6] Fu L, Kane C L and Mele E J 2007 Phys. Rev. Lett. 98 106803
[7] König M, Wiedmann S, Brune C, Roth A, Buhmann H, Molenkamp L W, Qi X.L and Zhang S C 2007 Science 318 766
[8] Haich D, Qian D, Wray L, Xia Y, Hor Y S, Cava R J and Hasan M Z 2008 Nature 452 970
[9] Zhang H, Liu C X, Qi X L, Dai X, Fang Z and Zhang S C 2009 Nat. Phys. 5 438
[10] Haich D et al 2009 Science 323 919
[11] Roushan P, Seo J, Parker C V, Hor Y S, Hsieh D, Qian D, Richardella A, Hasan M Z, Cava R J and Yazdani A 2009 Nature 460 1106
[12] Chen Y L et al 2010 Science 329 659
[13] Zhang J — M, Zhu W, Zhang Y, Xiao D and Yao Y 2012 Phys. Rev. Lett. 109 266405
[14] Sengupta P and Bellotti E 2015 J. Phys. Condens. Matter 27 405301
[15] Liu Q, Liu C X, Xu C, Qi X L and Zhang S C 2009 Phys. Rev. Lett. 102 156603
[16] Abanin D A and Pesin D A 2011 Phys. Rev. Lett. 106 136802
[17] Yu R, Zhang W, Zhang H-J, Zhang S-C, Dai X and Fang Z 2010 Science 329 61
[18] Bao L, Wang W, Meyer N, Liu Y, Zhang C, Wang K, Ai P and Xiu F 2013 Sci. Rep. 3 2391
[19] Qi X-L, Hughes T L and Zhang S-C 2008 Phys. Rev. B 78 195424
[20] Chang C — Z et al 2013 Science 340 167
[21] Qi X-L, Li K, Zhang J and Zhang S-C 2009 Science 323 1184
[22] Tse W — K and MacDonald A H 2010 Phys. Rev. B 82 161104
[23] Nomura K and Nagaosa N 2011 Phys. Rev. Lett. 106 166802
[24] Tse W — K and MacDonald A H 2011 Phys. Rev. B 84 205327
[25] Tse W-K and MacDonald A H 2011 Phys. Rev. Lett. 105 057401
[26] Mcintyre L J C et al 2014 EPL 107 57009
[27] Liu M et al 2012 Phys. Rev. Lett. 108 036805
[28] Cha J J, Williams J B, Kong D, Meister S, Peng H, Bestwick A J, Gallagher P, Gordon D G and Cui Y 2010 Nano Lett. 10 1076
[29] Cha J J, Claassen M, Kong D, Hong S S, Koski K J, Qi X L and Cui Y 2012 Nano Lett. 12 4355
[30] Liu N, Teng J and Li Y 2018 Nat. Commun. 9 1282
[31] Zhang L, Zhao D, Zhang Y, Yuan Y, Jiang G, Liao M, Zhang D, He K, Ma X and Xue Q 2017 Appl. Mater. 5 076106
[32] Irfan B and Chatterjee R 2015 Appl. Phys. Lett. 107 173108
[33] Min Z, Li L, Tao W Z, Sheng Y X and Yong Z 2014 Chin. Phys. B 23 076104
[34] Singh R, Shukla K K, Kumar A, Okram G S, Singh D, Ganeshan V, Lakhani A, Ghosh A K and Chatterjee S 2016 J. Phys. Condens. Matter 28 376001
[35] Zhang M, Lv L, Wei Z, Yang L, Yang X and Zhao Y 2014 Int. Jour. Mod. Phys. B 28 1450108
[36] Ashoush M A, El- Okri M M and Abd El-Fattah Z M 2017 J. Mater Sci: Mater Electron 28 3659
[37] Rosenberg G and Franz M 2012 Phys. Rev. B 85 195119
[38] Yoo T, Nasir A R, Bac S K, Lee S, Choi S, Lee S, Liu X and Furdyna J K 2017 AIP Adv. 7 055819
[39] Abd El-Fattah Z M and Ashoush M A 2018 J Mater Sci: Mater Electron 29 2593
[40] Hor Y S et al 2010 Phys. Rev. B 81 195203
[41] Niu C, Dai Y, Guo M, Wei W, Ma Y and Huang B 2011 Appl. Phys. Lett. 98 252502
[42] Zhou Z, Zabeik M, Lostak P and Uher C 2006 Jour. Appl. Phys. 99 043901
[43] Singh A, Ghosh A K and Chatterjee S 2018 J. Supercond. Nov. Magn. 31 299
[44] Sultana R, Gurjar G, Patnaik S and Awana V P S 2019 J. Supercond. Nov. Magn. 32 769
[45] Oveshnikov L N, Prudkoglyad V A, Selivanov Y G, Chizhevskii E G and Aronzon B A 2017 JETP Lett. 106 526
[46] Aronzona B A, Oveshnikov L N, Prudkoglyad V A, Selivanov Y G, Chizhevskii E G, Kugel K I, Karateev I A, Vasiliev A L and Lahderanta E 2018 Jour. of Magn. and Mag. Mat. 459 331
[47] Sultana R, Awana G, Pal B, Maheshwari P K, Mishra M, Gupta G, Gupta A, Thirupathaiah S and Awana V P S 2017 J. Supercond. Nov. Magn. 30 2031
[48] Aliev Z S et al 2019 Jour. Alloys & Comp. 789 443
[49] Lu H Z, Shi J R and Shen S Q 2011 Phys. Rev. Lett. 107 076801
[50] Hikami S, Larkin A I and Nagaoka Y 1980 Prog. Theor. Phys. 63 707
[51] Cha J, Kong D, Hong S-S, Analytis J G, Lai K and Cui Y 2012 Nano Lett. 12 1107
[52] Lu H Z and Shen S Q 2011 Phys. Rev. B 84 125138