# Roles of Surface and Bulk States in Magneto-transport Properties in Antiferromagnetically Ordered $Bi_{1.9}Dy_{0.1}Te_3$ Topological Insulator

Vinod K. Gangwar[a], Shiv Kumar[b], Mahima Singh[a], Zhang Yufeng[c], Chaoyu Chen[d], Eike F. Schwier[b], Kenya Shimada[b], Prashant Shahi[e], Yoshiya Uwatoko[c], Swapnil Patil[a], Anup K. Ghosh[f] and Sandip Chatterjee[a]

[a]*Department of Physics, Indian Institute of Technology (BHU) Varanasi 221005, India*
[b]*Hiroshima Synchrotron Radiation Center, Hiroshima University, 739-0046 Japan*
[c]*Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan*
[d]*Southern University of Science and Technology, Shenzhen, Guangdong 518-055, China*
[e]*Department of Physics, D.D.U. Gorakhpur University, Gorakhpur 273-009, India*
[f]*Department of Physics, Banaras Hindu University, Varanasi 221-005, India*

**Keywords:** topological insulator, magneto-transport, ARPES study

Topological insulators (TIs) have attracted much interest for many exciting physical phenomena like quantum anomalous Hall effect (QAHE), Majorana fermions, magnetic monopoles and with great possibilities of application in spintronics and quantum computing [1, 2]. Magnetic TIs provide a route to study the connection between topological surface states (TSS) and magnetism. In addition, finding the anomalous Hall effect (AHE) in topological states of matter is absolutely fascinating. In fact, transition metal-doped TIs have shown QAHE with long-range ferromagnetic ordering, which are suitable source materials for spintronic applications [3, 4]. Antiferromagnetic TIs have been extensively studied for their potential application in spintronics [5]. It was theoretically predicted that antiferromagnetic ordering does not always destroy TSS. It locally breaks the time-reversal symmetry (TRS) but maintains global TRS in combination with the translational symmetry. Therefore, the antiferromagnetic order can coexist with TSS [6].

We have synthesized $Bi_{1.9}Dy_{0.1}Te_3$ single crystals by a two-step melting method [7]. A stoichiometric mixture of highly pure Bi, Dy and Te was sealed in a quartz ampoule at a vacuum level of ~$10^{-6}$ torr. After that, the sealed quartz ampoule was slowly (60 $^{o}$C/h) heated up to 950 $^{o}$C and kept there for a period of 24 h. Then it was cooled at the rate of 5 $^{o}$C/h from 950 $^{o}$C to 550 $^{o}$C and hold at 550 $^{o}$C for 72 h, then slowly (60 $^{o}$C/h) cooled down to room temperature.

In order to observe the electronic structure and the effect of magnetic ordering in $Bi_{1.9}Dy_{0.1}Te_3$, we have carried out angle-resolved photoemission spectroscopy (ARPES) measurements. The high-resolution ARPES measurements have been performed with a focused ultraviolet laser beam (photon energy of 6.3 eV, the beam spot size of ~10 μm) equipped with VG Scienta R4000 electron analyzer at the Hiroshima Synchrotron Radiation Center (HiSOR), Hiroshima University, Japan [8]. Figure 1 shows the electronic structure of $Bi_{1.9}Dy_{0.1}Te_3$ taken along $(\bar{K} - \bar{\Gamma} - \bar{K})$ direction of the hexagonal surface Brillouin zone. The Dirac-cone-like TSS are clearly visible confirming topological non-triviality of the electronic structure of $Bi_{1.9}Dy_{0.1}Te_3$. The broad 'M'- shaped bulk valence band (BVB) is also observed at higher binding energies. The Fermi level ($E_F$) lies near to the bulk conduction band (BCB) and the position of Dirac Point (DP) is observed around −0.31 eV below the $E_F$, which lies inside the central wedge of the 'M'- shaped BVB. One can notice the ARPES intensity corresponding to the BCB at $E_F$ in Fig. 1(a) confirming the electron-doped nature in the bulk. Consequently, n-type nature revealed from the ARPES measurement is consistent with Hall and thermoelectric measurements. Figure 1 illustrates two-dimensional constant energy contour plots of the ARPES intensity at different energies (Fig. 1(c-k)). On approaching the DP from the $E_F$, the constant energy contour plot of the TSS is changed from a hexagram to a hexagonally warped structure, then to a circle of gradually reducing radius, and then finally it shrinks to a point, the DP, as is generally observed in

other TIs [9, 10]. Other than the TSS, the six-fold petal-like intensity pattern at energy -0.24 to -0.31 eV is also visible, which originates from the BVB. The obtained surface carrier density derived from the TSS is $\sim 1.5 \times 10^{13}$ cm$^{-2}$. In Fig. 1(b) only a single peak appears in the energy distribution curve (EDC) at the DP, which suggests the absence of gap opening at the DP [9, 10]. ARPES results support that $Bi_{1.9}Dy_{0.1}Te_3$ is a gapless magnetic topological insulator.

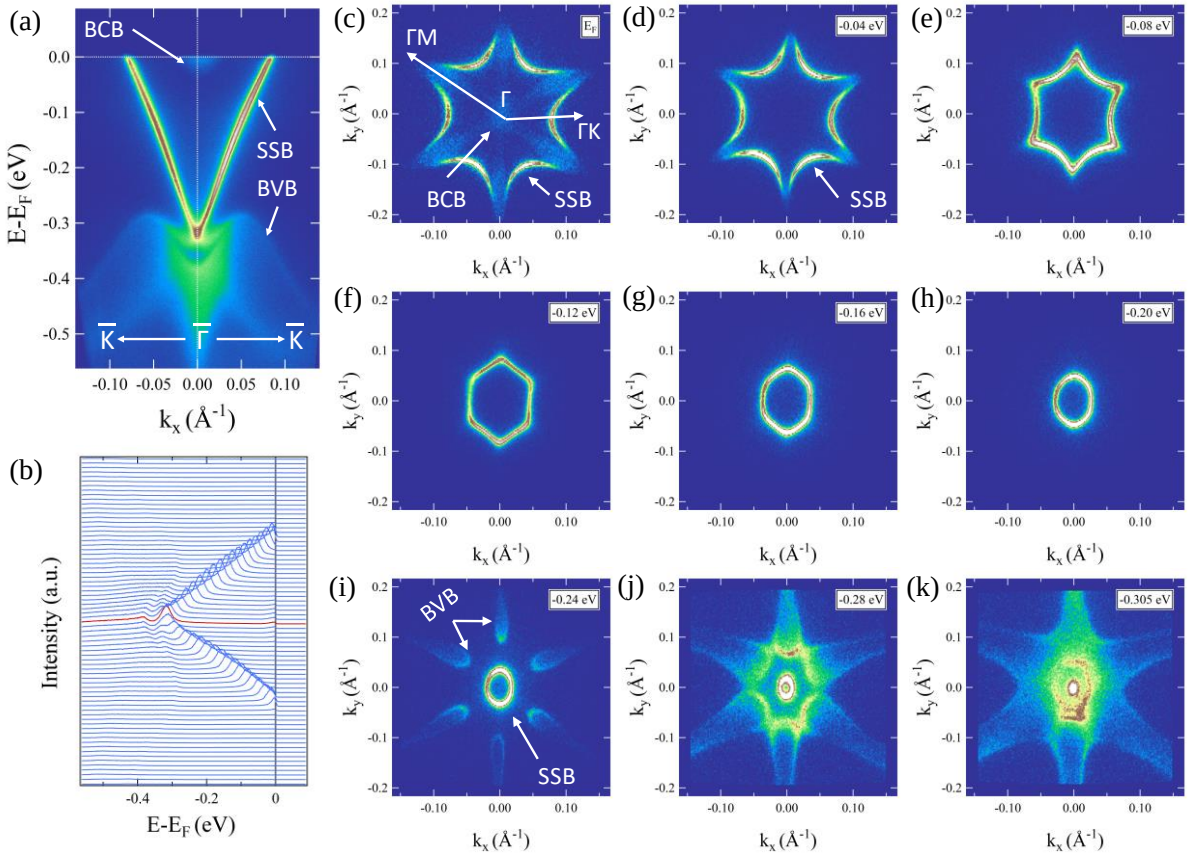


**FIGURE 1.** (a) Electronic spectra for $Bi_{1.9}Dy_{0.1}Te_3$ taken along ($\bar{K} - \bar{\Gamma} - \bar{K}$) direction (b) Energy distribution curve's (EDC's), (c) - (k) the plots of the iso-energy contours of the ARPES spectra at different energies.

## REFERENCES


1. X.-L. Qi, R. Li, J. Zang, S.-C. Zhang, *Science* **323**, 1184-1187 (2009).
2. M. Z. Hasan, C. L. Kane, *Reviews of Modern Physics* **82**, 3045-3067 (2010).
3. C.-Z. Chang *et al.*, *Nature Materials* **14**, 473-477 (2015).
4. J. S. Dyck, P. Hájek, P. Lošt'Ák, C. Uher, *Physical Review B* **65**, (2002).
5. T. Jungwirth, X. Marti, P. Wadley, J. Wunderlich, *Nature Nanotechnology* **11**, 231-241 (2016).
6. R. S. K. Mong, A. M. Essin, J. E. Moore, *Physical Review B* **81**, (2010).
7. A. Singh *et al.*, *Materials Research Bulletin* **98**, 1-7 (2018).
8. H. Iwasawa *et al.*, *Ultramicroscopy* **182**, 85-91 (2017).
9. K. Kuroda *et al.*, *Physical Review Letters* **105**, (2010).
10. Y. L. Chen *et al.*, *Science* **329**, 659-662 (2010).