Electronic and Magnetic Properties of Some Topological Materials

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By

Debarati Pal

DEPARTMENT OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI – 221005

Roll No. 17171003

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CHAPTER 8

Summary and future perspectives

8.1 Summary

This thesis is devoted to experimental studies of the structural, magnetic and electronic properties of doped Topological Insulator and as well as Weyl semimetals. The structural studies evinced unique structural transitions under the application of pressure which is very clean route to tune the lattice as well as electronic states. The simultaneous effect of physical and chemical pressure introduces complex band structure in these materials under study. The magnetic study unveils complicated spin dynamics with doping, such as- spin glass, cluster glass like metastable states at low temperature. Topological frustrated magnets, which can host both magnetic frustrations and Dirac quasiparticles, are highly demanding in recent quantum condensed matter classes. Another important concern of recent research development- “anomalous Hall effect” was also achieved with the successful precise choice of dopant. We also unravel the fact that the origin of such AHE is not always from intrinsic magnetism but from thermal or magnetic fluctuation. The effect of noncoplanar spin dynamic like in a triangular spin cluster or tilted cluster play a significant role behind such extraordinary effect. Moreover, the density functional theoy calculation draws the conclusion.

In chapter 3, we presented a systematic study of magnetotransport and magnetic properties of compensated semimetal MoTeP. The semiclassical two-band fitting of the Hall and longitudinal conductivity explain near-perfect carrier compensation at low temperature with very high carrier mobilities. The crossover from PMR to NMR at high field region is due to reduced spin scattering effects coming from defect induced ferromagnetism. At room temperature ρ_{yx} becomes nonlinear S-shaped at higher field, implying that both type of carriers is present in the material. The asymmetric spin polarized total DOS near Fermi level supports our experimental observation of defect induced ferromagnetism in MoTeP.

We established structural and vibrational anomalies from pressure induced angle dispersive synchrotron x-ray diffraction (ADXRD) and Raman spectra of the bulk that signify a metallic transition and an ETT at 0.26 GPa and 2 GPa respectively in TI $Sb_{1.9}Cu_{0.1}Te_3$. Our experimental investigations also provide evidences for three pressure induced structural transitions from rhombohedral $\rightarrow$ monoclinic C2/m $\rightarrow$ another monoclinic C2/c and finally to a disordered cubic Im-3m phase in chapter 4.

Another high pressure study on $Sb_{1.9}Fe_{0.1}Te_{2.85}S_{0.15}$ showed a change in Fermi surface topology at 2.5 GPa and 3 structural phase transitions from ambient one. It is to be noted that atomic radii of doped constituent atoms in Sb_2Te_3 drastically affects the ETT. However, its effect on structural phase transitions is not found to be very large. Instead of forming disordered monoclinic (C2/m) structure $Sb_{1.9}Fe_{0.1}S_{0.15}Te_{2.85}$ transforms to new monoclinic structure C2/c and subsequent structural transitions are observed at similar pressure range.

In chapter 5, we have studied magnetic, transport, Fermi surface properties and electronic properties of rare earth doped $BiSbTe_3$ system. The system exhibits AHE at a temperature far away from T_N. The spin frustration is observed from the bifurcation of ZFC-FC data and the frequency dependent ac-susceptibility measurements. Up to magnetic transition temperature it is the concomitant effect of magnetism and frustrated lattice that realizes this extraordinary effect. Additionally, at finite temperature the thermal fluctuation of the spins cause AHE to survive above T_N. The cluster glass state is confirmed by the slower dynamic of the spins and evaluated by Dynamic scaling. The presence of cluster formation was further assessed by departure of Arrhenius plot, and finally we concluded the intercluster interaction to be strong by VF fit. The nontriviality of the current material is proved by the π- Berry phase of Landau Fan diagram.

We investigated the unusual spin orders on topological insulators $Sb_{1.9}Fe_{0.1}Te_{2.85}S_{0.15}$ and $Bi_{1.9}Fe_{0.1}Te_{2.85}S_{0.15}$ in a quest for a material that can host both magnetic frustrations and Dirac quasiparticles at the same time. This in-depth study is portrayed in chapter 6. The dc magnetization along with the ac susceptibility data render the system a cluster SG type at low temperature due to the competive FM-AFM interactions present in the system. The dHvA oscillation consists of multiple frequencies corresponding to complex Fermiology.

In chapter 7, the impact of pressure induced electronic behaviour is inquired with the density functural theory approaches in Se doped WSMs compounds $MoTe_2$ and WTe_2. A metallic transition is observed near 3 GPa for both MoTeSe and WTeSe from a semimetallic behaviour at ambient condition. The present work depicts a pressure studies up to 10 GPa to explore the lattice parameters, volume changes and c/a anomaly.

The DFT calculation shows electronic topological transition (ETT) under the application of pressure in Sb_2Te_3 Topological insulator. Additionally, we found semiconductor to metal transition near 2 GPa with LDA approximation. The overall change in the Fermi surfaces is found to follow other topological insulators like Bi_2Te_3 and Bi_2Se_3. The topologically non-trivial surface state remains unchanged under pressure; however, the bulk band gap reduces.

8.2 Scope of future works

The interplay between topology and magnetism is emerging as the new frontier in fundamental quantum physics after the discovery of Topological materials. As we have already studied the AHE from the prospective of spin-chirality, thermal and magnetic fluctuations, tilted spin clusters in this thesis, we would like to further concentrate on Kagome magnets which is marquee system of magnetic frustration. Investigating materials with topological magnetic structures has always been a focus of significant research. These

2D Kagome lattices are ideal platform to investigate how Berry curvature can produce a large intrinsic AHC in noncollinear magnets. The AHC of all those high T_c systems-Mn_3Sn, $Co_3Sn_2S_2$, $LiMn_6Sn_6$, $GdMn_6Sn_6$, Co_2FeAl and $Co_3Sn_2S_2$ are of the order of 50-1000 $\Omega^{-1}cm^{-1}$ and attributed to coming from the Berry curvature of the electronic bandstructure.

Designing functional quantum materials requires an understanding of the interaction between the AHE and electronic structure in magnetic topological materials.

Additionally, the formation of unique quantum phases under severe conditions, such as a very high magnetic field and pressure, is one of the fascinating features of topological materials. Such research can reveal fascinating aspects of the quantum limit regime and can be very helpful in comprehending the intricate physics of topological materials. Such research can reveal fascinating aspects of the quantum limit regime and can be very helpful in comprehending the intricate physics of topological materials. Electrons can be pushed to the lowest Landau level (n=1), with very high magnetic fields. We search for novel transport phenomena in this limit, such as linear MR and quantum phase transition.

8.3 Applications

Topological materials' non-trivial band structures have sparked a great deal of interest in spintronics technology. Furthermore, magnetic sensors, magnetic switches, memory devices, and extremely efficient low-power electronics can all make use of large MR and ultrahigh mobility in topological semimetals.

Although the theoretical aspects of topological insulator materials are adequately recognized, there are numerous difficulties and ongoing efforts in solving the experimental challenges. One of the foremost experimental problems faced by the researchers associated with the synthesis of those materials in the bulk forms is unnecessary bulk residual carriers due to intrinsic defects. The advantage of investigating nanostructured topological surface states is that it lowers the effect of undesirable bulk electronic states in transport measurements as much as possible, allowing topological surface or edge states to contribute more easily. Therefore, material dimensions are crucial in the surface-dominant transport regime with a view to take advantage of the surface electrons' invaluable properties. One more advantage of the nanostructured materials is the easy modulation of Fermi level via field effect gating (FEG) which is difficult in case of bulk crystal because of large volume. Together with the sizeable surface to volume ratio in nano TI, FEG ensures surface dominated electron transport. Additionally, the extraordinary morphology of TI nanomaterials provides control over the topological surface states in reduced dimension such as nanoribbons [388], [389], nanoplates [390], nanorods [391], nanowires [392], nanotubes [393], nonorings [388] and quantum dots [394].

Although the word ‘topological insulators’ was invented a while ago, the field of topological materials (topological crystalline insulators TCI, WSMs, DSMs, NLSMs etc) has blossomed, and the current theoretical works indicates that ~25% of all the materials of our knowledge may be topological in nature [395]. In the recent years of condensed matter research, topological materials have sparked into a multidimensional field and suggests one of the most fascinating and significant research frontiers these days. Topological proximity effect with dissipation less conduction, field- effect transistors with fast- switching, broadband photodetector for optoelectronic devices, ultrafast photodetector for innovative photodetection technologies, topological p-n junction diode for electronic devices and qubits for robust quantum computers based on 1D topological superconductors, are crucial for potential device applications. The TI surface state is ideal for producing SOT via SHE, the effective control over the SOT by the gate voltage represent energy-efficient gate-controlled nonvolatile spintronic memory and logic devices. TIs are also shown to be very successful at converting spin to charge, implying that they could be used as spin detectors or efficient spin-to-charge converters. In summary, initial theoretical breakthroughs and subsequent experimental verification have led to current advances in the physics of topological insulators. The exotic metallic surfaces of these insulators could lead to the development of new spintronic/electronic devices and the discovery of newly quantum state with rich physics.