# Topological Insulators: A Modern Era of Condensed Matter Physics

**ARIJIT SAHA, Associate Professor-G**
*Institute of Physics, Bhubaneswar (India)*

In our day to day life, we come across different types of solid-state systems (materials) which can be classified as metals, semiconductors and insulators. Among them metals (*e.g.* Aluminum [Al], Copper [Cu] etc.) can carry current in presence of applied voltage. This occurs due to the presence of free electrons in them. Semiconductors (*e.g.* Silicon [Si], Germanium [Ge] etc.) which falls between metals and insulators, can also carry current in presence of doping (*n*-type or *p*-type). In contrast, insulators (wood, plastic, rubber etc.) are materials which are unable to carry current as electrons are tightly bound to the nucleus in them and cannot flow freely. Therefore, fundamentally intriguing questions naturally arise: (a) Can we realize a material which can have both metallic and insulating properties? (b) What is the physical mechanism behind that? (c) What are the possible applications of such materials?

During the last decade, the discovery of topological (Topology is a branch of mathematics which deals with the geometric objects that remain invariant or robust under smooth deformations, such as twisting, stretching etc.) insulators (TIs) revolutionizes the research activity in modern condensed matter physics via the understanding of the above-mentioned questions. Precisely, a topological insulator (TI), like an ordinary insulator cannot carry current via its bulk (interior). However, the boundary of these systems possess non-trivial states which can carry current, thus behaving as metal. For *e.g.,* a two-dimensional (2D) TI material has a one-dimensional (1D) boundary which can give rise to current if a voltage is applied between them. Similarly, the 2D surface boundary of a three-dimensional (3D) TI remains metallic and can carry current. Although, the ordinary insulators also own boundary, but they are also insulating similar to the bulk and cannot conduct current. Therefore, this remarkable property of TIs makes them distinct from other solid-state materials and thus they are considered to be the new phases of matter.

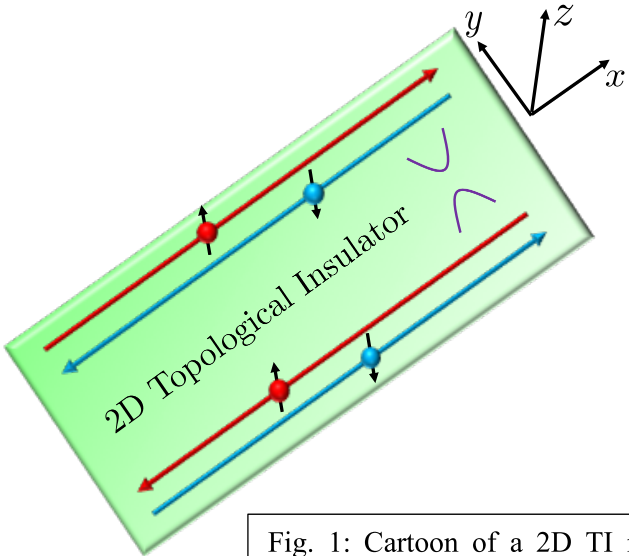


Fig. 1: Cartoon of a 2D TI in which the bulk is insulating and both the 1D boundaries are conducting channels. The upper boundary contains a forward electron with ↑ spin and a backward electron with ↓ spin. The spin and momentum directions are reversed for the lower boundary.

Now, one asks the questions, what is the physical reason behind this extra-ordinary feature of TIs? Why are they called topological? To answer these questions, we would like to acquaint the readers with some known facts. In atoms, electrons move in different orbitals around the nucleus in presence of an attractive potential. This closed motion results in orbital angular momentum. According to relativistic (*after Einstein's Special Theory of Relativity*) quantum mechanics, this orbital motion of electrons gives rise to a magnetic field in its rest frame. Interaction of this magnetic field with electron's spin angular momentum generates spin-orbit coupling (SOC). Furthermore, in a solid superposition (overlap) of atomic orbital wave-functions (in quantum mechanics electrons behave as waves in an atomic orbital. Like ordinary sound/light waves, electron waves can also overlap with each other and give rise to interference pattern similar to light waves) form different (conduction and valence) bands. In a metal, these bands are overlapping with each other and because of that metals are conducting. On the contrary, the conduction band and valence band is separated by a gap in an ordinary insulator. Hence, they are non-conducting.

The TI materials, in general, inherit strong SOC which respects *time-reversal symmetry*. (corresponds to a symmetry in which if one translates the time in backward direction, *i.e.* $t \rightarrow -t$, the underlying physical laws remain invariant). Due to the presence of the latter, the bulk conduction and valence bands are separated by an insulating gap like an ordinary band insulator. Moreover, SOC is responsible for band inversion in which the usual ordering of conduction band and valence band is inverted. In a simple-minded picture, the band gap changes sign from positive to negative value via the zero. This zero can be naively thought as the conducting boundary channels of TIs and this is known as the *"bulk-boundary correspondence"* (intrinsic relation between the topological bulk and the boundary states of matter) in literature. Therefore, the physical mechanism behind the appearance of such boundary metallic states is *"band-inversion"* (sign change of band gap) by large SOC in TIs.

In real materials, the presence of impurities (some other atoms) is unavoidable. Scattering of electrons with impurities gives rise to resistance. Then question arises that how far the intriguing properties of TIs survive in residence of impurities. Note that, the boundary conducting 1D channels of 2D TIs are unidirectional (either forward or backward moving electrons) as shown in Fig. 1. Hence, back-scattering is forbidden along these 1D channels as to encounter that, alongside momentum, spin of the carriers also has to be flipped. In that sense, these 1D metallic channels are robust or *"topological",* protected by time-reversal symmetry, and cannot be removed by local boundary perturbations (disturbance). Similar picture also holds for 3D TIs where the 2D boundary surface states are topological. Therefore, the breakthrough possibility of obtaining dissipationless current through TI systems drives them to be promising candidate for several applications.

As far as experimental progress of TI systems is concerned, they have been experimentally observed in a variety of 2D and 3D electronic systems, including Mercury-Telluride (HgTe) quantum wells, Bismuth-Antimonite (BiSb) alloys, and Bismuth-Telluride ($Bi_2Te_3$), Bismuth-Selenide ($Bi_2Se_3$) crystals etc. Apart from electronic materials, the concept of topology has received significant attention in *"photonic"* systems because light waves can also serve as a platform to investigate nontrivial bulk and boundary physics with the aid of carefully engineered photonic crystals and metamaterials. During the past several years, there has been significant progress in *"topological photonics"*. Furthermore, TIs can also be engineered by externally driving a trivial metal/non-topological system via laser light. This leads to a new filed of research known as *"Floquet topological insulator"*. Overall, a plethora of both theoretical and experimental challenges remain in this emerging paradigm of topological systems.

From application point of view, TIs carry potential applications in *"spintronics"* (electronics with electron's spin degree of freedom instead of charge) and *"topological quantum computation"*. In Fig. 1, it is shown that the forward and backward moving electrons along the 1D channels of 2D TI carry spin ↑ and ↓ respectively *i.e.* they are *"spin filtered"* in the sense that electrons with opposite spin propagate in opposite directions. Therefore, an applied voltage will induce opposite currents for the opposite spins, leading to a pure *"spin current"* (zero charge current). The latter is also dissipationless due to the topological character of the system. Hence, the unusual metallic boundary states of TI materials may result in to be the appropriate test bed for realizing future spintronic devices. Furthermore, the interface between a TI and a *"superconductor"* (materials which carry dissipationless supercurrent below a critical temperature) can allow the creation of an *'emergent'* particle (not actual electron, rather it emerges due to the interaction of electrons with the surrounding environment *e.g.,* other electrons) called *"Majorana fermion"* (MF) that neither material supports by itself. MF is its own antiparticle, is electrically neutral and is, in most respects, 'half' of an ordinary electron. Majorana fermions (MFs) can be implemented to design *"qubits"* (quantum bits; mechanical analogue of classical bits having value zero or one) which can encode quantum information of any value. Hence, MFs are one step towards the realization of a *"topological quantum computer"*, which would be exceptionally well protected from errors. Therefore, in combination with superconductors, TIs can lead to a new architecture for topological quantum bits.

Along the future direction, the field of "*topological photonics",* non-equilibrium and interacting version of topological band theory and "*higher-order topological systems"* will remain the prime focus of research for this decade. All in all, there are still surprises in store as we dig deeper into the realm of topological quantum matter.