International Journal of Humanities & Social Science Studies (IJHSSS)
A Peer-Reviewed Bi-monthly Bi-lingual Research Journal
ISSN: 2349-6959 (Online), ISSN: 2349-6711 (Print)
ISJN: A4372-3142 (Online) ISJN: A4372-3143 (Print)
Volume-IX, Special Issue, June 2023, Page No. 184-191
Published by Scholar Publications, Karimganj, Assam, India, 788711
Website: http://www.ijhsss.com
DOI: 10.29032/ijhsss.v9.iSpecial.2023.184-191

A Brief Review of Topological Insulator

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Abstract:
Topological insulators represent a new classes of materials with insulating bulk but having gapless surface states. Integer Quantum Hall Effect, discovered in 1980 was the first property with topological association in topological insulators. A summary is given for possible ways to confirm the topological nature in a candidate material. Various synthesis techniques as well as the defect chemistry that are important for realizing bulk-insulating samples are discussed. Characteristic properties of topological insulators are discussed with an emphasis on transport properties. The prospects of topological insulator materials for elucidating novel quantum phenomena that await discovery conclude the review.

Keywords: Topological Insulator, Synthesise of TI, Identification of TI, Applications.

Introduction: The exotic features of topological materials arise from the bulk-boundary correspondence principle applicable to a system comprising an interface of a topologically nontrivial insulator with a trivial one. This is because the nontrivial insulator is characterized by a topological invariant which cannot change at the interface unless the bulk energy gap is closed, leading to the appearance of states within the gap. [1] Historically, topological properties of the band structure were first identified by Thouless, Kohmoto, Nightingale, and den Nijs (TKNN) in the integer quantum Hall (QH) effect exhibited by a 2D semiconductor under high magnetic field. [2] They showed that the topology of the nontrivial Hilbert space can be specified by an integer topological invariant called TKNN invariant ν such that the Hall conductivity σ_{xy} is given by ν times e^2/h. ν is also called the first Chern number or the winding number and is equal to the Berry phase of the Bloch wave function calculated around the Brillouin zone (BZ) boundary divided by 2π. Subsequently, the quantum spin Hall (QSH) effect was proposed. Unlike the QH effect, the QSH effect requires no magnetic field and preserves time reversal symmetry. QSH insulators are essentially two copies of the QH system, in which the chiral edge state is spin polarized and the two states form a time-reversed pair to recover the overall TRS, as shown schematically in Figure 1. [3] Kane and Mele proposed a graphene model with spin-orbit

coupling (SOC) to realize such a system. [4] They showed that a finite SOC leads to the opening of a gap at the crossing point of the Dirac cone (the Dirac point). Furthermore, within some parameter range, a time-reversed pair of spin-polarized one-dimensional (1D) states appears at the edges of the finite lattice. In this model, the desired spin polarization of the edge state is induced by the SOC which has an inherent tendency to align spins in relation to the momentum direction, generally referred to as spin-momentum locking. The description of topological invariants was extended to 3D systems by Moore and Balents who predicted the appearance of topologically protected states with Dirac cone dispersion. [5] In band insulators, the strong SOC leads to band inversion with the p-orbital valence band being pushed above the s-orbital conduction band, an effect commonly used to screen for new topological insulator materials. 2D and 3D topological insulator materials offer opportunities to couple electromagnetic waves with the topologically protected edge or surface states to create edge or surface plasmons, respectively. While practical realizations of topological insulator materials will be discussed in next section, here we review the general optical properties of topological material systems, highlighting features related to surface states.

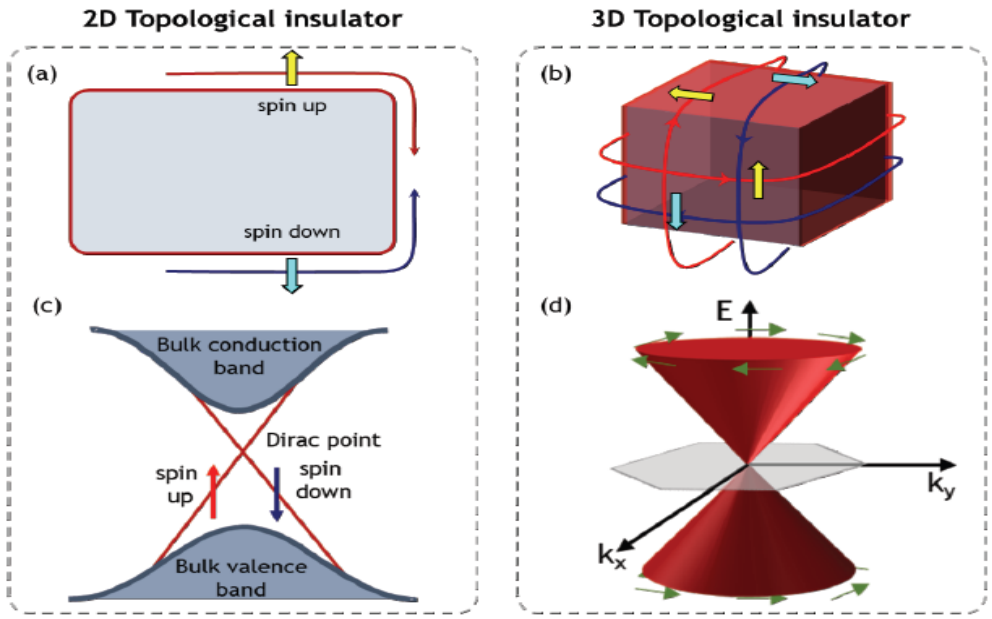

Figure 1. *Bulk-boundary correspondence and surface state dispersion: Schematic showing (a) 2D (b) 3D topological insulator material systems with topologically protected spin-polarized edge and surface states, respectively. These states arise from the non-trivial band structure of the bulk, which necessitates the appearance of topological surface states with Dirac dispersions at the interface with a trivial insulator or vacuum. Energy dispersion of (c) 2D edge states and (d) 3D surface states forming 1D and 2D Dirac cones, respectively.* [26]

Synthesis*:* In this section briefly discussed different techniques which are adopted and employed to synthesize of composite TI materials. The method of preparation is important as different methods give rise to different structures and morphologies with diverse research and applications. Various methods like solid state reaction, chemical synthesis, etc. have been used over the ages to synthesize single as well as polycrystals, nanostructures, thin films etc.

Solid state reaction : A customary synthesis procedure where solid reagents are subjected to a very high temperature to acquire single crystalline and/or polycrystalline materials is known as solid state reaction. Morphological and chemical properties of the reagents such as surface area, reactivity and free energy change with the solid-state reaction are the aspects that control solid state reaction. The other factors include reaction conditions like the pressure, temperature and the environment of the reaction which affects the solid state reaction. The advantage of solid-state reaction method includes the simplicity as well as large-scale production [6].

Chemical reactions: Chemical reaction, a process in which one or more substances, the reactants, are converted to one or more different substances, the products. Substances are either chemical elements or compounds. A chemical reaction rearranges the constituent atoms of the reactants to create different substances as products. Hydrothermal method is a chemical reaction in water in a sealed pressure vessel, which is in fact a type of reaction at both high temperature and pressure [7]. Solvothermal synthesis is generally defined as a chemical reaction taking place in a solvent at temperatures above the boiling point and pressures above 1 bar. The medium used in a solvothermal synthesis can be anything from water (hydrothermal) to alcohol or any other organic or inorganic solvent. [8]

Deposition methods: Thin Film Deposition is the technology of applying a very thin film of material – between a few nanometers to about 100 micrometers, or the thickness of a few atoms – onto a "substrate" surface to be coated, or onto a previously deposited coating to form layers. Thin Film Deposition is usually divided into two broad categories – Chemical Deposition and Physical Vapour Deposition Coating Systems. Chemical Deposition is when a volatile fluid precursor produces a chemical change on a surface leaving a chemically deposited coating. One example is Chemical Vapor Deposition or CVD used to produce the highest-purity, highest-performance solid materials in the semiconductor industry today. Physical Vapor Deposition refers to a wide range of technologies where a material is released from a source and deposited on a substrate using mechanical, electromechanical or thermodynamic processes. The two most common techniques of Physical Vapor Deposition or PVD are Thermal Evaporation and Sputtering. [27]

Molecular Beam Epitaxy (MBE) – This is the most widely employed technique to deposit high quality large area thin crystalline films with well-defined stoichiometry in ultra-high vacuum (UHV) environment (~ 10^{-9} torr). The essential mechanism is based on vapor phase transport where the elemental source materials are heated to high temperatures and the vapours deposit on the surface of a crystalline substrate. MBE allows the growth of

films with finely controlled stoichiometry and doping levels, notably compensated ternary or quaternary topological insulator chalcogenide crystals with high bulk resistivity, [28,29] topological superconductors and heterostructures.

Table 1: *Some Synthesis process for preparation of TI Materials.*

Materials	Synthesis method	Conditions	Properties	Ref.
$Fe_xBi_{2-x}Se_3$ topological insulator crystals	Solid state reaction methods	Pellets placed in quartz tube, Pressure: 10^{-3} Pa, 850 °C slowly cooled to 620 °C	Single crystals	[20]
Cu-doped topological insulator Bi_2Se_3	Bridgman Method	850 °C for 12 h, Cooled to 620 °C at 3 °C/h	Crystals with metallic appearance on the surface	[21]
Bi_2X_3 (X= S, Se, Te)	Hydro-thermal Reaction	Autoclave: 180–240 °C, 10 h	Plate-like particles with width ~1 μm thickness ~0.2 μm	[22]
Nickel doped bismuth selenide	Solvothermal Approach	Uniform dispersion (sonicated for 15 min) Autoclave 165 °C, 24 h	Nanoplates like structure size: 300–800 nm	[23]
Bi_2Se_3 nanowires	Chemical Vapor Deposition (CVD)	Ar flow, Tube furnace: 700 °C, 90 min	Nanowires with length up to 50 μm	[24]
Bi_2Se_3 thin films grown	Molecular Beam Epitaxy (MBE)	Ts:250 °C sample heated up to 300 °C, annealed for 1 h	Thin film, coalesced islands of triangular shape	[25]

Identification Process Of Ti Materials: In this section briefly discuss about different types of techniques which are employed to confirm whether a material is a TI or not. In the case of 2D TIs, one needs to probe the existence of helical 1D edge state, which is possible only through quantum transport experiments using nano-fabricated device structures. The

existence of the edge state can be seen through conductance quantization in the insulating regime. [9] Also, the helical spin polarization of the edge state may be detected by transport experiments using spin Hall effect.[10] For 3D TIs, the simplest and the most convincing is to observe the Dirac cone by ARPES experiments. To firm up the identification of a TI, one should employ spin-resolved ARPES to confirm that the Dirac cone is non-degenerate and is helically spin polarized. [11]

Unfortunately, not all materials are suitable for ARPES, which requires clean and flat surface that is usually obtained by cleaving single crystals. When single crystals are not available or the material does not cleave well, APRES becomes difficult. In such a case, one may rely on transport experiments. Ideally, if the bulk is sufficiently insulating and the surface carriers have high enough mobility, one would be able to confirm that the transport is occurring through the surface and that the surface carriers are Dirac fermions. The former can be done by looking at the sample-size dependence of the conductance, [12, 13] and the latter may be accomplished by elucidating the π Berry phase in the quantum oscillations from the surface state.[14] It should be emphasized that confirming the Dirac-fermion nature of the surface carriers is important, because trivial accumulation layer or inversion layer that may form on the surface of an insulator may also give rise to surface-dominated transport.[15]

The Dirac-fermion nature may also be confirmed by STS experiments in magnetic fields, because massless Dirac fermions present peculiar Landau quantization in which the level spacing changes as $\sqrt{N}$ and the zero-energy Landau level is pinned to the Dirac point; by looking at the bias-voltage dependence of the Landau quantization peaks, one can identify Dirac fermions.[16,17] Similarly, magneto-optics experiments to detect the Landau level transitions can be used for detecting the peculiar quantization scheme to identify Dirac fermions on the surface.[18] One should note that in reality, it is often very difficult to obtain sufficiently bulk-insulating samples of a candidate material. In that case, transport measurements are not very useful. If it is possible to detect the equilibrium spin current (which is carried only by the helical Dirac fermions and hence is not bothered by bulk carriers) by some electromagnetic means, [19] it would become a very useful tool for identifying a TI. However, feasibility of such an experiment is not clear at the moment.

Application and Future Scope: There have been great improvements in the materials properties of TIs in the past few years to make them suitable for fundamental research. Now there are a couple of choices for bulk-insulating TI materials in which the surface transport dominates over residual bulk transport at low temperature in bulk single crystals. Over the past decade, topological materials have grown into a very active and interdisciplinary field and represent one of the most fast-growing and impactful research frontiers nowadays. Besides having importance in the understandings of quantum matters at a fundamental level, research on Tls also bears much potential in various applications (electronics, spintronics, energy conversion and quantum computing Nanostructures obtained from direct chemical synthesis have their niche in the research of topological surface states in

topological materials, high- crystalline quality and controllable morphologies (nanowire, nanoribbon, nanoplates etc). As we summarized in this review, the synthesis of basic TI nanostructures has been established and there are various solid evidences in quantum transport (AB oscillations, ambipolar gating. 2D SdH oscillations, LMR. WAL) for the existence of robot topological surface states in TI nanostructures. However, part from the challenges that are general to TI materials (e.g. high concentration of bulk carriers), nanostructures also have their unique aspects (in particular, the small size) that make them difficult to study using spectroscopic techniques other than transport (ARPES, STM etc). With advancements in spectroscopic techniques (e.g. micro-ARPES) and efforts to maintain the pristine surface of nanostructures between sample growth and surface characterization, more fundamental studies of the surface states in TI nanostructures using direct spectroscopic tools are expected to shed more direct lights on critical issues like topological surface states vs. trivial surface states (from band-bending), dispersion relation, and quantization of 2D topological surface states due to quantum confinement in nanostructures. On the device application side of research the developments of electron transport in TI nanostructures outlined in this review have set the stage for further device work on TI nanostructures with more sophisticated control or functionality. Specifically, devices exploiting the spin-momentum locking and lattice distortion induced mirror symmetry breaking effects are of high interest in future research on TI nanostructures for spintronics and straintronics where the control of electron spin or application of strain is used to achieve device functionality. Finally, steps toward identifying Majorana fermions and topological q-bit in hybrid superconductor or TC nanostructure devices would be highly important and relevant to the development of quantum computing.

Acknoledgement: B.P. express sincere gratitude to Dr. Anal Biswas, Principal of Panchmura Mahavidyalaya and Dr. Arpita Bhowmick, IQAC coordinator of Panchmura Mahavidyalaya for providing this wonderful opportunity to work. The completion of the work would not have been possible without their help and insights.

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