A brief overview of Topological Insulator: Bismuth Selenide

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Abstract: This article gives a basic insight into one of the most researched topic nowadays-Topological Insulators (TI). A TI is basically a material which is insulating in bulk but conductive at surface. This article also discusses the results of transport measurements carried on topological insulators and the various methods of synthesis of a topological insulator. At last it focuses on Bismuth Selenide (TI): properties and synthesis techniques for its nanomaterials.

1. Introduction

Topology is a branch of mathematics which deals with the properties of objects which are consistent by smooth modifications to their geometry; smooth changes to a bulk insulator, such as structural modification under strain, cannot shift its topological class except by driving it through a metallic or magnetic state [1]. A topological insulator is a material that run as an insulator in its interior but whose surface contains conducting states, implies electrons can only move along the surface of the material. Topological insulators were determined in 2D in system containing HgTe quantum wells sandwiched between cadmium telluride in 2007.Topological-insulator surfaces are exceptions to the rule that all planar metals become insulators at low temperature in the presence of impurities or defects. The wave nature of electrons in quantum mechanics tends to amplify the effects of impurity scattering: an electron bouncing off many impurities often becomes trapped or 'localized', even when a classical particle would continue to diffuse. The theory of localization exquisitely predicts that at sufficiently low temperature, and beyond a critical amount of impurity scattering, one- and two-dimensional metals will become insulators- the diffusion of electrons that characterizes the material's conductivity will come to a halt.

However, there is a loophole. In most materials composed of heavy elements, the motion of electrons is linked to their spin (intrinsic angular momentum), and this coupling acts to delocalize electrons. Topological-insulator surfaces are effectively at the limit of infinite spin–orbit coupling, and no localization can occur until the impurity density is so high as to destroy the bulk insulator[1]. For a topological insulator to form, spin–orbit coupling must be strong enough to modify the electronic structure significantly, which suggests that heavy-element, small-band gap semiconductors are the most promising candidates. This suggestion stems from two points. First, spin–orbit coupling is a relativistic effect and is only strong for heavy elements. Second, if the bandgap is much larger than the energy scale of spin–orbit coupling, then spin–orbit coupling will not be able to change the phase [2]. The surface state of the next-generation topological insulators is closely related to the Dirac electronic structure of graphene, which has a linear energy–momentum relationship like that of a relativistic particle (and is known as a Dirac cone). In contrast, the surface of a topological insulator and that of graphene is that the topological insulator has only one Dirac point(or valley) and no spin degeneracy, whereas graphene has two Dirac points and is spin degenerate. This disparity has far-reaching consequences, including the possibility of generating new particles that have applications in quantum computing.

Nevertheless, initially a disadvantage in using a topological insulator for some purposes as opposed to graphene. In graphene, the chemistry of the carbon atoms naturally locates the Fermi level at the Dirac point (that is, the point at which the two cones intersect), where the density of states vanishes. This means that the density of carriers in graphene is highly tunable using an applied electrical field and allows applications of graphene in both basic science and microelectronics. The surface Fermi level of a topological insulator does not have any particular reason to sit at the Dirac point; conversely through a combination of surface and bulk chemical modification, tuning to the Dirac point in Bi_2Se_3 was demonstrated [2].

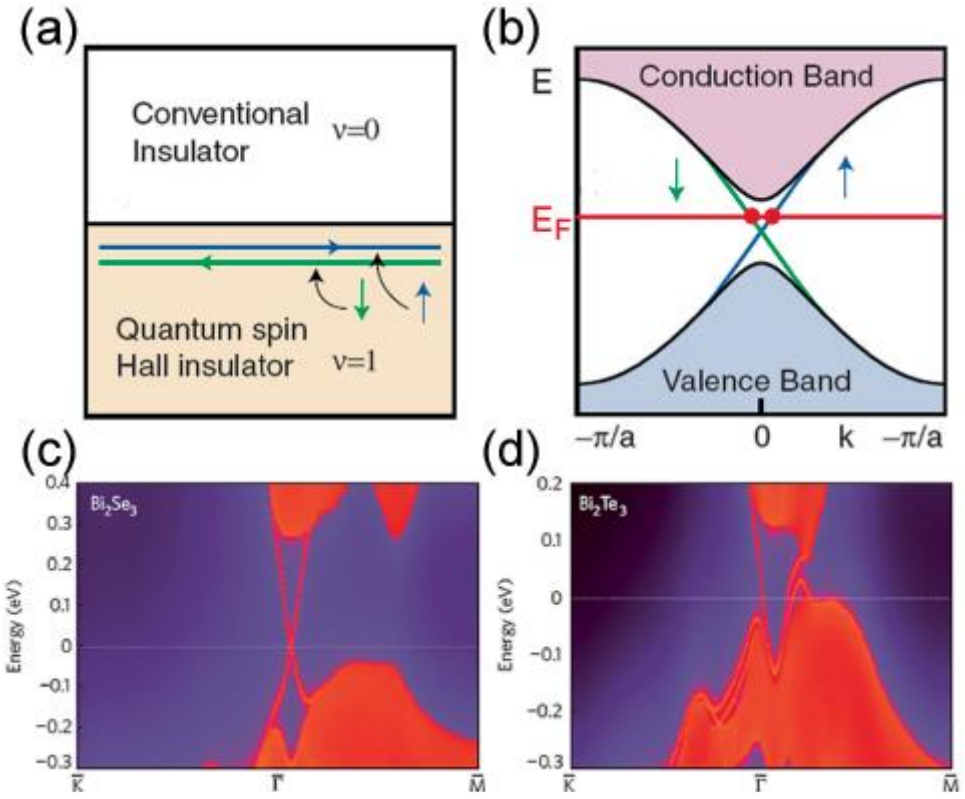

Figure 1 (a) Edge states form at the interface between a conventional insulator (topological invariant of zero) and a topological insulator (topological invariant of one). They are spin-resolved as denoted by two separate channels (green and blue). (b) Edge states possess momentum-spin locking property where the spin of the electron is determined by the direction of motion. (c) Local density of states of Bi_2Se_3on the [111] surface shows a surface state with a Dirac electronic dispersion. (d) Local density of states of Bi_2Te_3 on the [111] surface also shows a surface state with the Dirac point embedded in the bulk valence band.

2. Transport Measurements

Following effective spectroscopic examination, several transport measurements on TI bulk crystals, such as Bi_2Se_3 and Bi_2Te_3, and reported two-dimensional Shubnikov-de Hass (SdH) oscillations to indicate the presence of conducting surface electrons. In thin films, weak anti-localization was observed to show that electron carriers experienced large spin–orbit interactions, an essential ingredient for TIs. A crossover from weak anti-localization to localization was demonstrated in Cr-doped Bi_2Se_3 film and Fe-decorated Bi_2Te_3 film, which showed that magnetic impurities, such as Cr and Fe, could induce a gap in the otherwise gapless TI surface states by breaking time reversal symmetry. The anomalous Hall effect has also been observed when magnetic moments are induced in TI materials.

A genuine test in examining the TI surface states through transport is the moderately enormous residual bulk carriers that dominate the transport signal. In a perfect world, TIs should be bulk insulators. However, significant residual bulk carriers are unavoidable in real TI materials due to crystal defects such as Se vacancies in Bi_2Se_3. Effective tuning of the Fermi energy via compensation doping in bulk crystals, compositional tuning in MBE-grown $(Bi_{1-x}Sb_x)_2Te_3$ thin films and field-effect gating in thin films has been shown to reduce the bulk carriers significantly, but not completely. In Bi_2Te_2Se bulk crystals, the bulk carrier mobility was intentionally made extremely low, compared to the TI surface state mobility, so that the high bulk carrier density became irrelevant [4].

3. TI nanostructures

TI nanostructures offer several advantages over their bulk counterparts for investigating the fundamental nature of the TI surface states and for abroad range of technological applications. The most significant advantage of a nanomaterial is enhanced surface effects due to the large surface-to-volume ratio. Several groups have made TIs into nanostructures such as exfoliated flakes from bulk crystals and nanoribbons and nanoplates. The large surface-to-volume ratio in nanostructures serves as a valid platform to study the topological nature of the surface states. Single-crystalline nanomaterials are routinely obtained by various nanomaterial synthetic techniques with crystalline quality comparable to bulk synthesized materials. Various dopants and growth substrates can be incorporated in nanomaterial synthesis for a diverse set of electrical and optical properties. Heterostructures of multiple nanomaterials, either in a core/shell arrangement or in stacking of different nanomaterials along the length of the nanowire, are also routinely carried out. Thus, supreme-quality nanomaterials can be used as ideal platforms to study fundamental condensed matter physics questions. Another advantage that nanostructures offer for TI studies over bulk crystals and thin films is their unique morphology. TI nanostructures have well-defined morphology at the nanoscale, such as nanowires, nano-hexagons, nano-triangles, and nanoribbons whose cross-sections follow the symmetry of the underlying crystal structure. This results in transport conditions in which the TI surface electrons are forced to travel in a well-defined path at the nanoscale, ideal for interference-type experiments of the TI surface electrons such as Aharonov–Bohm (AB) oscillations [4].

4. Physical Synthesis

Various synthesis methods are available to make TI nanomaterials. Broadly, we divide the methods into two categories: dry, physical synthesis and wet, chemical synthesis. Physical synthesis includes mechanical exfoliation and nanomaterial synthesis such as vapor-liquid-solid (VLS), vapor–solid (VS), and metal-organic chemical vapor deposition (MOCVD) methods.[4]

5. Chemical Synthesis

Chemical Synthesis of TI nanomaterials, primarily the noncentro-symmetric zincblende HgTe-type family and the hexagonal centrosymmetric Bi_2Se_3 family of compounds, has been achieved with a diverse set of methods: colloidal, solvothermal, hydrothermal co-reduction, mechano-chemical, photochemical, galvanic displacement, and a microwave-assisted synthesis. Chemical methods offer significant practical advantages compared to bulk synthesis and physical nanomaterial synthesis. The synthesis time is relatively short requiring only a few minutes to a day and synthesis temperature can be fairly low (<300 °C). With these mild synthesis requirements, significant control both in morphology and chemical modification of the surface can be achieved. The crystalline quality of the chemically synthesized TI nanomaterials is high [4].

6. Bismuth Selenide

Bi_2Se_3 is a narrow gap semiconductor, contemplated for infrared detectors and thermoelectric applications. Recently, research on Bi_2Se_3 has attracted much interest because they are predicted to be three-dimensional(3D) topological insulators (TIs), a new class of quantum matter possessing conducting surface states with nondegenerate spins. In TIs, the strong spin-orbit coupling dictates robust, nontrivial surface states, which are topologically protected against backscattering from time-reversal invariant defects and impurities. Angle-resolved photoemission spectroscopy (ARPES) measurements on bulk single crystals of Bi_2Se_3 have verified the existence of the 3D TI phase. In particular, the surface states of Bi_2Se_3 forms a single Dirac cone inside a large bulk bandgap of 0.3 eV, thus being suggested as the reference material for the 3D TIs [3]. Single crystalline nanostructure, on the other hand, offers an attractive alternative system to study the surface states, for example, by transport measurements or surface scanning techniques. As the sample size shrinks, the contribution of surface states to electrical and optical properties is enhanced due to the increase of the surface-to-volume ratio. TI nanostructures are thus an excellent system to investigate the properties of

exotic surface states. Also, the study of mesoscopic transport properties is essential for wide applications of TIs in future spintronics devices. In combination with the absence of impurity states in the gap, this large bandgap indicates that topological insulator behavior may be seen at room temperature and greatly increases the potential for applications [5]. For three dimensional topological insulators, Bi_2Se_3 is likely to become part of such a second-generation class of material, superseding the first-generation BiSb. Another possible second-generation topological insulator is Bi_2Te_3 [5] . Bi_2Se_3 exhibits a layered, rhombohedral crystal structure in space group D^5_{3d} ($R3m^{-}$). Each charge-neutral layer consists of five covalently bonded atomic planes, Se-Bi-Se-Bi-Se, known as a quintuple layer. These quintuple layers are bonded together predominantly via van der Waals interaction to form the Bi_2Se_3 crystal. The conventional unit cell spans over three quintuple layers with lattice parameters a =4.14 Å and c =28.64 Å. Therefore, each quintuple layer has a thickness of =1 nm [3].

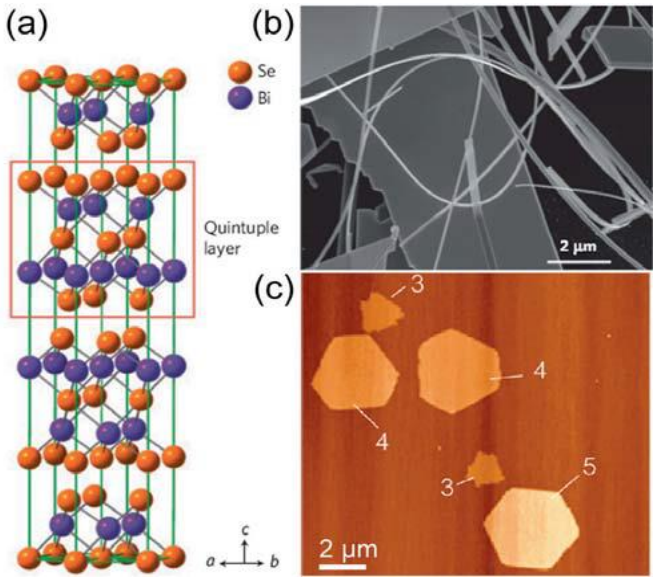

Figure 2- (a) Layered crystal structure of Bi2Se3 where the covalently bonded Se–Bi–Se– Bi–Se atomic planes make a ~1 nm thick quintuple layer. Neighboring quintuple layers interact by van der Waals force. (b) Scanning electron microscope (SEM) image of Bi2Se3 nanoribbons grown via VLS method. (c) AFM image of Bi2Te3 nano plates grown via VS mechanism. The numbers indicate the nanoplate thickness in nanometers.

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