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The Role of Defects in Modulating the Electronic Properties of Topological Insulators and Their Potential in Quantum Technologies

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Abstract

Topological insulators are electronic systems with a large energy gap and spin-polarized surface or edge states inhabiting the band gap. As a result, they have been addressed in spintronics, fault-tolerant quantum computing, quantum information technology, and spin-based quantum networks. Furthermore, they can be manipulated into three-dimensional topological Josephson junctions, which have been proposed for nuclear vibrational spectroscopy and metrology. Importantly, the interesting properties of topological insulators depend strongly on the large-scale band structures as well as the properties of the edge or surface states. As a result, modulating the electronic properties of these gapless states becomes crucial for these applications. Defects serve as a fundamental means of changing the electronic properties of topologically protected edge or surface states. Therefore, characterizing such "intrinsic" defects is crucial for improving the use of these materials for quantum technologies. In this paper, the question of how to identify and eliminate such defects using topological elements in Josephson junctions is addressed. The analysis and investigation demonstrate that there is an urgent need for a systematic study of the relationship between defects and electronic properties. There were important results due to the use of quantum technologies that deal with free carriers on the surface of topological insulators, which seeks to compensate for the surface charges that accumulate at extrinsic (intrinsic) defects, making it difficult to characterize these defects with appropriate techniques. The collected results show that smooth surfaces and increased bulk states are desirable conditions for defect observation and can be obtained if the space charge regions within the valence and conduction band gap are increased.

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1. Introduction

The field of topological insulators is rapidly emerging due to their unique attribute of hosting gapless surface states displaying Dirac cone-like dispersion. The proximity-induced superconductivity, large spin-orbit interaction, high mobility, and large g factor have made them potential candidates for spintronic and device applications [1]. The quantum informational field has seen immense development in quantum computing technology by exploiting spin-twin momentum-locked states in 2D topological insulators coupled to s-wave superconductors, where bottom surface states undergo the topological phase transition that disrupts the perfect Andreev reflection. The presence of defects and impurities in real-life materials can significantly modify the electronic properties of topological insulators; thus, controlling the electronic properties through the introduction of admixture is highly required [2]. However, rare reports are available demonstrating the experimental modification of the electronic properties of Bi_2Se_3 through post-synthesis treatment or by introducing external elements within the van der Waals gaps in conjunction with the required characterizations. Despite the potential

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of this material, a fundamental understanding of the effect of defects on its potential inevitable, particularly for the development of its ferroelectric and spintronic devices [3]. Several serious attempts have been made by both the scientific and two-dimensional material communities to unveil the phenomena behind defects in a two-dimensional materials. Regardless, most of the studies are purely theoretical or merely based on calculations, and no direct practical measurements have thus far been reported. Therefore, a deeper investigation regarding defects is essential to overcome the challenges that are mostly prompted by defects [4]. Typically, a device engineer would significantly benefit from the understanding of existing defects in the widely considered topological insulator material Bi_2Se_3 as shown in Fig. (1). One should know how defects occur in Bi_2Se_3, how they regulate its electronic properties, and also should know what are types of defects affecting the electronic characteristics of Bi_2Se_3, which is an interesting point forthcoming device industry applications. Thus, the importance of this topic prompted us to research its details, and therefore this article aims to find the topological properties of insulators [5].

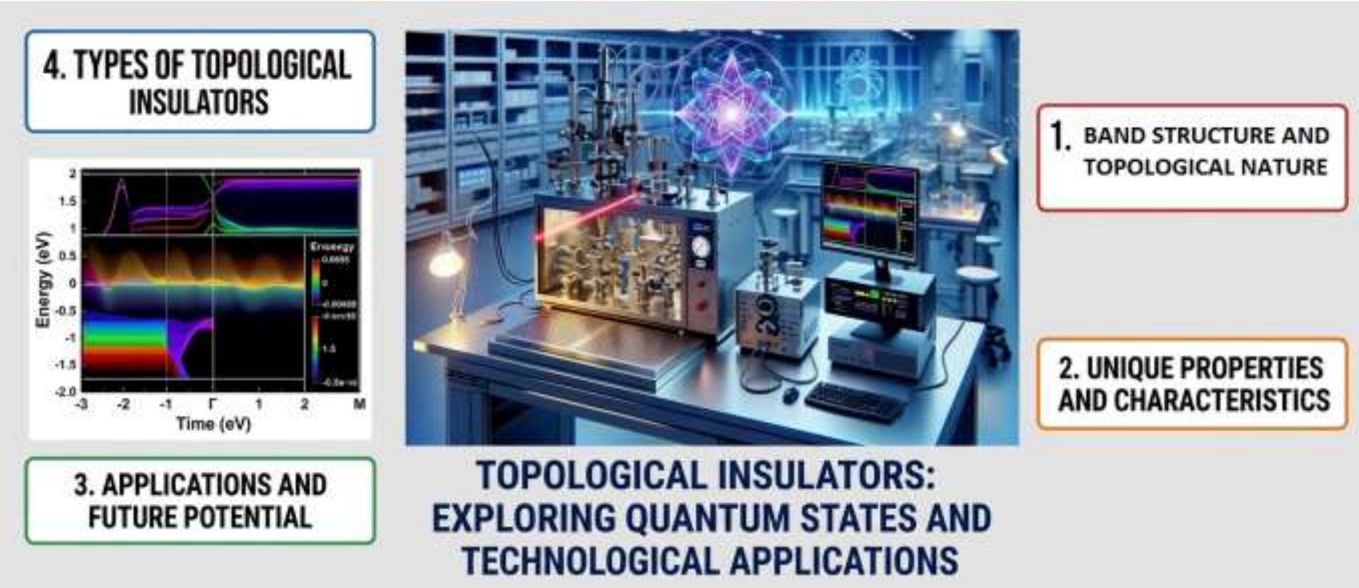

Figure 1. Topological Insulators: Exploring Quantum States and Technological Applications [5].

2. Fundamentals of Topological Insulators

A thorough understanding of higher-dimensional topological insulators originates from the study of one-dimensional classical conductors. These topological insulators - materials that are insulating in the bulk but conductive on their surface - are coined "topological" for two primary reasons: (1) the topological properties of the bulk band structure, e.g., the value of the integer Z2, "protect" the presence of conductive surface states; and (2) these surface states are non-dispersing and resemble the electronic states of free massless Dirac fermions that are topologically protected. Contrary to conventional insulators in which the electronic bands by definition do not intersect at the Fermi level, topological insulators are characterized by the presence of metallic surface consequent of the band inversion along the vertical or a set of momentum points [6]. The topology of materials is the study of robust properties in band structures named topological invariants. These characteristics are robust due to a global topological property - a concept inspired by genus in scholastic physics - and are mainly considered at integer values. Equally important to surface states are their unique dispersions that make topological insulators an exciting material candidate for next-generation technological applications [7]. Overall, the electronic properties of a topological insulator heavily rely on its surface. The topology of the bulk band structure prohibits all states in the bulk bandgap, except those that find refuge on the surface. For these topological surface states, in contrast to bulk states, they can behave as massless Dirac fermions whose velocity vector is a surface vector that points in the parallel direction to their *k* vector. This is a unique surface property that can only manifest due to the band inversion at a time-reversal invariant momentum point.

2.1. Basic Concepts and Definitions

Topological insulators are a new phase of quantum matter, which have insulating bulk but feature conducting surface states. It is theoretically proposed that the low-energy effective Hamiltonians of the surface states can be described in terms of Dirac cones for time-reversal invariant topological insulators and with a Dirac cone for single spin for quantum anomalous Hall insulators [8]. The existence of such Dirac cones is guaranteed by certain topological invariants that can be used to distinguish topological insulators from conventional ones. Defining the Z_2 invariant was initially proposed for the 2D systems characterized by the existence of the edge states [9]. Many other systems exhibiting the topological behavior have been considered theoretically and subsequently confirmed experimentally. In 2D systems, they are the quantum Hall phase with filling factor 1, the spin-Hall insulator, in 3D the HgTe quantum wells and $Bi_{1-x}Sb_x$, and in 3D Dirac/Weyl semimetal Cd_3As_2, Na_3Bi, and others [10]. In contrast to the usual insulators, the surface states of TIs are very robust against nonmagnetic defects and impurities, in the sense that they are completely absent in the isolated spectrum, but instead protected by topological invariants such as Z_2 in classical TIs or the first Chern number in QAHIs.

3. Electronic Properties of Topological Insulators

The central motivating discovery propelling this surge was the employment of new quantum technologies to establish topological insulators. These materials exhibit distinctive electronic properties, which suggests that they could be used to make perfectly conducting pathways for next-generation quantum computers and devices. Importantly, topological insulators have unusual states of electronic order for electrons in insulating materials. Because they describe electrons in a broad class of materials with a pre-existing topological label, these surface states offer an almost 'off-the-shelf' platform for new quantum device designs. On the one hand, any conducting pathway is very useful in designing electronics. In topological insulators with such surface states, the states need to be consecutively filled to carry current. But this electron 'filling'—and thus the conducting ability—cannot be changed by applying a traditional electrical voltage [11]. Instead, the current wakes up by applying a magnetic field or simply thermal effects. In contrast, traditional electrical wires have no such prerequisites, where current flows as soon as a voltage is applied. On the contrary, the outer edge of a topological insulator has a bizarre current-carrying mode. This state does not need to be filled in the same way. In principle, it could carry charges even up to the relatively high levels needed for practical use. In this mode, electrons are continuously added at one edge of the material while being removed from the opposite edge, this greatly reduces the amount of active control needed to switch on a wire that, at first glance, may be of practical use [12]. Nevertheless, such current carriers might be much more vulnerable to any type of disruption because they break up the usual demanding requirements for transporting modes of transportation. Introducing defects into topological insulators can in principle provide a straightforward means to modulate all these types of transport states and might provide a way to affect surface states while leaving the behavior of the bulk states untouched [13]. Thus, introducing defects or impurities allows control over the otherwise fully robust quantum states as Figs (2 and 3) show. In solid-state systems like topological insulators, the electronic properties are a complex mixture of fundamental behavior required by symmetry and random effects that lead to 'disorder physics' [14]. In the case of topological insulators, we also have to make subtle interplay between electrons that prefer to live in 'layers' and electrons that push against each other.

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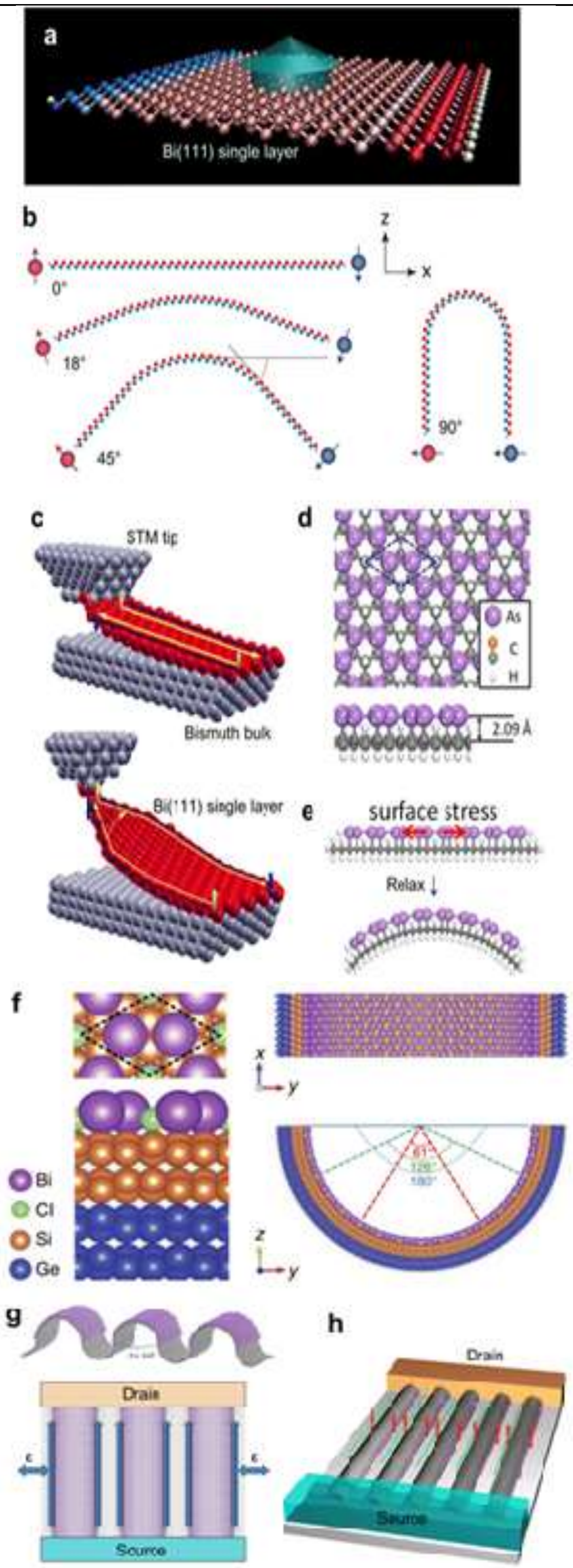

Figure 2. Schematic of the surface states of a topological insulator [14, 15].

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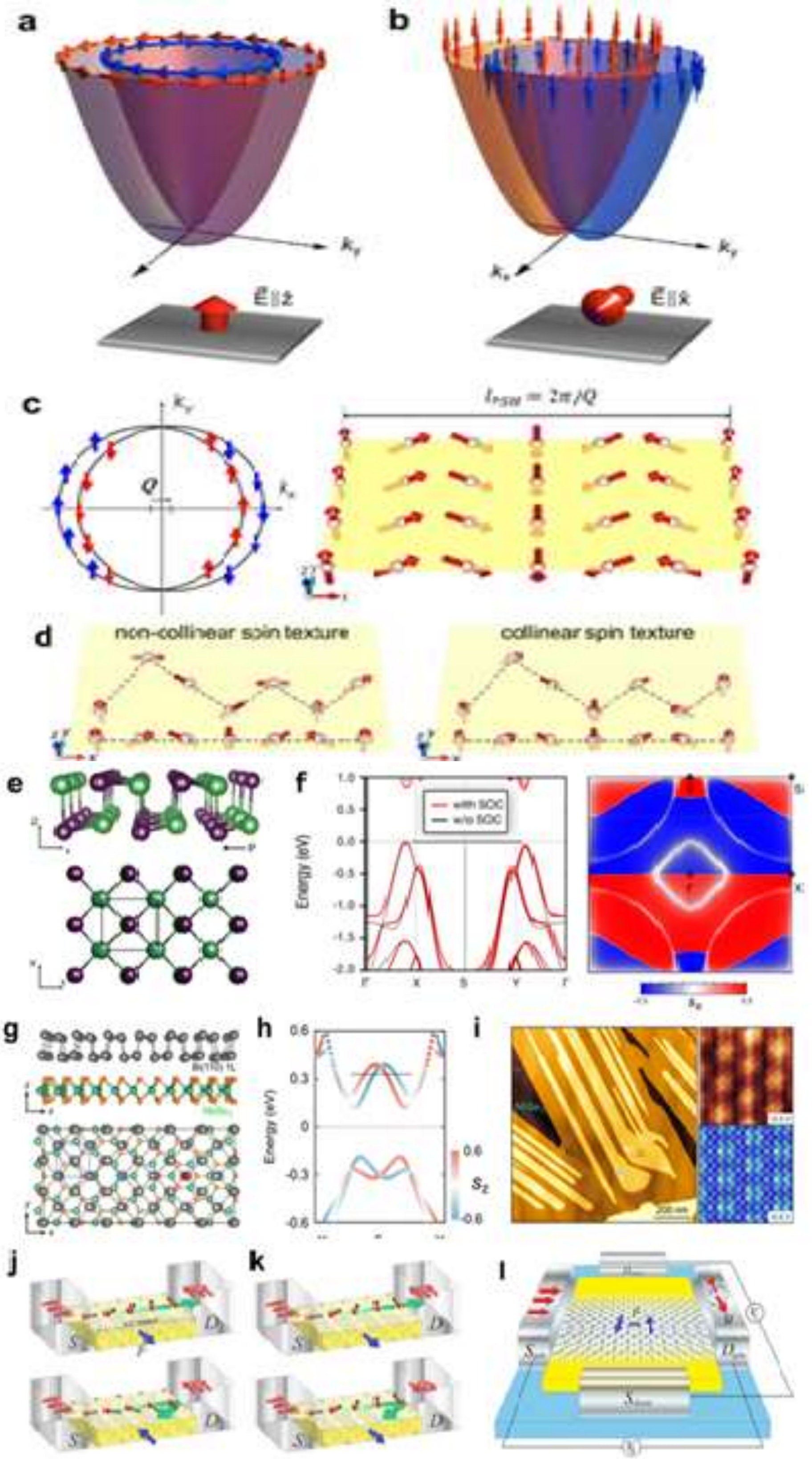

Figure 3. Schematic of the molecular bonds of a topological insulator [14, 16].

3.1. Topological Surface States

The essential ingredient for a material to be termed topological is the existence of topological order. Such order is, for example, intrinsic to the topology of the material. This intrinsic order gives rise to transport channels, which are confined in a region of the 2D momentum k-space, and are not affected by elastic impurity scattering and can therefore contribute to the transport. In materials with nontrivial Z_2 topological order, called topological insulators in the case of nontrivial band structure, the conducting states are the spin-polarized helical edge states [16, 17]. These states are confined to the edge; however, their presence and the nontrivial index of topological order are unambiguously set by their counterparts in the bulk. Topological surface states of topological insulators are possibly the most extensively considered features in predicting important electronic properties of topological matter, including surface spin polarization, spin-momentum locking, and the Dirac-type linear dispersion. These surface states appear as a result of the peculiar band structure topology and are essentially immune to elastic backscattering due to spin-momentum locking [18]. The time-reversal invariant property of the topological surface states also prevents the electrons from being elastically scattered back into the bulk. The spin of the carriers is locked perpendicular to the direction of their momentum, facilitating backscattering suppression. Therefore, as a result of band structure wrapping due to topological order, the movement of electrons on the surface of a topological insulator is exclusively 2D, whereas in the bulk it is 3D. As edge charge carriers play a vital role in the transport properties of materials, the presence of topological boundary states or surface states suggests a quantum regime effectively governed by the 2D surface [19, 20]. This means the charge carriers are not inhibited by the small energy gap needed to populate the bulk due to their confined movement. This makes it possible to have applications in future spintronic and quantum computing industries, which aim at rapid communication and enormous computational capabilities. Electronic behavior of devices relies largely on the surface states as they govern the flow of charge at a junction interface constructing, for example, electronic circuitry. In conditions where the surface states correspond to the bands around the Fermi level, the spin-momentum locking guarantees that the electrons on the surface move without scattering in the *xz*-direction. However, elastic scattering can occur between the electrons of different energy states. The quantized and gapless Dirac spectrum exhibited by the surface states grants topological insulator surfaces with perfect conductivity. Moreover, in the case of nontrivial surfaces, an electron helicity—a spin polarization parallel to its momentum—prevails at the Dirac point. This forms a long-lived surface current due to the scattering of the 2D helical surface carriers with minimal impurity assistance right at the Fermi energy [21, 11]. It was then predicted that the high charge-to-spin current conversion efficiency could pave the way for ultra-fast electronics by exploiting these unique properties for a wide range of high-speed applications. Therefore, it is preferably the surface states that promise a material as a potential candidate in such quantum technologies. Hence, this behavior of surface states motivated our investigation of the effect of the defects in the suppression of the spin-momentum locked electronic properties [22].

4. Defects in Topological Insulators

Topological insulators (TIs) are materials characterized by a bulk energy band gap with conducting states at the interface due to the presence of topological surface states (SSs). In the presence of time-reversal symmetry (TR), such states are protected by the Z2 topological invariant, ensuring that charge carriers are chiral and dissipationless along the boundary and that backscattering is forbidden. According to their band structure details, TIs are divided into strong and weak. The boundary electronic properties of the former are protected from time-reversal conserving perturbations, while those of the latter are isolated from the bulk. The interaction of electrons with topological SSs may result in different electronic phenomena of potential interest for the development of various quantum technologies. Guided by these observations, TIs can be categorized from another perspective as imperfect topological insulators [23, 24]. The potential of TIs as platforms for novel functionalities in quantum electronics has motivated significant research efforts in determining the influence of defects on the properties of TIs. An important motivation is the fundamental capability to view defects merely as 'inadvertent competitors' in the observation of topological phenomena, namely charge carrier dynamics, scattering, and electronic transitions. Such a study would lead to new strategies for materials optimization for quantum electronics through defect engineering [25]. The analysis of the literature also hints at a close tie between the defects perspective and the intrinsic topological properties. As a basic remark, substrates can give rise to a considerable number of dislocations in the TI films. These topologically trivial bond rotations and displacements are usually located close to the substrate in up to ten deep substrate layers, but they may propagate across to the TI layer [26].

4.1. Types of Defects

Topological insulators exhibit typical surface states with Dirac-like properties. The presence of these protective surface states makes them resilient to surfaces interacting with the surrounding materials to some extent. However, during growth and just after fabrication, these surface states may be compromised due to the interaction of the surfaces with elements from the environment. The defects can be classified into different categories. Depending on their shape and size, they can be classified as point, short-range line, long-range line, and extended. Based on their origin, the classification is bulk, surface, or mixed. Most importantly, behavior can be classified as trap, electrochemical, or microstructure [27]. Here, we solely focus on the shape and size of defects because any type of defect may have a trapped effect as well. Defects vary from a subatomic level to a continuum, involving extended surface to bulk effects. Classification is usually performed in terms of atomic scale arrangement, as revealed in imaging, followed by documenting the effect on electronic properties and stability in electrical conditions. In defect engineering, efforts to obtain a particular defect must revert to intentionally introducing the necessary precursors that would facilitate the desired active defect. In the case of defect characterization, classification is necessary before attempting to find the characteristics of an individual defect that either hinders bulk transport, acts as a mid-gap state or scatterer, or serves as a carrier generation site at the band edge (if it has a trap state) [28]. In order to do so, two guidelines must be established: (1) the determination of the length scale of the defects: whether point defect, line defect, or planar defects; and (2) the identification of point defects from line defects, planar defects, and their possible interactions. In both cases, images are very useful in the identification process. Indeed, for larger defects, this is an easy task. Threading radially from an extended defect, contamination stopped (no interaction zone at high contrast) is evident. Simulations are required for the establishment of relevant criteria to assist in point-extended defect identification. The defects can be point, line, or domain-wall-like defects. In the former categories, they are further subdivided into mixed adatom-vacancies, vacancies, and adatoms [29, 30]. Depending on their shape and size, how they were created (either by fabrication or ambient environment), and their stability, their electronic behavior varies greatly. Electrochemical mixed defects are surface-created via ion redox reactions that would only introduce a trapped state above the conduction band edge and no Fermi level pinning. If instead, the main defect is at the bulk level or long-range diffusion (electrochemical), then it would pin at the Fermi level. Conversely, when there is Fermi level pinning, the Fermi level is likely to be adjusted either via point or short-range line defects responsible for this band pinning defect. There is no doubt regarding the short-range line path: dislocations, grain boundaries, or coalesced growth from different nuclei, but the result is the same: short-range directional band pinning by inducing a trapped state in proximity to the contacting interface [31, 32]. This band-pinning behavior is not going to show if a grain or planar boundary dominates the trajectories between the two surfaces because it would have to cross free surfaces from the agglomeration of growth nucleation. And this is one of the reasons why samples are mostly purchased in polycrystalline form.

5. Effects of Defects on Electronic Properties

In the last section, a detailed account has been given regarding the defects in TIs, the various types of defects, and their impact on the structural and photophysical properties of the materials of interest [33]. In this section, we will submit a brief overview of the impact the defects can have on the electronic properties of TIs. Generally, defects can alter the band structure, the density of states, the band-gap values, and band edges, can induce and change the acceptor/donor character of the materials, and influence their electronic scattering processes [34, 20]. The defects that are present within the bulk and at the surface of the sample are responsible for altering the electronic properties due to the presence of the Fermi level within their energy range. Defects can also create resonant states below and within the band-gap of TIs at the surface, thus affecting the spin texture of the Dirac cone states and their associated spin-momentum locking. There are numerous types of defects that are reported to form during the synthesis and processing of TIs, and it is important to understand the effects of these defects on the intended operational properties of interest, which vary between different application areas in quantum technologies. The low-defect case is expected to show a high mobility for the two-dimensional surface state carriers, with the Fermi level preserved within the bulk gap [35, 16]. By contrast, engineering the defects could only be of interest in the π-surface case, to either enhance the metallic behavior and/or magnetic ordering, or to mitigate the Dirac cone carriers from scattering.

5.1. Scattering Mechanisms

On introducing crystals with topological surface states to the external environment, the photoinduced carriers inside the bulk can meet at the step edges of the crystals, and this is derived from the scattering of the defects. This effect plays a key role in the electron transport behaviors of the topological insulators. The code of topological materials at the edge and in the presence of surface defects is significant. In [36], the defects are including the surface states arising from terminating the topological crystals with cleaved surfaces, have a destructive impact on the unique properties of topological insulators and cause some difficulties associated with the enhanced characteristics. Now the analysis must consider the distinct defect models and ensure, through some of the obtained results, that the functioning of the Dirac electrons in the topological states is influenced by the scattering mechanisms described in the chosen models. The defects located on the surface of topological insulators, like vacancies, dislocations, and interstitials can be present in the triangular and hexagonal lattices; these defects can be related to some scattering mechanisms such as vacancies in the first line of the crystal surface model, closer to the step edge. Since electrons have a strong probability to undergo elastic scattering from the vacancies, they are unable to be directly delocalized sufficiently in alignment with their counterparts in the regular crystal [37, 35]. The surface and the geometrical positions of the single vacancy located in the first line are examined. The associated probability of attaching a carrier electron to the single vacancy of the first line for fixed energy is specified in units of Ra. Vacancies in the second line, however, show less influence, from which point the electrons interact through the free-field-like hopping mechanism near the black surface [38]. The lowest values of the resistance are assumed to be products of the energy-dependent period of the conductance fluctuations. This limits the relative contribution to reveal the accurate and appropriate value for the mean free path in cases of MF. Without any restrictions such as the long wavelength needed for measuring the mean free path, the picture obtained supports an underlying assumption [39]. A similar picture in cylindrical geometries is also observed, marked by the associated depletions. The same configurations in the smooth step, on the other side, do not show the valley, which presumably can be attributed to a less sensitive response of the accumulated carrier concentration since backscattering is not effective enough to prevent the reaching of compensated states. Critical behavior in the QSH state emerges since the Landau level splitting becomes suppressed when assuming additional time reversal symmetry due to the disorder considered to act as an Anti-LGT [40, 36]. Thus, infinitesimally small generated and the conjectured by their weak antilocalizing effect on transport shows the effect. Anomalous behavior and weak localization effect indicate higher conductance than that given a clean system.

6. Techniques for Defect Engineering

There are various methods for engineering defects in TIs to better control their electronic properties. They can be mainly divided into two categories: intrinsic defect engineering and extrinsic defect engineering. The former is associated with creating vacancies in the bulk or breaking the topological surface mode by substituting ions in the sublattice site or by annealing. The goal is to remove an adequate number of Se sites in the bulk with minimal damage to the surface. Atomistic calculations predict the creation of Se vacancies in the LixNbSe2 lattice via Li extraction, which leads to typical Nb-Se vacancies and the development of n-type character with carrier concentration reaching 3×10^{19} cm^{-3}. Doping with different metals during the material's growth creates non-paired holes, which break time-reversal symmetry when they migrate onto the surface. This might be applicable in the quest for Dirac half-metals [41, 42, 12]. An intrinsic or extrinsic defect in TIs can be introduced using ion implantation. Ions with energies in the range of 0.5–5 *MeV* penetrate the TI sample to very shallow depths of 30–180 *nm*. After implantation, defects have to be activated using either thermal or laser annealing. So far, ion irradiation has only been used to dope TIs in extremely thin films, where a considerable number of the implanted ions will stop inside the substrate [43, 24]. A low-power laser is then used to create defects in the surface region where the topological surface states perfectly reside. Defect engineering can also be performed at the growth stage by selecting the native substrate and the epitaxial growth conditions. The key is to prevent the creation of lattice and Schottky mismatches as well as consequent charge scattering at the interfaces [44, 45, 18]. The goal for all these is to grow as large a defect-free surface as possible and then tune it with other methods described here. Given their different natures, it is plausible that the effect of all these inflammation channels acting at the same time will be cumulative. While nobody has studied the simultaneous existence of all these multiple defect types on the electronic states of Sb_2Te_3, taking into account the results in the case of quantum dots, as well as the promising results shown, one could foresee a new era in the design of novel functionalities in quantum technology. The bipartite electronic states that these materials exhibit due to the 2D-layer-like topology of atoms render them particularly susceptible to disorder, and consequently, their use can be expanded to quantum technology to exploit, for example, Majorana states. It is shown that the combination of techniques helps us not only explore previously unexplored defect types but also control which are found and their concentration, which is paramount in creating topologically regulated states for quantum information applications. In addition to TIs, other materials of increasing relevance in different fields, such as topological superconducting wires in the case of Bi2Te3, reduced thermal conductance and UV light collection in ZnTe, are also known to change functionality with increasing concentration of defects. All these can be engineered through the combination of experimental inflammation methods if the proper channels are found.

6.1. Ion Irradiation

Ion irradiation has become a prominent method to tailor defects in topological insulators. The principles of ion irradiation involve the incidence of high-energy ions on a sample with gradients of incident ion energy ranging from a fraction of *eV* to a few *MeV*. Vibrational energy transfer to the atomic lattice may or may not happen according to the electronic energy-loss value because a sudden onset of electronic stopping means that part of the energy goes into producing more electronic excitation than heating the lattice [46, 47]. The minimal energy threshold for an atom to be displaced is typically denominated as a vacancy–interstitial production threshold, and the excess energy above this value can be useful in order to understand the vacancy–interstitial creation processes and the cascade stopping power. Grazing-incidence ion irradiation can also disrupt atomic layers underneath and not at the surface, but this effect is negligible in most applications. Not all primary knock-on atoms and ions have enough energy to move a target atom; for any given collision, the primary knock-on atom is enabled with sufficient energy to dislodge a secondary atom through its surface free energy [48, 49, 32]. In general, the fact that one can have precise control over defects allows for a more controlled examination of the topological properties in materials where these properties coexist with phase-boundary type metal-insulator transition or with magnetism because of its potential adoptability to realize devices and integrated quantum passives. The increase of the vacancy density in the topological insulator leads to further depression of the surface band at the Dirac point region. The most straightforward outcome of vacancy creation is the substantial feature broadening taking place, vividly disclosed by LT-STM. Ion irradiation is revealed to be a prominent defect engineering pathway that can effectively modify, tailor, and even create various pure lattice or hidden electronic changes and coexisting desired and stabilized non-magnetic metallic and non-topological behavior on different topological materials.

7. Applications of Defect-Engineered Topological Insulators

Defect-engineered topological insulators designed by controlling the doping or termination of topological materials modulate the characteristics of the Dirac surface state or bulk states by tuning the overall carrier concentrations or means of conduction. The appearance of low-energy localized in-gap states has been taken advantage of in the reported topological Kondo insulators. By modulating their appearance or absence, the former increases the disorder of the system and presumably its Kondo temperature. Moreover, in the context of quantum protocols and technologies, relying on scratches and impurities is challenging for larger-scale devices [50, 37]. The dream is to have a perfect surface with engineered defects, with adjustable characteristics such as being non-magnetic, localized, and having carriers with strong spin properties. This is of prime importance for quantum communication and information processing technologies, including an efficient spin filtering effect. The potential capability of a single magnetic adatom to localize the band gap due to exchange coupling has been a step towards an efficient quantum defect using topological insulators. This can, for instance, allow an efficient coupling with excitons in quantum dot structures or eventually switch on and off other kinds of interactions leading to a variety of functional devices. A notable realization of such a magnetic quantum dot was reported. Similarly, electrically charged defects in topological insulators can be exploited to reveal a characteristic sub-gap level associated with the electronic nature of topological states. An exceptional channel arises in any investigation of topological insulators where controlling the defects is crucial, namely in quantum computing, because the suppressed energy barrier within the topologically protected series of edge states shall encourage ballistic transport relevant for implementing the robust quantum transport anticipated for topologically protected states [51, 28].

7.1. Quantum Information Processing

In the modern era, defect-engineered TIs engineered with topological defects have played an important role in the context of quantum information processing. For instance, they can act as quantum wires to facilitate escorted transport of Majorana zero modes over long distances, which are known to have both topological protection and non-Abelian exchange statistics. Similarly, they can be used as spin-triplet superconducting couples to realize a qubit or storage boxes with large relaxation time scales, which are of great importance from the point of view of quantum computing or quantum hardware security [52, 11]. It is shown that there is another area where defects show promise is in the context of error-resilient bottomonium-based qubits. They are also being employed to realize the superfluid-universal topological qubits based on the disordered formation of weakly bound molecules. In this way, one can see that defect-engineered TIs could be helpful in many different protocols of quantum information processing compared to a perfect TI, due to their flexibility and potential in quantum technologies. The main challenge in realizing such protocols with defects is the protection of coherence in the presence of strong local impurities. In one direction, the tremendous experimental race to initially discover these systems has led to mounting evidence that such 'defective systems' may possibly already be supported in different platforms, while many such experimental results have emerged. On the other, comprehensive numerical studies have shown that various quantum properties of such devices are increasingly resistant to ambient noise. Thus, defects have been shown to be relevant for realizing parts of the vision outlined above in concrete physical settings. However, further insights are needed to determine if defects play an essential role at the confluence of TIs and quantum information processing. In our opinion, when viewed in terms of the big picture, the next phase of research and efforts should focus on exploring more setting-specific methods of harnessing exotic quantum phenomena known to be mediated by defects, to fully evaluate the potential role of defect-engineered TIs in upcoming quantum technologies. Table (1) presents a comparison of the most interesting previous studies, in which there were different studies dealing with member defects that are rarely examined, and comprehensive measurements are needed for the progress and implementation of topological insulators in computational and quantum communications. In particular, this review calls for desirable performance, future defect-monitoring design, and the optimal purpose of various devices for quantum technology. Regarding the importance of topological materials, smooth surfaces and increased bulk states are desirable conditions that can be obtained if the space charge regions are increased within the valence and conduction band gap.

Table 1. A comparison of the most interesting previous studies.

Ref.	Strengths	Weakness
[1], [4]	Unique Physical Properties of Topological Insulators	Complexity of Defect-Property Relationships
[5]	the use of Quantum Technologies	Energy and Cost Barriers
[2],[16],[21]	Robustness Against Disorder	Material Quality Challenges
[19], [44]	Topological Protection of Surface States	Unintended Side Effects of Defects
[32]	Defect-Induced Tunability	Material Quality Challenges
[36], [45]	Potential for Quantum Computing	Dependence on External Factors
[30], [19]	Spintronics Applications	Lack of Standardized Protocols
[12], [29], [37]	Resilience Against Disorder	Scalability Issues
[48]	Integration with Magnetic Materials	Limited Control Over Defect Engineering
[34],[47], [51]	Advances in Computational Modeling	Complexity of Defect-Property Relationships

8. Conclusions

In conclusion, defects, both intrinsic and extrinsic, consisting of acceptor-like and donor-like substitutions, play a very important role in modulating the electronic properties of topological insulators as indicated in Table (1). As far as, the importance of topological materials is concerned with the unique physical properties of topological insulators. Smooth surfaces and increased bulk states are desirable conditions that can be obtained if the space charge regions are increased inside the valence-conduction band gap. a particular kind of defect is relevant in terms of technological application, the use of quantum technologies and robustness against disorder make some restricted areas that requires quantum technologies for topological protection of surface states. These defects are expected to coexist as efficient quantum generators in reality. It has been confirmed that defects pave the way, and topological insulators have been planned for various quantum applications such as the anomalous Hall effect and quantum computation. The dual effect of defects, i.e., useful as well as harmful, is an interesting feature. They assist in experimenting with future electronics with enhanced transport functionality, yet they obstruct the formation of space charge regions required to acquire topological states. This required the production of some spintronic applications in order to withstand the disturbances. Such that, different defect member studies are relatively scarcely examined, and comprehensive measurements are required for the progression and implementation of topological insulators in computational and quantum communication. The existing and potential quantum modalities provide a new platform for programmers in computer network diversity, traffic law enforcement, and anti-counterfeiting collaborations. it is highly recommended that researchers from a variety of disciplines, from quantum mechanics to material science, should deal with various applications relies primarily on developments in computer modeling. In particular, this review calls for desirable performance, defect-observing futuristic design, and the optimum purpose of various quantum technology applications and integration with magnetic materials.

Conflict of Interest

We, as a cohesive team, worked with precision and cooperation to complete this research. There were no differences in points of view. On the contrary, our opinions were close and cooperative

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