New Pathways in Electronics and Optoelectronics Driven by New Physics of Nonconventional Materials

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Abstract **— Nonconventional materials (NCM) – 2D materials and topological insulators (TI) - have opened a gateway to search new physical phenomena and states of the condensed matter as well as to pave new platform of modern technology. This stems on their unique attributes - non-equivalence of electronic and dielectric states to vacuum ones, topological protection (reduced backscattering), spin-momentum locking property, magnetoelectric coupling, generations of new quasiparticles like Majorana fermions. Increasing the surface state contribution in proportion to the bulk is critical to investigate the surface states and for future innovative device applications. The way to achieve this is to configure NCM into nanostructures, which at the same time in combination with others materials significantly enlarge the variety of new states and phenomena. This article reviews the recent progress made in NCM and nanoheterostructures investigation. The state of art of different new scenario of engineering topologicaly interface states in the TI heterostructures are revealed, in particular by using polarization fields and antiferromagnetic ordering. Some of new proposals for innovative electronic and optoelectronic devices are discussed.**

Index Terms **— Two dimensional materials, topological insulator, nanostructures, grapheme, Dirac cone, spin-momentum locked states, spintronics, nanoelectronics, low dimensional phenomena, FET, LED**

I. INTRODUCTION

This year - 2015 - represents the tenth anniversary of modern grapheme and topological insulator research. The field of research in two-dimensional (2D) materials has been enjoying spectacular growth during the past decade. Over this decade, graphene has proven to be attractive for thin-film transistors owing to its remarkable electronic, optical, mechanical and thermal properties. Even its major drawback—zero bandgap—has resulted in something positive: a resurgence of interest in two-dimensional semiconductors, such as dichalcogenides and buckled nanomaterials with sizeable bandgaps. With the discovery of hexagonal boron nitride as an ideal dielectric, the materials are now in place to advance integrated flexible nanoelectronics, which uniquely take advantage of the unmatched portfolio of properties of two-dimensional crystals, beyond the capability of conventional thin films for ubiquitous flexible systems.

Still, there exists an entire periodic table of crystalline solid-state materials each having different electronic, mechanical, and transport properties, and the possibility to create single-atom or few-atom polyhedral thick 2D layers from any material remains [1.2]. Additionally, the past 8 years of grapheme research has yielded many methods for synthesizing, transferring, detecting, characterizing, and manipulating the properties of layered van der Waals materials. Furthermore, novel synthetic methods including topotactic, solution-based, solvothermal, and UHV surface epitaxial approaches have unleashed the potential to create new van der Waals solids and single-layer-thick materials. These established methods have enabled the field of 2D materials beyond graphene to mature very quickly.

Many novel materials that had been initially considered to exist only in the realm of theory have been synthesized. These include groups IV, III-VI and II-VI semiconductor analogues of graphene/graphane (the sp2/H-terminated sp3 derivatives) such as silicene and germanane. Similar to graphene, the properties at the single layer are also distinct from the bulk [2,3,4]. Furthermore, these 2D materials are useful building blocks that can be restacked and integrated into composites for a wide range of applications.

The unique qualities of 2D materials, such as their reduced dimensionality and symmetry, lead to the appearance of phenomena that are very different from those of their bulk material counterparts. This difference is perhaps most glaring in the transformation of the band structure as the single layer is approached. The two dimensional nature of these materials also plays an entirely mechanical role as they are inherently flexible,strong, and extremely thin. These materials exhibit other unique and potentially useful properties including high electron mobilities, topologically protected states, tunable band structures, and high thermal conductivities. The development of 2D materials is expected to improve current device technology, and their novel transport and topological properties might provide additional opportunities for spintronic devices and quantum computing.

Herein, we present a forward-looking review article that discusses the state-of-the-art of 2D materials and highlight the properties and advantages of single-, few-, and manylayer 2D materials in field-effect transistors, spin- and valley-tronics, thermoelectrics, , among many other applications.

TIs represent a new class of materials and they have sparked a massive search for new states and phenomena in condensed matter physics [5,6] . A TI can easily be identified by a few simple rules: the presence of large spin–orbit coupling, an odd number of band inversions between the conduction and the valence band by increasing the average nuclear charge, and a sign change of the symmetry of the

molecular orbitals. Last years a lot of different class of materials have identified as TI and interest to this new phase of mater continue to increase. Part of interest in TIs stems from the fact that they represent a new topological phase of non interacting electrons: the TI character of a material is its bulk property, nontrivially encoded in the wave functions of the occupied (valence band) states. However, it is the presence of the helical edge/surface states which leads to observable consequences. Their surface states are protected by time-reversal symmetry and show the Dirac cones connecting the inverted condsuction and valence bands [1]. Like the Hall state the "bulk" of the electron gas of TI is an insulator, but along its surface, the states can be gapless. Within a certain parameter range the surface states of TI are well described by a Dirac cone, allowing for parallels with graphene and relativistic physics, and prohibiting backscattering.. These Dirac cones constitute the topological transport regime, which has the gapless conducting and spin-momentum locked surface states leading to the suppression of backscattering. Such extraordinary surface states of the three-dimensional topological insulators may occur, as the term ''surface'' already suggests, only at the surfaces or, more generally, interfaces where the topological invariant changes [6].

Unlike graphene, the states on the Dirac cone on the surface of the TI are spin filtered; they have fixed spin directions for each wave number k. In such way among many new topics developed in such materials and nanostructures, the most exciting one may be spintronics.

Because the state at k and that at $-k$ have the opposite spins, the perfect backscattering from k to −k is forbidden. The gapless helical surface states with linear dispersion is similar to photons. Therefore, when two different TIs are attached together, the refraction phenomenon similar to optics is expected at the junction.

Furthermore, these 2D materials as well as TI are useful building blocks that can be restacked and integrated into composites for a wide range of applications. Exploring the properties of nanoscale NCM is a growing area of research and the present paper reveals some aspects of new interface and device physics of such materials. The spectrum and characteristics of topological NCM depending on geometrical configuration can be manipulates by different factors: electrical and magnetic fields, strain and deformation ets. For this reason NCM are being explored with a view towards applications, as a potential platform for tailoring nanostructures and nanomaterials properties. This topics cover the main part of the paper. The main nonconventional materials attributes and benefits of device applications are summarized in the Table 1.

TABLE 1. MATERIALS ATTRIBUTES

Key Properties	***Benefits Device Applications***
Electronic states non-equivalent to vacuum states	New rout of nanostructuringthrough interface states
Dielectric states non-equivalentto vacuum states	Metamaterisla devices
New states – Majorana fermions, Dirac monopol	Quantum computinghardware
Topological Protection (reduce backscattering)	High mobility/conductivity(*FET*)
Dirac fermions (linear E-k dispersion: $E = \hbar v_F k$)	Graphene-like physics and devices (electron "optics")
Spin-momentum locking	Spintronics (spin-polarized surface currentall-electrical spin-injection, etc.)
Magnetoelectric coupling	Magnetooptoelectronic

II. TWO DIMENSIONAL MATERIALS AND THEIR OPPORTUNITIES FOR NEW DEVICES

The fascination with two-dimensional (2D) materials that has started with graphene has spurred researchers to look for other 2D structures like for instance metal carbides and nitrides . In general, there are three main classes of materials that can be prepared as a singleatom or single-polyhedral-thick layer .

The most common class of crystalline structures that can be exfoliated as stable single layers are the layered van der Waals solids. These crystal structures feature neutral, single-atom-thick or polyhedral-thick layers of atoms that are covalently or ionically connected with their neighbors within each layer, whereas the layers are held together via van der Waals bonding along the third axis. One of the most well-studied families of van der Waals solids is the layered metal chalcogenides (LMDCs), the most common being MoS2. Neutral, dimensionally reduced hybrid organic/inorganic van der Waals derivatives of nonlayered solids have also recently been discovered. Dimensional reduction refers to the creation of novel crystal structures of metal-anion (M-X) frameworks by the addition of a reagent that disrupts the polyhedral connectivity along one or more dimensions while retaining a degree of the metal coordination geometry and general polyhedral connectivity.35 For example, it has been shown [2,4] that almost every II-VI, III-VI and III-V semiconductors that typically crystallizes into the three-dimensional sphalerite , wurtzite or hexagonal lattices, such as ZnS, GaSe, can be converted into atomically thin 2D crystalline frameworks when synthesized via solution-phase solvothermal techniques in the presence of alkylamine ligands.

The second class of materials that can be prepared as single or few layers features bulk crystal structures with charged 2D polyhedral layers that are typically held together with strongly electropositive cations or strongly electronegative anions such as halides, or OH. These

materials can then be easily dispersed onto substrates, with themajority of materials depositing as single to few layers. For example, recently, it was demonstrated that monolayers of silicon deposited on Ag(111) or ZrB2 organize into a puckered hexagonal graphene-like lattice with sp2 bonding configuration. This silicene material shares a similar band structure to graphene; however, the interactions with the substrate induce a band gap opening at the K point.

These materials display remarkably diverse electronic properties, ranging from metals to semiconductors to insulators. They also exhibit interesting strongly correlated electron phenomena, such as charge density waves and superconductivity [2,3].Meanwhile several hundreds of different two-dimensional materials are known, a substantial part of them is considered useful for transistors, and experimental transistors with channels of different two-dimensional materials have been demonstrated. In spite of the rapid progress in the field, the prospects of two-dimensional.

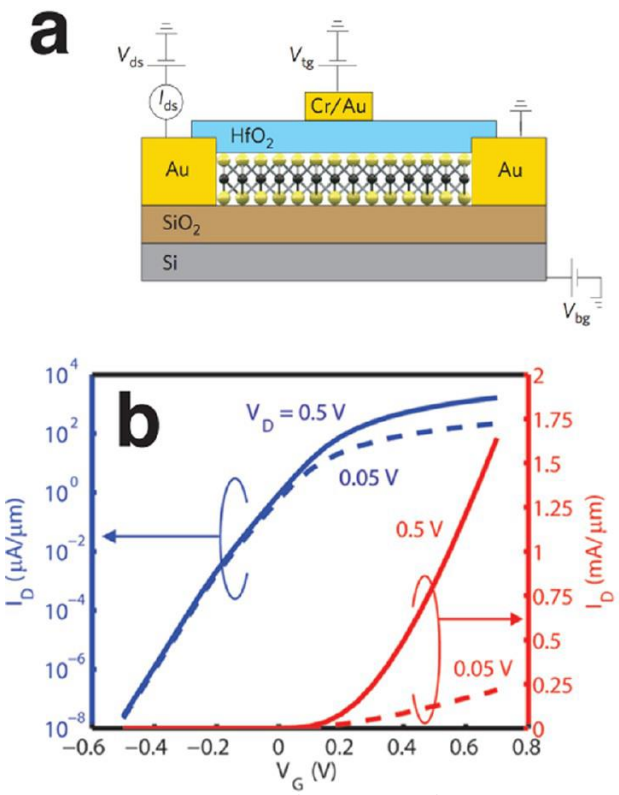

Fig.1 . Schematic illustration of cross section of MoS2 FET (a) and Transfer characteristic of a monolayer MoS2 transistor (b).

Among them, molybdenumdisulfide (MoS2; semiconductor), has attracted particular attention. To illustrate the potential of 2D materials for electronics we present the the recently results dealing with the performance of MoS2 transistors has been theoretically examined [7] using real space, self-consistent, and fully parallel non equilibrium Green's function transport simulation within a k 3 p approach and band structure fitted to first principles calculations. Figure 1 shows the drain current (ID) versus gate voltage (VG) characteristic for a simulated MoS2 transistor.

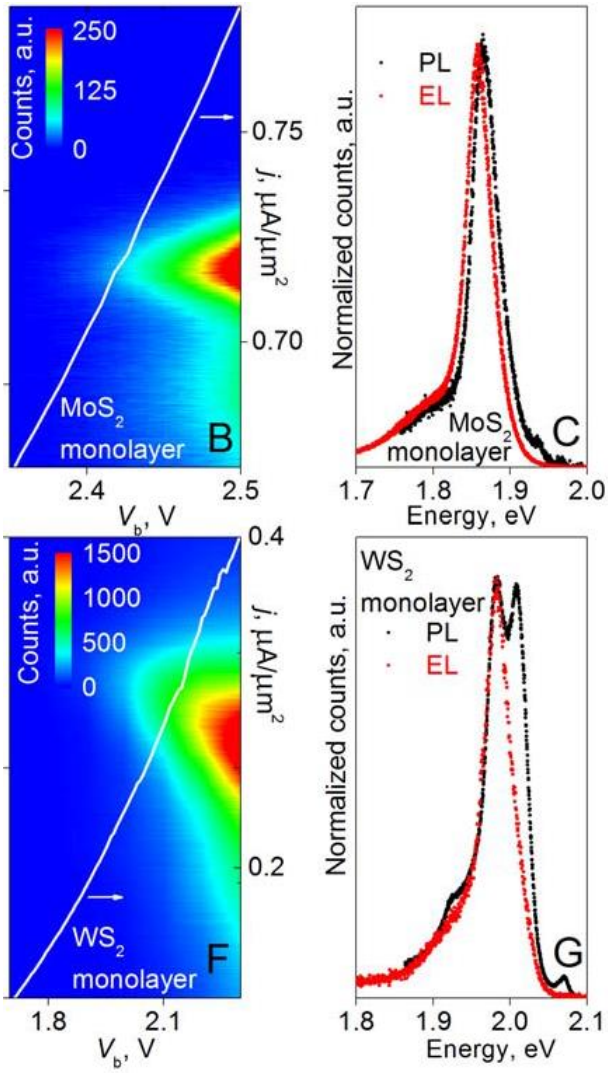

Fig. 2. EL spectra as a function of Vb for MoS2 and WS devices (B,F) and the omparison of the PL and EL spectra (C,G) for the same device.

The material tungsten diselenide (WSe2), is part of a class of single-molecule-thick materials under investigation for possible use in new optoelectronic devices — ones that can manipulate the interactions of light and electricity. By making diodes, it is possible to produce all three basic optoelectronic devices — photodetectors, photovoltaic cells, and LEDs. it should be possible to make LEDs that produce any color — something that is difficult to do with conventional materials. And because the material is so thin, transparent, and lightweight, devices such as solar cells or displays could potentially be built into building or vehicle windows, or even incorporated into clothing. On the Figure 2 we reproduce the luminescence characteristics of LED heterostructures based on MoS2 and WS2 [8].

Expanding charge-based microelectronics to take advantage of the spin and "valley" degrees of freedom is expected to increase computing power, reduce energy consumption, and enable the development of entirely novel devices.

Valley-tronics, as described above, is the manipulation of the population of degenerate low-energy valleys that are

exhibited in the band structure of some materials, including graphene and MoS2. Of particular relevance for electronic transport, these valleys are separated widely enough in momentum space that intervalley scattering is strongly suppressed.

Numerous applications demand the development of large area, flexible and conformal electronics. For example, wearable electronics require flexible displays, the cost of installing photovoltaic panels could be significantly reduced through the use of roll-to-roll processes, and "skin tattoos" with embedded electronic devices and sensors164 could revolutionize health care. However, there are several challenges limiting the traditional approaches for flexible and large area electronics. Two-dimensional materials, in general, could be an ideal choice for future flexible electronics [1]. By preparing the heterostructures on elastic and transparent substrates, it was shown that they can also provide the basis for flexible and semitransparent electronics. They tend to have excellent mechanical properties 2,3], can be prepared in polycrystalline form over large areas, can be transferred to arbitrary substrates.

The real diversity can be achieved if one starts to combine several such crystals in van der Waals heterostructures [1] Most attractive and powerful is the idea of band-structure engineering, where by combining several different 2D crystals one can create a designer potential landscape for electrons to live in. Rendering the band-structure with atomic precision allows tunnel barriers, QWs and other devices, based on the broad choice of 2D materials. Two-dimensional (2D) nanosheets, which possess atomic or molecular thickness and infinite planar dimensions, are regarded as the thinnest functional nanomaterials [3].

III. Topological Electronic States of TI Heterostructures

Topological insulators have unusual bulk properties that allow them to accommodate 2D electronic states on their surface. In TIs, strong spin_orbit effects create metallic electronic states on the materials' surfaces, while the bulk of the material remains insulating [5,6]. Furthermore, the surface bands of TIs have an interesting electronic property in which the spin of a surface electron is always perpendicular to its momentum. This extraordinary spin property does not allow electrons to be backscattered by impurities, suggesting electronic channels of high mobility. Gapless surface states in TIs originate from strong spin–orbit coupling in the bulk, and exhibit special electronic property of spin momentum locking due to time reversal symmetry.

TI nanostructures offer several advantages over their bulk counterparts for investigating the fundamental nature of the TI surface states and for a broad range of technological applications. The most obvious advantage of a nanomaterial is enhanced surface effects due to the large surface-to-volume ratio. At the same time there is another important advantage related to the nea physics of heterostructures combined by TI and others materials. In order to illustrate this aspect we analyze briefly the evolution of the topological surface states at the interface of TI with other materials.

We firrst analyze topological states bound to the nteface of TI and BI like PbTe/SnTe In Fig. 3 we show TIS energy dispersion of the [111] valley states formed at the PbTe/$Pb_{1-x}Sn_xTe$ heterointerface in the configuration of wide quantum well. The helical nature of these states can be seen by calculating the expectation values of spin operators , i.e. the spin vector is perpendicular to k, pointing clockwise (anticlockwise) for negative (positive) energy branch.

This helical nature of surface topological states of TI leads to new interface physics of heterojunction of two TI. In the case of two TIs, at the junction we expect a coupling between two surface states belonging to different TIs.

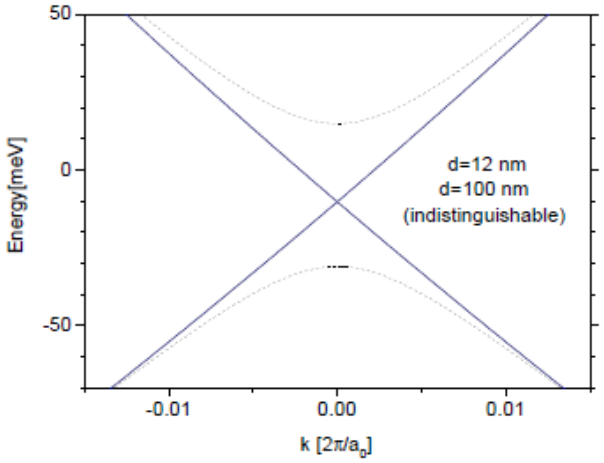

Fig. 3. Energy dispersion of TIS for PbTe/Pb0:54Sn0:46Te quantum well grown in [111] direction, with PbTe widths d of 12 and 100 nm (undistinguishable), plotted as a function of inplane wave k vector.

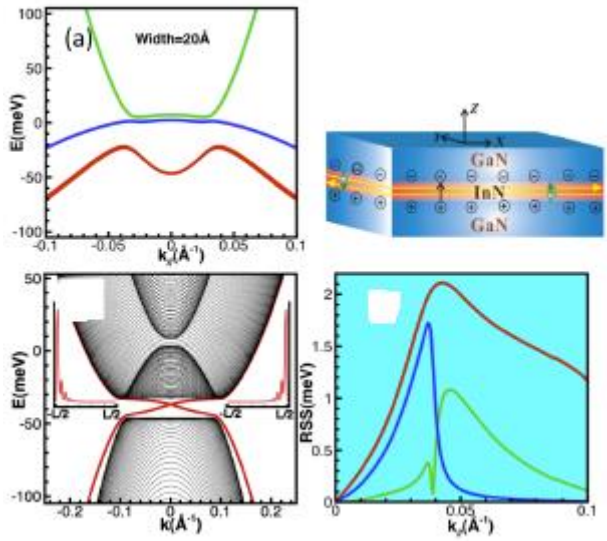

Fig.4 Band structure of a GaN/InN/GaN QW obtained on the basis of band kp model.

New aspect of TIS are generated in the topological insulator heterostructures with incorporated electrical polarization. To ilustrate the generation of TI states driven by the polarization field recently [9] the edge states of a Hall bar of GaN/InN/GaN quantum well have been analyzed (Fig.4). Another opportunity to tailor the TIS is offered by

the antiferromagnetic ordering of the materials, which constituted heterostructure

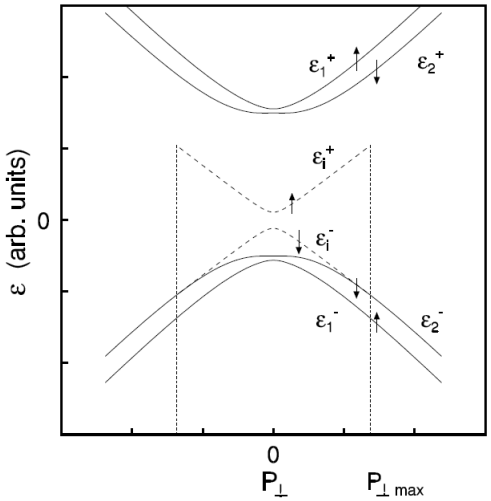

Fig.5 Energy spectrum of topological interface states in the heterostructure with antiferromagnetic ordering and electrical polarization.

We get that the interface states are situated nearer to the middle of the gap of the constituents (Fig.5). Thus if in the studied semiconductor heterojunctions the Fermi level, for example by means of doping, gets into one of the two-dimensional interface bands, then it leads to the magnetic ordering into the interfaceplane. The magnetic moment as it follows from the analysis is exponential attenuated moving away from the interface plane.

IV. Physical Basis for Ti-Based Efficient Devices

The most obvious aspect of TI and its characteristic TSS that can enable efficient devices is the **high mobility** of TSS expected from the ***topological*** described above. The high mobility surface state can be used as high conductivity (low resistivity) conduction channels with low joule heating, thus will be promising for low power dissipation (energy consumption) as either interconnect or transistor channels (where a gate is used to modulate the surface carriers and conduction). Topological insulators (TIs) have novel properties that may be exploitable for both conventional and novel device applications. While TIs are three dimensional (3D) materials, their electronic surface states are quasi-two dimensional (2D), with a gapless band-structure featuring Dirac cones much like graphene, although located at the Brillouin zone center, and fast carriers of perhaps half the velocity of those in graphene.

Recently [10] a scheme for a topological insulator field effect transistor. The idea is based on the gate voltage control of the Dirac fermions in a ferromagnetic topological insulator channel with perpendicular magnetization connecting to two metallic topological insulator leads. Theoretical analysis shows that the proposed device displays a switching effect with high on/off current ratio and a negative differential conductance with a good peak to valley ratio.

In addition to charge-based transport, the spin-momentum locked TSS with its spin polarized carriers may find important applications in spintronics (eg., as all-electric spin injectors based on TSS). Spin-based devices have the potential to further reduce energy dissipation related to conventional joule heating of charge transport. Perhaps the most intriguing features of TIs for device applications is the spin-helical locking of the surface states, which could make them a natural for spintronic device applications, providing a natural tool for translating between charge and spin transport. Thus, TIs could provide perhaps novel memory and switching possibilities, such as their own unique version of a giant spin Hall effect for spin transfer torque, while also allowing integration with conventional devices implemented in TIs.

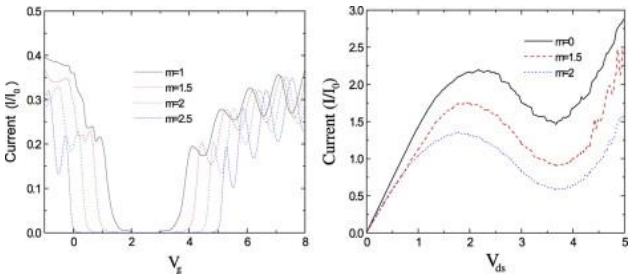

Fig.6. Transfer characteristics and output characteristics of the topological insulator field effect transistor

Based on this spin-momentum locking, a current flowing on the surface of a TI would be spin-polarized in a characteristic in-plane direction perpendicular to the current, and the spin-polarization would reverse when the current direction reverses. Observing such a spin-helical current in transport measurements is a major goal in TI research and applications. In [11] it is reported spin-dependent transport measurements in spin valve devices fabricated from exfoliated thin flakes of Bi2Se3 (a prototype 3D TI) with ferromagnetic (FM) Ni contacts. Applying an in-plane magnetic (*B*) field to polarize the Ni contacts along their easy axis, we observe an asymmetry in the hysteretic magnetoresistance (MR) between opposite *B* field directions. The observed asymmetric MR can be understood as a spin-valve effect between the current-induced spin polarization on the TI surface (due to spin-momentum-locking of TSS) and the spin-polarized ferromagnetic contacts. The results provide a direct transport evidence for the spin helical current in TSS. Optoelectronic measurements offer a unique way of probing topological surface states with a combination of ultrafast spectroscopy and electrical transport techniques. These integrated techniques enable the use of photon polarization to detect and manipulate helical spin texture as well as femtosecond time resolution of spin and charge dynamics using pump-probe optical spectroscopy. In addition, we can use advanced electrostatic gating geometries (e.g. top and bottom gates) to overcome intrinsic doping of the bulk by independently controlling the Fermi level of the top and bottom surface states. The goal of this research is to understand the fundamental properties of this exotic new class of quantum materials to further applications in novel topological insulator based electronics/photonics

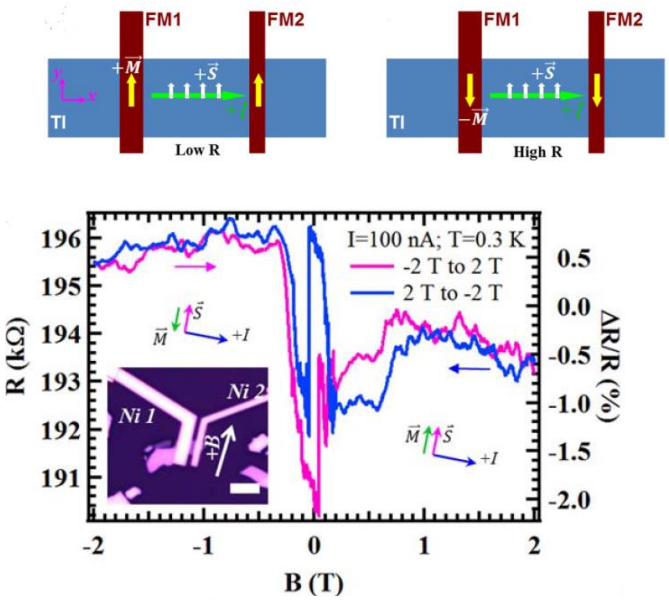

Fig.7 Scheme of the TI spin valve devices and MR characteristics.

Recent investigations [12] show broadband saturable absorption features at optical band, and even the microwave and terahertz band.

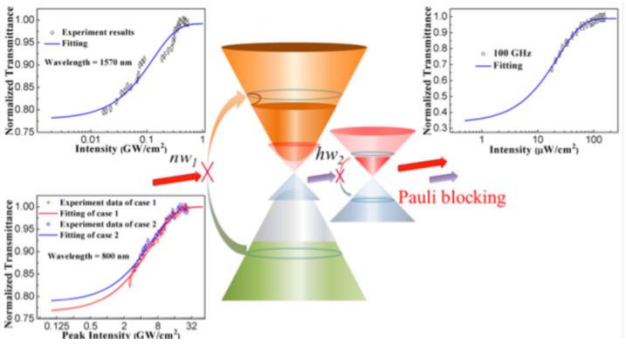

Fig.8 Saturable absorption curves and the schematic of two kinds of saturable absorption mechanisms in topological insulator: from surface state and bulk state.

Topological insulators (TI) are predicted to show a variety of very unusual phenomena when interfaced with magnetic and superconducting materials, ranging from induced magnetic monopoles, quantum anomalous Hall effect, Majorana and Weyl fermions, etc. Some of these exotic phenomena might be used for spintronics applications, magnetic recording and quantum computing, but problems with materials and very stringent constraints on physical parameters render the wide-spread applications extremely difficult. Additionally the surface states can play a role in energy science by enhancing thermoelectric effects in Bi2Te3 and Bi2Se3, which are well-known thermoelectric materials. [13]

V. Conclusions

We have briefly discussed an emerging trend in the study of 2D crystals which reveal interesting properties for potential applications. In particular, with graphene as the model system we have discussed the structural and electronic properties of some other 2D structural analogues of graphene such as silicene, germanene, h-BN, h-AlN and graphene/h-BN hetero-bilayer based on our current studies on these materials. ones. This provides us a flavor of the emerging new materials and their peculiar properties for potential novel applications. Understanding and tailoring the material properties of new and emerging materials at the nano-scale for desired applications are of great importance for fabrication and development of new and novel nano-devices. Considering that we are at the beginning of a new 2D era of material science, we should be interested for an entry into this new field of research, because the chances of success are high when a field is new. Due to their unique ability to form new electronic phase and generate new phase of the electronic systems at the surface and interface topological insulators stem at present in the center of materials and device physics investigations. Unique peculiarities of the topological surface states related to time-reversal symmetry, Dirac cones attributes of the spectrum and spin-momentum locking property open new gateway to reconfigure the electron systems at the contact of TI with BI as well as at the junction of two different TI. TSS in heterojunctions are converted in new type of two-dimensional electronic states – TIS - with very reach physics and new useful attributes to design electronic devices.

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