Topological Insulator Based Energy Efficient Devices

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ABSTRACT

Topological insulators (TI) have emerged as a new class of quantum materials with many novel and unusual properties. In this article, we will give a brief review of the key electronic properties of topological insulators, including the signatures for the unusual electronic transport properties of their characteristic topological surface states (TSS). We will then discuss how these novel properties and physics may be utilized for TI-based energy efficient devices, such as low-power-consumption electronics and high performance thermo-electrics. Furthermore, going beyond conventional single-particle, charge-based transport, to utilize coherent many-body coherent ground states such as excitonic condensates (EC), new and intriguing functionalities previously unexplored in electronic and energy devices may be realized with the potential to dramatically improve the energy efficiency.

Keywords: topological insulators, energy efficient electronics, transistors, thermoelectric, excitonic condensate

1. NOVEL ELECTRONIC TRANSPORT IN TOPOLOGICAL INSULATORS

1.1 Topological Insulators: a New Class of Electronic Materials with Exceptional Properties

Topological insulator (TI) (see review in [1,2]) is a new state of matter that has emerged in the last 2-3 years as one of the most actively researched subjects in condensed matter physics, with a wide range of physics and application potentials being explored or waiting to be explored experimentally. Conceptually, TI can be thought as a 3D generalization of 2D integer quantum Hall state (QHE) [3] and the surfaces of a TI are analogous to edge states of QHE, but without external magnetic fields (i.e. time reversal symmetry is preserved). Such a time-reversal symmetric (without external magnetic field) QHE-like state has been earlier studied theoretically and experimentally in 2D, particularly in HgTe quantum wells [4] , known as "quantum spin Hall state" (or 2D TI). Excellent reviews have been published on TI [1,2]. Below we briefly summarize some of key facts and properties about TI most relevant to our device applications.

The simplest "prototype" TI materials and the most commonly used ones in current TI research are Bi_2Se_3 & Bi_2Te_3 (which in fact for decades have been well known as thermoelectric materials and narrow-gap semiconductors) [1]. These 3D TI (illustrated schematically in Fig. 1) possess novel *topologically protected* (due to inverted band structure + spin-orbit interaction) *surface conducting states* even if the bulk is semiconducting (with a gap of ~0.3eV for Bi_2Se_3). Such "*topological surface states*" (TSS) have Dirac fermion dispersion (with some similarities but with also important difference with graphene) and support spin-polarized current (due to spin-orbit interaction induced spin-momentum locking) with high mobility and hold unique promise for low-power electronics, new spintronics and numerous other physics or application possibilities such as "axion" electrodynamics, topological quantum computing (majorana fermions, when interfaced with superconductors) and so on [1,2].

Electronic Properties of Topological Insulator Surface States. The key novelty of TI is on its surfaces, i.e., the "topological surface states" (TSS). Some key features of these surface electronic states and their relevance for device applications are summarized in Table 1:

1) They are "topologically protected" and (elastic) back scattering is suppressed in the absence of magnetic impurities. Such general immunity to various structural defects and imperfections (as long as nonmagnetic) give rise to expected high mobility of TI surface states and make them highly promising to be used in high speed/low power (low energy consumption) nanoelectronics.

2) They are gapless, consisting of linearly-dispersing (E vs k) Dirac fermions, with an *odd* number of Dirac cones (for simplest TI such as Bi_2Se_3, just one) on the surface. The Dirac fermion (linear dispersion) aspect is analogous to graphene [5] and could lead to novel, "relativistic" electronic devices utilizing the properties of such massless, Dirac

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electrons (eg. Klein tunneling, Veselago lensing etc.) [5]. On the other hand, there are also important differences from graphene (in which there are 2 Dirac cones, and electrons have both spin and valley indices, where electron momentum is tied to its "pseudospin" that comes from the sublattice degeneracy). Particularly, the pseudospin in graphene is now replaced by real spin in TSS (with spin-momentum locking) [6].

3) With strong spin-orbit coupling in these materials, in the surface states, the spin is "locked" relative to the momentum (displaying a "spin helical" pattern) [1,2,6]. A major consequence is that *a surface charge current is automatically spin-polarized* (reversing the current directions reverses the spins, and the polarization wraps around the whole surface helically, with the spin direction perpendicular to both the surface normal as well as electron momentum). This makes TI promising for electrically controlled spintronics applications (eg. as an "all-electrical" spin injector).

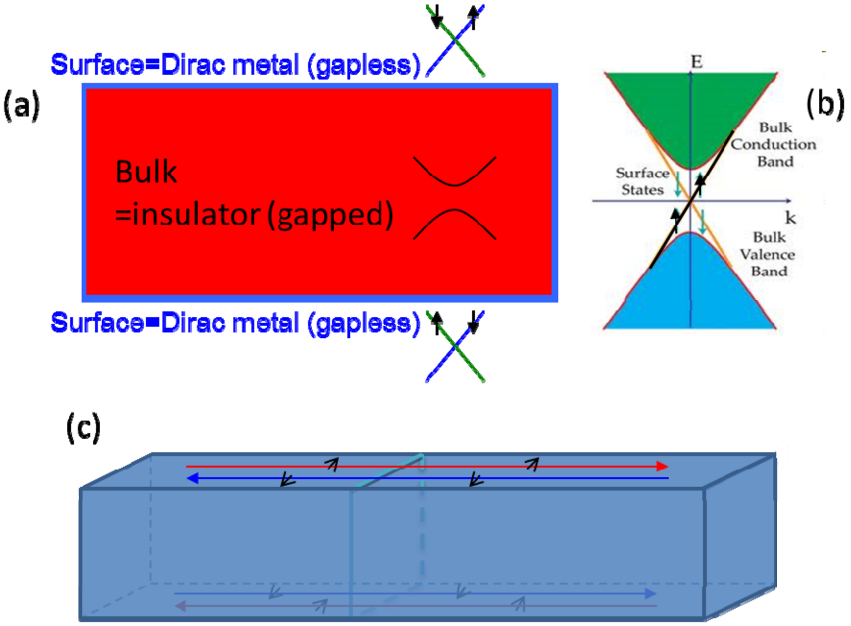

Figure 1. (a) Schematic of a topological insulator (TI), whose bulk is insulating, and whose surface has graphene-like conducting states, ie., the topological surface states (TSS). The surface state has spin-helical structure (spin-momentum locking, represented in c). (b) Schematic band structure of TI, with surface state bands (Dirac-like) residing between the bulk conduction and valence bands. (c) Schematic of spin-momentum locking and spin-polarized surface state. A surface current (long red or blue arrow) has in plane spin-polarization (indicated by black arrow), which reverses when current reverses. Opposite surfaces have opposite spin polarizations. The spin-current direction obeys left-handed rule.

Table 1. Some key properties of topological insulators and topological surface states with near-future device implications.

Topological Insulators: Key Properties & Practical Implications

Key Properties (Topological Surface State)	Benefits/Potential Device Applications
Topological Protection (reduce backscattering) [assuming time-reversal symmetry]	**High mobility/conductivity** (*FET*) [in the absence of magnetic impurities]
Dirac fermions (linear E-k dispersion: $E = \hbar v_F k$)	**Graphene-like physics and devices** (electron "optics")
Spin-momentum locking (in-plane spin polarization: $\hat{S} = \hat{k} \times \hat{n}$)	**Spintronics** (spin-polarized surface current, all-electrical spin-injection, etc.)

1.2 Accessing and revealing the transport signatures of topological surface state (TSS)

Ideally a topological insulator (TI) should have an insulating, undoped bulk with no charge carriers at low temperature, however experimentally most TI materials available today (eg., Bi_2Se_3 & Bi_2Te_3) have substantial bulk conduction, often due to a significant amount of unintentional doping in the bulk (eg. Se vacancies in Bi_2Se_3). This has been one major challenge for the transport and device studies of TI, as a highly conducting bulk would "short-out" the surface state conduction and mask the transport features associated with TSS (and not surprisingly, most of the experimental evidence for the TSS and TI properties have been first obtained using non-transport, surface-sensitive probes such as photoemission or scanning tunneling microscopy [1]). Thus in order to access, measure and utilize the unique electronic transport properties of TSS, the first key task is to reduce the bulk conduction, in order to enhance the contribution of surface state conduction. Several strategies have been used to accomplish this, including using various "doping engineering" in material synthesis to obtain low-bulk-doped TI crystals (eg. [7-9]), working with thin films (reduced bulk conduction, and using gating can further reduce the bulk carrier density) [10] etc.

The unique electronic transport features (related to the key properties listed in Table 1) of topological surface state conduction can be revealed in various ways, including the temperature dependence of resistivity (a good TI material should exhibit insulating behavior with conduction by metallic surface state at low temperature, eg [9]), Hall effect (deviation from standard linear Hall effect [8,9]), quantum transport features of 2D Dirac fermions such as SdH oscillations (exhibiting a "Berry's phase" [9,10]), as well as spin transport (probing spin-momentum locking) [11], etc.

2. TOPOLOGICAL INSULATOR BASED ENERGY EFFICIENT DEVICES

Defense Advanced Research Projects Agency (DARPA) started in 2011 three "MESO" programs dedicated to develop TI-based functional devices with ultrahigh performance and energy efficiency [12], such as TI-based interconnect, transistor and thermoelectric devices. Below we briefly review the physical attributes of TI that may generally enable energy efficient devices, in particular high performance thermoelectric devices (based on high-mobility TSS and even many-body coherent state such as excitonic condensation), which is the main focus of our Purdue-led MESO program.

2.1 Physical basis for TI-based energy efficient devices

The most obvious aspect of TI and its characteristic TSS that can enable energy efficient devices is the **high mobility** of TSS expected from the ***topological protection*** (reduced backscattering) 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). The topological protection reduces backscattering (which requires spin flip, due to spin-momentum locking, and is thus unlikely without magnetic impurities), although angled scattering is still possible and may limit mobility. In principle, the angled scattering can be further reduced by confining TSS into narrow 1D channel (eg. TI nanoribbons), promising further improved mobility (conductivity) or ballistic conduction. The topologically protected mobility (backscattering requires magnetic impurities or breaking time-reversal symmetry) would make such TSS channels *more immune to (nonmagnetic) structural imperfection*, a potential advantage compared to, eg., graphene and graphene nanoribbons (whose mobility can be severely reduced by backscattering caused by lattice defects, edge roughness etc.).

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.

Some of the most interesting opportunities for energy efficient devices emerge when TSS is *interfaced* with other nontrivial electronic/magnetic materials. For example, TSS interfaced with magnetism and magnetic materials may enable bandgap engineering (potential applications in low power transistors), dissipationless conduction channels based on quantum anomalous Hall effect [2] etc (such physics and devices are explored in the other DARPA MESO programs). Interfacing TSS with superconductors may further realize "Majorana fermions" [1,2] which may help realize fault-tolerant topological quantum computers.

Topological excitonic condensate (TEC). When one TSS is brought close to another TSS (either from the same TI, but the opposite surface, or from another TI) with opposite carriers, excitons (electron-hole pairs) may form and condense into an excitonic condensate (EC) (Fig. 2a) under appropriate conditions [13]. Such an EC is a coherent many-body state, and would be an electronic superfluid with dissipationless electronic transport, thus could enable ultralow power (and highly energy efficient) devices such as "BisFET" (first proposed for EC in graphene double layers) type transistors [14], dissipationless interconnects, and ultrahigh performance thermoelectric devices [15] (Fig. 2b). Such a "topological EC" is an important scientific objective currently being pursued by the Purdue-led DARPA MESO program.

2. 1A Topological Insulator Thermoelectric Devices

The high mobility TSS of TI can not only enable low power dissipation transistor or interconnect channels, it may also lead to high performance thermoelectric device (TED), including thermoelectric coolers or thermo-to-electric energy converters – both important devices for energy management, generation and efficiency. For TED, the performance is most commonly measured by the "figure of merit" (closely related to the TED efficiency) $ZT=S^2\sigma T/\kappa$, where S, σ and κ are the Seebeck coefficient, electrical conductivity and thermal conductivity of the channel, and T is the temperature [16]. The current state of the art ZT is around 1-3, and improving ZT to above ~6 could revolutionize thermoelectric technology. It has been realized that one key to improve ZT is to decouple electrical (σ) and thermal (κ) transport, and most of the progress in the past decades in improving ZT has come from strategies to reduce κ [16]. TI brings another strategy in this regard, as it can naturally decouple electrical transport (dominated by surfaces) from thermal transport (dominated by bulk). The high mobility TSS (high σ) can potentially enhance ZT in a TED based on TI surface state (see also several recent TI-based TED proposals utilizing high-mobility TSS to enhance ZT [17,18]; we also note that the most common TI material such as Bi_2Te_3 is already an excellent thermoelectric material currently employed in TEDs, though mainly based on bulk properties and not utilizing TSS). Even more dramatic enhancement of ZT (σ) may be attained in a proposed TI surface excitonic TED [15] using coupled complementary TSS as channels and based on superfluidic excitonic transport (Fig. 2b).

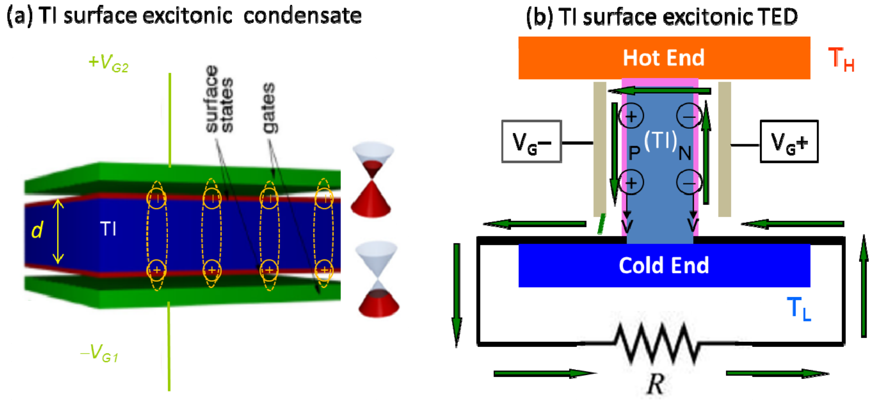

Figure 2. (a) Schematic of a topological excitonic condensate based on two coupled, complementary TI surfaces (figure based on Ref. [13]). (b) Schematic of a topological insulator surface excitonic thermoelectric device [15], based on counterflow electronic transport (excitonic transport) of two coupled p-type and n-type TI surfaces. Each surface is controlled by a gate to induce proper carrier type and density. High mobility TSS may enhance the ZT, and if excitonic condensate occurs, the superfluidic (dissipationless) electronic transport may further enhance the ZT dramatically.

2.2 DARPA MESO Program "Topological Insulator Coherent Energy Devices (TICED)"

Purdue Universities leads one of the TI-related DARPA MESO programs in partnership with 3 other universities (UT Austin, Princeton, British Columbia) and RTI International. Our program, "Topological Insulator Coherent Energy Devices", has two major goals: 1) Develop TI thermoelectric devices (TED) based on TI surface states, and use and control the high mobility TSS to achieve enhanced ZT; 2) Develop TI surface excitonic devices to realize excitonic condensate (EC), which may further and dramatically enhance ZT in a TI surface excitonic TED as proposed in [15] (Fig. 2b). Some of the prototype TI devices fabricated in this program are shown in Fig. 3, including a TI FET to control TSS (Fig. 3a), gated TI thermoelectric device to realize and study thermoelectric transport based on TSS (Fig. 3b), and a double-TI excitonic device (Fig. 3c, with some practical advantage over originally proposed [15] single-TI based excitonic device structure in Fig. 2a as it is more challenging to electrically isolate the two TSS's from a single-TI). These devices form the foundation to build and explore various tunable TSS-based TED and TI excitonic devices.

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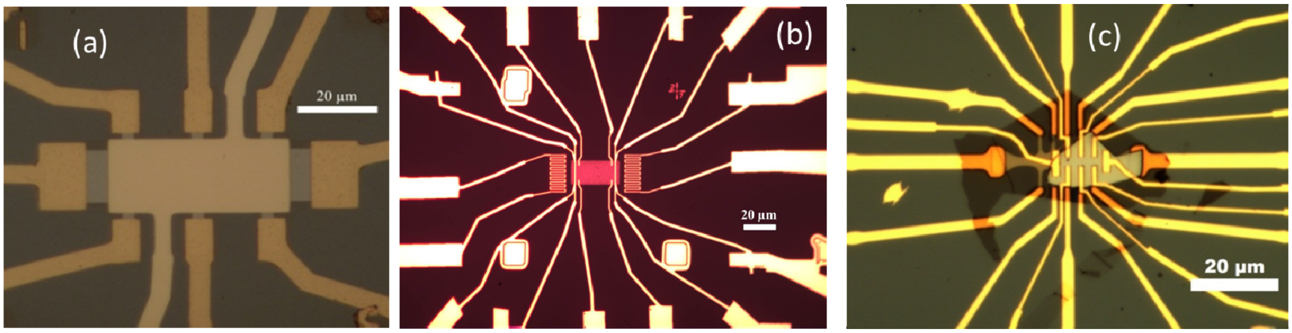

Figure 3. Representative TI devices fabricated in the Purdue-led DARPA MESO program “Topological insulator coherent energy devices”. Details of the devices and their performance will be published elsewhere. (a) A top-gated TI field effect transistor (courtesy T. Wu *et al.*, [19]). (b) A TI thermoelectric device with microfabricated heaters and thermometers (courtesy J. Tian *et al.* [11]). The device also has a back gate to tune the carrier density and bulk versus surface state conduction. (c) A double-layer TI excitonic device with two stacked TI films separated by a thin BN dielectric (courtesy T. Wu *et al.* [19]).

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