Topological Surface States: Science and Potential Applications
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ABSTRACT

Topological surface states are a new class of electronic states with novel properties. In this talk, I will review the properties of these novel quantum states and highlight some of their key properties that may be harnessed for potential applications. In particular, I will describe efforts in which combination of voltage controlled magnetism and topological surface states may be used to realize a novel low voltage transistor.

Keywords: Topological insulators, topological surface states, high mobility surface electrons

1. INTRODUCTION

In the last few years, through a set of theoretical and experimental developments, it has become clear that insulators can actually be divided into two categories. The first is the “ordinary” insulator such as diamond in which electrons fully occupy energy bands (which derive their character from atomic orbitals). The next available electronic states are rather far away in energy. This energy gap is what renders diamond and silicon insulating. The second group are the topological insulators, in which the energy gap between the occupied and empty states is fundamentally modified due to the spin-orbit interaction. The interaction between electrons’ spin and orbital angular momentum has its roots in the physics of relativity, where the electric and magnetic field can be interchanged depending on the vantage point of an observer. This interaction plays a role in materials composed of heavy elements such as Bi or Sb. In topological insulators, the spin-orbit interaction is so strong that the insulating energy gap is inverted—the states that should have been at high energy above the gap appear below the gap. This twist in the order of electronic states, like the twist in the Mobius band, cannot be “unwound” (this accounts for the topological nature of the new class of insulators). As a result, we have highly conducting metallic states on the surface—a feature not seen in ordinary insulators. Moreover, these surface states have been theoretically predicted and experimentally demonstrated to have electrical properties that are fundamentally different from other two-dimensional conducting states discovered to date. They are immune to backscattering from ordinary defects and can carry electrical currents even in the presence of large energy barriers that stop other electronic states. Underlying the novel properties of these topological surfaces states are their unusual spin texture (with the so-called π Berry phase) and their light-like (Dirac) energy-momentum relation. The prediction and confirmation of these novel electronic states have led to an explosion of activity in this area of physics. The findings may have a transformative impact on the future of electronic devices.

Collaborations between several groups at Princeton are responsible for a number of groundbreaking experimental work in the field of topological insulators during the last few years. Princeton groups have led the research in this field by providing the first confirmation of two-dimensional topological surface states and by demonstrating some of their fundamental and exotic properties. By combining high-resolution angle resolved photoemission spectroscopy with high quality crystal growth, experiments have unambiguously demonstrated the existence of topological surface states in a wide range of Bi and Sb-based compounds. [1-3] In particular, using the power of atomic scale spectroscopy with the scanning tunneling microscope (STM), we have demonstrated that topological surface states are immune to backscattering that strongly suppresses electrical transport for normal electronic states such as those of simple metals (as in a Cu wire).[4] Such experiments have also provided evidence that these states transmit through crystalline barriers that stop other surface states. [5] Finally, isolating the electrical transport through these states, relative to the current carrying states of the bulk of the samples, to show that they have high electrical mobility. [6] Together these discoveries point to a great potential for the use of topological surface states for electronic and optical applications and have attracted a great deal of attention from both the scientific community. [7-10]

The field of electronics based on topological surface states is yet to be realized. However, theoretical efforts over the last few years provide important guidelines as to how these novel states may be manipulated and providing a basis for considering device-like structure based on these states. In this paper, we provide an overview of one potential approach
to realize a low-power electronic device based on topological surface states. This work is still in its infancy and requires several key improvements to properties of topological insulators and their surface states.

2. NEED FOR LOW POWER TRANSISTORS & TOPOLOGICAL SURFACE STATES

The continuous improvement in performance derived from CMOS scaling over the past 40 years is coming to an end. While density scaling is expected to continue for at least the next ten years, transistor and circuit-level performance is now severely limited by power constraints. [11] Traditionally, CMOS power has been contained by reducing the operating voltage in each generation. Supply voltages have thus scaled significantly from the 5 V technologies used in the 1970’s to the ~1 V technologies found in manufacturing today. Further voltage reduction below 1V, however, is restricted by fundamental limits in threshold voltage and gate oxide thickness scaling. Without sufficient voltage scaling, CMOS power has thus increased to the point where laptops are lap-warriors, high performance computing is limited by the cooling power available, and mobile computing performance is limited by battery life. It is fair to say that a low voltage transistor would fundamentally change the world.

Given the possibility that topological surface states can have high mobility, it is important to consider the possibility that these states can be used to realize a low power transistor. Our approach relies on the fact that the energy spectrum of topological surface state can only be gapped when time-reversal symmetry is broken, as in the presence of a perpendicular magnetic or exchange field. [12-13] While this feature makes these electronic states immune to ordinary perturbations that disrupt surface states on conventional materials, it also provides a novel method to modulate electrical transport through the topological surface state. Figure 1 illustrates the concept behind modifying the electronic structure of topological surface states with Dirac-like energy dispersion when they are put in proximity to a magnetic insulator, the magnetic orientation of which can be manipulated. The key idea is that when perturbed with a perpendicular magnetic exchange field, the electronic structure near the Dirac point is gapped and transport through the topological surface state is turned off. This concept can be considered for possible use as a basis for a transistor device based on topological surface states.

2.1 Ferrimagnetic-Insulator-on-Topological-Insulator-Transistor Concept (FITT)

To realize a low-voltage transistor base in topological surface state, in a collaboration with researchers at Princeton, Penn, Penn State, IBM, and Cornell, we are aiming to combine advances in the discovery of topological surface states with another recently discovered effect—voltage control of the magnetic anisotropy of thin films. Recent work has shown that the application of a voltage bias can be used to rotate the magnetic anisotropy of thin ferromagnetic films from in-plane to out-of-plane by re-populating orbitals at the interface of the ferromagnetic film (Figure 4).[14-16] This phenomenon, if realized for an insulating ferro or ferrimagnetic layer, can be used to apply a controllable magnetic exchange interaction at the surface of a topological insulator. A schematic geometry of a Ferrimagnetic-Insulator-Topological Insulator-Transistor (FITT) is shown in Figure 2. The voltage-controlled magnetic exchange...
field of the ferrimagnetic insulator would modulate the current through surface states of the topological insulator. The FITT is in the on-state when the magnetic anisotropy lies in the surface plane and in the off-state when it is rotated perpendicular to the surface of the topological insulator, where it induces a gap in the energy spectrum of topological surface states. For the largest on/off ratio, the chemical potential of the topological insulator should be tuned close to the Dirac point in the energy spectrum of the topological surface state, about which the magnetism-induced gap is centered. The size of the energy gap will be proportional to the strength of the exchange interaction at the interface, which will determine the leakage current through the FITT device in the off-state and its dissipation in this state.

The topological insulator device, such as FITT described here, is a fundamentally new approach to pursue post-CMOS technology. Although recent advances in carbon nanotubes and graphene have also created new opportunities and inspired novel schemes for the realization of carbon-based transistors, most of these approaches still exploit concepts similar to those used in today’s conventional transistors. The FITT device described here relies on new quantum effects. At the heart of the FITT are the current-carrying Dirac electronic states at the surface of a topological insulator. Graphene also possesses Dirac electrons, and its electronic transport properties rely on the A-B sub-lattice difference that gives rise to a breaking of pseudo-spin degeneracy. In contrast to graphene, the high mobility flow of electrons in topological surface states should be sensitive only to breaking of time-reversal symmetry, a feature that we exploit in the FITT device by controlling magnetic anisotropy. Again, this type of current modulation is fundamentally different from electronics based on molecular, nanotube, or graphene-based approaches. The opening of the exchange-induced gap in a topological surface state is a new phenomenon that has no parallel in conventional electronics. Finally, the gating approach we propose to use in our device also relies on a newly discovered phenomenon, namely voltage control of the magnetic anisotropy of thin films. Extension of this discovery to magnetic insulator thin films operating at low-voltages will provide the key element to realize the FITT device. The FITT is in the on-state when the magnetic anisotropy lies in the plane surface and in the off-state when it is rotated perpendicular to the surface of the topological insulator, where it induces a gap in the energy spectrum of topological surface states. For the largest on/off ratio, the chemical potential of the TI should be tuned close to the Dirac point in the energy spectrum of the topological surface state, about which the magnetism-induced gap is centered. The size of the energy gap will be proportional to the strength of the exchange interaction at the interface, which will determine the leakage current through the FITT device in the off-state and its dissipation in this state.

2.2 Challenges in realization of FITT device

The ability to construct the FITT device relies on the optimization of the topological insulator material to achieve high surface to bulk conduction ratio. This is a current fundamental limitation to all proposed approaches for device development based on these materials. The conductance ratio has a fundamental impact on the on/off ratio of the FITT device as well as its off-state power dissipation. The key problem is that many of the topological insulator materials discovered to date are small band gap semiconductors, hence small number of bulk defects give rise to bulk conduction through non-topological states, and hamper the performance of any device based on topological surface states. In the last year, we have made significant contribution to solving this problem by first applying various growth techniques (such as Bridgman and zone-refining) to crystal growth as well as search and discovery of new topological insulators with smaller carrier-donating defects. For example, recent efforts at Princeton have lead to discovery that Bi$_2$Te$_2$Se is a topological insulator with bulk resistivity exceeding 6 ohm-cm at low temperatures. [17]

The second major challenge in realizing the FITT device is the development of voltage controlled magnetic exchange gate. While the phenomena of voltage induced change of magnetic anisotropy has been demonstrated for metallic systems, it has not been extended to magnetic insulator, which would be required for the current project. Finally, the successful integration of a magnetic insulator material with topological insulators is the other key component needed to realize the proposed FITT device. The choice of material and the quality of the interfaces will strongly influence the size of the magnetic exchange gap, and hence will directly impact the device metrics. For example, using molecular-beam-epitaxial methods to grow topological or magnetic insulators will provide sharp interfaces that would be required for the proposed device.
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REFERENCES