EMERGENT MULTIFUNCTIONAL NANOELECTRONICS BASED ON OXIDE COMPOUNDS AND TOPOLOGICAL INSULATOR MATERIALS

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Abstract. *With the recent development in material growth method including molecular beam epitaxy, pulsed laser deposition and metalorganic chemical vapor deposition, atomically engineered oxide and other materials like topological insulators become available, thus opening the door to the novel emergent nanoelectronics and nanospintronics. Some aspects of emergent multifunctional nanoelectronics based on oxide compounds and topological insulator materials are highlighted. The oxide multiferroics are characterized by an interesting new physics and they provide possibilities for applications in modern and future nanoelectronics. The underlying magnetic and electrical properties of a bulk system can change significantly when confined to a thin film and nanoheterostructures. Nanoscale lateral confinement of a quasi–two-dimensional electron realized at a lanthanum aluminate–strontium titanate interface is illustrated for transistor applications. Nanodevices operating as a hot-electron transistor (HET) and permeable-based transistor (PET) in the common-base in the heterostructure of (001)-oriented SrTiO3(STO)/La0:7Sr0:3MnO3 (LSMO)=Nb:STO, is analysed. The discovery of topological insulators has become one of the most exciting recent developments in condensed matter physics and they become the materials platform for a new emergent multifunctional nanoelectronics and nanospintronics. The surfaces of topological insulators enable the transport of spin-polarized electrons while preventing the "scattering" typically associated with power consumption. Because of such characteristics, these materials hold great potential for use in future transistors, memory devices and magnetic sensors that are highly energy efficient and require less power. The first step to field effect transistor is illustrated for Bi2Te3 nanoribbons. The device potential for topological insulator nanotubes are analyzed. New memory device concept based on the intrinsic topological insulator attribute- Berry curvature is revealed.*

Keywords: *multifunctional nanoelectronics*, *nanospintronics, topological insulato,r memory device concept,*

I. Introduction

Semiconductors have been the workhorse of modern electronics industry for decades. To obtain ever higher device integration densities, the size of metal-oxide-semiconductor field-effect transistors (MOSFET) have been successfully reduced in scale for over four decades, in accordance with Moore's law. Now, due to the intrinsic limitations, the scaling of MOSFET devices is truly reaching fundamental limits. Alternative device concepts are necessary not only to maintain the increase of integration intensity but also to promote the integration of greater functionality.

Needless to say, there have been a huge number of scientists and engineers keep pushing the progress of IC technology, resulting in a numerous improvements in all aspects of science and engineering, i.e. materials, device structures, processes, manufacturing methodology, infrastructures, guided by the Moore's law. There is, however, widely shared concern today that as we approach future technology nodes beyond sub-20nm, diminishing return in device performance and density

combined with serious increase in on-chip power consumption have forced us to seek even broader scope of research and development for possible alternatives beyond simple scaling of the minimum etc, which might capture unique positions in either or both in main stream integrated circuits and uniquely new application spaces such as bio-medical, energy and environment with further in-depth understanding and technological break-through for controlling their haracteristics.

With the recent development in material growth method including molecular beam epitaxy , pulsed laser deposition and metalorganic chemical vapor deposition, atomically engineered oxide and other like topological insulator interfaces become available, thus opening the door to the novel emergent nanoelectronics and nanospintronics.

The broad and enthusiastic study of oxide magnetoelectric multiferroics, materials developing simultaneous magnetic and ferroelectric structures, is motivated evenly also by the rich physics underlying the spin-charge ordering in these materials and their potential application for pioneering new devices [1]. The oxide multiferroics are characterized by an interesting new physics and they provide possibilities for applications in modern and future nanoelectronics. The underlying magnetic and electrical properties of a bulk system can change significantly when confined to a thin film and nanoheterostructures. From a practical experimental standpoint, it is generally easier to apply large electric fields to thin film samples rather than bulk crystal, because these require relatively smaller bias voltages. Several aspects of emergent nanoelectronics based on manganite oxide materials are reviewed in the first part of the paper.

Because of their potential application in spintronic devices such as next-generation spin-based transistors, the quest for new materials with significant spin-orbit interactions in the electronic ground state is an area of intense research. Spin-orbit interactions mixes up- and down-spin states and, in the context of spintronics, can be quantified by an admixture parameter in the electron and hole states. Since the spin-orbit interaction increases rapidly with atomic number, materials containing heavy elements are natural candidates for this field of inquiry. A novel oxide material containing heavy Iridium atoms displays remarkable properties dominated by spin-orbit interactions in the Iridium 5d valence states. Several compounds of these materials are identificated as topological insulators [1].

More than three decade ago there was established that spin-orbit interaction (SOI) has an important pattern on band structure of solid state matter. Among different qualitative features induced by SOI the band inversion of electronic spectrum near the Fermi level has been discovered. Such type of electronic spectrum was identified in different type of semimetalic and narrow-gap semiconductors Bi1-xSbx, Pb1-xSnxTe, Bi2Te3, HgTe, TlBiTe2 etc. In the context of low dimensional structure investigations geometry.Applications of mechanical strain to silicon MOSFET channel for improved transport characteristics, introduction of high k/metal gate, material alternatives for conductive channel of silicon MOSFET such as germanium and/or III-V semiconductor, intensive study for partial replacement of on-chip interconnects with optical interconnect, new memory phenomena

thereby feasibility of new memory devices such as phase change, resistive switching in chalcogenides, metal oxides, polymers etc are only a part of such efforts. Also mentioned should include a variety of "nano" materials such as carbon nanotube, graphene, topological insulator

the band spectrum inversion was shown to generate new type of interface gapless states with linear spectrum at the heterocontact boundaries. Last years investigations [2] have reopened the interest to materials with inverted band spectra. Due to new type of the symmetry break like that characteristic for the integer and fractional quantum Hall effects the electronic states was shown to have topological nature and materials have been named toplogical insulators (TI). In these materials new state of condensed matter is realized and on their basis a new platform for nanoelectronics and spintronics is developed in the last years. In TI a new state of matter appear, distinguished from a regular band insulator by a nontrivial time-reversal topological invariant, which characterizes its band struc-

ture, and non-trivial interplay of charge and spin degree of freedom of band electrons. In results new physics and phenomena related to this states have greatly emerged. Several of such new TI properties are reviewed in the last part of the paper as well as some emergent nanoelectronics and nano-spintronics applications.

II. Oxide materials

Oxides exhibit an extremely wide variety of electrical, magnetic and optical properties, including superconductivity, piezoelectricity, ferroelectricity, pyroelectricity, ferromagnetism and multiferroicity. Transition metal oxides, which are strongly correlated electronic systems, are particularly fascinating [1,3]. Their properties result from strong interactions between spin, charge, orbital and lattice (Fig.1). The several competing states give rise to complex phenomena and rich phase diagrams.

But where does this broad range of phenomena come from? For a start, the bonds between the ions in an oxide crystal tend to have a more polar character than in a conventional semiconductor such as silicon, which means that the electrons have stronger interactions with each other; they are said to be correlated. Moreover, the crystal structure of oxides is highly adaptable to changes in composition — many different chemical elements can be incorporated into the prototypical perovskite structure. This can not only be used for a very broad tuning of the carrier density in the crystal through doping, but it also increases the design flexibility in crystal composition. The latter is crucial to the development of improved materials such as ionic conductors for electrochemical applications, and moreover facilitates a wide range of different oxide compounds that can be deposited on top of each other in thin-film devices.

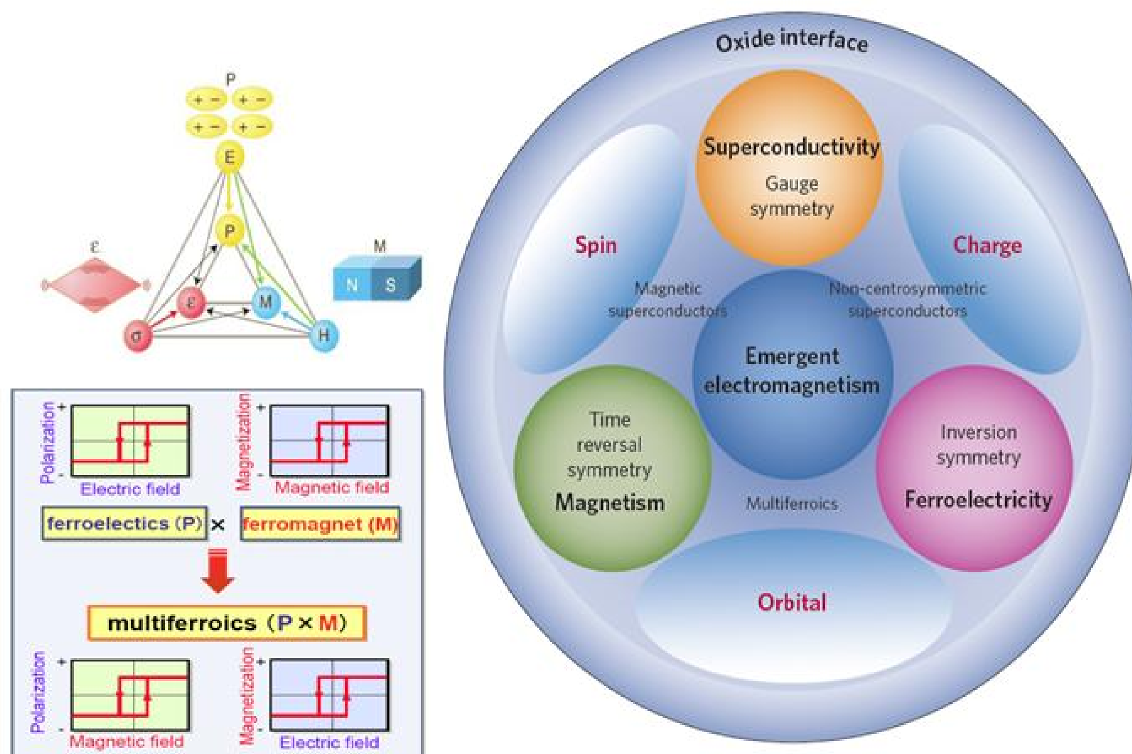

Fig.1 Schematic diagrams showing the correlated electron systems in oxides

Transition metal oxides (TMOs) are ideal for the study of electron correlations, because the transition metal s electrons are transferred to the oxygen ions, and the remaining strongly correlated d electrons determine their physical properties such as electrical transport, magnetism, optical response, thermal conductivity and superconductivity. These electron correlations constrain the number of electrons at a given lattice site, and induce a local entanglement of the charge, spin and orbital degrees of freedom. This gives rise to a variety of phenomena, for example, Mott insulators, various charge, spin and orbital orderings, metal–insulator transitions, multiferroics and superconductivity1. In recent years, there has been a burst of activity to manipulate these phenomena, as well as to create new ones, using oxide heterostructures [4].

The working definition of a complex oxide is an inorganic solid consisting of more than one metal cation and oxygen anions. The simplest of the complex oxides contain (only) two metal cations in distinct, well-defined sublattices. For example, the perovskites have the formula ABO_3, where twelve-coordinate A-site cations are at the corners of the unit cell (u.c.), six-coordinate B-site cations are at body center positions, and six-coordinate O anions are at face-center positions. The structural and compositional diversity of complex oxides is realized by the ease with which different metal cations that can be placed within the A- and B-site sublattices. For instance, the A sites can be populated by mixtures of alkaline earth and rare earth cations, and the B sites can be occupied by first and second row transition metal cations. The wide range of functional properties exhibited by complex oxides is then a direct consequence of the chemical identity of the constituent cations and the associated structural distortions.

Perovskite oxides are a large family of materials of great fundamental and applied interest. In many cases, the structural and lattice-dynamical features of the compounds are critical to determine their properties. A transition metal ion (M) in perovskite like materials $LnMnO_3$ is surrounded by six oxygen ions, which produce a crystal field acting on M with cubic symmetry. As a consequence, the originally five-fold degenerate 3d orbitals are split into three-fold degenerate t_{2g} orbitals (xy, yz, zx orbitals), and two-fold degenerate e_g orbitals (x^2-y^2, $3z^2-r^2$ orbitals). These orbitals have a different sign for the wavefunction depending on the radial direction, which sometimes results in the cancellation of the overlap integrals with the p orbitals of the O ions between two neighbouring M ions. Perovskite-like manganites $La_{1-x}Ca_xMnO_3$ (LaCax) exhibit a variety of physical properties depending on the Ca concentration x. The strong correlation among the magnetic, electronic, orbital and transport properties of manganites makes these systems particularly sensitive to external perturbations, such as temperature variation, application of stress or high pressure.

Most notably, this is the case of ferroelectric perovskites, whose spontaneous polarization is usually the result of a tructural phase transition and related compounds such as magnetoelectric multiferroics { whose properties can be greatly enhanced by engineering the lattice response to external fields. Exhibiting a wide range of phenomena such as magnetism, superconductivity, ionic conduction and ferroelectricity, oxide materials are finding yet multiple applications.

3. Oxide Nanostructures and Nanoelectronics

Progress in oxide thin-film growth technology during the past decade has led to a large number of breakthroughs. The range of functional properties that can be achieved in bulk complex oxides by mixing and matching cations generates tantalizing possibilities when considering single layers and superlattices prepared by epitaxial thin-film growth techniques. By combining a high degree of stoichiometric control with the reduced dimensionality in the growth direction achievable by ultrathin film and small-period superlattice growth, it is in principle possible to create artificially structured materials with novel properties not realized in the bulk. For example, $LaAlO_3$ and

SrTiO3 are electrical insulators, but, grown on top of each other under the right conditions, they form a highly conducting layer at their interface.

Oxide interfaces are of interest because in many transition-metal compounds the electrons are strongly correlated: the motion of one carrier depends crucially on the motion of all the others. Strongly correlated electron systems support interesting and potentially useful effects, including magnetism with high Curie temperatures, superconductivity with high transition temperatures, metal– insulator transitions and multiferroicity.

The rapidly improving expertise in the fabrication of oxide interfaces promises a greater ability to investigate, optimize and control correlated electron behaviour by varying chemical composition, lattice strain and precise crystal structure, and carrier confinement in ways that previously would have been impossible.

Oxide interfaces are characterized by higher areal carrier densities and much shorter electron confinement lengths than conventional semiconductor interfaces, possibly opening up new device modalities beyond those arising from the correlated electron properties Recently nanoscale lateral confinement of a quasi–two-dimensional electron gas was demonstrated at a lanthanum aluminate–strontium titanate interface [4]. Control of this confinement using an atomic force microscope lithography technique allows to create tunnel junctions and field-effect transistors with characteristic dimensions as small as 2 nanometers. On the basis of the experimental finding that nanoscale conducting regions can be created and erased using voltages applied by a conducting AFM probe, various multiterminal devices have been constructed. The writing and erasing process allows for a remarkable versatility in producing quantum mechanical tunneling barriers (Fig.2). Scanning with a negative bias restores the insulating state, presumably by shifting the local density of states in the SrTiO3 upward in energy (24), thus providing a barrier to conduction (Fig.2, inset). I-V curves are acquired after each pass of the tip. All these I-V characteristics are highly nonlinear (Fig. 1D), showing vanishing conductance at zero bias, and a turn-on voltage Von (defined as the voltage for which the current exceeds 10 nA) that increases monotonically with tip voltage (Fig. 1).

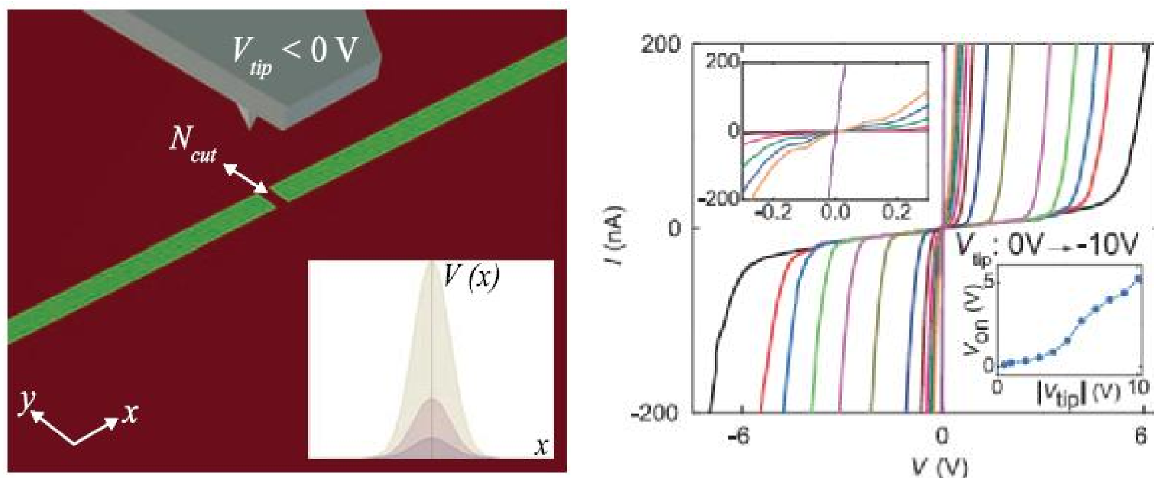

Fig.2. Sketch illustrating how a potential barrier is created in LaAlO3-SrTiO3 heterostructures by scanning a negatively biased AFM probe. Inset: Sketch of the barrier potential. I-V characteristics

The developed nanoscale structures are representative of a versatile family of nanoelectronic devices operating at the interface between a polar and a nonpolar oxide insulator. The conducting nanostructures have dimensions comparable to those of single-walled carbon nanotubes, yet they can be freely patterned and repeatedly modified. Their ultimate suitability for logic and memory applications will depend on a variety of factors, such as the mobilities of the charge carriers, how effectively power dissipation can be minimized, and whether this system can be integrated with sili-

con.

A nanodevices operating as a hot-electron transistor (HET) and permeable-based transistor (PET) in the common-base configuration were elaborated [5] in the heterostructure of (001)-oriented SrTiO3(STO)/La0:7Sr0:3MnO3 (LSMO)=Nb:STO (Fig. 3).

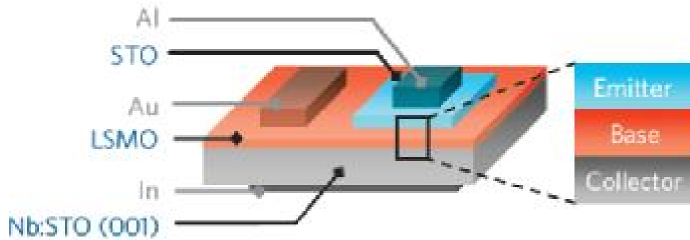

Fig.3 A schematic illustration of heteroepitaxial perovskite metal-base transistor

In the HET electrons are injected from the BE junction across the base and above the BC Schottky barrier (Fig. 4). Characteristics of the HET device operating in the common-base configuration are shown in the Fig.4, IC is measured as a function of the collector voltage (VCB) at different fixed values of IE. An important characteristic feature of HETs is complete electrostatic screening by the base. Because the emitter and collector are separated by the base metal, VCB is fully screened and has no feedback on VEB in the common-base output characteristics as shown in Fig.4.

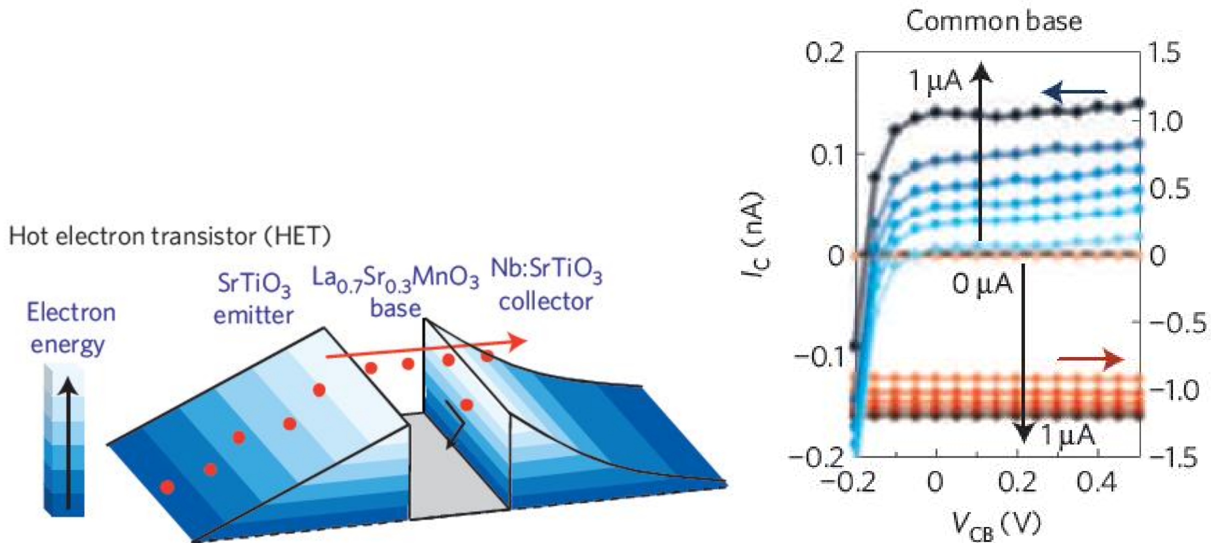

Fig.4. Schematic illustration of the HET and its common-base output characteristics and voltage feedback.

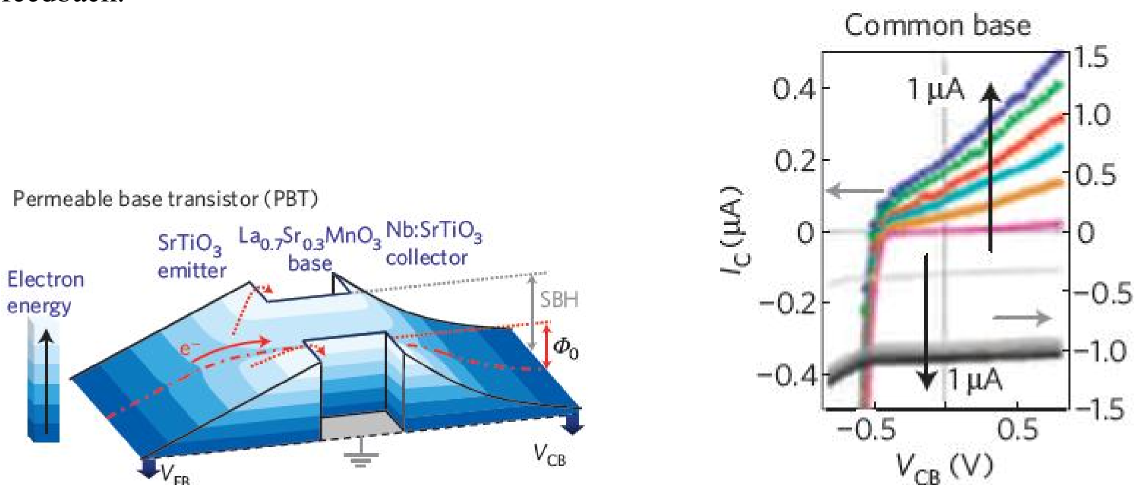

Fig.5. Schematic illustration of the PBT and its common-base output characteristics and voltage feedback.

As a representative example, the common-base output characteristics and voltage feedback for a permiable base transistor are shown in Fig.5.

Thus a new three- terminal device platform was demonstrate for perovskite oxide heterostructures, which should prove useful for hot-electron spectroscopy of heterostructures incorporating strong electron interactions and quantum wells, as well as magnetically active junctions. In the hot-electron regime, the low current gains are far from commercial relevance as basic transistors, and they are comparable to those of metal-base spin-valve transistors.

4. Topological Insulator Materials

An ordinary insulator such as glass cannot conduct electricity because electrons are not free to move through the material, but physicists have recently discovered a special type of insulator that behaves some what differently. The electrons inside or in the bulk of these 'topological insulators' behave like the electrons in conventional insulators. However, topological insulators have surface states in which electrons can flow as easily as in a metal.

The discovery of topological insulators has become one of the most exciting recent developments in condensed matter physics [6-7]. Topological insulators are electron systems with a bulk gap and gapless edge states which are robust at presence of time- reversal symmetry. In two-dimension, a topological insulator has counter-propagating edge states with opposite spin polarization. Since the edge states carry unidirectional spin current, this state is also known as the ''quantum spin Hall (QSH) insulator'' [6]. The key reason that the QSH insulator is a new state of matter is that the back-scattering between left and right moving edge states is forbidden due to Kramers degeneracy [6]. The suppression of back-scattering can be understood intuitively as a con- sequence of perfectly destructive interference between two back- scattering processes in which the spins are rotated clockwise and counter-clockwise [7]. The surface state of a simplest three-dimensional topological insulator is a 2D ''Dirac fermion'' with linear dispersion and spin locked with the direction of velocity, which is a direct generalization of the QSH edge states. The same argument of back-scattering suppression holds for the surface states of three- dimensional topological insulators.

Because topological order is a global, non-local property, it is rather difficult to measure in the general situation. In a few important cases, such as the integer and fractional quantum Hall effects, and the topological insulators, the topological properties give rise to certain quantized responses [6-7]. These examples have topologically protected gapless boundary modes that dominate the responses. However, often there is no obvious ''nice'' response that can be computed or observed in experiment. The entanglement entropy and the entanglement spectrum have emerged as two important measures of the quantum entanglement and the topological properties.

One important result to emerge from the study of the ES of topological insulators is that a gapless ES can persist under some conditions where the physical edge spectrum becomes gapped. For example, applying a magnetic field to an topological insulator will gap the surface states but leave the entanglement spectrum gapless. These exotic properties result from the combined effect of spin–orbit interactions and time-reversal symmetry, and thus topological insulators are usually composed of heavy elements (Bi, Se, Te, Hg and so forth) because the larger nuclear charges of such elements lead to stronger spin–orbital coupling.

5. Topological Insulator Nanoelectronics and Nanospintronics

Perhaps most importantly, the surfaces of topological insulators enable the transport of spin-polarized electrons while preventing the "scattering" typically associated with power consumption,

in which electrons deviate from their trajectory, resulting in dissipation. Because of such characteristics, these materials hold great potential for use in future transistors, memory devices and magnetic sensors that are highly energy efficient and require less power. Bismuth telluride and selenide are well known as a thermoelectric material, but recently was also estblish to be a three-dimensional topological insulator with robust and unique surface states [6,7]. Recent experiments with bismuth telluride bulk materials have also suggested two-dimensional conduction channels originating from the surface states. But it has been a great challenge to modify surface conduction, because of dominant bulk contribution due to impurities and thermal excitations in such small–band-gap semiconductors. Experimental evidence for the modulation of such surface states by using a gate voltage was tested in Bi2Te3 nanoribbons [8]. The nanoribbon acts as the channel in the device and is connected to electrodes made of titanium and gold (Fig. 1). In such a device, the gate voltage controls the Fermi level, and therefore the carrier density, of the material. If the Fermi level is moved into the gap between the bulk conduction and valence bands, then the transport properties of the FET are completely governed by the surface states and can be clearly seen. The new findings shed light on the controllability of the surface spin states in topological insulator nanoribbons and demonstrate significant progress toward high surface electric conditions for practical device applications.

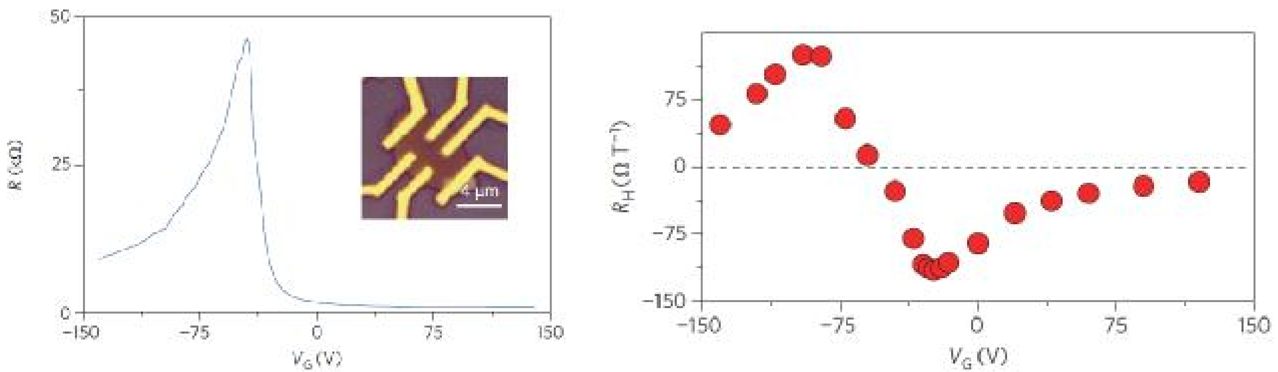

Fig. 6 Ambipolar field effect in ultrathin nanoplates of (BixSb1–x)2Te3

Another variant to assure high surface electric conditions can be realised in the topological insulator nanotube [9]. Due to a high surface-to-volume ratio, a variation in the ratio of the nanotube external radius to internal radius provides a 50-fold decrease in the topological insulator band gap compared to the respective bulk value (Fig.7).

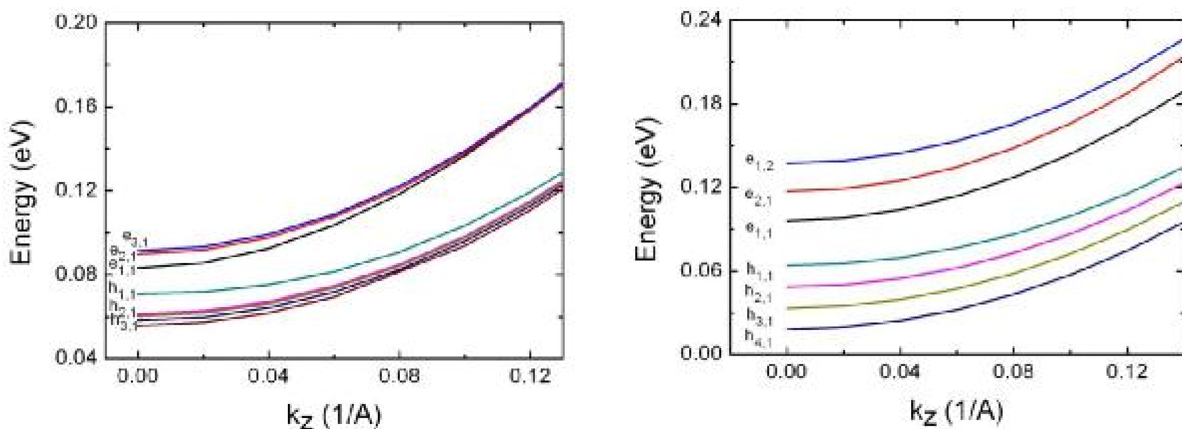

Fig.7 Electronic structure of TI Bi2Te3 nanotube with an external radius of 60 nm and interrnal radius of 10 nm (left) and nanowire with a radius of 10 nm (right)

The size dependence of the topological insulator nanotube band gap is much stronger than that for the topological insulator nanowires (Fig.7). The topological surface atatesforming inside the bulk gap (Fig.4) corresponds to one dimensional bands indexed by total angular momentum.   .

New memory device concept on the TI was proposed using the intrinsic TI attribute- Berry curvature [10]. The basis for proposed device is the Hall effect mediated by the k-space Berry curvature in the presence of spin-orbit coupling. In TI-based magnetic memory cell a bit is stored via the exchange coupling of the TI surface states. The magnetism induces a finite k-space Berry curvature in thesurface states, thereby driving the Hall effect (Fig.8).The readout (Hall) voltage of the cell is related directly to the Hall conductivity, which is highly sensitive to the magnetization of the surface (i.e., the stored bit) but which is insensitive to weak disorder, cell imperfections, and cell geometry. The memory cell is illustrated in Fig. 8, based on a 3D TI block (e.g., Bi2Te3, Bi2 Sb3, Sb2Te3). In memory cell, a bit is stored by the magnetization M of the FM-doped TI surface, with, say, a ''1'' (''0'') being stored by an upward (downward) pointing M. Writing to the cell would require a writing field whose field strength exceeds the magnetic coercivity of the surface.

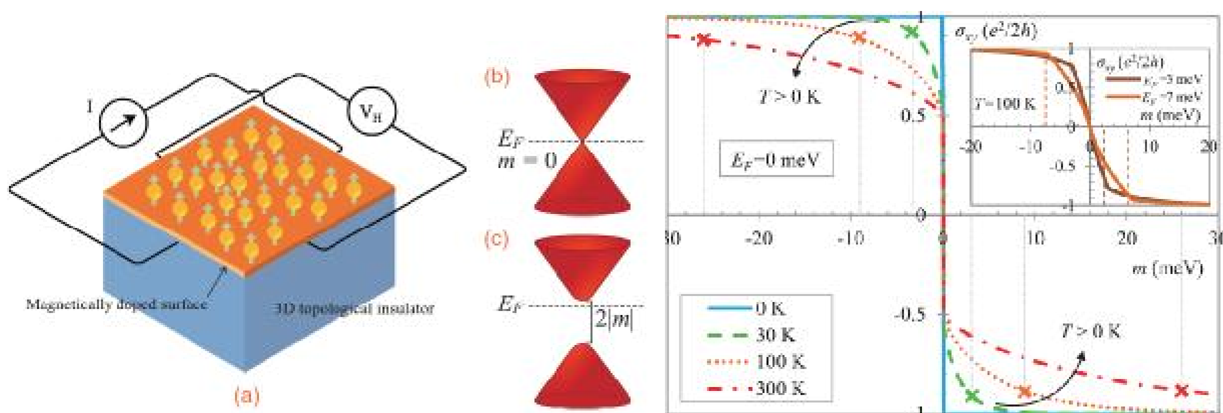

Fig. 8. Structure of proposed memory cell, based on a TI block with amagnetically doped surface (left) and Hall conductivity as a function of magnetization for various temperatures.

6. Conclusions

Oxide and topological insulator nanoelectronics is a area of rapid improvement and discovery and can offer new routes to solve the problems of chip integration as well as to develop efficient multifunctional nanodevices.

The crystal structure of oxides is highly adaptable to changes in composition — many different chemical elements can be incorporated into the prototypical perovskite structure as example. This can not only be used for a very broad tuning of the carrier density in the crystal through doping, but it also increases the design flexibility in crystal composition. The range of functional properties that can be achieved in bulk complex oxides by mixing and matching cations generates tantalizing possibilities when considering single layers and superlattices prepared by epitaxial thin-film growth techniques. By combining a high degree of stoichiometric control with the reduced dimensionality in the growth direction achievable by ultrathin film and small-period superlattice growth, it is in principle possible to create artificially structured materials with novel properties not realized in the bulk. Progress in oxide thin-film growth technology during the past decade has led to a large number of breakthroughs. Recently nanoscale lateral confinement of a quasi–two-dimensional electron gas was demonstrated at a lanthanum aluminate–strontium titanate interface. Control of this confinement using an atomic force microscope lithography technique allows to create tunnel junctions and field-effect transistors with characteristic dimensions as small as 2 nanometers. A new three-

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