Invited talks
(in alphabetical order)

Vanishing density of states in weakly disordered Weyl semimetals

Alexander Altland

Institute for Theoretical Physics, Universität zu Köln, Germany

The Brillouin zone of the clean Weyl semimetal contains points at which the density of states (DoS) vanishes. Previous work suggested that below a certain critical concentration of impurities this feature is preserved including in the presence of disorder. This result got criticized for its neglect of rare disorder fluctuations which might bind quantum states and hence generate a finite DoS. In this talk I review the situation and discuss why even rare fluctuations are not capable of generating spectral density at the Weyl points. This means that the nodal points remain sharply defined in the presence of weak disorder.

Dirac materials and search for novel organic materials

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In the first part of the talk I will discuss general properties of Dirac Materials [1]. Applications of DM as an exciting platform for developing new physics are rapidly growing. I will discuss the status of the field, our work on DM materials and proposals for extension of DM concept beyond Fermi statistics to materials hosting bosonic excitations. I will also present the recently developed Organic Materials Database (OMDB) hosting electronic band structure calculations for thousands of organic and organometallic materials [2]. We use OMDB to facilitate the search for materials with desired properties like organic Dirac material and materials with small gaps. Examples of the use of database will be given. The OMDB database is freely accessible online at https://omdb.diracmaterials.org/

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Topology in Magic Angle Graphene

Andrei Bernevig

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Higher-order topological insulators and superconductors

Piet Brouwer

Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, Germany

Topological insulators combine an insulating bulk with gapless states at their boundaries. This talk introduces "higher-order topological insulators", which are crystalline insulators with a gapped bulk and gapped crystalline boundaries, but topologically protected gapless states at the intersection of two or more boundaries. I'll show that reflection symmetry and other spatial symmetries can be employed to systematically generate examples of higher-order topological insulators and superconductors, although the topologically protected states at corners or at crystal edges continue to exist if the crystalline symmetry is broken.

Spin transport in graphene interfaced with topological insulators

Aron W. Cummings,[1] Jose H. Garcia,[1] Kenan Song,[1] Roberto Robles,[1] Pabol Ordejón,[1] and Stephan Roche[1]

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Owing to its small spin-orbit coupling (SOC), graphene has proven to be an efficient carrier of spin [1], making it promising for spintronics applications. However, a small SOC prevents the active manipulation or generation of spin currents. Recent work has thus focused on interfacing graphene with high-SOC materials such as transition metal dichalcogenides or topological insulators (TIs), in the hope of inducing strong SOC in graphene while maintaining its superior charge transport properties [2–6].

In this talk, I will present our group's recent efforts to describe the nature of SOC and spin transport induced in graphene by proximity to TIs. We find that spin transport in these systems is distinguished by a giant spin lifetime anisotropy, with spins oriented in the graphene plane relaxing much faster than spins pointing out of the plane. This anisotropy arises from the specific nature of the SOC induced in the graphene layer, and depends strongly on the symmetry of the graphene/TI interface; see figure below [7]. In addition to predicting a giant spin lifetime anisotropy, these calculations can also help to explain recent measurements of spin lifetime in these systems [8]. On the applied side, giant spin lifetime anisotropy may also prove useful for spintronics, for example as an orientation-dependent spin filter.

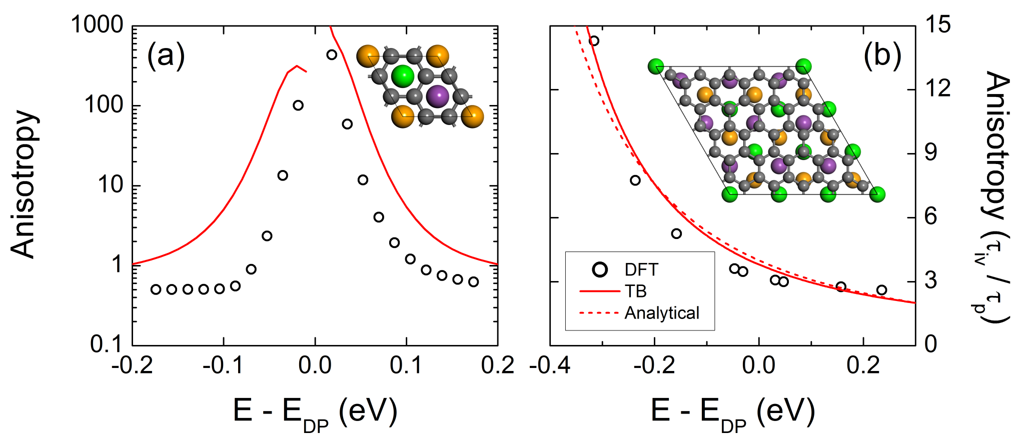

FIG. 1. Anisotropic spin relaxation in a graphene/TI heterostructure. Panel (a) is for a highly commensurate unit cell, while panel (b) is for a larger unit cell that samples a variety of lattice alignments.

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[6] A.W. Cummings et al., Phys. Rev. Lett. **119**, 206601 (2017).
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Transport in topological Majorana box qubit networks

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In this talk, I will first discuss the Majorana box qubit proposal, both the topological insulator nanowire platform and for the semiconductor platform. We then discuss networks of tunnel-coupled Majorana boxes as a toolbox for building interesting topological phases. Finally, I will discuss how transport through small networks can elucidate basic nonlocal phenomena due to Majorana zero modes.

Antiferromagnetic insulators $MnPn_2Ch_4$, based on them heterostructures with topological insulators and non-trivial topology

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Since the discovery of three dimensional topological insulators (TIs), the time-reversal symmetry breaking and surface band gap opening have been considered as core ingredients for the observation of novel phenomena, like image magnetic monopole or quantum anomalous Hall effect (QAHE). There are two approaches used to break the time-reversal symmetry in TIs or at their surfaces: the doping by transition-metal atoms and magnetic proximity effect. The latter approach based on formation of magnetic insulator (MI) films on the TI surface has several advantages against the former one such as spatially uniform magnetization and absence of the dopant-induced scattering.

Recently it has been demonstrated that the MI/TI heterostructure characterized by out-of-plane magnetization and massive Dirac state with the gap of ≈100 meV can be achieved due to spontaneous formation of new MI phase on the surface of TI [1]. It was shown that co-deposition of Mn and Se atoms on Bi_2Se_3 surface results in formation of well-ordered hexagonal $MnBi_2Se_4$ septuple layer (SL) owing to diffusion of deposited atoms inside the Bi_2Se_3's topmost QL. The performed DFT calculations have confirmed that it is energetically more favorable to incorporate the MnSe bilayer into the QL to form a SL rather than leave it ontop of QL. The gapped Dirac state in this MI/TI heterostructure is localized predominantly within the SL and thus the magnetic Mn layer interacts strongly with the topological surface state due to the spatial overlap of the respective wave functions that provides a large magnetic gap. On the other hand this technique also allows potential realization of recently proposed planar MI/TI heterostructures on base of SLs of the related compound $MnBi_2Te_4$ [2,3] In fact, both $MnBi_2Se_4$ and $MnBi_2Te_4$ compounds, predicted to have the same crystal and magnetic phases [4], are structurally and compositionally compatible with a number of the tetradymite-like TIs and therefore are of great potential for construction of the SL-based MI/TI heterostructures characterized by non-trivial Chern number. Bulk phases of these SL-structured van der Waals materials being insulators with interlayer antiferromagnetic coupling for magnetic moments on Mn atoms demonstrate band inversion which makes them antiferromagnetic topological insulators (AFMTI). The AFMTI phase was predicted to be a playground for different fundamental phenomena such as half-integer quantum Hall effect and axion electrodynamics, therefore the discovered $MnPn_2Ch_4$ systems can be a solid platform for their realization.

On the other hand, the revealed mechanism of Mn-based SL formation can be expanded to understanding of atomic structure of the MBE grown thick MI films on the substrate of layered topological insulators of the Bi_2Se_3 family. As shown by total energy calculations the continuing deposition of the atoms of magnetic insulator on-top of, e.g. $MnBi_2Se_4$ SL leads to immersion of the atoms of deposited material into the interior of SL and to formation of $Mn_NBi_2Se_{3+N}$ block, i.e. MnSe film sandwiched by the remnant layers of QL [5]. Such an immersion growth of the MI film results in formation of the smooth interface with TI, which guarantees the absence of the strong interface potential producing the trivial interface states. It was shown this mechanism is universal for many MI/TI structures and it can be easily verified in the experiment by the analysis of chemical composition of the outermost layers of the forming heterostructure.

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Band gap formation in the surface state of topological insulators

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Three dimensional topological insulators (TIs) are characterised by a massless Dirac surface state, which is protected by the time reversal symmetry. The time reversal symmetry can be broken by introducing a magnetic order, which leads to the opening of a band gap in the surface state of topological insulators. This property is highly desired for many applications, e.g. for a realisation of quantum anomalous Hall effect. A magnetic order in topological insulators can be introduced by doping with magnetic impurities such as transition metal or lanthanide magnetic ions. Several experiments demonstrated recently this effect in Bi2Se3, Bi2Te3, and other topological insulators using mainly V, Cr and Mn magnetic dopants. However, it is known that impurities, defects or other surface/bulk imperfections may also lead to the opening of band gap in the TI surface state despite the topological protection by the time reversal symmetry. Unfortunately, in many cases the origin of the band gap can not be determined experimentally. In my talk I analyse recent experimental results in this research field using a first-principles approach based on the multiple scattering theory and a coherent potential approximation. Finally, I present a simple method, which makes it possible to reveal the origin of the band gap in these systems.

Visualizing a nematic domain wall in bismuth: a tunable platform for topological edge modes

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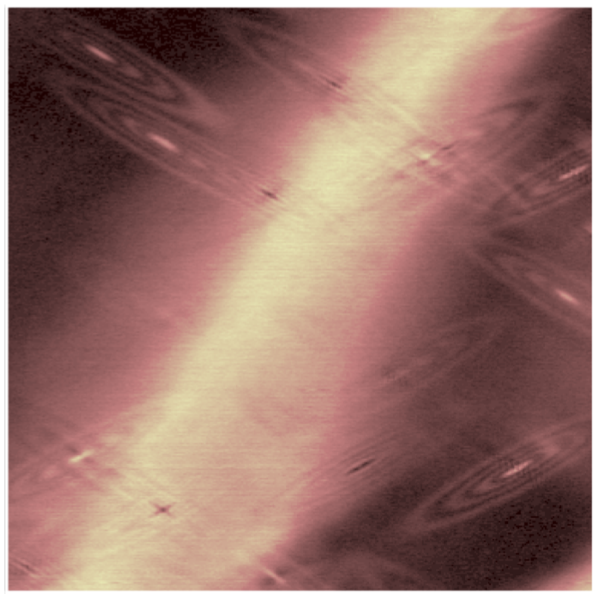
Gapless edge modes are often realized at boundaries between topologically distinct phases. These can occur not only at physical edges of a system, but also at interfaces within a sample, such as domain walls between different broken symmetry phases. In this talk, I will describe scanning tunneling microscope measurements that allow us to locally probe a nematic domain wall and its edge excitations on the surface of bismuth. The valley degeneracy in this material is lifted at high field to produce nematic quantum Hall states with broken rotational symmetry. By directly imaging the resulting anisotropic Landau level wave functions, we detect an abrupt switch in valley occupation across the domain wall. Spatially resolved spectroscopy shows enhanced low-energy differential conductance at the boundary and matches well to theoretical modeling, which predicts counter-propagating valley-polarized edge states. Moreover, by tuning Landau level filling, we can change the number of modes at the interface, which affects the degree of inter-valley scattering and hybridization of the one-dimensional states.



Magnetic Weyl Semimetals!

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Topology a mathematical concept became recently a hot topic in condensed matter physics and materials science. One important criteria for the identification of the topological material is in the language of chemistry the inert pair effect of the s-electrons in heavy elements and the symmetry of the crystal structure [1]. Beside of Weyl and Dirac new fermions can be identified compounds via linear and quadratic 3-, 6- and 8- band crossings stabilized by space group symmetries [2]. Binary phoshides are the ideal material class for a systematic study of Dirac and Weyl physics. Weyl points, a new class of topological phases was also predicted in NbP, NbAs. TaP, MoP and WP2. [3-7]. In magnetic materials the Berry curvature and the classical AHE helps to identify interesting candidates. Magnetic Heusler compounds were already identified as Weyl semimetals such as Co2YZ [8-10], in Mn3Sn [11,12] and Co3Sn2S2 [13].

The Anomalous Hall angle helps to identify even materials in which a QAHE should be possible in thin films. Besides this k-space Berry curvature, Heusler compounds with non-collinear magnetic structures also possess real-space topological states in the form of magnetic antiskyrmions, which have not yet been observed in other materials [14].

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Proximity effects in graphene, bilayer graphene and carbon nanotubes

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Electronic structure of graphene, tiny band gap and spin-orbit coupling, limits its spintronics applications as an efficient spin channel. Novel 2d semiconductors or magnetic semiconductors involved in vertical van der Waals stacks allow graphene to borrow some of their specific properties. The emergent proximity effects as enhanced spin-orbit or exchange coupling offer new perspectives for graphene spintronics [1]. In heterostructures of 2d transition metal dichalcogenides and graphene both the orbital and spin properties can be efficiently controlled by gating. Such design offers a new materials basis for applications, such as a optospintronics [2]. Specifically, graphene on WSe_2 exhibits a giant spin anisotropy and is predicted to host protected pseudohelical states [3,4] present within bulk spin-orbit gap of about 1 meV. Bilayer graphene on transition metal dichalcogenides is even more appealing as the spin properties of the proximitized bilayer graphene can be turned on and off by gate voltage, creating a platform for spin-orbit valves and spin transistors [5]. Magnetic proximity effects in bilayer graphene on semiconducting ferromagnets are predicted to yield field-effect magnetism [6], which opens a potential for a whole new class of phenomena and device concepts. I will also talk about proximity orbital and spin effects in chiral semiconducting carbon nanotube (8,4) in vicinity to $NbSe_2$, which provide a prospect of engineering a device realizing topological superconductivity with Majorana fermions.

I acknowledge support from Ministry of Education, Science, Research and Sport of the Slovak Republic.

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From the parity anomaly to a Majorana fermion - realization of the ultrarelativistic physics in topological insulators

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A realization of the high energy ideas in the solid state physics lab, like the parity anomaly or Majorana fermions, is one of new directions of current research. Topological insulators are perfect materials to realize both of these phenomena.

Topological insulators (TIs) have a bulk energy gap that separates the highest occupied band from the lowest unoccupied band while gapless energy electronic states that are protected by time reversal symmetry live at the edge (2D TIs) or surface (3D TIs). When doped with the magnetic impurities the TIs show the quantum anomalous Hall effect i.e. a single circulating chiral mode at the boundary of 2D TI. Interestingly, in the odd space-time dimensions, one would expect that the formation of the quantum anomalous Hall effect is directly connected to the parity anomaly. We prove theoretically this relation and discuss the experimental consequences [1,2].

On the other hand, a topological insulator in the proximity to an s-wave superconductor is the prefect material to detect signatures of Majorana fermions. S-wave superconductor on the top of the surface states of 3D TI generates s-wave and p-wave pairing mixture in the surface state due to the spin-momentum locking [3]. We predict that in the Josephson junction setup, namely superconductor (S) /surface state of topological insulator/superconductor (S), existence of this p-wave component leads to novel features in transport like superconducting Klein tunneling i.e. the perfect transmission of hybridized Majorana states for normal incidence, the non-sinusoidal current phase relation [4] and unusual phase-dependent thermal conductance [5]. Further, we propose the experimental setups to observe signatures of Majorana fermions in the ac Josephson effect on TI hybrid structures [6] as well as in topological superconductors based on the hexagonal lattices [7].

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Topological exciton insulator phase in two-dimensional semiconductor systems

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Exciton insulator was firstly proposed by Prof. Mott in 1961[1]. When the binding energy of exciton in these systems is larger than the single-particle bandgap, the systems becomes unstable, and open a bandgap forming an exciton insulator phase[2-3]. This concept has been widely studied theoretically and confirmed experimentally in recent years[4-7].

Here, We demonstrate theoretically the existence of topological exciton insulating phases in two-dimensional (2D) semiconductor systems, based on the multi-band k*p theory and the BCS-like many-body theory. We consider two kinds of systems: InAs/GaSb quantum wells [8] and 2D Van der Waals heterostructures[9]. In InAs/GaSb quantum wells, i.e., a 2D topological insulator, we demonstrate theoretically that the ground state of the system is no longer the 2D topological insulator, but a topological exciton insulator when the Coulomb interaction between electrons and holes is included. The system displays the topological edge states for the inverted band case with strong spin-orbit interactions. We find that the topological exciton insulator phase can still survive even under very strong in-plane magnetic fields up to B=35T. For a 2D VdH system, we find that a perpendicular electric field can decrease the bandgap, which even becomes smaller than the exciton binding energy, leading to the formation of exciton insulator phase[9]. Due to large exciton binding energy, the exciton insulator phase in the 2D VdH system could be observed at room temperature.

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Emergent topological phases in correlated systems by laser irradiation

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We propose a possible way to realize topological superconductivity with application of laser light to superconducting cuprate thin films. Applying Floquet theory to a model of d-wave superconductors with Rashba spin-orbit coupling, we derive an effective model and discuss its topological nature. Interplay of the Rashba spin-orbit coupling and the laser light effect induces the synthetic magnetic fields, thus making the system gapped. Then the system acquires the topologically non-trivial nature which is characterized by Chern numbers. The effective magnetic fields do not create the vortices in superconductors, and thus the proposed scheme provides a promising way to dynamically realize a topological superconductor in cuprates.

We further study the nature of laser-irradiated Kondo insulators. Applying Floquet theory to a periodic Anderson model, we find two generic effects induced by laser light. One is the dynamical localization, which suppresses hopping and hybridization and the other is the laser-induced hopping and hybridization, which can be interpreted as a synthetic spin-orbit coupling or magnetic field. The Kondo effect under laser light qualitatively changes its character depending on whether the hybridization is on-site or off-site. In topological Kondo insulators, linearly polarized laser light realizes phase transitions between trivial, weak topological, and strong topological Kondo insulators, whereas circularly polarized laser light breaks time-reversal symmetry and induces Weyl semimetallic phases. Our results pave the way for dynamically control the Kondo effect and topological phases in heavy fermion systems.

Majorana Qubits

Leo Kouwenhoven

Microsoft Station Q at Delft University of Technology, The Netherlands

Majoranas in semiconductor nanowires can be probed via various electrical measurements. Tunnel spectroscopy have revealed zero-bias peaks in the differential conductance. New observations include quantum superpositions of Majorana states leading, for instance, to a 4pi current phase relation or a fractional Josephson effect. When the existence of Majoranas is firmly established, the next challenge is to build Majorana qubits. We discuss the different qubit schemes and report on our first building blocks. The promise of Majorana qubits is that the error rate is very low yielding a relatively simple scalable architecture.

[1] https://arxiv.org/pdf/1710.10701.pdf

[2] https://arxiv.org/pdf/1707.04899.pdf

Topological Materials

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Topological materials host various novel quantum phases of electrons which are characterized by band topology and topologically protected surface/edge states. Despite recent progress, intense world-wide research activity in search of new classes of topological materials is continuing unabated. This interest is driven by the need for materials with greater structural flexibility and tunability to enable viable applications in spintronics and quantum computing. We have used first-principles band theory computations to successfully predict many new classes of 3D topologically interesting materials, including Bi_2Se_3 series, the ternary half-Heusler compounds, $TlBiSe_2$ family, Li_2AgSb-class, and $GeBi_2Te_4$ family as well as topological crystalline insulator (TCI) SnTe family and Weyl semimetals TaAs, $SrSi_2$, $(Mo,W)Te_2$, Ta_3S_2, and LaAlGe family. I will also highlight our recent work on unconventional chiral fermions in RhSi and several material candidates for new TCI.

Induced superconductivity in HgTe-based topological insulators

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Since the discovery of topological edge states in HgTe/CdTe quantum wells over a decade ago, a variety of topological phases has been realized in the material system. We can now access 2D and 3D topological insulator (TI) physics as well as a Dirac- (or Weyl-) semimetal phase. Furthermore, we succeeded in preparing CdTe/HgTe core-shell nanowires which are predicted to harbor a helical Luttinger liquid. In this talk, I will discuss the exciting physics that emerges when we combine this unique material in heterostructures with conventional superconductors. I will review the experimental evidence for the fractional Josephson effect in Josephson junctions with TI weak links and present recent results on Josephson devices with the Dirac-/Weyl-semimetal and CdTe/HgTe core-shell nanowires.

Low temperature, high-resolution photoemission on systems of topological interest

Emile Rienks

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We will show two examples in which angle-resolved photoemission directly contributes to the understanding of topological materials: We present results on thin films of the magnetically doped tetradymite semiconductors Bi2Te3 and Bi2Se3 that provide a route to realize the quantum anomalous Hall effect [Liu]. In Mn-doped Bi2Te3 we find clear signs of the opening of a large gap (100 meV) below the temperature where magnetic order is established. This effect is not seen in its sibling Bi2Se3: While Mn-doping does gap the topological surface state in this material [Sánchez-Barriga], we find this gap to be unaffected by magnetic order. Photoemission experiments therefore directly reveal the presence and magnitude of the magnetic gap.

We further address the question whether samarium hexaboride, arguably the most prominent heavy fermion semiconductor, is also a topological insulator. This suggestion [Dzero] would significantly extend the scope of topological insulators, and has been intensively tested since [Allen]. Our results show that the features observed in earlier studies do not have the attributes of topological surface states. Instead we propose a compelling alternative mechanism to explain robust surface metallicity in this material [Hlawenka].

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Novel Quantum Spin Hall Paradigm in 2D Honeycomb Layers: Bismuthene

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We present a novel route to quantum spin Hall (QSH) systems and their dissipationless helical edge channels, based on wide-gap 2D honeycomb layers on insulating substrates. The first such experimental realization is Bismuthene on SiC, which exhibits a huge bulk gap of ~0.8 eV and spatially confined conductive edge states [1]. By combining experiment and theory, we explain that this material combination represents a new wide-gap QSH paradigm which specifically exploits the large on-site spin-orbit coupling. The tunneling spectra recorded on the edge states display power-law behavior and universal scaling, consistent with the expectations for tunneling into a Tomonaga-Luttinger liquid. This underpins the 1D nature of the edge states. They are energetically positioned in the band gap of both the Bismuthene film and the substrate, respectively, which promises robust edge channel conductance even at room temperature.

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Superconducting proximity effect in two-dimensional semiconductor-superconductor structures

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Progress in the emergent field of topological superconductivity relies on synthesis of new material combining superconductivity, low density, and spin-orbit coupling (SOC). Theory indicates that the interface between a one-dimensional semiconductor with strong SOC and a superconductor hosts Majorana-modes with nontrivial topological properties. We discuss the recent developments in epitaxial growth of Al on InAs nanowires was shown to yield a high quality superconductor-semiconductor system with uniformly transparent interfaces and a hard induced gap, indicted by strongly suppressed subgap tunneling conductance. We have developed a two-dimensional (2D) surface InAs quantum wells with epitaxial superconducting Aluminum, yielding a planar system with structural and transport characteristics as good as the epitaxial nanowires. The realization of 2D epitaxial superconductor-semiconductor systems represent a significant advance over wires, allowing extended networks via top-down processing. We present our recent developments in materials synthesis and growth of these density-controlled surface 2D electron-gases and demonstrate Josephson junctions with highly transparent contacts. These developments have lead to unprecedented control over proximity effect in semiconductors where electron densities can be tuned using a gate voltage. We discuss potential applications of this new material system that can serve as a platform for low power circuits, gate-based qubits as well as exploring topological superconductivity for computation.

Topological Phase Transitions in Magnetic Topological Insulators

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In magnetic topological insulators (MTIs), the spin-momentum locking as well as the magnetization-induced mass-gap shows up to form the ideal 2D Weyl fermion system at surface. With control of the magnetizations on the top and bottom surfaces of the thin film, quantum anomalous Hall (QAH) state and quantum magnetoelectric (axion insulator) state can be formed and therein the topological magneto-optical effects may show up. As a hallmark of the QAH state, the quantum chiral edge conduction (CES) on the magnetic domains walls, which are reconfigurable in terms of the magnetic-domain writing procedure, is demonstrated. The MTI film with the decreased thickness undergoes the topological transition between the QAH sate and trivial insulating state with varying the magnetic field (magnetization) direction between the normal and in-plane of the film. When the magnetization on the top and bottom surfaces is further changed from parallel to anti-parallel on the basis of the magnetic-ion (Cr, V) modulation-doped MTI heterostructure, the topological transition undergoes between the QAH state with CES and the axion insulator state without CES, accompanying the colossal magnetoresistance exceeding million %. These magneto-transport and magneto-optical properties related to the topological phase transitions of the MTI heterostructures are presented.