Topological insulators: Materials - Fundamental Properties - Devices

Topological insulators are materials that are electrically insulating in the bulk but can conduct electricity due to topologically protected electronic edge or surface states. Since 2013, the German Research Foundation (DFG) has been supporting the Priority Program „Topological Insulators: Materials - Fundamental Properties - Devices“ (SPP 1666). The program has three areas of activity: (i) Understanding and improvement of existing topological insulator materials, regarding the size of the band gap and intrinsic doping levels, to enable room temperature applications, (ii) explore the fundamental properties necessary for the development of device structures, and (iii) discover new materials to overcome deficits of current materials and explore new properties.

A considerable number of collaborative works resulted from the activities of the SPP members and the scientific subject as a whole has gained momentum with many initiatives worldwide. In 2016 the Nobel Prize in Physics was awarded to D. J. Thouless, F. D. M. Haldane and J. M. Kosterlitz "for theoretical discoveries of topological phase transitions and topological phases of matter". This led to a further increase of the awareness for this research field and reflected the fact that topology has nowadays entered and changed our perception of the solid state.

The present issue exemplifies and summarizes contributions from the priority program. We have 20 articles, of which 9 are feature articles and 11 are original articles. The three areas of activity are reflected in the present issue.

An example of area (i) is the work of Pereira *et al.* (202000346) who optimized the molecular beam epitaxy (MBE) growth of Bi_2Te_3 achieving a low level of defects. A modified procedure enabled the growth of Bi_2Te_3 on ferrimagnetic oxides. In these systems, magnetotransport indicates a magnetic proximity effect on the topological surface state. Mussler (202000007) suppressed bulk carriers further in $(Bi,Sb)_2(Te,Se)_3$ and minimized crystal dislocations and twin domains despite the large lattice mismatch imposed by Si(111) substrates. He further demonstrated the *in situ* growth of topological insulator-superconductor Josephson junctions. Jafarpisheh *et al.* (202000021) used physical vapor deposition to grow flakes of Bi_2Se_3 and $(Bi,Sb)_2(Te,Se)_3$ with varying thicknesses on several different substrates and employed Raman spectroscopy for characterization. They encapsulated these flakes in BN and performed a comparison of transport properties with bulk exfoliated samples.

Mesoscopic conductors such as nanowires and nanoribbons promise an enhanced effect of topological surface states in transport. Giraud and Dufouleur (202000066) review quantum transport of single-crystal nanostructures. In quantum confined nanowires, in which the transport length exceeds the diameter, quantum interference is investigated in the form of Aharonov–Bohm oscillations and, at 100 mK temperatures, reproducible conductance fluctuations.

In area (ii), Morgenstern et al. (202000060) perform angle-resolved photoemission and scanning tunneling spectroscopy (STS) and point out the use of STS for the identification of weak topological insulators and of four-tip scanning tunneling microscopy for in-situ transport measurements without the need for extra contacts. In this way, Bi_1Te_1 consisting of Bi_2Te_3 and Bi_2 layers is identified as a dual topological insulator, combining a weak topological insulator and a topological crystalline insulator phase. A switchable topological phase is identified in the commercial phase-change material

$Ge_2Sb_2Te_5$: its conducting phase is a topological insulator. Another switchable topological phase is reported in angle-resolved photoemission by Rader et al. (202000371): $Pb_{1-x}Sn_xSe$, switches from topological crystalline to Z_2 topological insulator by adding 1 to 2% Bi. They also argue that the surface states of the topological Kondo insulator candidate SmB_6 are trivial. They further show that Bi_2Te_3 doped by Mn is actually a heterostructure consisting of $MnBi_2Te_4$ and Bi_2Te_3 layers and that this system gives rise to a magnetic gap at the Dirac point, required for the quantum anomalous Hall effect. In the same context, Riha et al. (202000088) investigate vanadium-doped $BiTe_{2.4}Se_{0.6}$ single crystals by angle-resolved photoemission and transport experiments which both support that the surface states in this system are gapless. Weak antilocalization is observed and an enhanced phase coherence length is derived from the data.

Scanning tunneling microscopy and STS are valuable methods for topological insulator research. In all – except for the simplest layered – systems, the characterization and identification of surface terminations is crucial and for SmB_6 it is one of the aspects that render the assignment of SmB_6 to a topological insulator controversial. Wirth *et al.* (202000022) performed therefore a direct comparison between the (100) surfaces of SmB_6 and EuB_6. They introduce a double-bias technique to compare different bias voltages on the same probed area. Quasiparticle interference (QPI) in STS has been an important experimental method since the beginning of topological insulator research, revealing fundamental scattering properties of topological surface states. Rüßmann *et al*. (202000031) derive a Green function-based formalism for the *ab initio* computation of Fourier-transformed QPI images and apply it to magnetic defects embedded in the surface of Bi_2Te_3.

The work of Braun and Ebert (202000026) closes a gap in the theoretical description of direct and inverse photoemissoin experiments by studying the spin texture of surface-barrier-induced image states using one-step inverse photoemission calculations for Bi_2Se_3 and metal surfaces. The spin texture and degree of spin polarization of topological surface states is important for the use of topological insulators in spintronic devices and a determination of these properties is desirable independently of photoelectron spectroscopy with possible complications from final state effects. Götte and Dahm (202000032) derived a formalism to determine the out-of-plane spin from spin Hall effect tunneling spectra. They test the method using realistic tight-binding models of Bi_2Se_3 and Sb_2Te_3.

HgTe is the material where the quantum spin Hall effect was experimentally confirmed for the first time. $Cd_xHg_{1-x}Te$ in the topological insulator phase has advantages in terms of group velocity and band gap size over HgTe and tuning of x allows comparing the normal and inverted state and also reaching a linear dispersion for the critical concentration in between these states. Ganichev *et al.* (202000023) conducted terahertz cyclotron resonance in transmission, photocurrent, and photoconductivity and were able to experimentally distinguish 2D from 3D transport. They also found that a sharp interface in terms of the Cd concentration profile is crucial for the appearance of the topologically protected state. Photocurrent spectroscopy of topological materials for higher energies, from near-infrared to the visible range, has been reviewed by Kiemle et al. (202000033). Spacial resolution enables photocurrent images across the Hall bar. Photogalvanic effects within the surface states – such as a circular photogalvanic effect – are separated from other effects such as thermoelectric currents by pump-probe spectroscopy. In Bi_2Te_2Se they find a lifetime of nonequilibrium charge and spin populations of several 100 ps at room temperature. The pump-probe technique in angle-resolved photoemission has been reviewed by Güdde and Höfer (202000521).

Mid-infrared pump pulses cause in the topological surface state of Sb_2Te_3 a strong asymmetry in momentum space equivalent to the generation of macroscopic photocurrent. The strongest asymmetry is reached with linearly polarized light, a small helicity dependence can be observed in a particular experimental geometry. In contrast to this optical interband excitation, terahertz excitation of Bi_2Te_3 leads to a substantial *intraband* redistribution of electrons in momentum space. Comparable scattering times of ~1 ps are obtained in both experiments.

Several different directions have been explored in area (iii). Heterostructures enable various proxmity effect that influence topological phases. The ferromagnetic insulator EuS interfaced with Bi_2Se_3 showed a strong modification of magnetic structure and critical temperature that could not be clarified so far. Meyerheim *et al.* (202000290) studied the growth of EuS on Bi_2Se_3 in detail by surface X-ray diffraction and observed sharp interfaces on the atomic scale. Based on this structural characterization, *ab initio* calculations predict the magnetic structure of the EuS at the interface predicted to depend on the extent of n-doping from the Bi_2Se_3. Also the possibility of an enhanced Néel temperatures was investigated in this way. Zollner and Fabian (202000081) investigated heterostructures of graphene with Bi_2Se_3, Bi_2Te_3, and Sb_2Te_3 theoretically and predict that induced spin-orbit coupling and charge doping can be strongly tuned by gating. These results are important for gate-tunable spin-charge conversion which is currently explored in experiments.

The existence of topological insulators based on strong electron correlation has unequivocally been confirmed. Na_2IrO_3 is one of the theoretically proposed correlated topological insulators for which experimental evidence is still outstanding. Dziuba *et al.* performed a combined electrical transport and STS study of *in situ* cleaved Na_2IrO_3. They observe an unusual surface conductivity that does not disappear at low temperatures.

Nodal semimetals are novel materials with a unique Dirac-type bulk dispersion and comprise also topologically protected systems. Pronin and Dressel (202000027) review optical conductivity of different types of nodal semimetals and point out the strengths of the method in this material class, such as bulk sensitivity and high energy resolution. Weyl semimetals are topologically protected but in contrast to nonmagnetic Weyl semimetals which depend on broken inversion symmetry, magnetic Weyl semimetals have remained elusive until recently. Dyck et al. (202000067) grew the theoretically predicted ferromagnetic Weyl semimetal Co_2TiGe by sputter deposition as the growth method most relevant for applications. They observed that physical properties are close to those of bulk samples but not sufficient to conclude from the magnetotransport data on Weyl semimetallicity.

Trifunovic and Brouwer (202000090) reviewed higher order topological phases, e.g., 3D crystals that show protected hinge or corner states, and their role for the classification of topological crystalline insulators as well as superconductors. They also pointed out that, as an alternative to full classification, searches by symmetry-based indicators resulted in the discovery of many new topological insulator materials and the same can be expected for topological superconductors.

In the six years of this priority program topological insulators developed from a mere curiosity to a material class that entered many fields of applied research. According to theoretical databases, one out of four materials is topological, including novel variants like Weyl semimetals and Chern insulators. The rising field of two-dimensional materials incorporates many of these compounds and opens new pathways to engineer topological properties, e.g. in twisted bilayer graphene or transition metal dichalcogenide heterostructures. The fabrication of magnetic topological insulators clears the way to realize the integer quantum Hall effect, being the basis for the electrical resistance in quantum metrology, without the need for high external magnetic fields. Finally, in combination with superconductivity, topological insulators are the basis for topological qubits that constitute a promising but demanding platform for quantum computing. These are just a few developments that support the viewpoint that topological insulators and other classes of topological materials that emerged over the years will remain an active field of research in the years to come.

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Oliver Rader, Gustav Bihlmayer, and Saskia F. Fischer

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Oliver Rader studied physics in Cologne and obtained his Ph.D. from Free University Berlin. After a postdoctorate at the University of Tokyo, he has been at Helmholtz-Zentrum Berlin, where he heads a department. He is a professor at the University of Potsdam. His research involves graphene and other 2D materials and currently aims at the functionalization of topological insulators with magnetism using synchrotron radiation methods.

Gustav Bihlmayer got his Ph. D. from the University of Vienna where he studied chemistry and also did postdoctoral studies in the field of *ab initio* calculations of solids and surfaces. He is now a staff scientist at Forschungszentrum Jülich where he uses and develops density functional theory based methods to computationally explore relativistic effects, including topological and magnetic properties, in low dimensional systems.

Saskia F. Fischer studied physics in Stuttgart and Bristol. She joined the Max-Planck Institut für Metallforschung and obtained her Ph. D. from the University of Stuttgart. She obained her habilitation and has been lecturer at Ruhr-Universität Bochum. After scientific visits at the University of Buffalo she became professor at Humboldt-Universität zu Berlin in 2010 and heads the Novel Materials group. Besides her engagement for topological insulators she has also served in the program committee for the priority program on nanostructured thermoelectric materials.