TT 15: Focus Session: Evolution of Topological Materials into Superconducting Nanodevices (joint session HL/TT)

The focus session intends to span the arc between topological materials and superconducting nanodevices, both experimentally and theoretically. Such structures are interesting for applications in future topological quantum circuits. In recent years, the number of topological materials and the knowledge about them has rapidly increased. As part of the focus session, material properties of layered systems made of topological materials, especially in combination with superconductors, are discussed. On the other hand, the special challenges in the nanofabrication of these materials for use in future topological quantum processors are addressed. Another focus is the quantum transport in nanoscale hybrid structures.

Organized by Thomas Schäpers, Philipp Rüßmann, and Peter Schüffelgen

Time: Monday 15:00–18:00 Location: EW 202

TT 15.1 Mon 15:00 EW 202

Transport studies in selectively grown topological insulator multiterminal Josphson junctions — •Gerrit Behner[1,2], Alina Rupp[1,2], Abdur Rehman Jalil[1,2], Kristof Moors[1,2], Dennis Heffels[1,2], Detlev Grützmacher[1,2], and Thomas Schäpers[1,2] — [1]Peter Grünberg Institut (PGI-9), Forschungszentrum Jülich, 52425 Jülich, Germany — [2]Jara-Fundamentals of Future Information Technology, Forschungszentrum Jülich and RWTH Aachen University, Germany

The combination of an ordinary s-type superconductor with three-dimensional topological insulators creates a promising platform for fault tolerant topological quantum computing circuits based on Majorana braiding. The backbone of the braiding mechanism are three terminal Josephson junctions. It is crucial to understand the transport in these devices for further use in quantum computing applications. We present low-temperature measurements of three-terminal $Bi_{0.8}Sb_{1.2}Te_3$ Josephson junctions fabricated, based on a combination of selective area growth and shadow mask evaporation. The transport properties of the junction are mapped out as a function of bias current and magnetic field. The bias current maps reveal a variety of transport phenomena, i.e. multiple Andreev reflections suggesting the successful fabrication of a fully coupled three-terminal junction. The junctions seem to be in good agreement with a resistively and capacitively shunted junction model, but also reveal the influence of intrinsic asymmetries and their effect on the transport in the junctions.

TT 15.2 Mon 15:15 EW 202

Quasparticle poisoning effects on electron transport through a Majorana wire — •Florinda Viñas Boström[1,2] and Patrik Recher[1,3] — [1]Institut für Mathematische Physik, Technische Universität Braunschweig, D-38106 Braunschweig, Germany — [2]Division of Solid State Physics and NanoLund, Lund University, Box 118, S-221 00 Lund, Sweden — [3]Laboratory of Emerging Nanometrology, D-38106 Braunschweig, Germany

Majorana bound states have been suggested as building blocks for fault-tolerant quantum computational devices. However, a problem for both Majorana based and other types of superconducting qubits, is quasi-particle poisoning, where an additional quasiparticle changes the parity of the superconducting condensate. In this work, we show how quasi-particle poisoning affects electron transport through a Majorana wire coupled to current leads on each side of the wire, using an open systems approach combining master equations with full counting statistics. To describe the correct low-energy physics for current and noise, we include sequential- and co-tunneling processes in our description. We believe that our study will be a guide both for future theoretical work, and to analyze transport experiments of such setups.

TT 15.3 Mon 15:30 EW 202

Andreev spectrum of Josephson junctions with topological insulator nanostructures — •Dennis Heffels, Peter Schüffelgen, Kristof Moors, and Detlev Grützmacher — Peter Grünberg Institute 9, Forschungszentrum Jülich, 52425 Jülich, Germany

Josephson junctions and the presence of Andreev bound states play an important role in quantum information and quantum materials research, forming an integral part of SQUIDs and superconducting qubits, for example. The bound states within a Josephson junction have a phase-dependent spectrum known as the Andreev spectrum. The investigation of this spectrum with phase-sensitive measurements can be used to characterize exotic types of superconductivity, such as topological superconductors with Majorana bound states. Here we present a method to efficiently calculate numerically detailed Andreev spectra, based on a scattering matrix method and (3D) tight binding, for different junction geometries, chemical potential and disorder profiles, etc. We apply this method to proximitized topological insulator (TI) nanostructure-based junctions in which Majorana bound states are expected upon application of an external magnetic field. In this setup, the spin-momentum-locked topological surface states give rise to highly unconventional Andreev spectra and corresponding current-phase relationships, both in the topologically trivial and nontrivial superconducting regimes.

TT 15.4 Mon 15:45 EW 202

Realistic modeling of proximitized magnetic topological insulator nanoribbons — •Eduárd Zsurka[1,2,3], Julian Legendre[3], Daniele Di Miceli[3,4], Llorenç Serra[4], Thomas Schmidt[3], and Kristof Moors[1,2] — [1]PGI-9, Forschungszentrum Jülich — [2]JARA-Fundamentals of Future Information Technology, Jülich-Aachen Research Alliance, Forschungszentrum Jülich and RWTH Aachen University — [3]Department of Physics and Materials Science, University of Luxembourg — [4]Department of Physics, University of the Balearic Islands

Proximitized magnetic topological insulator nanoribbons (PMTINRs) are a potential platform for the practical realization of the Majorana zero-energy mode (MZM) [1]. Here, we present a realistic description of PMTINRs and similar superconductor-topological insulator heterostructures. Both bulk and effective surface-state models are used to capture the low-energy electronic spectrum, with realistic parameters extracted from *ab initio* calculations. Using numerical simulations, we study in a tight-binding framework the properties of PMTINRs. Particular attention is given to the thin-film limit, where theoretical results have been conflicting on the topology of the hybridization gap. Magnetic and nonmagnetic disorder, as well as device imperfections, can all be detrimental to the formation of MZMs in PMTINRs. We aim to clarify what are the optimal conditions to obtain MZMs in PMTINRs, that are robust against such effects.

[1] C.-Z. Chen, Y.-M. Xie, J. Liu, P. A. Lee, and K. T. Law, Phys. Rev. B 97, 104504 (2018).

TT 15.5 Mon 16:00 EW 202

Transport in core/shell GaAs/InAs/Al half-shell nanowire-based hybrid devices — •Farah Basarić[1,2], Patrick Zellekens[3], Russell Deacon[3], Vladan Brajović[1,2], Alexander Pawlis[1,2], Gerrit Behner[1,2], Hans Lüth[1,2], Detlev Grützmacher[1,2], Koji Ishibashi[3], and Thomas Schäpers[1,2] — [1]Peter Grünberg Institut (PGI-9), Forschungszentrum Jülich, 52425 Jülich, Germany — [2]JARA-Fundamentals of Future Information Technology, Jülich-Aachen Research Alliance, Forschungszentrum Jülich and RWTH Aachen University, Germany — [3]RIKEN Center for Emergent Matter Science and Advanced Device Laboratory, 351-0198 Saitama, Japan

Epitaxially grown core-shell GaAs/InAs nanowires provide a heterostructure with transport properties governed by the angular momentum states in the InAs shell. Besides conventional polymorphic GaAs/InAs nanowires, phase-pure core/shell nanowires featuring only wurtzite crystal structure along the axis were studied by magnetotransport measurements under an axial magnetic field. Transport regime analysis for both nanowire types indicates the presence of Aharonov-

Bohm-type oscillations, while magnetotransport analysis suggests a strong effect of disorder reduction for phase-pure nanowires. This is manifested by the presence of the quasi-ballistic transport regime, indicating superior transport properties of the phase-pure nanowire. Combining phase-pure GaAs/InAs nanowires with an in-situ deposited superconducting Al half-shell, a gate-controlled Josephson junction was fabricated.

TT 15.6 Mon 16:15 EW 202

Van der Pauw measurements for the optimization of magnetic topological insulators — •Jan Karthein[1,3], Jonas Buchhorn[1,3], Kaycee Underwood[1,3], Abdur Reman Jalil[1,3], Peter Schüffelgen[1,3], Detlev Grützmacher[1,2,3], and Thomas Schäpers[1,3] — [1]Peter Grünberg Institut (PGI-9), Forschungszentrum Jülich, 52425 Jülich, Germany — [2]Peter Grünberg Institut (PGI-10), Forschungszentrum Jülich, 52425 Jülich, Germany — [3]JARA-Fundamentals of Future Information Technology, Jülich-Aachen Research Alliance, Forschungszentrum Jülich and RWTH Aachen University, 52425 Jülich, Germany

Quantum anomalous Hall insulators are proposed to be a platform for the realization of chiral Majorana edge modes when coupled to a superconductor by the proximity effect. The quantum anomalous Hall state has already been achieved in magnetic topological insulators but inducing superconductivity into these materials remains a challenge. We present a measurement scheme based on the van der Pauw method that allows to get fast insights into the electrical transport properties of thin films at low temperatures prepared by molecular beam epitaxy. On the example of Cr-doped $(Bi_xSb_{1-x})_2Te_3$ the effect of different growth parameters is investigated and compared to Hall bar measurements. The van der Pauw method enables a fast feedback loop between growth and transport measurements. This will help to establish a reliable epitaxial growth of quantum anomalous Hall insulator thin films and allow to systematically search for promising material compositions to induce superconductivity into magnetic topological insulators.

15 min. break

TT 15.7 Mon 16:45 EW 202

Topology of finite size magnetic topological insulator/superconductor heterostructures — •Julian Legendre[1], Eduárd Zsurka[1,2,3], Daniele Di Miceli[1,4], Llorenç Serra[4,5], Kristof Moors[2,3], and Thomas L. Schmidt[1] — [1]Department of Physics and Materials Science, University of Luxembourg — [2]PGI-9, Forschungszentrum Jülich — [3]JARA-Fundamentals of Future Information Technology, Jülich-Aachen Research Alliance, Forschungszentrum Jülich and RWTH Aachen University — [4]Institute for Cross-Disciplinary Physics and Complex Systems IFISC (CSIC-UIB) — [5]Department of Physics, University of the Balearic Islands

Heterostructures of magnetic topological insulators (MTIs) and superconductors (SCs) in two-dimensional (2D) slab and one-dimensional (1D) nanoribbon geometries have been predicted to host chiral Majorana edge states or Majorana bound states (MBS), respectively. We study the topological properties of such MTI/SC heterostructures upon variation of the slab geometry from wide slabs to quasi-1D nanoribbon systems and as a function of the chemical potential, the magnetic doping, and the induced superconducting pairing potential. To do so, we construct effective symmetry-constrained low-energy $\mathbf{k}\cdot\mathbf{p}$ Hamiltonians accounting for the real-space confinement. Transitions between topological phases are then signalled by sign changes of the resulting gap magnitude at the Γ point. For confined slab geometries, as the chemical potential, the magnetic doping and/or the width of the slab are varied, we observe a periodic sign change of the bulk gap, which entails reentrant MBS at the ends of the nanoribbon.

TT 15.8 Mon 17:00 EW 202

Proximity induced superconducting gap in Bi-containing thin TI and highly ordered TI films grown on the Nb(110) surface — •Artem Odobesko, Felix Friedrich, Robin Boshuis, and Matthias Bode — Julius-Maximilians-Universität Würzburg,Physikalisches Institut, Experimentelle Physik II, Am Hubland, 97074 Würzburg, Germany

A superconductor (SC) in contact with a non-SC metal leads to a proximity effect, wherein Cooper pairs from the SC infiltrate the metal. The proximity effect has recently regained attention due to its potential for achieving topological superconductivity within heterostructures of 3D topological insulators (TI) combined with conventional s-wave SC. Theoretical predictions suggest the emergence of Majorana zero-energy modes within the vortices of such TI/SC heterostructures. The magnitude of the proximity-induced gap is pivotal for the robustness of Majorana zero modes and in general distinct from proximity pairing correlations. The current experiments are aimed at examining the induced SC-gap on the exposed surface of thin Bi-containing slabs -Bi(111), Bi(110) and Bi_2Te_3 - grown on Nb(110) substrate. The characteristics of the induced SC-gap are not solely dependent on the thickness of the slab; they are also strongly influenced by the matching of Fermi surfaces between the SC and non-SC materials at their interfaces. The band structure correspondence and band bending at the interface, plays a crucial role in generating a robust proximity-induced SC-gap. It underscores the necessity to explore compatible pairs of SC and non-SC materials for effective band matching.

TT 15.9 Mon 17:15 EW 202

Selective growth of magnetic topological insulator nanostructures via molecular beam epitaxy — •Max Vassen-Carl, Peter Schüffelgen, and Detlev Grützmacher — Peter Grünberg Institute, Forschungszentrum Jülich, Jülich, Germany

Magnetic topological insulators (MTIs) have great potential for hosting Majorana zero modes [1]. To achieve this, MTI nanostructures are a promising candidate. In such devices, the chiral edge modes (CEM) of the MTI are predicted to hybridise [2]. To verify this prediction, other groups have etched MTI films into thin Hallbars [3]. This etching process is prone to damage the edge states.
In this work a new molecular beam epitaxy (MBE) technique is presented, which enables the selective growth of MTI structures for the first time. Transport measurements on such devices provide insights into the size dependence of CEM in MTIs.

[1] D. Burke et al., arXiv 2302.10982 (2023)
[2] Chen et al., Phys. Rev. B 97, 104504 (2018)
[3] Zhou et al., Phys. Rev. Lett. 130, 086201 (2023)

TT 15.10 Mon 17:30 EW 202

Conductance asymmetry in proximitized magnetic topological insulator junctions with Majorana modes — •Daniele Di Miceli[1,2], Eduárd Zsurka[2,3,4], Julian Legendre[2], Kristof Moors[3,4], Thomas Schmidt[2], and Llorenç Serra[1,5] — [1]Institute for Cross-Disciplinary Physics and Complex Systems IFISC (CSIC-UIB) — [2]Department of Physics and Materials Science, University of Luxembourg, 1511 Luxembourg, Luxembourg — [3]PGI-9, Forschungszentrum Jülich — [4]JARA-Fundamentals of Future Information Technology, Jülich-Aachen Research Alliance, Forschungszentrum Jülich and RWTH Aachen University — [5]Department of Physics, University of the Balearic Islands

Magnetic topological insulators are outstanding candidates for the realization of topological 1D and 2D superconducting phases when coupled by proximity to ordinary *s*-wave superconductors. We study normal-superconductor-normal junctions made of narrow (wirelike) or wide (filmlike) magnetic topological insulator slabs with a central proximitized sector. Specifically, we investigate how the electronic transport depends on the topological phase of the central superconductor when the voltage bias is split asymmetrically between the two normal leads of the junction. The occurrence of charge-nonconserving Andreev processes entails a nonzero conductance related to an electric current flowing to ground from the proximitized sector of the junction. We show that topologically protected Majorana modes require an antisymmetry of this conductance with respect to the point of equally split bias across the junction.

TT 15.11 Mon 17:45 EW 202

Transport spectroscopy on $(Bi,Sb)_2Te_3$ nanoribbons proximitized by aluminum as parent superconductor — •Benedikt Frohn, Tobias W. Schmitt, Vanessa S. Bello, Dennis Heffels, Albert Hertel, Michael Schleenvoigt, Abdur R. Jalil, Kristof Moors, Peter Schüffelgen, and Detlev Grützmacher — Peter Grünberg Institut, Forschungszentrum Jülich & JARA Jülich-Aachen Research Alliance, D-52425 Jülich, Deutschland

One-dimensional topological insulator nanowires which are proximitized by an s-wave superconductor and are exposed to an in-plane magnetic field are predicted to become topological superconductors [1, 2]. So far, realizing a strong proximity effect in such structures has remained an experimental challenge. In this talk, I present transport spectroscopy results on $(Bi,Sb)_2Te_3$ nanowires with Al as parent superconductor. All materials are grown via molecular beam epitaxy in a single growth run consisting of six subsequent deposition steps. To prevent diffusion of Al into $(Bi,Sb)_2Te_3$ and creating a transparent interface, we employ a thin diffusion barrier made from Pt. These devices are fabricated using stencil lithography [3] and possess contacts with varying barrier strength made of AlOx. This enables us to study the density of states and therefore to search for topological features within the induced superconducting gap, of which we measure the dependences of different magnetic field directions as well as temperature.

[1] Cook et al., Phys. Rev. B 86, 155431 (2012)
[2] Heffels et al., Nanomaterials 13, 723 (2023)
[3] Schüffelgen et al., Nat. Nanotechnology 14, 825-831 (2019)