FINAL REPORT
INTERNATIONAL RESEARCH AGENDAS PROGRAMME
(PLEASE UPLOAD THE SIGNED AND STAMPED FORM ONTO THE ELECTRONIC DATABASE)

Project title:	International Centre for Interfacing Magnetism and Superconductivity with Topological Matter MagTop	
Agreement no.:	MAB/2017/1	from Feb. 1, 2017 to Dec. 31, 2023
Project leader:	Prof. Tomasz Dietl, Prof. Tomasz Wojtowicz	

NB: Unless otherwise stated in the question, the information provided should refer only to the last period of the project's implementation.

1. INFORMATION CONCERNING THE PROGRESS OF THE RESEARCH

1.1 Please provide an overview of the scientific progress in all research groups, describe main common goals achieved (1000 to 5000 words)

The core MagTop's activity is directed to solve **grand challenges** of topological matter interfaced with magnetism and superconductivity, and to discover experimentally and theoretically unanticipated topology-related phenomena that enlarge research horizons and, possibly, lead to new applications. Best recruitment and management practices, developed with the strategic partner unit, Julius Maximilian University of Würzburg, and the International Scientific Committee, chaired by Professor Laurens Molenkamp, have contributed significantly to the high R&D standing of the MagTop unit.

Since 2019, the MagTop unit at the Institute of Physics, Polish Academy of Sciences (IFPAN) has been running with the planned organizational structure: it has consisted of six groups headed by: **Tomasz Dietl** (**Theory Group**, ON6.1 in the IFPAN nomenclature), **Tomasz Wojtowicz** (**MBE Group**, ON6.2), **Vinayak Bhat** (**Characterization Group**, ON6.3), **Mircea Trif** (**Dirac Group**, ON6.4), **Carmine Autieri** (**Majorana Group**, ON6.5), and **Marcin Matusiak** (**Weyl Group**, ON6.6), though V. Bhat had to return to India on October 31st 2023. Each group has been composed of at least three junior members, i.e., young doctors and PhD students, eighteen financed by the MagTop project, and two by other research grants. Furthermore, eight doctors with research and development experience enhance MagTop's group research proficiencies (see Sec. 2). The total number of research staff, counting in **full positions** and taking PhD students into account, was 30 in 2023, coming from ten countries or from fourteen counting alumni (Sec. 3). The purchased **specialized equipment** for magnetic resonance and Brillouin scattering studies, together with capabilities, continuously upgraded to the state-of-the-art level, for **bulk and epitaxial growth** of topological materials, **processing**, **charge and heat transport** experiments up to 16 T, are supplemented by grants for **computation time** and access to European **large facilities**. The present MagTop Project ended on Dec. 31st 2023 but the MagTop community had applied to the Foundation for Polish Science for a continuation of support within the International Research Agenda FENG Programme. As shown and updated in the home page www.MagTop.ifpan.edu.pl, MagTop researchers have to date co-authored **274 publications** (available to the public at large *via* green open access depository arXiv), out of which 218 are in journals indexed in the JCR list, delivered **101 invited talks,** and contributed to **291 conference presentations**.

As clear from this report, MagTop's management has successfully encouraged extensive collaborations with international partners and industrial companies, as described in Secs. 4 and 1.2, 5, respectively. As an example of fruitful international collaborations we can quote two multi-institutions' papers just accepted to *Nature*, to which MagTop young researchers contributed in a critical way (see pp. 6 and 8). With no doubt, MagTop's strength has also resulted from the wide-ranging in-house synergy between materials developers, experimental and device

physics, theoreticians, and computational materials scientists. For instance, one of ten most downloaded *Phys. Rev. B* papers in 2023 resulted from the Weyl and Majorana Groups' collaboration (see p. 8). Finally, we note that MagTop's community has been successful in earning third-party projects that are listed in Sec. 6.

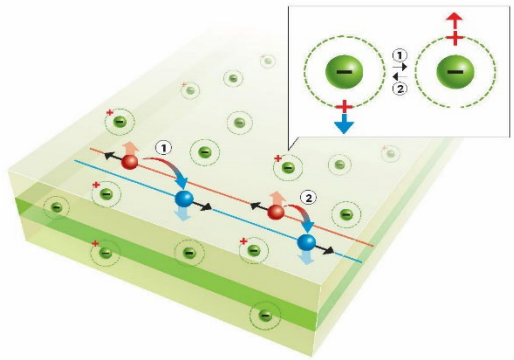
In addition to joint publications with **over 40 research institutions** world-wide (Sec. 4), cooperation agreements have been signed with the **Central Office Measures**, **six industrial companies**, and **six patents** (three by MagTop, three jointly with cooperating companies – **PUREMAT**, **PREVAC**, and **Robert Bosch GmbH**) have been submitted to the European Patent Office, one already approved. Importantly, one patent resulted in a product that is offered by PREVAC. Furthermore, joint papers have been published with VIGO Photonics, PUREMAT, and Robert Bosch GmbH. In this way, all ambitious **Indicators of the MagTop Project are being fulfilled**. Furthermore, as outreach actions, MagTop researches have co-organized **five international conferences** and have carried out various **science popularization** activities for the public at large and high-school research enthusiasts.

We present here 24 research highlights the MagTop community is especially proud of, grouped into five subfields, with addresses of relevant publications or preprints. The highlights are grouped into five major topics: **(1) Quantum spin Hall and quantum anomalous Hall materials; (2) Topological crystalline insulators; (3) Weyl semimetals; (4) Towards Majorana zero modes and beyond; (5) Beyond topological electronic matter.** A list of publications concerning accomplishments not discussed explicitly here is given in the MagTop home page.

Quantum spin Hall and quantum anomalous Hall materials

1. Understanding the quantum spin Hall effect [Theory and Majorana Groups]

Unlike in the quantum Hall effect [1,2] and quantum anomalous Hall effect, the quantization precision in the quantum spin Hall effect depends on unavoidable background impurities and defects [3,4]. However, doping with magnetic ions restores the quantization accuracy [3,4]. In specific systems, topologically trivial edge states [5] and spontaneous formation of excitonic liquid can play a role [6].



Destructive role of acceptors occupied by holes in the quantum spin Hall effect regime, e.g., in HgTe quantum wells. Two backscattering processes between helical states are allowed in the presence of electron-hole exchange and spin-orbit interaction: (1) spin-conserving and (2) spin non-conserving leading to backscattering for spin-momentum locking case. As the Kondo limit is reached, the scattering rate is large provided that no bound magnetic polarons are formed around occupied acceptors (after [3,4]).

[1] I. Yahniuk *et al.*, npj *Quantum Materials* **4**, 13 (2019); [2] I. Yahniuk *et al.*, arXiv:2111.07581 (2021); [3] T. Dietl, *Phys. Rev. Lett.* **130**, 086202 (2023); [4] T. Dietl, *Phys. Rev. B* **107**, 085421 (2023) [Editors' suggestion]; [5] N. M. Nguyen *et al.*, *Phys. Rev. B* **107**, 045138 (2023); [6] T. Paul *et al.*, *Phys. Rev. B* **106**, 235420 (2022).

2. Theory of magnetic impurities in topological semiconductors and quantum anomalous Hall effect in HgTe quantum wells [Theory and Majorana Groups]

A consensus appeared [He Ke *et al.*, *Annu. Rev. Cond. Mat. Phys.* **9**, 329 (2018); Y. Tokura *et al.*, *Nat. Rev. Phys.* **1**, 126 (2019)] that the enhanced interband magnetic susceptibility leads to a strong and foremost ferromagnetic coupling between transition-metal spins in quantum anomalous Hall effect materials. A series of MagTop's works [1-5] shows why superexchange, rather than interband Van Vleck/Bloembergen-Rowlad mechanism, dominates exchange coupling between localized spins in topological materials and why there is no ferromagnetism in Fe-doped topological systems [4] but may appear in Cr- [4,5] and V-doped [6] case.

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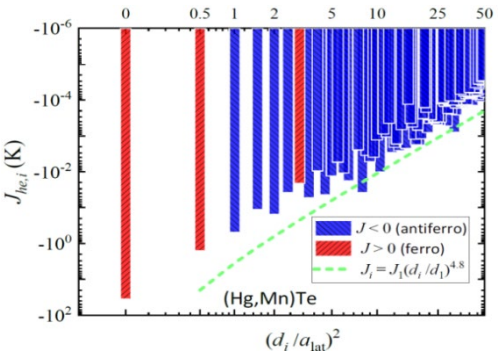
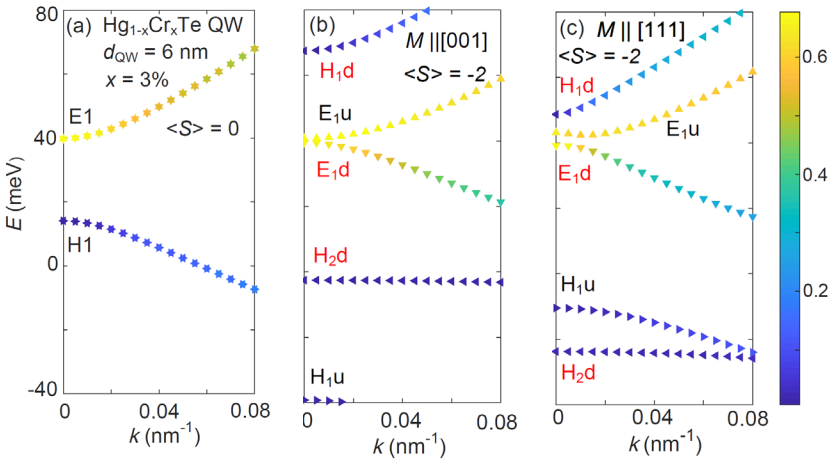


Contribution of the interband (he) Van Vleck-Bloembergen-Rowland mechanism to the exchange energies J_i in topological (Hg,Mn)Te vs. the pair distance d_i. The interband term contains a dominating ferromagnetic self-interaction component ($J_{he,i}$ at d_i = 0). The total interaction including superexchange is sketched by the green line (after [3]).

However, the obtain results [6] show that V may act as a resonant donor in the HgTe conduction band, which may hampers a shift of the Fermi level to the topological gap. In contrast, the quantum anomalous Hall effect is predicted for (Hg,Cr)Te quantum wells for the magnetization vector tilted away from the growth direction (see Figure)



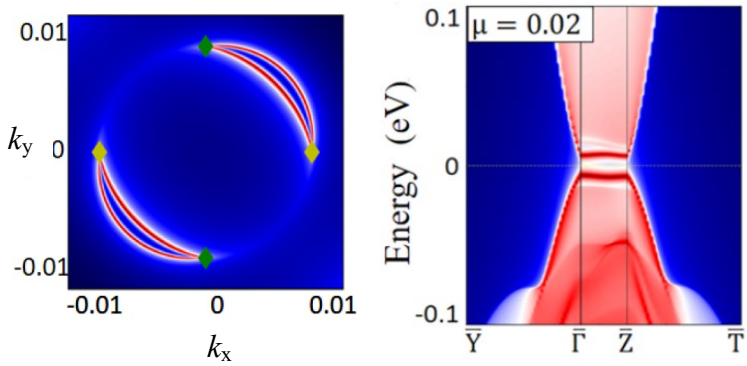
Spin-resolved subbands in a (Hg,Cr)Te/(Cd,Hg)Te quantum-well (QW) in the absence of Cr magnetization (a) and for magnetization along [001] (perpendicular to QW) and [111] directions (b,c). Colors show fractional contribution of s-like Kohn-Luttinger amplitudes and triangles spin up and down at k = 0. QAHE can appear for the Fermi level in the gap between E_1u and E_1d in (c) (after [5]).

[1] C. Śliwa, T. Dietl, Phys. Rev. B **98**, 035105 (2018); [2] C. Autieri *et al.*, Phys. Rev. B **103**, 115209 (2021); [3] C. Śliwa *et al.*, Phys. Rev. B **104**, L220404 (2021) [Editors' suggestion]; [4] Y. Satake *et al.*, Phys. Rev. Materials **4**, 044202 (2020) [Editors' suggestion]; [5] C. Śliwa and T. Dietl, arXiv:2310.19856 (2023); [6] G. Cuono et al., arXiv:2312.16732 (2023).

Invited talks: T. Dietl, *Improving Quantization Accuracy in Quantum Spin and Anomalous Hall Effects*, International Workshop „Topological Matter – Applications to Metrology", PTB, Braunschweig, Germany, 2-3 November, 2023; *QAHE limits*, TOCHA Winter School "Topological Electronics and Bosonics: from Concepts to Devices, Aussois, France, 28 Jan- 2 Febr., 2024; W. Brzezicki, *Unprotected edge modes in quantum spin Hall insulator candidate materials*, Superstripes 2023, Ischia, Italy, 26 June- 1 July, 2023.

3. New topological phases in mercury compounds [Majorana Group and Theory Groups]

Since the beginning of the era of topological materials, HgTe has been one of the most attractive compounds due to a large band inversion that makes it a robust topological system [B. A. Bernevig *et al.*, Science **314**, 1757 (2006); M. Koenig, *et al.*, Science **318**, 766 (2007). MagTop's computational team engineered new topological phases of two kinds of HgTe-based superlattices, one preserving time-reversal symmetry and another violating it by magnetic ions.



Fermi arcs (red) in a HgTe/HgSe superlattice around the Γ point and projected onto (001) surfaces (left panel). Diamond markers indicate Weyl points with chirality −2 (yellow) and +2 (green) (after [1]). Surface states (red) on the (100) surfaces in HgTe/MnTe superlattices (right panel). A small gap is visible but the system represents the axion insulator phase protected by $C_2 \cdot T$ symmetry (after [2]).

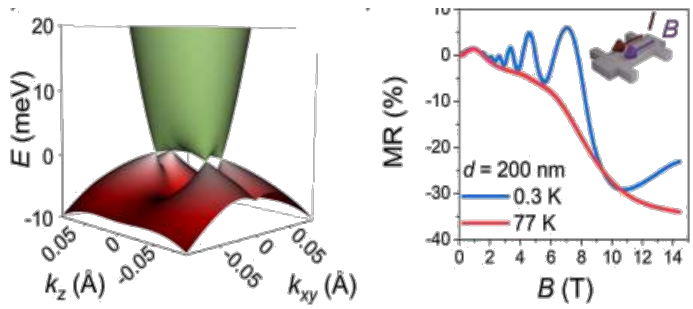
[1] R. Islam *et al.*, *Phys. Rev. Research* **4**, 023114 (2022); R. Islam *et al.*, *Phys. Rev. B* **107**, 125102 (2023).

Invited talk: C. Autieri, *New topological phases in HgTe-based system*, 25th International Conference on the Electronic Properties of Two-Dimensional Systems (**EP2DS-25**) and 21st International Conference on Modulated Semiconductor Structures (**MSS-21**), Grenoble, France, 9- 14th July 2023.

4. Developing quantum spin Hall materials: grey tin and mercury compounds [MBE and Weyl Groups]

Experimental and theoretical studies carried at Wuerzburg University, MagTop, and elsewhere call for extensive progress in developing 3D, 2D, and 1 D systems of non-magnetic and magnetic mercury-based chalcogenides, and related topological materials such as grey tin, in order to find new topological phases (such as axion insulator) and explore of interplay between Kondo, Luttinger, and magnetic polaron effects in a topological setting. MagTop's MBE Group has launched an extensive programme on the growth and characterization of grey tin and, in collaboration with the University of Rzeszów, is striving to develop its own MBE growth technology for mercury compounds' quantum structures that so far were taken from Novosibirsk [1].

One of discoveries made for compressively strained α-Sn deposited onto CdTe substrates is the observation of a negative slope of *both* resistance ρ(B) and thermoelectric power *S*(*B*) as a function as the magnetic field applied along the electric current [2,3] (see figure). That finding supports strongly the appearance of a current and heat flow between Weyl cones, the effect known as chiral anomaly.

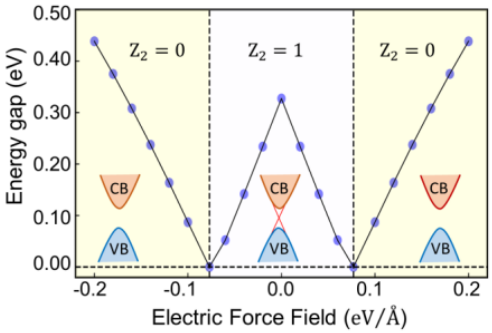


Band structure of compressively strained α-Sn/CdTe in in-plane magnetic field B = 10 T showing Weyl semimetal band structure and an example of α-Sn magnetoresistance in a magnetic field parallel to the current, measured at two temperatures, and assigned to chiral anomaly (after [2]).

[1] I. Yahniuk *et al.*, arXiv:2111.07581 (2021) [publication withdrawn after Russian war against Ukraine]; [2] J. Polaczyński *et al.*, arXiv:2309.03951 (2023); [3] Weyl Group, to be published.

5. Predicting new quantum spin Hall systems in atomically-thick 2D materials [Majorana Group]

In quantum spin Hall (QSH) materials studied so far the longest topological protection length is of the order of a few micrometers and the operation temperature is too low for potential applications. MagTop's researchers have theoretically demonstrated a large topological gap and a strong sensitivity to an electric field of $MoSi_2N_4$ and related 2D systems [1-6].

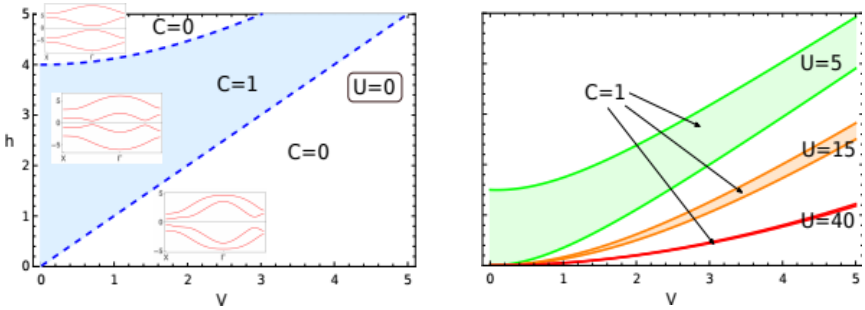


Topological invariant Z_2 and band gap of 1T'-$MoGe_2P_4$ as a function of the applied out-of-plane electric field. The critical electric force fields $qE_C = \pm 0.077$ eV/Å, within which the quantum spin Hall phase exists, are marked with vertical dashed lines (after [6]).

[1] R. Islam *et al.*, *Phys. Rev. B* **104,** L201112 (2021); [2] G. Hussain *et al.*, *Appl. Surf. Sci.* **590**, 153131 (2022); [3] G. Hussain *et al.*, *Physica* E **144**, 115471 (2022); [4] G. Hussain *et al.*, *J. Magn. Magn. Mat.* **563**, 169897 (2022); [5] R. Islam *et al.*, *Phys. Rev. B* **106**, 245149 (2022); [6] R. Islam *et al.*, Adv. Electron. Mater. **9**, 2300156 (2023).

6. Quantum and topological phase transitions in interacting systems [Theory Group]

One of the central questions in the field of condensed matter physics is understanding the microscopic mechanisms governing phase transformations in systems with strong electron correlations. MagTop's theoretical teams addressed conditions for the appearance of quantum or topological phases in selected systems, including (i) a subtle interplay between itinerant ferromagnetic and antiferromagnetic correlations in various strongly correlated metals under pressure [1-3]; (ii) the formation of the quantum anomalous Hall phase for electrons experiencing the Rashba interaction, Zeeman splitting, and ionic potential, and (iii) the effect of many-body interactions on the Chern insulator clarifying a misleading notion of the first-order topological transition (see Figure) [4]; the formation of a topological Mott insulator in odd-integer filled Anderson lattice model incorporating odd-parity hybridization between orbitals with different degrees of correlations introduced in the Hatsugai-Kohmoto spirit [5].



Topological phase diagrams (Chern number C) vs. ionic potential V and Zeeman field h for uncorrelated system U = 0 (left panel) and correlated case for selected values of U. Solid lines denote transitions at which spectral gaps do not close [4].

[1] M. M. Wysokiński, *Sci. Rep.* **9**, 19461 (2019); [2] M. M. Wysokiński, *Phys. Rev. B* **97**, 041107(R) (2018); [3] G. Cuono *et al.*, *Phys. Rev. B* **104**, 024428 (2021); [4] M. M. Wysokiński and W. Brzezicki, Phys. Rev. B **108**, 035121 (2023); [5] K. Jabłonowski et al., Phys. Rev. B **108**, 195145 (2023).

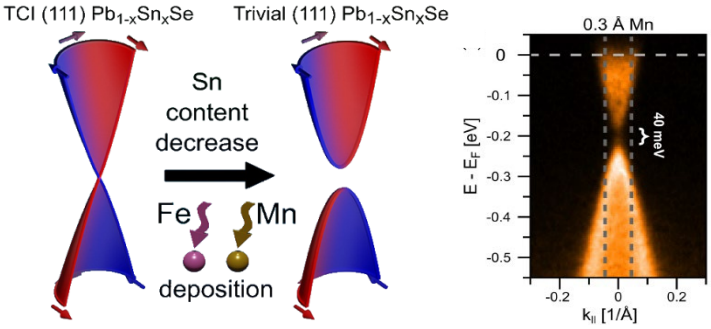
Invited talks: M. M. Wysokiński, *Mechanism for pressure driven transitions between itinerant ferromagnetism and antiferromagnetism in correlated materials*, Superstripes 2019 Meeting, Ischia, Italy, 23-29 June, 2019; *Two-channel Stoner mechanism for ferromagnetic/antiferromagnetic phase transitions in metallic magnets*, Quantum Ferromagnetism and Related Phenomena Conference, Dresden, Germany, 6-10 May, 2019.

Topological crystalline insulators (TCI)

7. Interfacing topological materials with magnetic metals [MBE Group]

Whether magnetism really opens a gap in topological surface states has become one of most intriguing question in topological physics [see, e.g., Y. L. Chen *et al.*, *Science* **329**, 659 (2010); E. D. L. Rienks *et al.*, *Nature* **576**, 423 (2019)]. MagTop's researchers demonstrated that the effect may come from chemical substitution of heavy

cations by lighter ones, rather than from the effect of time-reversal symmetry breaking. At the same time, spin-momentum locking, relevant for spin current generation, remains present on the both sides of the topological phase transition [1].

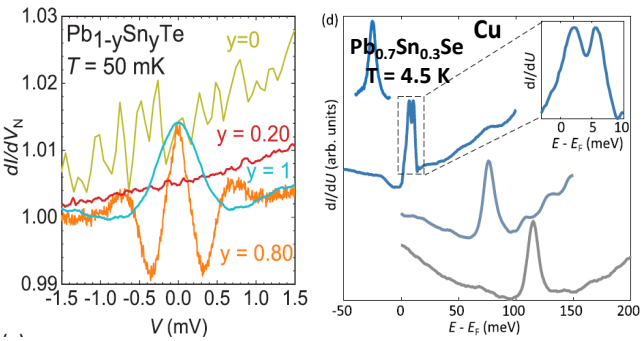


Deposition of a transition metal on the surface of a topological crystalline insulator (TCI) n-type $Pb_{1-x}Sn_xSe$ opens a gap in the surface Dirac cones (ARPES, right panel), but helical spin texture is preserved (after ([1]).

[1] B. Turowski *et al.*, *Appl. Surf. Sci.* **610**, 155434 (2023).

8. One-dimensional topological states along surface atomic steps [Weyl, Majorana, and Theory Groups]

High-quality TCI crystals grown at IFPAN/MagTop allowed to demonstrate by scanning tunneling spectroscopy (STS) the presence 1D higher-order topological states residing at the edges of odd-atom-high steps at (001) $Pb_{1-x}Sn_xSe$ hosting TCI states [P. Sessi *et al.*, *Science* **354**, 1269 (2016)]. The presence of 1D topological states in the 3D systems constitutes experimental demonstration of higher order topological states, as extensively discussed theoretically [F. Schindler *et al.*, *Sci. Adv.* **4**, eaat0346 (2018)].Those 1D states undergo hybridisation splitting by coupling to neighbouring steps [1]. Experimental [2] and theoretical [3] arguments were presented that step states account for Andreev-like point-contact spectra observed in a number of topological systems, including TCI, the insight corroborated by STS data showing a gap when metal overlayers shifted the Fermi energy to those states [4].



Scanning tunnelling spectroscopy [2] (left panel) and point contact spectroscopy [3] (right panel) showing features for Sn concentrations corresponding to the topological phase. Deposition of Cu shifts the Fermi energy towards 1D states leading to the appearance of a gap in the energy spectrum [2], as predicted in Ref. 4 to explain the origin of the point contact spectra [3].

Recently, Dr Rajibul Islam of the Majorana Group carried out *ab initio* computations, essential to support the claim about the discovery of exotic higher-order topology gapless states at step edges in α-As [5]. Rajibul is one of the three first authors with the equal contribution.

[1] J. Jung *et al.*, *Phys. Rev. Lett.* **126**, 236402 (2021); [2] G. Wagner *et al.*, *Nano Lett.* **23**, 2476 (2023); [3] G.P. Mazur *et al.*, *Phys. Rev. B* **100**, 041408(R) (2019) [Editors' suggestion]; [4] W. Brzezicki *et al.*, *Phys. Rev. B* **100**, 121107(R) (2019); [5] Md. S. Hossain *et al.*, arXiv:2401.04845 (2024), *Nature*, accepted (January 2024).

Invited talks: W. Brzezicki, *Topological effects in SnTe-class multilayers and nanowires,* Superstripes 2022, Frascati, Rome, Italy, June 20-24, 2022; T. Dietl, *Zero-energy modes in topological materials: experimental observations and proposed models*, Materials Research Meeting 2019, Yokohama, Japan, 10-14 December, 2019.

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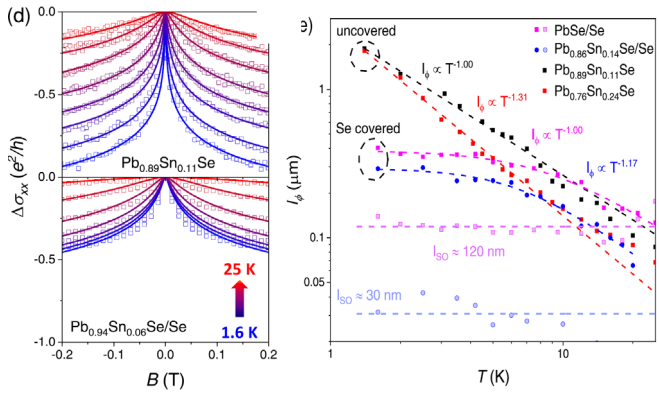
9. Interfacing topological crystalline insulators with amorphous semiconductors: breaking of reflection symmetry [MBE and Theory Groups]

Topological crystalline insulators (TCIs) have revealed that topologically protected gapless surface states can be brought about by crystal symmetries. MagTop's researchers demonstrated experimentally and theoretically that breaking of reflection symmetry by an overlayer of an amorphous semiconductor leads to a temperature independent phase coherence length controlling quantum localization magnetoresistance [1]. Furthermore, in agreement with MagTop's ARPES data [2], spin-momentum locking and, thus quantization of the Berry phase, exists on the both sides of the topological phase transitions [1].



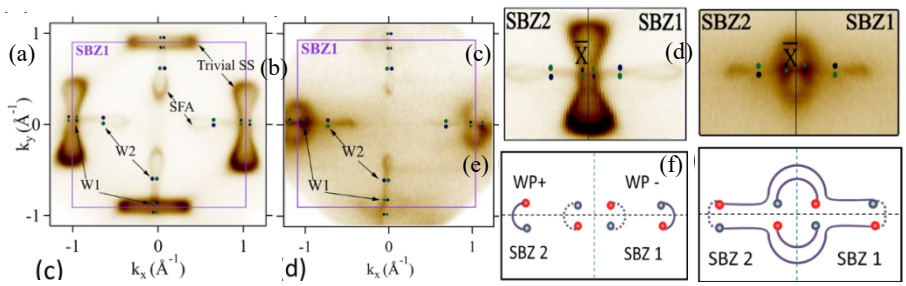
Evolution of the WAL magnetoresistance with increasing temperature in uncovered (left, upper panel) and Se covered (left, lower panel) epilayers. Experimental points (empty squares) are fitted using one-channel Hikami-Larkin-Nagaoka expression for a strong spin-orbit interaction (solid lines). Right panel shows, that $l_\varphi(T)$ in uncovered epilayers do not saturate down to 1.5 K (black and red), while in Se covered epilayers l_φ saturates below 5-7 K (blue and magenta) (after [1]).

[1] A. Kazakov *et al.*, *Phys. Rev. B* **103**, 245307 (2021); [2] B. Turowski *et al.*, *Appl. Surf. Sci.* **610**, 155434 (2023)].

Weyl semimetals

10. Interfacing Weyl semimetals with heavy metals: Lifshitz transition in surface bands [Theory and Majorana Groups]

Revealing and functionalizing interfacing effects is in the heart of MagTop's activities, and brought a number of surprising developments in the case of topological crystalline insulators with gapless 2D and 1D Dirac states at the surface, as described in other highlights. MagTop's studies demonstrated that deposition of heavy metals Pb and Nb on the surface of Weyl semimetal NbP strongly affects non-topological surface states and displaces arches connecting Weyl points, substantiating a theory of the topological Lifshitz transition [G. E. Volovik, *Low Temp. Phys.* **43**, 47 (2017)] .



ARPES visualization of P-terminated surface of NbP before (a,c) and after deposition of 1 ML of Pb (b,d) (after [1]). Possible reconstruction of topological arches is also shown (e, f).

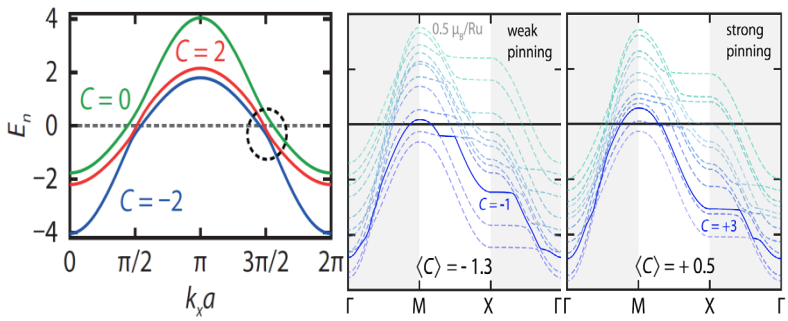
[1] A.S. Wadge *et al.*, *Phys. Rev. B* **105**, 235304 (2022).

11. Interfacing Weyl metals to polar insulators: topological reconstruction of bands [Theory and Majorana Groups]

Charge transfer that appears at the interface of ultrathin itinerant ferromagnet $SrRuO_3$ and polar insulator $LaAlO_3$ exceeds capacities of ordinary electrostatic gates. MagTop's theoreticians, after determining the Chern numbers for a $SrRuO_3$ monolayer [1], showed that such interfacial doping affects the spin-orbit interaction driven Berry curvature, and in an extreme case leads to a change of the sign of the anomalous Hall conductivity below Curie

temperature [2]. This effect is due to a conversion of the Chern numbers of partially occupied bands, i.e., due to topological reconstruction in the momentum space, occurring in the presence of both strong or weak charge pinning (redistribution) in the Weyl metal layer.

A unique expertise of Dr hab. Wojciech Brzezicki in the spin-orbit physics allowed him to perform a comprehensive analysis of the orbital and spin-orbital textures in Sr_2RuO_4, which indicated a possible presence of hidden symmetry-breaking spin-orbital chiral currents phases. Furthermore, he proposed a methodology based on circularly polarized spin-selective angular-resolved photoelectron spectroscopy to probe them. Those exotic phases were indeed revealed experimentally [3].



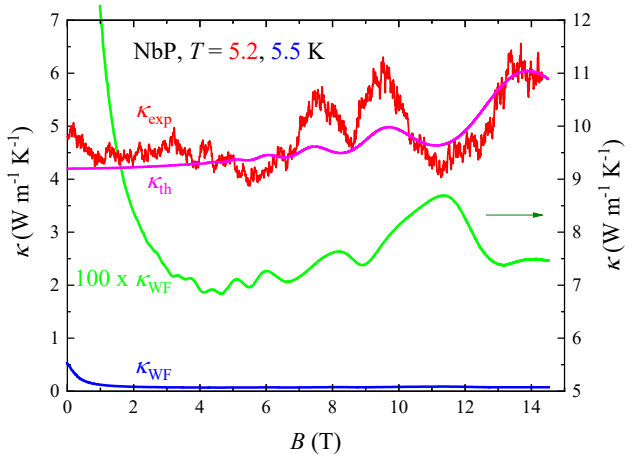
Chern number C for Ru t_{2g} bands for a single monolayer (left panel) [1] and bilayer of $SrRuO_3$ (right panels). Different magnitude of the charge transfer between the two monolayers leads to a sign change of an average C value and of the anomalous Hall conductivity (after [2]).

[1] D. J. Groenendijk *et al.*, *Phys. Rev. Research* **2**, 023404 (2020); [2] T.C. van Thiel *et al.*, *Phys. Rev. Lett.* **127**, 127202 (2021); [3] F. Mazzola *et al.*, *Nature*, accepted (January 2024). Wojciech Brzezicki is one of two first authors with the equal contribution.

Invited talk: W. Brzezicki, *Berry phase effects in the layered topological metals,* Electronic Correlations, Emergent Phenomena, and Quantum Materials, Amalfi, Italy, April 10th – April 14th 2022; C. Autieri, *Competing sources of Berry curvature and charge reconstruction at the oxide interface*, Unconventional transport in superconducting & magnetic systems with spin-orbit coupling, Workshop OSS2022, Vietri sul Mare, Italy, 14-17 Nov. 2022 .

12. Heat vs charge transport in Weyl semimetals [Weyl and Majorana Groups]

Topologically non-trivial materials exhibit a variety of extraordinary transport phenomena affecting both charge and heat flow. The latter is considered to be more robust to experimental artefacts that may appear in electrical measurements [D. Vu et al., *Nat. Mat.* **20**, 1525 (2021)]. MagTop's Weyl group found novel effects in thermal conductivity, the chiral zero sound, leading to the breaking to the Wiedemann-Franz law (see Figure), and the thermal chiral anomaly, i.e., heat flow between opposite chiral subbands, in two different Weyl semimetals: NbP [1] and NdAlSi [2]. Furthermore, a change in sign of the anomalous Hall and Nerst effects with the magnetic field direction was discovered experimentally and described theoretically in the noncollinear Weyl semimetal CeAlSi. [3].

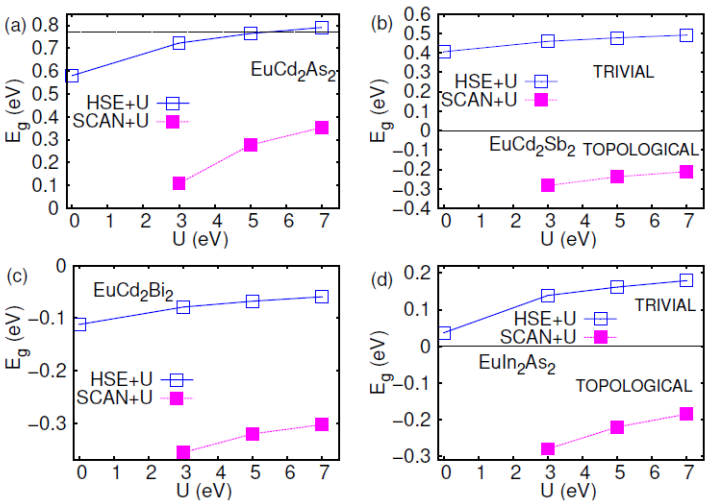


Magnetic field dependence of the thermal conductivity (κ_{exp}) of NbP at $T = 5.2$ K (uppermost red line) compared to the electronic thermal conductivity (κ_{WF}) calculated from the Wiedemann-Franz law at $T = 5.5$ K (lowermost blue line). The middle (cyan) line shows $\kappa_{WF}(B)$ multiplied by 100 (right axis). The pink line is the total thermal conductivity including the calculated CZS contribution (κ_{th}) (after [1]).

[1] P.K. Tanwar *et al.*, *Phys. Rev. B* **106**, L041106 (2022); [2] P.K. Tanwar *et al.*, arXiv:2305.04650; [3] Md. S. Alam *et al.*, Phys. Rev. B **107**, 085102 (2023) [one of ten most downloaded Phys. Rev. B papers in 2023].

13. Fixing the topological phase diagram for Eu-based antiferromagnets and related compounds [Theory and Majorana Groups]

Surprising physics of magnetic topological materials and possible applications in sensors, metrology, computing, and catalysis [B. A. Bernevig *et al*. *Nature* **603**, 41 (2022)] have triggered experimental and computational search for compounds with robust topological functionalities coexisting with or brought about by a magnetic order. In particular, high-throughput first-principles calculations, implementing the density functional theory (DFT) within the generalized gradient approximation (GGA)+Hubbard *U*, indicated that 130 compounds out of 430 magnetic materials studied have topological phases when scanning *U*, primarily having Weyl points [Y. Xu *et al.*, *Nature* **586**, 702 (2020)]. MagTop's researchers called those results into question demonstrating that more computationally demanding approaches are necessary to properly identify topological classes and, in particular, explain [2] the experimentally observed band gap in $EuCd_2As_2$ and its red shift in a magnetic field [1]. As shown in Figure, hybrid functional method (HSE) is the method properly explaining the gap magnitude and allows one to predict the topological class of particular compounds.



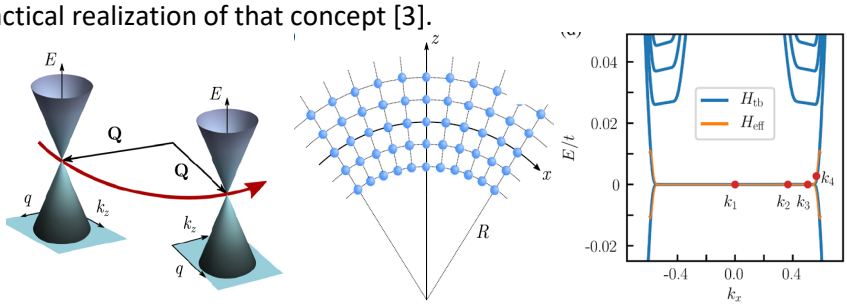
Band gap for (a) $EuCd_2As_2$, (b) $EuCd_2Sb_2$, (c) $EuCd_2Bi_2$ and (d) $EuIn_2As_2$ as a function of the Coulomb repulsion U in the AFM configuration with spins along the a-axis by considering HSE+U hybrid functional method (blue solid line). SCAN+U approach results are for comparison shown by purple dashed line. The horizontal dashed line for $EuCd_2As_2$ represents the experimental value[1]. Negative band gaps point to the topological phase (after [2]).

[1] D. Santos-Cottin *et al*., Phys. Rev. Lett. **131**, 186704 (2023); [2] G. Cuono *et al*., Phys. Rev. B **108**, 075150 (2023).

Invited talk**:** C. Autieri, *Design of new topological materials,* International Conference on Crystal Growth and Epitaxy, Naples, Italy, 30 July-4 August 2023.

14. Three-dimensional flat bands [Majorana and Dirac Groups]

After explaining how the flat band in twisted graphene can carry a non-zero supercurrent [1], MagTop's theoreticians demonstrated that strain engineering can be used to generate quasi-flat three-dimensional energy bands in materials known as topological nodal-line semimetals, thereby paving the way to tunable correlated phases in three-dimensional materials [2]. HgTe/CdTe superlattices, as core-shell nanowires, can constitute a practical realization of that concept [3].



In a nodal-line semimetal, Dirac cones are formed with respect to the perpendicular momentum components q and k_z (left). Strain profile (middle) leads to a flat band (right) (after [2]).

[1] Xiang Hu *et al.*, *Phys. Rev. Lett.* **123**, 237002 (2019); [2] A. Lau *et al.*, *Phys. Rev. X* **11**, 031017 (2021); [3] R. Islam *et al.*, *Phys. Rev. Research* **4**, 023114 (2022).

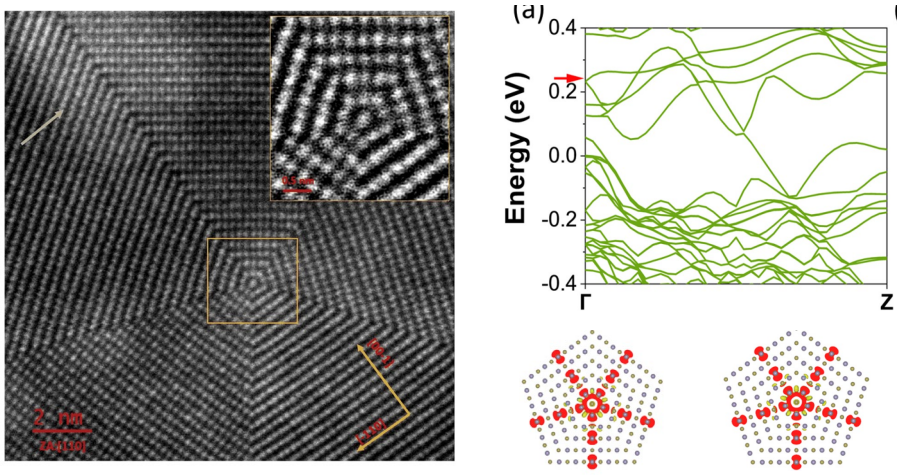
Invited talk: T. Hyart, *Correlated states in flat-band systems and topological properties of surface steps in the SnTe material class*, Coherence in Fermionic Matter: Fermion Pairing in Cold Atoms and Superconductors, Bad Honnef, Germany, 13-16

October, 2019; Mini-workshop on Topology, Superconductivity and Spin-orbit physics, Tsinghua University, Beijing, China, 17 May, 2019.

Towards Majorana zero modes and beyond

15. Nanowires of topological crystalline insulators [MBE, Weyl, and Majorana Groups]

Given the retraction of *Nature* and *Science* papers claiming observations of Majorana zero-modes (MZM) but showing--as know now--disorder related effects, further progress requires advances in materials science [N. P. de Leon et al., *Science* **372**, eabb2823 (2021)]. Such a progress can be attained in labs such as MagTop/IFPAN having unbeatable experience in bulk and epitaxial growth of II-VI and IV-VI compounds and quantum device structures, including nanowires [1, J. Sadowski *et al.* *Nanoscale* **10**, 20772 (2018), arXiv:2211.08154]. In the context of searching for new materials platform, IV-VI topological crystalline insulator nanowires emerge as a perspective system for MZMs and higher-order topology, as indicated by theoretical work carried at MagTop [2] and then performed combining growth, characterization, and theoretical efforts [3]. Figure below depicts an example of a novel $Pb_{1-x}Sn_xTe$ pentagonal nanowire and corresponding band structure computations showing a band connecting the valence and conduction band [3].



Atom-resolved STEM image of five-fold $Pb_{1-x}Sn_xTe$ nanowire of the diameter of the order of 100 nm grown by MBE. The corresponding band structure computations reveal a band connecting the conduction and valence band. Lower panels show charge distribution (red) of two degenerate bands marked by arrow in the upper panel. The Fermi energy is set to zero (after [3]).

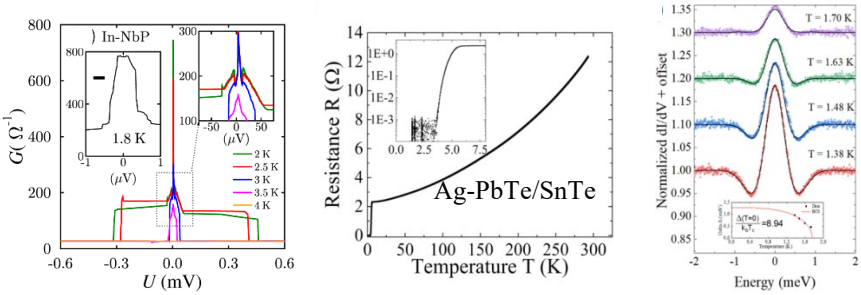
[1] P. Baranowski *et al.,* Nanoscale **15**, 4143 (2023); [2] N. M. Nguyen *et al.*, *Phys. Rev. B* **105**, 075310 (2022); [3] G. Hussain *et al.*, arXiv:2401.03455 (2024).

Invited talk: W. Brzezicki**,** *Topological effects in SnTe-class multilayers and nanowires,* Superstripes 2022, Frascati, Rome, Italy, June 20-24, 2022.

16. Search for topological superconductivity [Weyl, Theory, MBE Groups]

As, so far, the experimental signatures that identify a topological superconductor (TSC) are elusive [see, e.g., M. Mandal *et al.*, arXiv:2303.15581] and there has been no conclusive experimental observation of Majorana bound states in proximitized topologically trivial semiconductors [see, e.g., R. Hess *et al.*, *Phys. Rev. Lett.* **130**, 207001 (2023)], particularly timely is search for intrinsic or proximitized superconductivity in topological materials. MagTop/IFPAN's growers and experimentalists, in addition to work on nanowires discussed above, have been exploring three other paths: (i) Weyl semimetals with superconductors' overlayers [1]; topological crystalline insulators in the form of (ii) bulk crystals [2]; (iii) superlattices [3] (see Figure). Surprising and not yet understood results, calling for further work, have been gathered.

On the theoretical side, the Majorana Group in collaboration with with Bosch Center for Artificial Intelligence, proposed a machine-learning approach for classifying the topological states of 2D chiral superconductors based on local density of states data that can be obtained by scanning tunneling microscopy or possibly by nanoARPES [4].

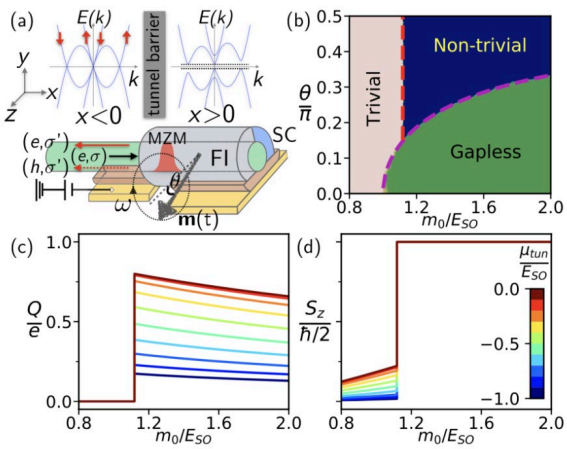


Differential conductance and four contact conductivity in In-NbP [1] and Ag-PbTe/SnTe super-lattices [3] showing signatures of superconductivity in topological materials.

[1] G. Grabecki *et al.*, Phys. Rev. B **101**, 085113 (2020); [2] G. P. Mazur *et al.*, Phys. Rev. B **100**, 041408(R) (2019); [3] P. Sidorczak *et al*. (unpublished); [4] P. Baireuther *et al*., European Patent Application*:* EP21209049.2; SciPost Phys. Core **6**, 087 (2023).

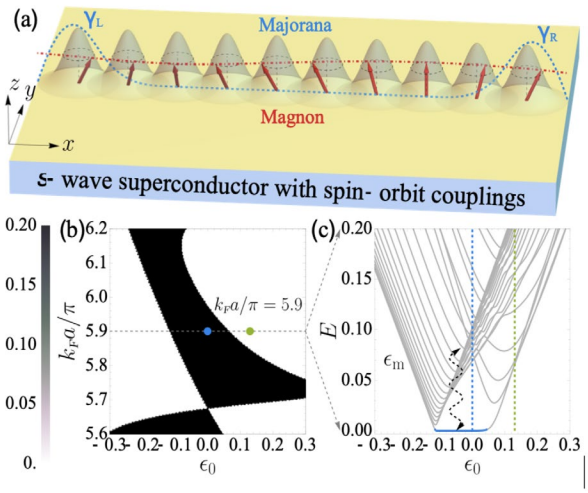
17. Detecting Majorana zero modes [Majorana and Dricac Groups]

One of the most challenging aims in the current condensed matter physics research is the demonstration of non-Abelian Majorana statistics — the underlying fundamental property that would enable the realization of a topological quantum computer. Though not experimentally proven, it is theoretically well established that Majorana zero modes (MZMs) can be realized in semiconducting nanowires with strong Rashba spin-orbit coupling in the presence of induced superconductivity and external magnetic field. MagTop's team studied theoretically ferromagnetic-semiconducting-superconducting hybrids with MZMs, and demonstrated that this system; (i) constitutes a novel topological charge, spin, and heat transistor [1,3]; (ii) shows quantization of spin under spin pumping conditions [2].



(a) Rashba nanowire (green) with proximity induced superconductivity (blue) and magnetization (gray) supports MZM (red). The precessing magnetization m(t) pumps spin and charge into the lead due to the normal and Andreev reflection processes. (b) Topological phase diagram of the nanowire as a function of the exchange coupling m_0 and the precession angle θ. (c), (d) The pumped charge Q and spin S as a function of m_0 for different tunnel barriers μ_{tun}. The pump spin is quantized to $S_z = \hbar/2$ in the topologically nontrivial regime (after [2]).

Another relevant system that can host MZM consists a chain of ferromagnetically coupled magnetic atoms, see Figure below. MagTop researchers showed that the susceptibility associated with the feedback of electrons on the magnonic spectrum shows a difference when the zero modes originate from true Majorana end-modes and trivial zero modes, respectively. They demonstrated also that such differences are robust against moderate disorder [4].

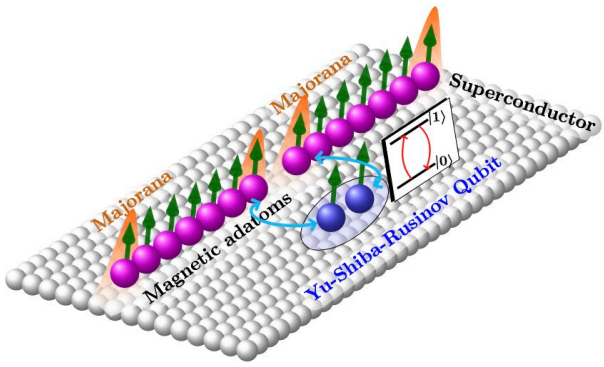


A chain of ferromagnetically coupled adatoms on a two-dimensional s-wave superconductor harboring Majorana zero modes (MZMs). The uniform magnonic mode (red dotted line) interacts with the MZMs (blue dashed line), altering its dynamics. (b) Topological phase diagram of the effective one-dimensional model as a function of $k_F a$ and ε_0 . The dotted lines indicate the boundary between topological (gray shaded) and non-topological (white) phases. The magnitude of the gap can be inferred from the shaded degree. (c) A line cut at k_F a/π = 5.9, where the blue (green) dashed line corresponds to the blue (green) dot in (b) and lies in a topological (normal) phase. The curved arrow indicates the interaction between the MZM and the uniform magnonic excitation ε_m. The parameters are N = 30, ξ_0 = 10a, and λ_R = 0.05v_F , where v_F is the Fermi velocity (after [4]).

[1] V. Fernández Becerra *et al.*, *Phys. Rev. B* **103**, 205410 (2021); [2] V. Fernández Becerra *et al.*, *Phys. Rev. Lett.* **130**, 237002 (2023); [3] V. Fernández Becerra *et al.*, European patent nr EP3975275A1, submitted; [4] P. -X. Shen *et al.*, *Phys. Rev. Research* **5**, 033207 (2023).

18. Quantum computing with magnetic adatoms in superconductors [Dirac Group]

Magnetic impurities in s-wave superconductors provide a viable platform for realizing a topological quantum computer based on Majorana zero modes (MZMs). However, MZMs alone do not provide a universal set of quantum gates and manipulating coherently quantum degrees of freedom in these systems remains an open challenge. MagTop's team introduced a new type of quantum bit, a Yu-Shiba-Rusinov qubit [1], stemming from two nearby magnetic impurities on a superconductor and demonstrated how to determine relevant quantum gate and topological characteristics, including interactions with MZMs, by scanning tunneling microscopy-electron spin resonance techniques [1,2], couplings to microcavity modes [3], and dynamic magnetic susceptibility [4].



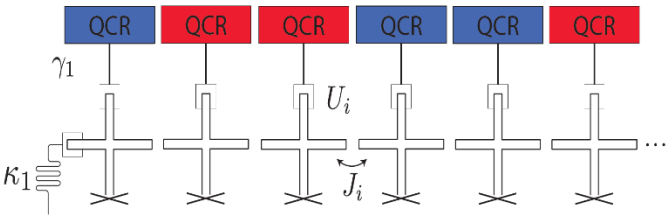
Two magnetic adatoms (blue balls) deposited on an s-wave superconductor generate an electronic Shiba that encodes a YSR qubit {⟨0|, ⟨1|}. Coupling this molecular qubit to Majorana zero modes hosted by topological Shiba chains (pink balls) and controlling the orientatiob of the adatoms spins in STM-ESR setups (green arrows) allows to implement a universal set of quantum gates (after [1)].

[1] A. Mishra et al., *Phys. Rev. X Quantum* **2**, 040347 (2021); [2] A. Mishra et al., *Phys. Rev. B* **103**, L121401 (2021); [3] Pei-Xin Shen *et al.*, *Phys. Rev. Research* **3**, 013003 (2021); [4] Peixin Shen *et al.*, Phys. Rev. Res. **5**, 033207 (2023).

Invited talk: M. Trif, *Berry-phase induced entanglement of spin qubits in a microwave cavity*, Workshop at Collège de France on Cavity Control of Quantum Matter, Paris, October 17-18th 2022.

19. Topological systems with dissipation: the discovery of long-range entanglement [Theory and Majorana Groups]

Making coupling to the reservoir a resource rather than an obstacle emerges as one of the most promising roads in topological quantum computing. MagTop's researchers proposed a 1D non-Hermitian model, in which they revealed the presence of a hidden Chern number [1]. They used that model to describe lasing in a polariton system [2] and, most recently, to examine a chain of transmon devices [3], the qubits of the most mature quantum computers. The dynamics of this system with dissipation, examined employing the third quantization methods, revealed the presence of controllable long-range quantum entanglement between distant end states of the chain.



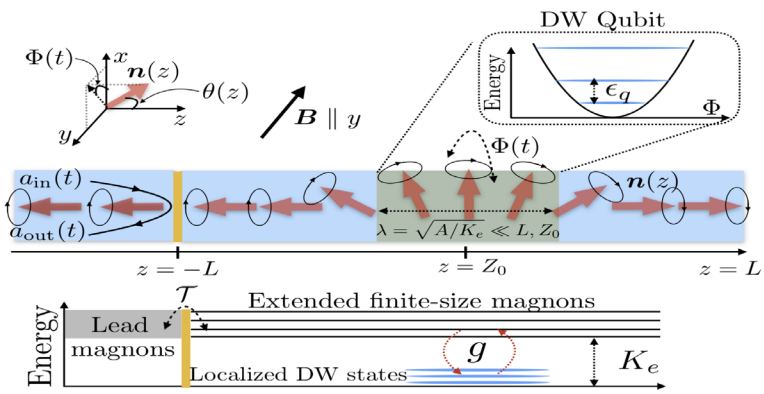
Non-Hermitian Bose-Hubbard transmon ABBA chain (A – blue, B – red) with the on-site and inter-site energies U_i and J_i, respectively. The dissipation strength is tuned by the coupling to the measurement circuit κ_i and loss caused by the quantum circuit refrigerator γ_i (QCR) (after [3]).

[1] W. Brzezicki *et al.*, *Phys. Rev. B* **100**, 161105(R) (2019); [2] P. Comaron *et al.*, *Phys. Rev. Research* **2**, 022051(R) (2020); [3] W. Brzezicki *et al.*, *Phys. Rev. B* **107**, 115146 (2023).

Beyond topological electronic matter

20. Magnonics meets topological quantum computing [Characterization and Dirac Groups]

Magnetic domain walls (DWs) are topological defects that exhibit robust low-energy modes that can be harnessed for classical and neuromorphic computing. However, the quantum nature of these modes has been elusive thus far. In collaboration with UCLA, the Dirac Group investigated the interaction between domain walls in nanowires of ferromagnetic insulators (such as YIG) and the surrounding spin waves for unravelling the *quantum* nature of DWs [1], the situation presented in Figure. The researchers demonstrated that magnons can mediate long-range entangling interactions between qubits stored in distant DWs, which could facilitate the implementation of a universal set of quantum gates. The proposal relies only on the intrinsic degrees of freedom of the ferromagnet, and can be naturally extended to explore the quantum dynamics of DWs in ferrimagnets and antiferromagnets, as well as quantum vortices or skyrmions confined in insulating magnetic nanodisks.



Ferromagnetic wire harboring a domain wall (DW) and supporting high-energy magnonic modes. The former harbors low-energy modes which, when quantized, can encode reliable qubits. Magnons couple to the DW via Berry phase terms and, when excited, can manipulate and detect the DW quantum states, which can be established from the power spectrum of the emitted magnons (after [1]).

On the experimental side, the Researchers at EPFL together with the MagTop's Characterization Group, demonstrated the multidirectional long-distance quantum coherence of short-wave magnons [2]. This

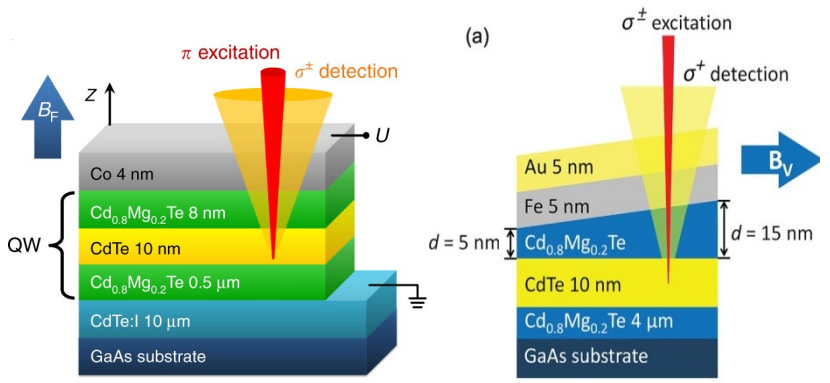
collaboration provided also important information on magnonic excitations in kagome artificial spin ices [3,4] and in artificial quasicrystals. In general terms, the accumulated data form a key asset for functional wave-based logic, neural networks, and the emerging in-memory computation.

[1] M. Trif and Y. Tserkovnyak, arXiv:2401.03164; [2] S. Watanabe et al., Adv. Mater. **35**, 2301087 (2023); [3] V. S. Bhat *et al*. Phys. Rev. Lett. **125**, 117208 (2020); [4] V. S. Bhat and D. Grundler, Appl. Phys. Lett. **119**, 092403 (2021); [5] S. Watanabe *et al*., Sci. Adv. **7**, eabg3771 (2021); [6] V. S. Bhat *et al*., Commun. Phys. **6**, 193 (2023).

Invited talks: M. Trif, *Cavity magnonics with domain walls in insulating ferromagnetic wires,* International Workshop: Condensed Matter Solitons, Center for Theoretical Physics of Complex Systems, Daejeon, South Korea, June 28 – 30, 2023.
V. Bhat, *Spatially Resolved Magnon Modes in Kagome Artificial Spin Ices with Topological Defects*, Magnetism and Magnetic Materials (MMM) Conference, USA, 2-6 November, 2020.

21. Interfacing ferromagnets and semiconductors: phonon-mediated exchange [MBE Group]

How to control a long-range phonon-mediated exchange interaction discovered by photoluminescence of CdTe quantum well (QW) in a hybrid Co/(Mg,Cd)Te/CdTe/(Mg,Cd)Te heterostructure grown by MBE at IFPAN [V. L. Korenev *et al.*, *Nat. Phys.* **12**, 85 (2016)]? Figure presents two structures fabricated by MagTop/IFPAN MBE teams, which made it possible to affect that exchange by low voltage *U* [1] and by the distance between the ferromagnetic layer and CdTe QW [2].

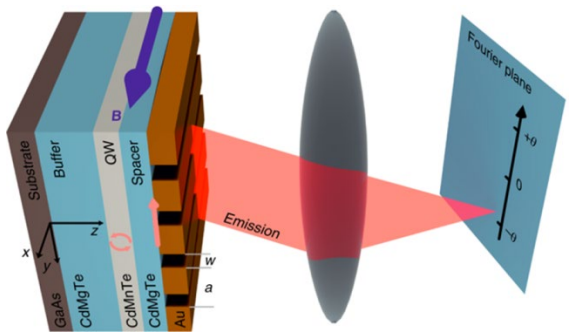


Hybrid structures grown in a two-chamber MBE set-up allowing for magnetooptical probing of exchange coupling between ferromagnetic layers (Co or Fe) and carriers in CdTe QW vs. voltage U (left panel) (after [1]) and distance d (right panel) (after [2]).

[1] L. Korenev *et al.*, *Nat. Commun.* **10**, 2899 (2019); [2] I. V. Kalitukha *et al*., *Nano Lett.* **21**, 2370 (2021).

22. A new class of transverse magneto-optical phenomena with potentials for applications in nanophotonic circuits [MBE Group]

High-quality quantum structures produced by MagTop/IFPAN MBE groups became building blocks of hybrid plasmonic-semiconductor nanostructures, which were used by MagTop's collaborators to demonstrate [1] and study in details [2] new phenomena of transverse magnetic routing of light emission (TMRLE), as well as to demonstrate optical controll of transverse electron spin components normal to the direction of light propagation [3]. In these hybrids, the plasmonic metal grating of Au was fabricated by electron beam lithography and lift-off on the surface of structure containing a diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$ quantum well (QW) (see Figure).

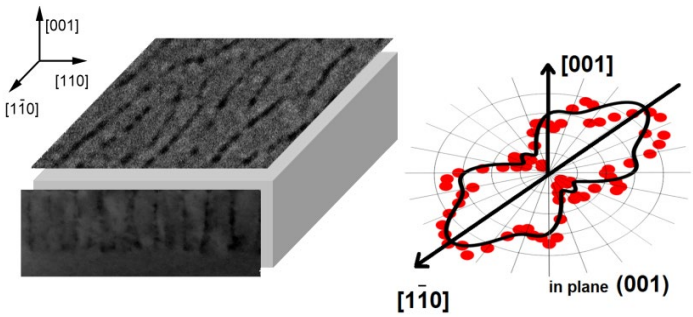


Schematic representation of experimental setup to demonstrate the TMRLE effect. An external in-plane magnetic field B is applied to the plasmonic structure (left part). The angular distribution of light emitted by the structure is converted by a lens into a spatial distribution in the Fourier plane (right) and recorded by a two dimensional CCD matrix (after [1]).

[1] F. Spitzer *et al.*, *Nature Phys.* **14**, 1043 (2018), corrections; [2] L. Klompmake *et al.*, *Phys. Rev. Research* **4**, 013058 (2022)
[3] I. A. Akimov *et al.*, *Phys. Rev. B* **103**, 085425 (2021).

23. Nematicity in solids: role of anisotropic spinodal decomposition and orbital polarization [Weyl and Theory Groups]

The origin of nematicity, *i.e.*, in-plane rotational symmetry breaking, and in particular the relative role played by spontaneous unidirectional ordering of spin, orbital, or charge degrees of freedom, is a challenging issue of magnetism, unconventional superconductivity, and quantum Hall systems. While MagTop's and collaborators' results indicated uneven d_{xz} and d_{yz} orbital occupation in a superconducting iron pnictide pointed to the important role of orbital polarization [1], experimental and theoretical results for $In_{1-x}Fe_xAs$ demonstrated that anisotropic distribution of Fe cations at the growth surface (that has a lower symmetry than the bulk) can lead to a quenched nematic order of alloy components, which then governs low-temperature magnetic and magnetotransport properties [2].



Non-uniform and anisotropic distribution of Fe cations in a 200 nm-wide slab of (In,Fe)As (black lines along the [1-10] crystallographic direction) according to HR-TEM (left panel) and the corresponding low-temperature anisotropic magnetoresistance (right panel) (after [2]).

[1] D. Rybicki *et al.*, *Phys. Rev. B* **102**, 195126 (2020); [2] Ye Yuan *et al.*, *Phys. Rev. Materials* **2**, 114601 (2018).

Invited talks: T. Dietl, *Phase separations and nematicity of transition metal impurities*, 25th Congress and General Assembly of the International Union of Crystallography Prague, Prague , Czechia, 14 – 22 August, 2021; The 2nd Kavli ITS Workshop on Magnetic Semiconductors, Beijing, China, 15-16 January, 2020; 16th RIEC International Workshop on Spintronics and 8th JSPS Core-to-Core Workshop on "New-Concept Spintronic Devices", Sendai, Japan, 9-12 January, 2019.

24. Altermagnetism [Majorana Group]

In recent two years, altermagnets have been discovered as an additional class of materials alongside the ferromagnets and conventional antiferromagnets. This novel class of materials exhibits non-relativistic spin-splitting in the collinear antiferromagnetic phase which brings these materials to host properties of both the ferromagnetism and antiferromagnetism phase. Similar to ferromagnets, these materials exhibit non-zero net magnetization in the reciprocal space which leads to non-relativistic spin-splittings while the net magnetization in real space is zero as in a typical antiferromagnet. The key to observing such phenomena in materials is certain crystal symmetries. MagTop researchers examined interplay between altermagnetism and nonsymmorphic symmetries, which generates large anomalous Hall conductivity by semi-Dirac points induced anticrossings [1]. In

noncentrosymmetric altermagnets, the role of Dzyaloshinskii-Moriya interaction in generating weak ferromagnetism was discussed [2]. Furthermore, a substantial enhancement of the band splitting by strong electron correlations was found in certain transition metal oxides [3]. Another relevant theoretical analysis concerned altermagnetism in thin films, interfaces [4], and topological materials [4,5]. The accumulated insight helped in interpreting experimental results for altermagnetic MnSe [6].

[1] A. Fakhredine *et al.*, Phys. Rev. B 108, 115138 (2023); [2] C. Autieri *et al.*, arXiv:2312.07678 (2023); [3] G. Cuono *et al.*, J. Magn. Magn. Mat. **586**, 171163, (2023); [4] R. M. Sattigeri *et al.*, Nanoscale **15**, 16998 (2023); [5] G. Cuono *et al.*, Phys. Rev. B **108**, 075150 (2023); [6] M. J. Grzybowski *et al.*, arXiv:2309.06422 (2023).

1.2 Results of research which may potentially be applicable to market (up to 250 words)

A new design of magnetron for sputtering of ferromagnetic materials was proposed in cooperation with PREVAC and joint application with European Patent Office was submitted (patent application number: EP4283011A1). In the agreement **on joint rights to a patent and joint patent**, MagTop already granted PREVAC the right, against payment, to use the invention in a new line of two inch sputtering sources.

In collaboration with VIGO a possibility of production of industrial-standard detectors from IV-VI/II-VI multilayers was investigated. Photonically optimized detector structures designed on basis of PbTe/CdTe quantum wells with various configurations were tested at VIGO. Very promising outcomes of these tests resulted in design of a new type of structures intended for multi-color, tunable infrared detectors. Solutions proposed in this case (European patent applications: EP23461604.3 and EP23461603.5) are quite universal and can also be incorporated into design of detectors or emitters of electromagnetic radiation outside infrared range.

A method of identifying topological invariants in superconductors with the help of a neural network was developed in collaboration with Robert Bosch GmbH (European patent application number: EP4184389A1). A new idea of “judges” proposed in this invention can also find a broad applications in the area of machine learning and more generally for artificial intelligence.

Together with PURAMAT a method to produce bulk thermoelectric nanocomposites of PbTe and CdTe was proposed (European patent number: EP4036057B1, see patent certificate). Apart from its direct potential for effective thermoelectric energy conversion devices such nanocomposite can find it application in monolithic cooler/infrared detector devices.

2. INFORMATION ABOUT SENIOR POST DOCS (independent researchers), VISITING SCIENTISTS AND TECHNICIANS and their contribution to the final implementation during the last year of the project

(Please provide a list of all senior post-docs, visiting scientists and technicians with a short description of how their tasks and performance contributed to the overall goals of the project.)

A total of 10 doctors with advanced R&D experience were involved in the MagTop project realization, 8 of whom worked in the final year of the project and are listed below, along with the dates of their part-time employment. They were all selected through open international competitions, in line with the MagTop project's employment rules. One of them, Dr Wojciech Brzezicki, initially worked at MagTop as a young doctor, and the other, Dr Carmine Autieri started as a doctor with advanced R&D experience and later became the leader of the Majorana Group (and is therefore not on the list).

The role of doctors with advanced R&D experience was absolutely crucial, as each of them added the expertise needed to achieve the overall goal of the wide-ranging project. A total of six experimental experts were recruited (position 1 to 6) and 4 theoretical experts (position 7 to 8, and Dr hab. Carmine Autieri and Dr Aleksei Shorokhov).

Their areas of expertise and specific research tasks and additional responsibilities are listed next to each of their names. Their key contribution to the scientific output of the project can best be understood by the fact that they are co-authors of the vast majority of all 218 articles that have appeared in JRC-listed journals and an additional 22 articles in other journals and arXiv.

Regarding the contribution of the members of MagTop's technical staff, who were also selected in open competitions, to the project's objective, it should be emphasized that, although they are not always co-authors of publications, without them none of the papers containing the experimental part, nor the four patent applications, could have been produced.

On the one hand, they took care of the very complex scientific equipment used for the project, starting from the preparation of specification for the public tenders, through the installation and starting up operation of the equipment, to its use during experimental studies. The individual contribution of the technical staff member concerned is outlined below.

This contribution also included close cooperation with hi-tech companies (Dr Krzysztof Fronc with PREVAC sp. z o.o., Dr Michał Szot with PUREMAT Technologies). To emphasize how important this contribution was, it is sufficient to mention that Dr Krzysztof Fronc is one of the authors of a patent application submitted with PREVAC to the European Patent Office and concerning a new type of sputtering source for magnetic metal (publication number EP4283011A1), and Dr Michał Szot is co-author of a patent with PUREMAT (patent number: EP4036057B1, see patent certificate). Dr Szot is also a co-author of other two patent application submitted in 2023 (with numbers: EP23461604.3 and EP23461603.5.)

Doctors with advanced R&D experience:

1. Prof. dr hab. Andrzej Wiśniewski – *Expert in magnetism and superconductivity* (from 3.03.2017, ½ of full time job)

   Research tasks: Growth of bulk Weyl semimetals, their structural characterization, interfacing with superconductors, and doping with magnetic impurities; applications to synchrotron centers and ARPES studies.

   Additional responsibilities: contacts with companies; coordination of patent applications, MagTop's promotion.

2. Dr. Tomasz Wojciechowski – *Expert in fabrication of nanostructures* (from 20.03.2017 to 31.05.2018, ½ of full time job, from 1.06.2018, ¾ of full time job, from 1.11.2022 full time job)

Research tasks: Nanostructurization and EDX characterisation of topological materials; research collaboration with VIGO Photonics S.A. and PUREMAT Technologies.

Additional responsibilities: training newcomers in operation and technical supervising of specialist equipment for nanostructurization and processing; expert technical support for tender procedures; supervision of budget issues.

3. Dr. Valentine Volobuev – *Expert in the MBE growth of topological matter* (from 4.12.2017, full time job)

   Research tasks: Growth of IV-VI compounds in the new MBE chamber for the growth of IV-VI compounds and metal overlayers and their structural characterization as well as ARPES studies.

   Additional responsibilities: training newcomers in MBE growth technology; co-supervising of PhD student MSc Bartłomiej Turowski; applications to synchrotron facilities; handling collaboration with the Johannes Kepler University in Linz.

4. Dr. hab. Krzysztof Dybko – *Expert in the low-temperature transport measurements of topological matter* (from 17.12.2018, ½ of full time job)

   Research tasks: Carrying on heat and electrical transport studies and as well as point contact spectroscopy of topological crystalline insulators.

   Additional responsibilities: Developing experimental setup for studying low-T electrical and heat transport in the presence of magnetic fields up to 14.5 T.

5. Prof. dr hab. Tomasz Story – *Expert in IV-VI topological materials* (from 1.04.2019, ½ of full time job)

   Research tasks: the growth of bulk TCIs their doping with magnetic impurities, structural characterization and studies. Assessing thermoelectricity of topological materials.

   Additional responsibilities: contacts with companies (especially with Helioenergy); MagTop promotion.

6. Dr. Aleksei Shorokov – *Expert in the study of nonequilibrium phenomena in topological matter* (from 1.06.2019 until 31.12.2019, full time job)

   Research tasks: In collaboration with other groups carrying on beyond state of the art theoretical studies of relevant systems stimulating and interpreting experimental results, and opening new research horizons.

7. Dr. hab. Piotr Wojnar– *Expert in the MBE growth of semiconductor nanowires* (from 20.04.2023, ½ full time job)

   Research tasks: Designing of II-VI and IV-VI nanowire nanostructures, including nanowires made of topological crystalline insulator. Growing these nanowires by molecular beam epitaxy (MBE) method. Designing and performing various types of experimental studies of grown nanostructures. Critical analysis of experimental data and preparing scientific publications.

   Additional responsibility: Co-supervision of two PhD students

8. Dr. hab. Wojciech Brzezicki– *Expert in symmetries and classification of topological materials* (employed as postdoc from 2.10.2017 and after completing habilitation (awarded by the Prime Minister of Poland for Outstanding Habilitation)), he was promoted to doctor with advance R&D experience position from 1.10.2019 full-time and from 1.02.2020 - ½ of full-time job at MagTop and full-time job at the Jagiellonian University)

9. Dr. hab. Cezary Śliwa– *Expert in the theory of semiconductors and magnetic semiconductors* (from 20.04.2023, ¾ full time job)

   Research tasks: Carrying out theoretical studies of spin-dependent interactions between magnetic ions in topological II-VI and IV-VI semiconductors, including topological insulators, semimetals, topological crystalline insulators, and other topological materials. Critical analysis of existing theoretical and experimental data concerning magnetic topological matter. Preparing scientific publications.

10. Dr. Yosuke Satake– Visiting Scientist from Japan (three months in 2018, not financed by MagTop)

Research tasks: Studies of the Magnetic-field-induced topological phase transition in Fe-doped $(Bi,Sb)_2Se_3$ heterostructures.

Technical Staff:

1. Dr. Krzysztof Fronc – *chief specialist in the area of high vacuum deposition of materials via sputtering and evaporation techniques* (from 10.02.2020, ½ of full time job, from 1.0.2023 full time)

   Tasks: Carrying out technological processes of deposition of normal metals, ferromagnets and superconductors in the hybrid structures made of topological materials. Development of spattering technique for ferromagnetic materials.

2. Dr. Eng. Dawid Jarosz – *specialist in the area of molecular beam epitaxy of mercury-based II-VI compounds* (from 6.03.2020, ½ of full time job)

   Tasks: Carrying out technological processes of MBE growth of layers and nanostructures of II-VI compounds in the MBE Laboratory of the Center of Microelectronics and Nanotechnology of the University of Rzeszów. Developing growth technology of II-VIs with Mn and Cr.

3. Dr. Michał Szot - *specialist in the area of thermoelectric and infrared optical measurements of IV-VI compounds* (from 1.09.2020, ½ of full time job, from 20.04.2023, ¾ of full time job)

   Tasks: Conducting thermoelectric and optical characterization of IV-VI and II-VI chalcogenides, both in the form of solid crystals and nanostructures grown by the MBE method. Development of optical and thermoelectric methods of research on topological matter. Conducting research to assess the applicability of the detected phenomena, the obtained materials and the developed experimental methods as well as filing patent applications.

4. MSc Wojciech Zaleszczyk – *specialist in molecular beam epitaxy* (from 19.04.2017 to 31.05.2018, ½ of full time job, from 1.06.2018, ¾ of full time job, from 1.04.2023 full time job)

   Tasks: (i) Conducting research in the area of MBE growth of topological materials; (ii) Studies of grown materials with the use of various experimental methods: scanning electron microscopy (SEM, EDX, CL), optical and electrical transport methods.

   MSc Zaleszczyk is the person responsible for the operation of the entire MBE laboratory.

5. MSc Eng. Jędrzej Korczak – *specialist in the growth of bulk crystals of topological materials* (from 10.01.2019, ½ of full time job)

   Tasks: Conducting research covering technological processes of the growth of bulk crystals of IV-VI topological materials, growth of substrate crystals and synthesis of source materials for the molecular beam epitaxial (MBE) growth of topological nanostructures.

6. MSc Eng. Jakub Grendysa - *a specialist in the area of molecular beam epitaxy of mercury chalcogenides* (from 4.03.2020, ½ of full time job)

   Tasks: Carrying out technological processes of MBE growth of HgTe-based layers and nanostructures in the MBE Laboratory of the Center of Microelectronics and Nanotechnology of the University of Rzeszów. Developing technology of the growth of HgTe-based epilayers and nanostructures containing Mn and Cr.

7. MSc Daniel Jastrzębski – *specialist in the area of single crystals growth* (from 19.09.2022 ½ of full time job)

   Tasks: (i) Growth of single crystals exhibiting topological properties and their structural and microstructural characterization (X-ray, SEM, EDX); (ii) Technical and IT support of the technological apparatus.

8. Paweł Ungier – *electronic specialist* (from 18.09.2018, ½ of full time job, from 5.06.2020 full time)

   Tasks: (i) Technical and IT support of the "clean room" laboratory and apparatus located in this laboratory, including apparatus for molecular beams epitaxy; (ii) Minor repairs and adaptations of electronic apparatus and vacuum equipment used by MagTop; (iii) Participation in MBE processes of growth of topological

structures; (iv) Technical support of the experimental setups for low temperature magnetotransport studies of topological materials.

Apart from solving everyday problems, Mr. Ungier has made an important contribution to the launching of the new experimental setups for magnetotransport studies of topological materials at temperatures down to 300 mK, which is based on the the Heliox ^{3}He cryostat.

9. MSc Jakub Polaczyński – *specialist in the area of electron beam lithography and low temperature studies of transport properties of materials* (from 15.10.2021 till 31.07.2023 ½ of full time job)

   Title of the project: "Investigation of magnetotransport properties of MBE-grown layers of topological Dirac semimetal grey tin"

   Tasks: (i) Fabrication of nanostructures and devices from materials with topological properties using electron beam lithography, etching and metal deposition; (ii) Characterization of the produced nanostructures by scanning electron microscopy technique (SEM, EDX) and by ultra-low temperature and high magnetic field transport studies; (iii) Technical and IT support of the measuring apparatus.

10. MSc Bartłomiej Turowski – *specialist in the area of molecular beam epitaxial (MBE) growth of IV-VI materials* (from 15.10.2021 until 30.09.2022 ½ of full time job, from 1.10.2022 full time job)

    Title of the project: "MBE growth, characterization and ARPES studies of topological structures based on lead-tin selenides and grey tin"

    Tasks: (i) Carrying out technological processes of the molecular beam epitaxial (MBE) growth of IV-VI nanostructures with topological properties; (ii) Characterization of the produced nanostructures by scanning electron microscopy technique (SEM, EDX) and angle resolved photoemission spectroscopy (ARPES); (iii)Technical and IT support of the technological and measuring apparatus.

11. MSc Ashutosh Wadge – *specialist in the area of transport measurements and ARPES* (from 7.10.2022 ½ of full time job)

    Title of the project: "Interplay between superconductors (S) and Weyl semimetals (WSM): to investigate Fermi surface modifications at the interface of S/WSM"

    Tasks: (i) Transport measurements and angle-resolved photoemission spectroscopy (ARPES) studies of single crystals exhibiting topological properties. (ii) Technical support and development of apparatus used for transport measurements.

12. MSc Tania Paul – *specialist in the area of many body phenomena in topological materials* (from 2.03.2023 ½ of full time job))

    Title of the project: "Effect of interactions in topological systems"

    Tasks: (i) Theoretical studies of many-body phenomena in topological materials aimed at identifying effects responsible for breaking topological protection in the field of quantum spin Hall phenomenon. (ii) IT support for other MagTop's employees (mainly on the software side).

13. MSc Arathi Das Moosarikandy – *specialist in the area of spin pumping study in topological materials* (from 16.10.2023 full time job)

    Title of the project: "Nano structuring topological quantum materials and their study using transport and magnetodynamic techniques

    Tasks: (i) Experimental studies of the topological and electronic properties of SnTe and PbSnSe heterostructures using the spin pumping method with ferromagnetic resonance spectroscopy (ii) Technical support of apparatus based on Quantum Design Dynacool and vector network analyzer, as well as apparatus for spattering of ferromagnetic materials and scanning electron microscopy.

3. **Please provide a description of the level of staff internationalization.**

(Please provide information about the number of international and returning researchers holding all types of R+D positions in the IRAP unit: team leaders, post docs, PhD students, students, senior post-docs, visiting scientists, technicians. A researcher is considered international if they are non-Polish citizens. A researcher is considered returning if they are Poles who came to Poland no earlier than two years before joining the project after at least a 9 months long period of research work outside Poland. ***Please consider in your response the entire period of project implementation.****)*

Position type	*Total number of researchers*	*Number of International researchers*	*Number of Returning researchers*
Team Leaders	7	4	0
Post docs	16	12	2
PhD students	16	11	0
Students	3	0	0
Senior Post-docs	9	2	0
Visiting scientists	1	1	0
Technicians	11	0	0

4. INFORMATION ABOUT ALL SCIENTIFIC PARTNERS

A. **Please provide a brief description of your cooperation with foreign partners and its most notable results (scientific, business, promotional)**

Foreign institution	*Country*	*Form of cooperation*	*Number of involved researchers*	*Effects*
Advanced Institute for Material Research, Tohoku University:	Japan	joint experimental and theoretical research	11 foreign 2 MagTop	1. T. Dietl *et al.*, Journal of Semiconductors **40**, 080301 (2019), arXiv:1909.02999 (2019), 2. A. Bonanni *et al.*, chapter in book: Handbook of Magnetism and Magnetic Materials eds. Michael Coey, Stuart Parkin , publ. Springer (2021), 3. Y. Satake *et al.*, Phys. Rev. Materials **4**, 044202 (2020) [Editors' Suggestions]], Invited talk: T. Dietl, at 5 th Polish-Japanese Spintronics Workshop, Warsaw, 13-14 November, 2023. 3 months stay of PhD student Yosuke Satake
Julius-Maximilians-Universität Würzburg	Germany	joint experimental research	13 foreign 6 MagTop	1. G. Wagner *et al.*, Nano Lett. 23, 2476 (2023), arXiv:2209.068379 (2022), 2. S. Chusnutdinow *et al.*, Appl. Phys. Lett. 117, 072102 (2020), 3. R. V. Cherbunin *et al.*, Phys. Rev. B **101**, 241301(R) (2020),

				arXiv:1903.01276 (2019), 4. S. Chusutdinow *et al.*, Materials **16**, 4211 (2023), 5. J. Jung *et al.*, Phys. Rev. Lett. **126**, 236402 (2021), arXiv:2105.07774v1 (2021) trip of team leaders, discussion of best practices in research, recruitment, technology transfer, equal opportunities and international cooperation
Department of Physics, Boston College,	USA	joint experimental and theoretical research	2 foreign 6 MagTop	1. P. K. Tanwar *et al.*, Phys. Rev. B **108**, L161106 (2023), 2. M. S. Alam *et al.*, Phys. Rev. B 107, 085102 (2023)
Technische Universität Dortmund	Germany	joint experimental and theoretical research	8 foreign 1 MagTop	**Total of 20 joint publications**, 5 of them are: 1. F. Spitzer *et al.*, *Nature Phys.* **14**, 1043 (2018), corrections 2. L. Korenev *et al.*, *Nat. Commun.* **10**, 2899 (2019) 3. S. V. Poltavtsev *et al.*, Sci. Rep. **9**, 5666 (2019) 4. I. V. Kalitukha *et al.*, Nano Letters **21**, 2370 (2021), 5. F. Godejohann *et al.*, Phys. Rev. B **106**, 195305 (2022).
University of Nottingham	**Great Britain**	joint experimental and theoretical research	4 foreign 2 MagTop	M. J. Grzybowski et *al.*, AIP Advances **9**,115101 (2019), Visits of PhD student Michał Grzybowski to Nottongham
University of Salerno	Fisciano, Italy	joint experimental and theoretical research	8 foreign 3 MagTop	**Total: 18 joint publications and 2 preprints**, 4 of them: 1. T. C. van Thiel *et al.*, Phys. Rev. Lett. **127**, 127202(2021), 2. O. Maistrenko *et al.*, Phys. Rev. Research **3**, 033008 (2021), 3. D. J. Groenendijk et *al.*, Phys. Rev. Research **2**, 023404 (2020), 4. N. Gauquelin *et al.*, Nano Lett. 23, 7782 (2023), Dr. Giuseppe Cuono was employed as a Young Doctor from 16.11.2020 to 30.11.2023.
Guilin University of Technology	China	joint experimental and theoretical research	12 foreign 1 MagTop	**Total: 5 joint publications**. 3 of them: 1. F. Xiao *et al.*, Phys. Rev. B **105**, 115110 (2022), arXiv:2111.019919 (2021) 2. W. Wang *et al.*, Phys. Rev. B **105**, 035119 (2022), 3. X. Gong et *al.*, Phys. Chem. Chem. Phys. **25**, 6857 (2023)
Johannes Kepler University Linz	Linz, Austria	joint experimental and theoretical research	6 foreign 10 MagTop	1. R. Adhikari *et al.*, Phys. Rev. B **100**, 134422 (2019) 2. A. Kazakov *et al.*, Phys. Rev. B **103**,

				245307 (2021) 3. A. V. Galeeva *et al.*, Nanomaterials **11**, 3207 (2021) 4. J. Krempasky *et al.*, Phys. Rev. Lett. **126**, 206403 (2021) 5. R. Rechciński *et al.*, Adv. Funct. Mater. **31**, 2008885 (2021).
Microsoft Station Q and **College of William and Mary**	USA		4 foreign 3 MagTop	**Total: 4 joint research papers**, 2 of them: 1. Xiang Hu et *al.*, Phys.Rev.B **105**, L140506 (2022) 2. A. Lau et *al.*, Physical Review X **11**, 031017 (2021)
University of Cambridge	United Kingdom	joint experimental and theoretical research	6 foreign 2 MagTop	1. Y. Li et *al.*, Phys. Rev. B **101**, 241405(R) (2020) [Editors' Suggestions] 2. Y. Li *et al.*, Communications Physics **3**, 224 (2020).
Université Paris-Saclay, CNRS	France	joint experimental and theoretical research	2 foreign 4 MagTop	1. M. Trif, P. Simon, Adv. Quantum Technol. **2019**, 1900091 (2019), 2. A. Mishra *et al.*, Phys. Rev. B **103**, L121401 (2021) 3. A. Mishra *et al.*, PRX Quantum 2, 040347 (2021) 4. P. -X. Shen *et al.*, Phys. Rev. Research **5**, 033207 (2023).
Korea Advanced Institute of Science and Technology	South Korea	joint experimental and theoretical research	4 foreign 1 MagTop	1. G. B. Sim et *al.*, Phys. Rev. Research **2**, 023416 (2020) 2. H. S. Kim *et al.*, Phys. Rev. B **102**, 155113 (2020)
École Polytechnique Fédérale de Lausanne EPFL	Switzerland	joint experimental and theoretical research	4 foreign 1 MagTop	1. V. S. Bhat *et al.*, Phys. Rev. Lett. **125**, 117208 (2020) 2. S. Watanabe *et al.*, Science Advances **7**, eabg3771 (2021) 3. V. S. Bhat *et al.*, Appl. Phys. Lett. **119**, 092403 (2021) 4. S. Watanabe *et al.*, Adv. Mater. **35**, 2301087 (2023) 5. V. S. Bhat *et al.*, Commun. Phys. **6**, 193 (2023),
University of Leipzig	Germany	joint experimental and theoretical research	1 foreign 1 MagTop	A. Kreisel *et al.*, Phys. Rev. Research **3**, 033049 (2021)
Aalto University	Finland	joint experimental and theoretical research	2 foreign 5 MagTop	**Total 8 joint papers,** 3 of them: 1. T. Hyart et *al.*, Phys. Rev. Research **4**, L012006 (2022), 2. A. Lau et *al.*, Physical Review X **11**, 031017 (2021) 3. N. M. Nguyen et *al.*, Phys. Rev. B **105**, 075310(2022),.
College de France	France	Majorana dynamics from microwave spectroscopy	1 foreign 1 MagTop	O. Dmytruk, M. Trif, Phys. Rev. B **107**, 115418 (2023)
University of California	USA	joint experimental and theoretical research	1 foreign 1 MagTop	M. Trif, Y. Tserkovnyak, arXiv:2401.03164
University of New South Wales	Australia	joint experimental and theoretical research	1 foreign	Magtop's seminar on September 22, 2023 of Prof. Oleg Tretiakov, Head of Topological Spintronics and Quantum

				Materials group: *Skyrmions and Beyond in Ferromagnetic Topological Materials and, Antiferromagnets*
Purdue University	USA	joint experimental and theoretical research	2 foreign 2 MagTop	1. A. Kazakov *et al.*, Phys. Rev. Lett. **119**, 046803 (2017), 2. G. Simion et *al.*, Phys. Rev. B **97**, 245107 (2018).
University of North Texas	USA	joint experimental and theoretical research	1 foreign 1 MagTop	C. Autieri *et al.*, Phys. Rev. Materials **3**, 084416 (2019)
University of Hamburg	Germany	joint experimental and theoretical research	2 foreign 2 MagTop	O. A. Awoga *et al.*, arXiv:2308.07961(2023) Joint organization of Northern Lights Conference, Reykjavik, 12-15 October, 2022. Mircea Trif won the project *Theory of quantum twists and its supercurrents* competition „Generation Partnerships – Thematische Netzwerke", sponsored by the University of Hamburg.
Bosch Center for Artificial Intelligence	Germany	joint theoretical research	1 Bosch 2 MagTop	1. European Patent application EP4184389A1 2. P. Baireuther et *al.*, SciPost Phys. Core **6**, 087 (2023)
Tata Institute of Fundamental Research	India	joint experimental and theoretical research	2 foreign 7 MagTop	1. R. Islam *et al.*, Adv. Electron. Mater. **9**, 2300156 (2023), 2. R. Islam *et al.*, Phys. Rev. Research 4, 023114 (2022),
The Maharaja Sayajirao University of Baroda	India	joint experimental and theoretical research	2 foreign 1 MagTop	B. R. Dhori *et al.*, J. Phys.: Condens. Matter **36**, 055702 (2024),
Université Grenoble Alpes	Grenoble, France	joint experimental and theoretical research	3 foreign 3 MagTop	W. Solarska et *al.*, ACS Omega 8, 40801 (2023).
Linnaeus University, Kalmar	Sweeden	joint experimental and theoretical research	2 foreign 10 MagTop	1. G. Hussain *et al.*, http://arxiv.org/abs/2401.03455 (2024) 2. R. Islam *et al.*, Phys. Rev. B 107, 125102 (2023)
Aarhus University	Denmark	joint experimental and theoretical research	4 foreign 2 MagTop	D. Curcio *et al.*, Phys. Rev. B 108, L161105 (2023)
Beihang University	China	joint experimental and theoretical research	5 foreign 2 MagTop	1. Z. Muhammad *et al.*, ACS Appl. Mater. Inter. 14, 35927 (2022) 2. Z. Muhammad et *al.*, 2D Mater. 10, 025001 (2023)
University of Fribourg	Switzerland	joint experimental and theoretical research	4 foreign 1 MagTop	D. Santos-Cottin *et al.*, Phys. Rev. Lett. **131**, 186704 (2023)
University of Maryland	USA	joint experimental and theoretical research	11 foreign 1 MagTop	D. J. Campbell *et al.* npj Quantum Materials **6**, 38 (2021)
Howard University	USA	joint experimental and theoretical research	1 foreign 2 MagTop	R. Islam *et al.*, Physical Review B **104**, L201112 (2021)
University of Tokyo	Japan	joint experimental and theoretical research	1 foreign 2 MagTop	A. Nigro *et al.*, Materials **15**, 1027 (2022)

European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund

b. Please provide a short overview of cooperation with Polish partners and its most notable results (scientific, potentially transferable to the market, promotional)

Polish institution	*Country*	*Form of cooperation*	*Number of involved researchers*	*Effects*
University of Warsaw	Poland	joint experimental and theoretical research	5 University of Warsaw 3 MagTop	**Total of 12 joint research publications**, 3 of them: 1. D. Yavorskiy et *al.*, Materials **13**, 1811 (2020) 2. C. Śliwa et *al.*, Physical Review B **104**, L220404 (2021), arXiv:2107.13388 (2021) „Editors' suggestion" 3. J. Strasdas et *al.*, Nano Lett. **23**, 10342 (2023),
National Synchrotron Radiation Centre SOLARIS, Jagiellonian University	Cracow, Poland	joint experimental and theoretical research	6 SOLARIS 13 MagTop	**Total: 5 joint research publications**, 3 of them: 1. B. Turowski *et al.*, Appl. Surf. Sci. **610**, 155434 (2023), 2. A. S. Wadge *et al.*, Phys. Rev. B 105, 235304 (2022) 3. A. S. Wadge et *al.*, J. Phys.: Condens. Matter 34 125601 (2022)
University of Rzeszów	Poland	joint experimental and theoretical research	9 University of Rzeszów 4 MagTop	**Total of 7 joint research publications.** 3 of them: 1. M. Marchewka et *al.*, Materials **16**, 1968, (2023) 2. W. Wołkanowicz et *al.*, ACS Omega 8, 45834 (2023) 3. D. Jarosz et *al.*, ACS Omega **8**, 32998 (2023)
CENTERA Center for Terahertz Research and Applications, Institute of High Pressure Physics PAS	Poland	joint experimental and theoretical research	2 CENTERA 2 MagTop	I. Yahniuk *et al.*, Phys. Rev. Applied 18, 054011 (2022).
PUREMAT	Poland	joint experimental and theoretical research	1 PUREMAT 3 MagTop	European Patent: *A method of obtaining bulk PbTe-CdTe nanocomposite.* EP4036057 Joint research publication: M. Szot et *al.*, arXiv:2212.14616 (2022)
VIGO	Poland	joint experimental and theoretical research	2 VIGO 5 MagTop	G. Hussain et *al.*, J. Phys. D: Appl. Phys. **55**, 495301 (2022)
Prevac	Poland	joint experimental and theoretical research	1 Prevac 1 MagTop	European Patent application, invention: *Device for magnetron sputtering from target* (EP4283011).

5. INFORMATION ABOUT COMERCIALIZATION STRATEGY AND CO-OPERATION WITH BUSINESS PARTNERS)

5.1. Description of good practices introduced in the field of intellectual property management, knowledge transfer, and collaboration with the industry and barriers, if any, to achieving results in this area of project implementation. (up to 500 words)

The following practices introduced by MagTop have proven successful and helped in establishing successful collaborations with entrepreneurs:

1. Regular meetings and mutual visits of small groups or individual researchers between MagTop and industrial facilities.
2. Exchange of application-relevant ideas and results with early decision on equal partnership in patent applications.
3. Identifying mutual benefits from testing of promising new materials or device concepts in industrial environment (manufacturing prototypes using industrial tools).
4. Ensuring protection of intellectual rights of MagTop researchers in discoveries of immediate commercial potential: signing mutual agreements with industrial partners on financial and organizational conditions of using the invention in commercial practice.
5. Active use of full legal support by patent lawyers in selecting and preparing new patent applications.
6. Ensuring active support of administrative units of IFPAN in preparing collaboration and knowledge-transfer agreements.

A significant difficulty, due to the lack of experience in this field, was the issue of preparing collaboration agreements and agreements on joint rights to a patent and joint patent**,** as well as patent applications. On the one hand, the agreements had to be formulated in such a way as to exclude the financing of companies from public funds, on the other hand, they should take into account benefits for entrepreneurs. This required the help of specialized lawyers and, when submitting patent applications, the help of a specialized patent office. Such assistance was provided by both the Foundation for Polish Science and lawyers cooperating with the Institute of Physics of the Polish Academy of Sciences. This does not change the fact that, for example, it took over a year to conclude contracts with Bosch and PREVAC. This required multiple exchanges of proposed agreement texts and online meetings during which the point of view, conditions and limitations of each party were explained. This aspect of cooperation has been very time-consuming.

One of barriers encountered by MagTop concerns a nation-wide problem of attracting technically and technologically talented students to start professional careers in research. More dynamic promotion of projects ideas and possibilities will be required in various media and at universities.

5.2. Describe activities and examples of achievements in bringing research results into business practice (up to 350 words)

On October 18, 2019, at the MagTop site, Workshop “Topological matter meets entrepreneurs” was organized. During Workshop MagTop’s senior employees: Tomasz Dietl, Tomasz Story, Tomasz Wojtowicz introduced MagTop’s project and in-house capabilities. In the second part, entrepreneurs and representative of FNP delivered

their lectures: Artur Trajnerowicz (VIGO Photonics) *"VIGO System – production capabilities and development of semiconductor IR detectors"*, Olgierd Jeremiasz (Helioenergia) *„Helioenergia - R&D efforts in electrical power engineering and electronics"*, Andrzej Mycielski (PUREMAT) „Puremat Technologies as a partner of MagTop", Kinga Słomińska *„Science- Industry cooperation in IRAP projects"*. Next, lecturers and entrepreneurs visited MagTop's laboratories.

On January 30, 2020 the group of eighteen MagTop's employees visited VIGO and met with VIGO's R&D staff. After short description of the VIGO company profile by Dr. Trajnerowicz, Prof. Dietl introduced MagTop as a whole and expertise of its researchers, six of whom presented talks. MagTop's employees visited the VIGO's labs and production hall. Owing to that meeting, research collaboration started and has concerned theoretical modeling of detector structures (joint publication J. Phys. D: Appl. Phys. **55**, 495301 (2022)), etching, processing, and characterization of detector structure, contacts, and noise, as reported in details in the yearly MagTop's reports.

One of the collaboration output are two MagTop's inventions concerning IR detectors submitted to European Patent Office EPO (EP23461604.3 and EP23461603.5). Another invention of the MagTop and PUREMAT company, already patented in EPO (EP4036057B1), protected also outside Europe, concerned a new thermoelectric composite material. Presently, MagTop inventors of those three patents have joint their forces with VIGO to develop an entirely new device involving thermoelectric cooling and IR detection in a single integrated semiconductor structure.

Another example of the achievement in bringing research results into business practice concerns deposition of magnetic metals, which constitutes the core of MagTop's materials development activity. Here a joint invention of MagTop and the PREVAC allows for magnetosputering of high quality magnetic layers. This invention was submitted to the EPO (EP4283011) and, following agreement between IFPAN and PREVAC, is now a part of PREVAC market offer.

The attachment to the present report, CO-OPERATION WITH ENTREPRENEURS, contains further information and examples.

5.3 Please fill in the *CO-OPERATION WITH ENTREPRENEURS form and attach it to this report*

6. INFORMATION ABOUT STEPS TOWARDS FURTHER DEVELOPMENT OF THE IRAP UNIT AND SECURING ITS SUSTAINABILITY

(Please provide information about steps taken and planned towards securing sustainability and development of the IRAP unit and specifically all additional funding proposals that have been submitted by the IRAP unit staff, where the information is available please state whether the application was successful. ***Please consider in your response the entire period of project implementation.****)*

Since January 1st, 2024, the MagTop unit operates in the durability mode making use of positions obtained by MagTop researchers via open competitions put forward by IFPAN as well of numerous projects gathered earlier by MagTop researchers. There are also pending applications, including the one to the Foundation for Polish Science, the MAB/FENG Programme, which would make it possible to maintain and put to even higher level research profile and visibility gained during seven years of MagTop activities.

The list of past, present, and pending projects follows.

External projects

MagTop's researchers have been extending a spectrum of MagTop topics by gathering external research projects from National Science Centre (NCN) and other grant giving institutions. All of these projects were approved by ISC MagTop as awarded to individual PIs for purposes consistent with the IRAP/MagTop project objectives:

Current and completed projects:

1. Title: *Limitations for Protected Transport and Exotic Topological States in Topological Semiconductors*
   SONATA Bis, National Science Centre, Poland
   PI: Wojciech Brzezicki,
   Duration: 5 years, started in April 2020,
   Budget: 1 899 940 PLN,
   Currently executed at MagTop.
2. Title: Study of the effect of the nanostructured periodic and quasicrystal nanomagnet lattices on magnon-photon coupling
   SONATA Bis, National Science Centre, Poland,
   PI: Aleksandr Kazakov, (newly appointed PI, after V. Bhat left Poland),
   Duration: 5 years, started in March, 2021,
   Budget: 3 664 760 PLN,
   Currently executed at MagTop.
3. Title: *Harnessing the environment for topological quantum computing*
   OPUS, National Science Centre, Poland,
   PI: Mircea Trif,
   Duration: 3 years, started in January 2022,
   Budget: 1 131 604 PLN,
   Currently executed at MagTop.
4. Title: *Generation Partnerships – Thematische Netzwerke*
   Networking project, sponsored by the University of Hamburg.
   Co-PI: Mircea Trif,
   Currently executed at MagTop.
5. Title: *Magnetism, Berry-curvature engineering and topology in chalcogenide superlattices and heterostructures*
   EC Marie Skłodowska-Curie Individual Fellowship,
   PI: Alexander Lau (carried out under supervision of Tomasz Dietl and Mircea Triff),
   Duration: two years, started in August2021,
   Budget: 137 625,60 EUR,
   Completed at MagTop in May 2023.
6. Title: *Topological phases in II-VI semiconductor compounds: heterostructures and magnetically doped systems*
   PRELUDIUM, National Science Centre, Poland,
   PI: Rajibul Islam,
   Duration: two years, started in January 2021
   Budget: 134 760 PLN
   Completed at MagTop in January 2023.

7. Title*: Quantum Simulators of open systems and non-equilibrium topological matter*
   Polish National Agency for Academic Exchange, NAVA,
   PI: Marcin Płodzień,
   Duration: two years, started in September 2021,
   Budget: 295 000 PLN,
   Completed at Institut de Ciències Fotòniques: Castelldefels, Catalunya, ES in October 2023.

Newly acquired projects:

8. Title: *Chalcogenide nanostructures as a versatile platform for quantum bits (ChalQ)*
   Long-term program to support Ukrainian research teams at the Polish Academy of Sciences, carried out in collaboration with the U.S. National Academy of Sciences with the support of external partners.
   PI: Valentine V. Volobuiev,
   Duration: 3 years,
   Budget 2 452 200 PLN;
   Granted: started on January 1st, 2024
9. Title: *Resistance standard from semimagnetic semiconductors*
   Polish Metrology II, Polish Ministry of Education and Science
   PI: Tomasz Dietl, Co-PI: Tomasz Wojtowicz,
   Duration: 2 years,
   Budget: 944 900 PLN,
   Granted to be started in February 2024

Equipment projects:

From the Foundation for Polish Science (FNP) within the framework of the "Competition for funding the purchase of specialized apparatus within the framework of the IRA Program":

10. Name of the apparatus: *Equipment package for the GENxplor MBE system*
    (primarily for the MBE Group)
    PI: Tomasz Wojtowicz
    Duration: 2019 - 2021
    Budget: 4 351 250 PLN
    Completed at MagTop in March 2021.
11. Name of the apparatus: *Variable Temperature and Magnetic Field Characterization (VTF) equipment package* (primarily for the Characterization Group):
    PI: Vinayak Bhat
    Duration: 2019 - 2021
    Budget: 3 848 518,38zł PLN
    Completed at MagTop in June 2021.

Project applications awaiting decision

13. Title: *International Centre for Interfacing Magnetism and Superconductivity with Topological Matter - MagTop*
    MAB-FENG, Foundation for Polish Science, call FENG.02.01-IP.05-002/23,
    PI: Tomasz Dietl, co-PI Tomasz Wojtowicz, Mircea Trif, Maciej Zgirski,
    Duration: 5 years,
    Budget 29 995 000 PLN,
    Submitted: 30.06.2023, Awaiting decision.

14. Title: *SymPhysAI: Symbolic artificial intelligence for hidden topological orders in quantum physics*
    HORIZON-TMA-MSCA-PF-EF (HORIZON TMA MSCA Postdoctoral Fellowships - European Fellowships),
    HORIZON Unit Grant, call 101154696
    PI: Peixin Shen,
    Duration: 2 years,
    Budget 139 953,60 EUR,
    Submitted: 13.09.2023, awaiting decision

15. Call: HORIZON-CL4-2024-QUANTUM-01-SGA
    Title: *Initiative for European Semiconductor-based large-scale quantum computing platform technologies.*
    (Developing the first large-scale quantum computers (SGA))
    Topic: HORIZON-CL4-2024-QUANTUM-01-SGA
    Type of Action: HORIZON-RIA
    Proposal number: 101174557
    Proposal acronym: QLSI2
    MagTop's PI: Mircea Trif
    Budget: IFPAN/MagTop: 178 000 EUR
    QLSI2 brings together the expertise of 23 partners from 9 countries with the ambition to demonstrate a cloud-accessible 200-qubit semiconductor-based quantum computer by the end of 2027.
    Submitted: 17.01.2024, awaiting decision.

Furthermore, MagTop researchers have continued to be successful in obtaining grants for computer and time at **large European facilities** in the reporting period:

Recent successful applications for measurement time at large facilities (and these executed last year)

1. Title: *Investigation of correlation effects in Fermi surface of magnetic ions (V, Cr) substituted Weyl semimetal NbP*
   PI: Andrzej Wisniewski
   Proposal to SOLARIS National Synchrotron Radiation Centre (URANOS beam line
   Executed in the period: 11- 16 April 2023.
2. Title: *Spin-polarization of Dyakonov-Khaetskii States in (001) Grey-Sn on Insulating Substrates*
   Proposal to SOLARIS National Synchrotron Radiation Centre, Submitted: 30.09.2023
   PI: Valentine V. Volobuiev,
   Granted for implementation in 2024.
3. Title: *Topological crystalline insulator phase in the (100) quantum wells of the cubic SnSe*
   Proposal to SOLARIS National Synchrotron Radiation Centre, Submitted: 2.10.2023,
   PI: Aleksandr Kazakov;
   Granted for implementation in 2024.
4. Title: *Spin polarization of Dirac-Rashba surface states in topological crystalline insulator*
   Proposal to SOLARIS National Synchrotron Radiation Centre, Submitted: 2.10.2023,
   PI: Valentine V. Volobuiev;
   Granted for implementation in 2024.

Computer time projects operating during the recent year only (as an example):

Grants on the supercomputer TOPOLA (ICM, Warsaw).

1) Identifier: g91-1418, Applicant: Giuseppe Cuono
2) Identifier: g91-1426, Applicant: Giuseppe Cuono

Grant on the supercomputer OKEANOS (ICM, Warsaw).
3) Identifier: g91-1419, Applicant: Giuseppe Cuono

Grant on the supercomputer Eagle (Poznan Supercomputing and Networking Center)
4) Identifier: No. 609, Applicant: Giuseppe Cuono

Grant on the supercomputer GALILEO (CINECA, Italy)
5) Identifier: IsC93 "RATIO", Applicant: Carmine Autieri
6) Identifier: IsC99 "SILENTS", Applicant: Carmine Autieri
7) Identifier: IsC105 "SILENTSG", Applicant: Carmine Autieri
8) Identifier: IsB26 "SHINY", Applicant: Carmine Autieri

List of recent successful applications for computer time:

Grants on the supercomputer TOPOLA (ICM, Warsaw).
1) Identifier: g96-1808, Applicant: Giuseppe Cuono

Grant on the supercomputer OKEANOS (ICM, Warsaw).
2) Identifier: g96-1809, Applicant: Giuseppe Cuono

Grant on the supercomputer Eagle (Poznan Supercomputing and Networking Center)
3) Identifier: No. pl0223-01, Applicant: Giuseppe Cuono
4) Identifier: No. pl0267-01, Applicant: Raghottam M. Sattigeri

Grant on the supercomputer GALILEO (CINECA, Italy)
5) Identifier: IsB27 "SLAM", Applicant: Carmine Autieri

7. WAS THE PROJECT IMPLEMENTED ACCORDING TO THE SCHEDULE ATTACHED TO THE AGREEMENT ?

YES X NO ☐

If the answer is no, please provide an explanation :

8. WAS THE PROJECT IMPLEMENTED IN ACCORDANCE WITH THE PRINCILPES OF EUROPEAN COMMUNITY POLICIES?

YES X NO ☐

If the answer is no, please provide an explanation :

9. WAS THE PROJECT IMPLEMENTED AS DESCRIBED IN THE APPLICATION FOR FUNDING, INCLUDING MODIFICATIONS ACCEPTED DURING ITS IMPLEMENTATION, IF ANY? WERE THE OBJECTIVES OF THE RESEARCH AGENDA ACHIEVED (Please consider aspects such as number of research groups; organizational structure; sustainability of the unit.)?

YES X NO ☐

Please provide a short description of the actions undertaken.

10. WERE THE PROJECT INDICATORS ACHIEVED AS DESCRIBED IN THE APPLICATION FOR FUNDING, INCLUDING CHANGES ACCEPTED DURING ITS IMPLEMENTATION?

(*If the answer is no, please provide an explanation.*)

All but one of the project's indicators, namely the number of filled patent applications, were achieved and even exceeded, using the methods of their calculations specified in the indicator metrics.

The declared values of some of these indicators were increased during the course of the project due to both the purchase of two types of specialist equipment, thereby increasing the experimental potential of the MagTop unit, and the extension of the project's duration by 23 months.

In particular, the indicator "Number of foreign scientists in the supported projects", which was eventually declared as 15 reached, reached the value of 33 at the end of the project, indicating that the internationalization of the unit was better than planned.

Another important indicator, "Number of international scientific publications - indexed in the Journal Citation Reports list," which was finally declared as 120 (50 was declared in the original grant application), reached 218, proving the project's great scientific success.

With regard to the indicator "Number of filed patent applications", the MagTop unit declared the value of this indicator at 6 to be achieved at the end of the project, and actually filed a total of 6 applications with the European Patent Office to protect declarations of priority for inventions.

Of these six applications, one patent has already been granted (patent number: EP4036057B1, see patent certificate) and three other have been published in the EPO's Bulletin (publication numbers: EP4184389A1, EP3975275A1, EP4283011A1). However, since the last two application were filled in 2023 (application numbers: EP23461604.3 and EP23461603.5) they have not yet been published in the Bulletin, as the publication time is much longer than 6 months, usually 18 months. Therefore, according to the methods of calculating this indicator specified in its metrics, the value achieved by the end of 2023 is 4. However, the declared value of this indicator will be achieved next year, during durability period of the Project.

I hereby confirm that the information contained in the second midterm research report are true. I am aware of the legal consequences of stating false information in legally binding document, as stated in article 271 of the Penal Code.

Attachment to the project:

- **ATTACHMENT 1** ***CO-OPERATION WITH ENTREPRENEURS***
- **Documents regulating the terms of cooperation with business (e.g. Collaboration Agreement/ Letter of Intent etc.) should be kept in the IRAP unit in accordance with the documentation policy. The Foundation and other authorized institutions may request them for consideration.**

Date: 05.02.2024

Signature of the Laureate

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Stamp of the Unit