Foundation for Polish Science

THIRD MID-TERM RESEARCH 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 1 February, 2017 to 31 January, 2020**
Project leaders:	**Prof. Tomasz Dietl and Prof. Tomasz Wojtowicz**	

NB: The information below should reflect the status of the project after the first three years of its implementation and should concern the whole institution

1. INFORMATION CONCERNING THE PROGRESS OF THE RESEARCH(1000 to 5000 words)

1.1 Please provide an overview of the scientific progress in all research groups, main common goals of the groups and collaboration between groups

Objectives

MagTop researchers in collaboration with other scientific divisions at the Institute of Physics, Polish Academy of Sciences (IFPAN) as well as with numerous academic and industrial partners, are currently carrying on **experimental and theoretical** research aiming at resolving major challenges of non-magnetic, magnetic, and superconducting topological materials and their interfaces:

(1) What microscopic mechanisms are responsible for an unexpectedly short protection length in 2D topological insulators and thus hampering the existence of accurate quantization of the resistance in the quantum spin Hall regime? What is the nature of a long Hall plateau of the hole uppermost Landau level in HgTe-based quantum wells? Is it of relevance for quantum Hall resistance standards?

(2) Can quantized topological Hall effects be observed in topological crystalline insulators? Will they be advantageous for metrological applications?

(3) What are the effects of interfacial 2D topological states on properties of metal-semiconductor junctions such as ohmic characteristics, Fermi level pinning, Schottky barrier parameters, Andreev reflectivity, spin-pumping efficiency, Rashba splitting of bands? In which way are these effects beneficial for infrared/THz detectors and energy harvesting devices?

(4) What is the origin of zero-bias conductance peaks in point-contact spectroscopy of topological surfaces? Is superconductivity or rather other collective states involved? Are novel functionalities associated with this effect?

(5) Are there new functional platforms, such as topological nanowires or systems with higher order topological states, for hosting quasiparticles with non-Abelian statistics suitable for quantum topological computing?

(6) Which spin-spin coupling mechanisms account for magnetic properties of topological materials doped with transition metals? How to stabilize magnetism at high temperatures?

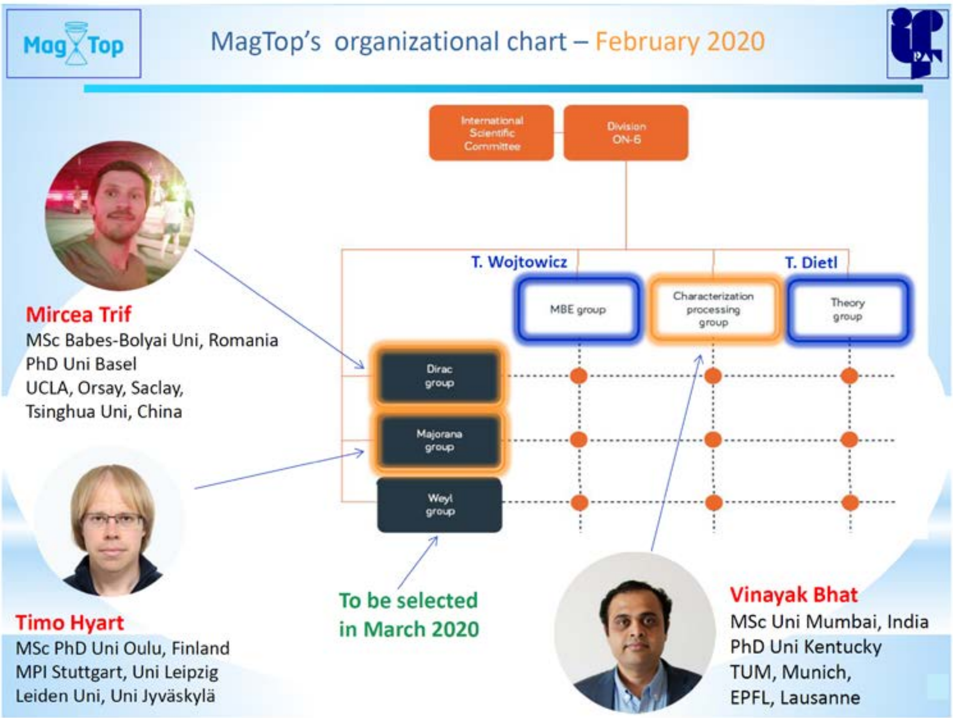
(7) Are there new effects or functionalities created by incorporating magnetism and superconductivity to Weyl semimetals?

(8) What are the effects of the interplay between strong correlation and topological properties? Can one find an efficient way to determine topological invariants in complex systems?

(9) In addition to addressing the above challenges, the MagTop researches are committed to look for not yet discovered phenomena, functionalities, methodologies, and research directions in the broadly understood topological physics and its applications for market products.

MagTop organizational structure

The International Centre for Interfacing Magnetism and Superconductivity with Topological Matter – MagTop is a part (dubbed scientific division ON-6) of IFPAN, which is a legal person. Along with the IFPAN Director and the Foundation for Polish Science (FNP), MagTop activities are supervised by the International Scientific Committee (ISC) chaired by Prof. Laurens Molenkamp. Julius-Maximilians-Universität (JMU) in Würzburg is MagTop’s foreign strategic partner unit. The current MagTop’s organization chart is shown below.



Theory (ON-6.1) and MBE Groups (ON-6.2), headed by IRAP laureates Tomasz Dietl and Tomasz Wojtowicz, respectively, exist from the MagTop beginning (Febr. 1st, 2017). Timo Hyart, Mircea Trif, and Vinayak Bhat, i.e., leaders of Majorana (ON-6.5), Dirac (ON-6.4), and Characterization (ON-6.3) Groups were employed in

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April 2018, April 2019, and May 2019, respectively. The selection procedure of the sixth group leader will be completed in March 2020.

According to IFPAN's rules, all employees, including senior postdocs and persons providing (often high level) technical support, and referred to as technicians for brevity, are assigned to some group (team). However, as it is clear from this report, there are strong interactions and collaborations between the groups (including sharing of equipment) so that contributions of both senior postdocs and technicians are essential for the whole MagTop.

MagTop in numbers

Since the MagTop start, the number of senior postdocs, postdocs, and PhD students has now increased to 8, 8, and 10, respectively. The recruitment procedure, supervised by MagTop's ISC and FNP, has resulted in bringing together **young scientists from twelve countries**, which, together with numerous collaborations, makes MagTop be a truly international unit, in accord with the IRA Programme mission. It is expected that the number of equivalent **full-time positions of 33** (including PhD students, technical and administrative staff) will be reached around June 2020.

Over a rather limited time of groups' existence, as detailed and updated in the home page www.MagTop.ifpan.edu.pl, MagTop members have co-authored **72 publications** in prestigious scientific journals (available to public at large *via* a green open access depository arXiv), **submitted additionally 14 manuscripts** (posted in arXiv), delivered **52 invited talks** and contributed to **97 conference presentations**. Furthermore, as outlined in this report, considerable attention has been paid to set solid and mutually beneficial ties with entrepreneurs and with the JMU, MagTop's foreign strategic partner unit. IFPAN, on behalf of MagTop, has signed **collaboration agreements** with **four academic** institutions and **two companies**.

Overview of expertise and resources

A competitive edge of MagTop is a broad range of available state-of-the-art or beyond state-of-the-art expertise and resources including:

(i) Growth and structural characterization of **bulk topological crystalline insulators** (TCIs) – lead-tin chalcogenides (Pb,Sn)(Se,Te), also doped with magnetic ions, primarily Mn, which turns diamagnetic semiconductors into dilute magnetic semiconductors (semimagnetic semiconductors) or dilute ferromagnetic semiconductors – Prof. Tomasz Story and Jędrzej Korczak (ON-6.1)

(ii) Growth and structural characterization of **bulk Weyl semimetals** (WSMs) – niobium and tantalum pnictides, also doped with 3d transition metals (Mn, V) – Prof. Andrzej Wiśniewski, Dr. Przemysław Iwanowski, and PhD Ashutosh Wadge (ON-6.1)

(iii) **MBE** growth, structural, and optical characterization of quantum structures (heterostructures, superlattices, nanowires, quantum dots, modulation doping) of **wide gap II-VI chalcogenides** (Cd,Zn,Mg,Mn)(Te,Se) – Prof. Tomasz Wojtowicz, MSc Wojciech Zaleszczyk, and PhD Rafał Rudniewski (ON-6.2)

(iv) **MBE growth** and structural characterization of quantum structures of **topological crystalline insulators IV-VI chalcogenides** (Pb,Sn,Mn,V,Eu)(Te,Se) with metal overlayers – Prof. Tomasz Wojtowicz, Dr. Valentine Volobuev, and PhD Bartłomiej Turowski (ON-6.2). This activity is made possible by a specialist equipment grant from FNP (4 351 250 PLN)

(v) **MBE** growth of quantum structures of **topological insulators zero- and narrow-gap II-VI tellurides (Hg,Cd,Mn,Cr)Te** – in collaboration with the University of Rzeszów – Prof. Tomasz Wojtowicz, Dr. Zhifeng Yu, Dr. Dawid Jarosz, MSc Jakub Grendysa (ON-6.2 since March 2nd, 2020)

(vi) **Magnetron sputtering and vacuum deposition of metal overlayers** Dr. Krzysztof Fronc and Dr. Tomasz Wojciechowski (ON-6.2); Dr. Vinayak Bhat (ON-6.3).

(vii) **Nanostructurization** (e-beam and photo-lithography, focus ion beam) and processing (wet and ion etching, gating, metal deposition, contacting, nanowires' handling, …) – Dr. Tomasz Wojciechowski, Dr. Aleksandr Kazakov, PhD Jakub Polaczyński (ON-6.2); Dr. Vinayak Bhat, Dr. Bhanu Joshi, PhD Pradosh Sahoo, and PhD Arathi Das Moosarikandy (ON-6.3).

(viii) Low-temperature (down to **mK) charge and entropy magnetotransport** – Prof. Tomasz Dietl, Prof. Tomasz Story, and Dr. Krzysztof Dybko (ON-6.1); Dr. Aleksandr Kazakov and Dr. Zahir Muhammad (ON-6.2); Dr. Vinayak Bhat, Dr. Bhanu Joshi, PhD Pradosh Sahoo, and PhD Arathi Das Moosarikandy (ON-6.3).

(ix) Global and local **spin wave spectroscopies** and **spin pumping** of/to topological materials – Dr. Vinayak Bhat, Dr. Bhanu Joshi, PhD Pradosh Sahoo, and PhD Arathi Das Moosarikandy (ON-6.3). This activity is made possible by a specialist equipment grant from FNP (3 850 000 PLN).

(x) ***Ab initio*** studies of topological and strongly correlated materials – Dr. Carmine Autieri, PhD Rajibul Islam, PhD Ghulam Hussain; **variational** methods – Dr. Marcin Wysokiński (ON-6.1).

(xi) Effective Hamiltonian methods (***kp*, tight binding**) for magnetism, disorder effects, and spintronics in topological materials – Prof. Tomasz Dietl (ON-6.1).

(xii) Effective Hamiltonian methods with application to determine theoretically **topological invariants, Berry phases, collective ground states, and quantum transport phenomena** in various topological systems, geometries, quantum structures, and interfaces – Dr. Timo Hyart, Dr. hab. Wojciech Brzeziński, Dr. Victor Fernandez Becerra, Dr. Marcin Płodzień, PhD Tania Paul, PhD Minh Nguyen Nguyen (ON-6.5).

(xiii) Quantum and classical spin and Majorana fermion **dynamics** in applications to spintronic devices, spin pumping, and fault tolerant topological quantum computing – Dr. Mircea Trif, Dr. Archana Mishra, Dr. Alexander Lau (ON-6.4).

(xiv) **ARPES** of topological and interfacial states at large synchrotron facilities – Prof. Tomasz Story, Prof. Andrzej Wiśniewski, Dr. Przemysław Iwanowski (ON-6.1); Dr. Valentine Volobuev (ON-6.2); PhD Bartłomiej Turowski (ON-6.2).

Overview of groups' activities and research outcome

Two research groups, ON-6.3 headed by Dr. Vinayak Bhat and ON-6.4 headed by Dr. Mircea Trif, have been formed during the reporting period. Their leaders arrived in Warsaw in the beginning of May and end of March 2019, respectively, so that their MagTop's affiliated publication list count so far 3 positions.

The **Characterization Group of Dr. Bhat** (ON-6.3) has recruited one postdoc (Dr. Bhanu Joshi) and two PhD students (Pradosh Sahoo and Arathi Das Moosarikandy). A major part of the research period was spent on preparing the application for the FNP competition for getting specialist equipment. The group won the funding of 3,850,000 PLN (1 million US Dollars) to acquire a unique equipment package to study electrically and optically both global and local spin dynamics of band carriers or spin waves in magnetically ordered topological systems, but also to reveal more exotic quasiparticles yet to be discovered in topological matter.

At the same time, samples of $Pb_{1-x}Sn_x Se/Ni_{81}Fe_{19}$ on BaF_2 substrates are grown and processed at MagTop to study, in collaboration with Prof. Alberta Bonanni of Johannes Kepler University in Linz, spin pumping phenomena by using the inverse spin Hall effect and ferromagnetic resonance spectrometer. Once the newly purchased equipment is available at MagTop, these samples will be studied by using broadband inverse spin Hall effect spectrometer for frequencies ranging from 2 GHz to 40 GHz and by local Brillouin light scattering spectroscopy.

The Dirac Group of Dr. Mircea Trif (ON-6.3 is now fully operating**:** two postdocs have been recruited (Dr. Archana Mishra, started in August, and Dr. Alexander Lau, started in November), necessary equipment (computers and software) have been acquired, and it is expected that a PhD student will be recruited in the near future. Several valuable pieces of theoretical information have been gathered, for instance, on the local density of states around magnetic impurity of states of 2D superconductors, ways of non-invasive manipulation of such states, and determining their lifetime from FMR measurements. These results will be extended to lattices, the goal being to both detect and manipulate the topology and the possible Majorana end modes. An alternative approach is explored, i.e., using supercurrents instead of dynamics to manipulate the band structure. The dynamical process of braiding Majorana fermions in the presence of the coupling to photons in a microwave cavity is examined too.

The ability to transport spin without dissipation is a major goal in spintronics, with spin superfluidity being promoted as the ultimate solution for classical spin currents. This phenomenon is addressed in Dr. Trif's quantum magnets by studying the spin superflow in spin one-half quantum spin chains. A plethora of novel spin superflows is found, and unravels their strong influence on the entanglement between the spins, and proves robustness against external perturbations. These findings can be exploited directly to applications or to other theoretical directions, such as quantum information with spin qubits or generalization to two-dimensional quantum spin systems. Importantly, these studies are directly relevant to experimental developments in Dr. Bhat's group, and **Dr. Trif's group looks for ways to test their theoretical predictions by using Dr. Bhat's new equipment for studying local and global spin dynamics.**

Dr. Alexander Lau works together with Dr. Timo Hyart on studying emergent 3D flat bands in topological nodal-line semimetals under strain. The possibility of inducing 3D flat bands in nodal-line semimetals by strain was theoretically established. In the next step, the emerging correlated phases will be investigated, and **materials to be developed at MagTop proposed**.

Selected accomplishments of Theory (ON-6.1), MBE (ON-6.2), and Majorana (ON-6.3) groups

The reports of these group activities, particularly in the second and third year of the MagTop operation, present a comprehensive description of the obtained results, gathered in 86 articles co-authored by members of these three most established groups. Here we present the **current status of five topics** that exemplify MagTop's strength resulting from synergy of growth, characterization, experiment, and theory as well as the collaboration of these three groups towards the achievement of the common goal. Three of these topics: the interfacing of (i) magnetic and (ii) superconducting metals to topological materials as well (iii) magnetotransport properties of 2D topological HgTe quantum wells are at the heart of the Agenda, and their possible studies were discussed in the original proposal. Two other topics concern new and unanticipated phenomena associated with interfacing of (iv) normal metals and (v) amorphous semiconductors with topological materials.

(i) Interfacing magnetic metals with topological surface of $Pb_{1-x}Sn_xSe$

Magnetic order in 2D layers is required for low power ultra-compact spintronic applications as well as it is of interest for studies of new phenomena in the area of low-dimensional magnetism and for the creation of new topological phases. Having this in mind, the magnetically-doped surface of a topological crystalline insulator (TCI) $Pb_{1-x}Sn_xSe$ epilayers in (001) and (111) orientation has been studied by ARPES. The experiments were performed at SOLARIS synchrotron (Kraków) and HZB BESSY II (Berlin). The epilayers were grown on both (001)-KCl and (111)-BaF_2 substrates within the collaboration of senior postdoc Dr. Volobuev (MBE Group) with Prof. Springholz at JKU in Linz. The samples were covered in-situ in the MBE chamber by amorphous Se and then were decapped in the ARPES preparation chamber by Se re-evaporation.

For (001) oriented (Pb,Sn)Se films ARPES investigations were performed near the X points of the surface Brillouin zone, and for (111) oriented ones near Γ and M points at photon energies 17-18 eV. ARPES $E(\boldsymbol{k})$ spectra and 3D maps were obtained at temperatures of 10, 78, and 300 K. Magnetic doping of (Pb,Sn)Se surface was achieved by in-situ deposition of Mn and Fe with deposition steps 0.025-0.1 ML.

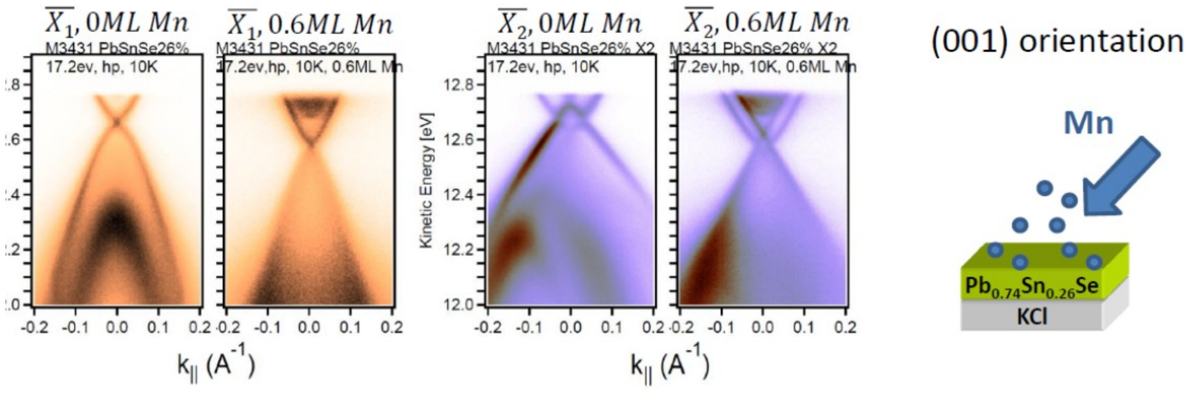


Fig. 1 ARPES spectra of (001) $Pb_{1-x}Sn_xSe$ epilayers before and after Mn deposition (SOLARIS).

After each deposition ARPES spectra were recorded (see Fig. 1). In contrast to a theoretical prediction, it was observed that submonolayer deposition of either Mn or Fe on (Pb,Sn)Se (111) and (001) did not open the band gap in the topological surface states (TSS). On the other hand, we found that the deposition of either Mn or Fe on (Pb,Sn)Se (111) resulted in band bending bringing chemical potential upward into the conduction band. As a consequence of the bending, a QW formed near the surface. QW states in conduction band were well resolved in obtained ARPES images. Introducing additional potential to initially compensated polar (111) surface creates Rashba splitting, which increases with increasing transition metal thickness and finally saturates. However, the Rashba effect was absent for (001) oriented films since this plane contains both metal and chalcogen atoms. Furthermore, the deposition of Mn with submonolayer thickness on (Pb,Sn)Se (001) decreases a distance in the ***k*** space between Dirac points of the double Dirac cone. This apparently is connected with the diminishing of hybridization between the cones due to the presence of a strong potential gradient introduced by surface doping. These spectra provide novel information about the sensitivity of TSS to magnetic impurities and can be useful for the implementation of a topological crystalline insulator in spintronic devices.

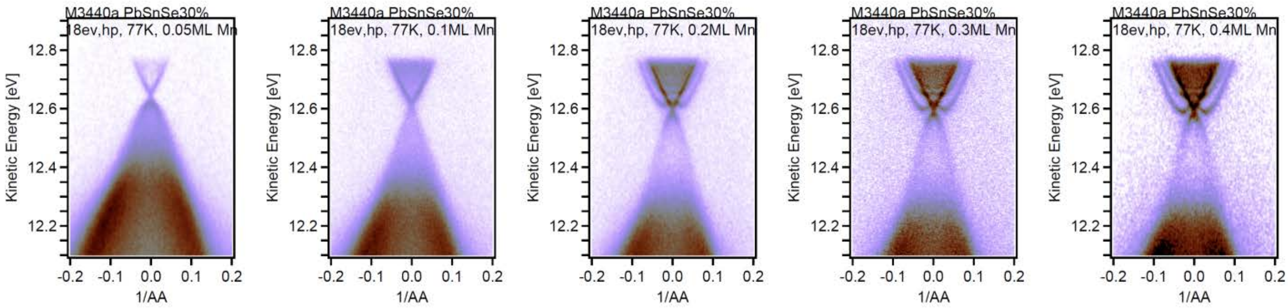


Fig. 2. ARPES images of 1um of $Pb_{0.7}Sn_{0.3}Se$ (111) film after deposition of 0.05, 0.1, 0.2, 0.3, 0.4 ML of Mn, respectively. Data were obtained at 77K in the vicinity of Γ bar point at photon energy of 18 eV (BESSY II).

Novel effects of the coexistence of TSS with Rashba states and changing the width of double Dirac cones were observed. Rashba parameter calculated from experimental ARPES data can reach values of about 2 eV/Å (typical value for other giant Rashba splitted materials), making this system perspective for spin torque devices. The Rashba and topological surface states, being characterized by unique helical spin texture, can provide an efficient mechanism for charge-spin interconversion and for the creation of a building platform for future spintronic devices. Manipulation of the magnetization through spin-orbit torques is one of the primary goals of spintronics. Therefore, hybrid topological insulator/magnetic material (TI/MM) junctions can provide one of the possible practical applications of topological insulators in the field of spintronics. Recently, it has been shown experimentally that the spin-orbit-torque ratio in topological TI/MM heterostructures can be enhanced three times if Rashba spin-orbit coupling is introduced.

Motivated by these experiments Dr. W. Brzezicki and Dr. T. Hyart (Majorana Group) have started examining the problem of the coexistence of surface Dirac cones and giant Rashba splitting theoretically. They addressed the question of how the Schottky barrier formation at the interface is influenced by the topological surface states expecting that the surface potential has a qualitatively different shape than in usual metal-semiconductor interfaces. The ARPES experiments discuss above indicate that Rashba-split bands originating from the surface potential caused by the metal-semiconductor interface can coexist with the topological surface states [Figs. 2 and 3(a)]. Numerical calculations indicate that this would not be possible in the case of the usual shape of the interface potential. However, their theoretical calculations indicate that such kind of coexistence (without hybridization) can occur if the surface potential is modified due to the presence of the topological surface states [Fig. 3(b)]. In this way, it is possible to obtain a situation where the Rashba-splitted band (black isolated band within the bulk energy gap) coexists (without hybridization of the states) with the topological surface states (green) in agreement with the experiment. These numerical calculations indicate that for the usual shape of the interface potential, these bands would always hybridize, leading to avoided crossing. This means that the Schottky barrier formation is qualitatively different in the case of topologically nontrivial materials. More detailed *ab-initio* computations are currently under development in collaboration with Dr. C. Autieri (Theory Group).

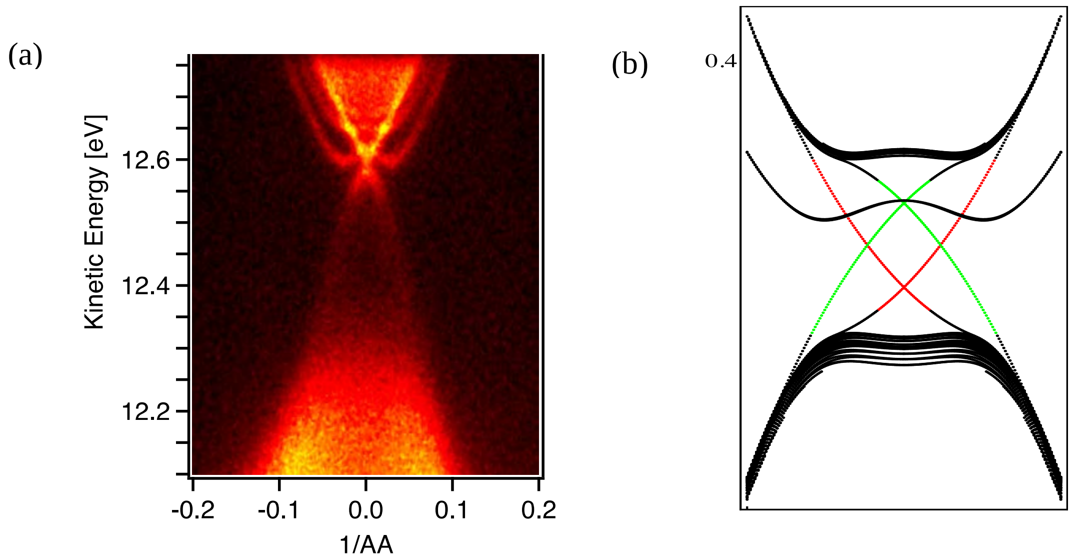


Fig. 3: (a) ARPES measurement of the spectrum of surface states for $Pb_{1-x}Sn_xSe$ material in the presence a thin layer of Mn (thickness less than a monolayer) [V. Volobuev et al., MBE group] showing the coexistence of surface Dirac cones and giant Rashba splitting (b) Calculated spectrum where the effect of topological states on the surface potential is taken into account explaining this surprising experimental result [W. Brzezicki and T. Hyart, Majorana Group].

(ii) <u>Interfacing superconducting metals with topological surface of Weyl semimetal NbP</u>

As shown by Leo Kouwenhoven's group in Delft, semiconductor nanowires proximitized by a superconductor show zero-energy Majorana excitations in a magnetic field [Zhang *et al.* Nature (2018)], a groundbreaking discovery on the way to develop hardware for topological quantum computing. It is anticipated that proximitized topological nanowires will show Majorana modes even without external magnetic fields.

In MagTop, a possibility of inducing superconductivity in type-I Weyl semimetal through coupling its surface to a superconductor is investigated. Single crystals of NbP are grown in Prof. Andrzej Wiśniewski's lab by a chemical vapor transport method and thoroughly characterized by XRD, EDX, and SEM as well as by ARPES at SOLARIS in Kraków. The determined surface band structure reveals the presence of topological arches, as shown in Fig. 4.

Transport measurements are performed by Andrzej Dąbrowski, a PhD student supervised by Dr. hab Grzegorz Grabecki at IFPAN. The mobility spectrum show four peaks indicating that the carriers participating in the conductance have four different mobilities. For studies of interface transmission, the (001) surface of the crystal has been covered by several hundred nm thick metallic layers of either Pb, or

Nb, or In, making use of the expertise of the MBE group. Upon cooling, when the metals become superconducting, all three types of junctions show conductance increase, pointing out the Andreev reflection as a prevalent contribution to the subgap conductance:

G. Grabecki, A. Dąbrowski, P. Iwanowski, A. Hruban, B.J. Kowalski, N. Olszowska, J. Kołodziej, M. Chojnacki, K. Dybko, A. Łusakowski, T. Wojtowicz, T. Wojciechowski, A. Wiśniewski, ***Conductance spectra of (Nb, Pb, In)/NbP superconductor/Weyl semimetal junctions***, arXiv:1908.07359, Phys. Rev. B 101, 085113 (2020)

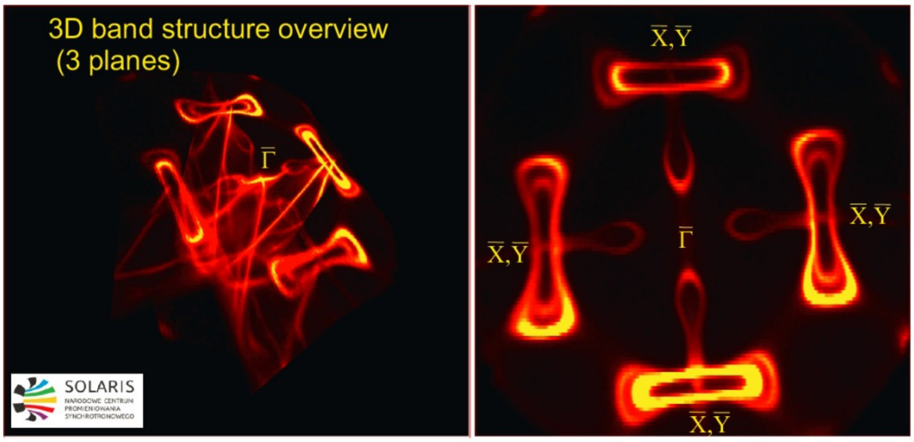


Fig. 4 Results of angular-resolved photoemission studies of MagTop's NbP single crystals –3D overview and band structure cross-section showing pockets and arches specific to Weyl semimetals [after Grabecki et al., Phys. Rev. B 101, 085113 (2020)].

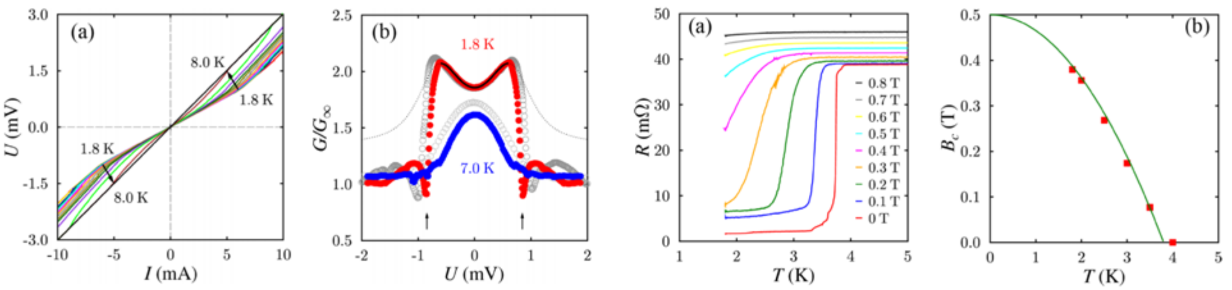


Fig. 5 Two left panels show data for a Nb-NbP junction: (a) Voltage-current characteristics U-I measured at various temperatures in the range from 1.8 to 8 K, and at zero magnetic field. (b) Differential conductance at 1.8 and 7 K obtained just after fabrication of the junction (full dots points) and after 20 months of storing at room temperature (empty dots). Solid/dotted curve is calculated with modified BTK model neglecting current-induced S-N transition (indicated by arrows). Two right panels show data for In-NbP junctions: (a) temperature dependence of resistance at various magnetic fields; (b) the critical field B_c shows temperature dependence suggesting the presence of superconductivity originating from indium nanocrystals diffused to NbP [after Grabecki et al., Phys. Rev. B 101, 085113 (2020)].

In the case of Pb-NbP and Nb-NbP junctions, differential conductance spectra are satisfactorily described by modified Blonder-Tinkham-Klapwijk (BTK) model, as shown in Fig. 5. However, the absolute value of the conductance is much smaller than that for the bulk crystal, indicating that the transmission occurs through only a small part of the contact area. An opposite situation occurs in In-NbP junction, where we observe a high and narrow peak at zero bias, i.e. a sharp decrease of junction resistance (Fig. 5). The conductance at the peak reaches the bulk value indicating that almost whole contact area is transmitting and, additionally, a superconducting proximity phase is formed in the material. Making use of SIMS data, we interpret this result as being caused by indium diffusion into NbP, where the metal atoms penetrate the surface barrier and form a transparent superconductor-Weyl semimetal contact inside. The observation directly demonstrates the possibility of inducing superconductivity in a type-I Weyl semimetal.

(iii) Topological properties of HgTe quantum wells

While recent *ab initio* screening of 27,000 compounds indicates that about 27% of them show topological features [Vergniory *et al*., Nature (2019)], the family of 2D topological insulators, i.e., of candidate materials for the quantum spin Hall effect [Bernevig *et al*., Science (2006); Koenig *et al.,* Science (2007)] contains only two members: quantum wells of HgTe and atomically thin layers of WTe_2. The former is grown successfully by Wuerzburg's and Novosybirsk's MBE groups. Currently, MagTop is in the process of developing an MBE program dedicated to the growth of mercury-cadmium tellurides doped with transition metal impurities in collaboration with the University of Rzeszów.

Professor Wojciech Knap, now a PI of the CENTERA IRA project at the Institute of High Pressure Physics, Polish Academy of Sciences, has been bringing HgTe quantum well wafers (shown in Fig. 6) from Novosybirsk to Warsaw in the frame of the French-Polish-Russian TERAMIR project. These wafers have been processed to micro Hall bars and measured at IFPAN (Magda Majewicz – IFPAN PhD student supervised by Tomasz Dietl – she defended her PhD thesis on Sept. 24, 2019) and more recently by W. Knap's PhD student Ivan Yahniuk and MagTop's Dr. Alexander Kazakov (MagTop's MBE Group). In particular, M. Majewicz mastered complex low-temperature processing of Hg-based multilayers and fabricated by electron beam lithography a series of gated microstructures (Fig. 7) containing n-type HgTe quantum wells of the width d = 8 nm, corresponding to the topological regime (inverted band structure). Investigations of these microstructures by local and non-local resistance allowed her to determine the protection length that, as shown in Fig. 8, is of the order of 2 μm.

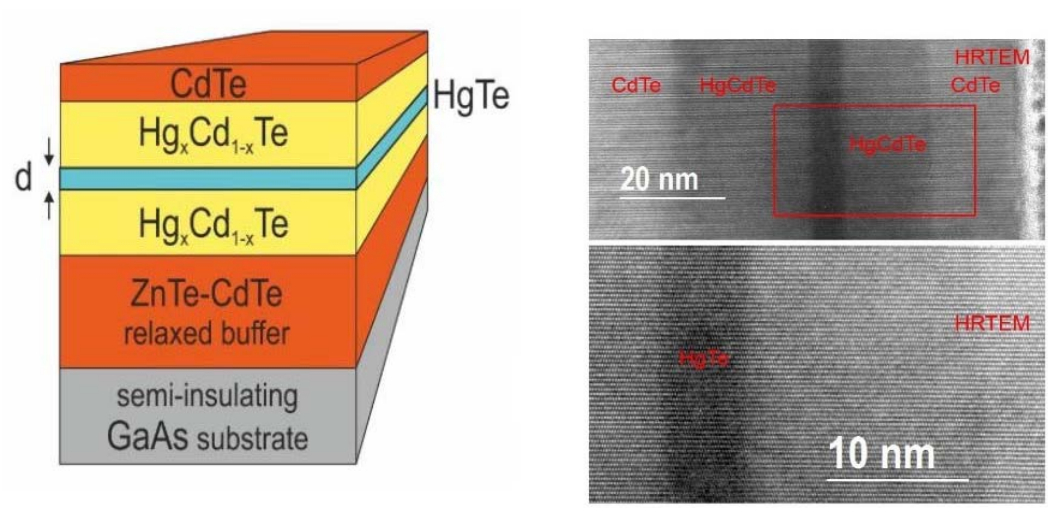


Fig. 6 Layout of studied HgTe-CdTe multilayers obtained by MBE [S.A. Dvoretsky et al. – Novosibirsk] and their visualization by high-resolution electron microscopy [S. Kret et al., IF PAN]

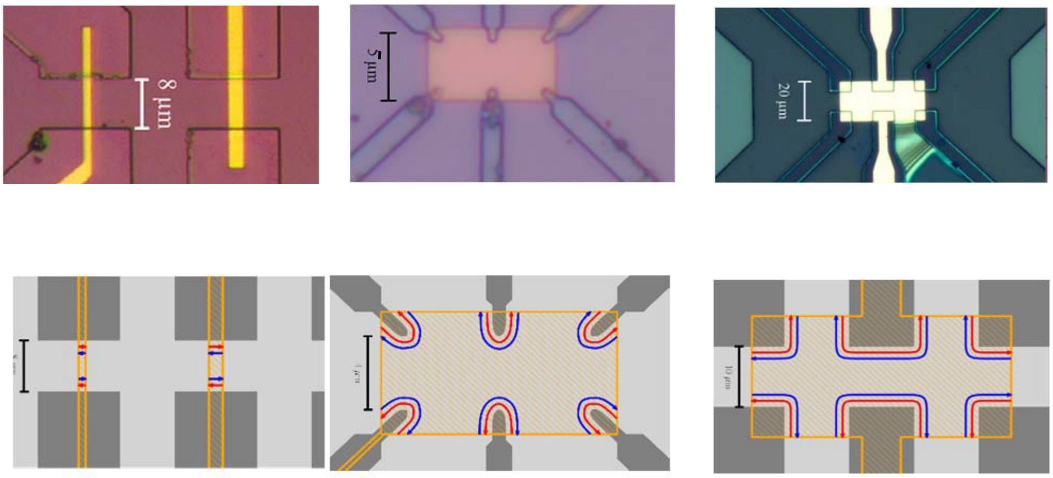


Fig. 7 SEM visualization (upper panels) and schematic layout (lower panels) of microstructures for charge transport measurements obtained by electron beam lithography and wet etching [M. Majewicz et al. – IFPAN/MagTop]. Bright regions correspond to metal gate electrodes, either finger-like (left panels) or global (central and right panels panels). Dark regions (in schematic pictures) are etched isolating tranches separating successive contacts to gated regions. Blue and red lines show schematically topological edge channels.

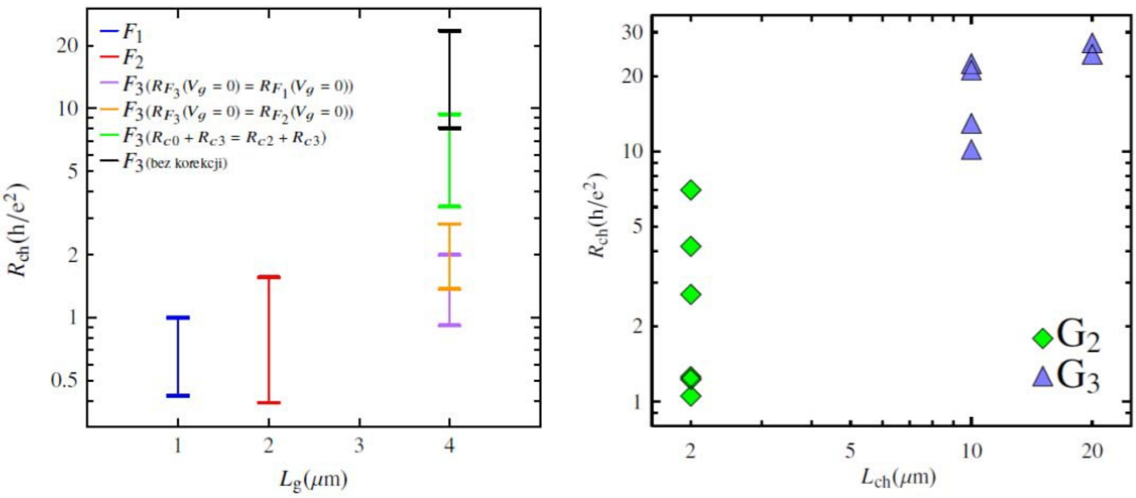


Fig. 8 Single edge channel resistance as a function of the finger gate length (left panel) and channel length for devices with global gates (right panel). The results indicate that channel of the length up to 2 µm show an approximately quantized value of h/e^2 [M. Majewicz et al., in preparation]

These results substantiate the initial data of Molenkamp's group and reemphasize the question about the origin of short topological protection length of 2D topological insulators. The recent Wuerzburg result point to charge impurities residing in the gate insulator [Luncher et al. Phys. Rev. Lett. (2019)]. In contrast, MagTop's Majorana Group [T. Hyart and W. Brzezicki] has found in numerical calculations that CdTe/HgTe quantum wells can, in addition to the usual quantum spin Hall edge states, support a large number of additional edge modes. T. Hyart, W. Brzezicki and N. Minh Nguyen are now continuing the investigation of these additional modes. It has been found that these additional edge states are described by a topological invariant originating from mirror symmetry and approximate spin-rotation symmetry. In collaboration with C. Autieri [MagTop's Theory Group], current studies aims at answering the question of how these additional modes depend on the composition of the heterostructure. According to this new insight, these modes contribute to the breakdown of the topological protection of quantum spin Hall edge modes, and we plan to design a heterostructure where the topologically quantized edge mode transport can be observed in much longer devices.

One of the most surprising discoveries, relevant to the resistance standards, is the appearance in the field of 3 kOe of a well quantized Hall plateau corresponding to the uppermost hole Landau level, as shown in Fig. 9. Yahniuk *et al.* have studied this effect experimentally and theoretically concluding that in the inverted band structure case screening of scattering potentials by holes residing in side maxima of the valence subbands accounts for the phenomenon:

I. Yahniuk, S. S. Krishtopenko, G. Grabecki, B. Jouault, C. Consejo, W. Desrat, M. Majewicz, A. M. Kadykov, K. E. Spirin, V. I. Gavrilenko, N. N. Mikhailov, S. A. Dvoretsky, D. B. But, F. Teppe, J. Wróbel, G. Cywiński, S. Kret, T. Dietl, W. Knap, ***Magneto-transport in inverted HgTe quantum wells***, arXiv:1810.07449, npj Quantum Materials **4, 13** (2019)

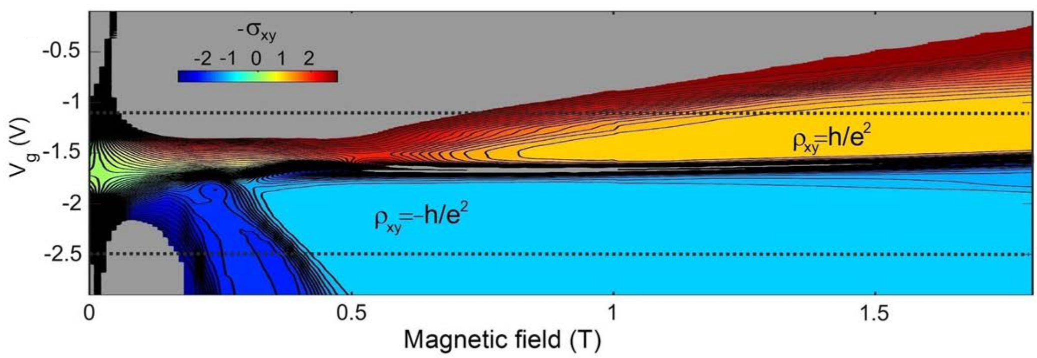


Fig. 9 Hall conductivity of a gated HgTe quantum well at 1.7 K as a function of the magnetic field and gate voltage showing a wide and well quantized hole plateau [after Yahniuk et al. npj Quantum Mater. ***4****, 13 (2019)]*

(iv) Interfacing normal metals with topological surfaces of $Pb_{1-x-y}Sn_yMn_xTe$

This work, initiated by PhD student Grzegorz Mazur, started in early 2017 (*i.e.,* at the MagTop beginning), and has been carried out in collaboration between MagTop's groups headed by Tomasz Dietl and Timo Hyart, and involved a number of MagTop researchers: Prof. Tomasz Story and Jędrzej Korczak (growth); Dr. Krzysztof Dybko, Dr. Alex Kazakov and Grzegorz Mazur (processing and mK measurements); Dr. hab. Wojciech Brzezicki and Dr. Marcin Wysokiński (theoretical interpretation). An important contribution concerning sample processing comes for Alexander Kazakov [MagTop's MBE Group]. The studies in question for (Pb,Sn)Te and magnetic (Pb,Sn,Mn)Te were preceded by two fundamental findings for (Pb,Sn)Se single crystals grown and studied by Prof. Story's group: the demonstration that (Pb,Sn)Se for sufficiently high Sn content is a crystalline topological insulator [Dziawa *et al.* Nat. Mater. (2012)] and that there exist (higher order) 1D topological states along odd surface atomic steps [Sessi *et al.*, Science (2016)]. MagTop's results have been published in two papers in Phys. Rev. B Rapid Communications:

1. G. P. Mazur, K. Dybko, A. Szczerbakow, J. Z. Domagala, A. Kazakov, M. Zgirski, E. Lusakowska, S. Kret, J. Korczak, T. Story, M. Sawicki, and T. Dietl, ***Experimental search for the origin of low-energy modes in topological materials***, arXiv:1709.04000, Phys. Rev. B 100, 041408(R) (2019) [Editors' suggestion]

2. W. Brzezicki, M. M. Wysokiński, T. Hyart, ***Topological properties of multilayers and surface steps in the SnTe material class***, arXiv:1812.02168, Phys. Rev. B 100, 121107(R) (2019).

The key experiment was point-contact *I-V* spectroscopy down to 50 mK and up to 6 T, which revealed the existence of a collective phase in metal/($Pb_{1-y-x}Sn_yMn_x$)Te junctions for *y* corresponding to the topological band ordering, and *x* to diamagnetic, paramagnetic, and ferromagnetic cases, as shown in Fig. 10. This new low temperature phase has also been recently found by others in a number of junctions of metals to topological systems. Surprisingly, despite the **absence of global superconductivity** in these systems, the features in d*I*/d*V* decay critically with temperature and the magnetic field in **accordance with the BCS theory**, as depicted for Ag/($Pb_{1-y-x}Sn_yMn_x$)Te in Fig. 1. This new and surprising effect persists for contacts of ferromagnetic metals (e.g., Co) and in the case of a ferromagnetic semiconductor (Pb,Sn,Mn)Te. The presence of local superconductivity associated with strain, interface states, superconducting precipitates (our suggestion), and misfit dislocations has been invoked but not demonstrated. Within the MagTop model (Brzezicki et al. Phys Rev. B (2019)], the Fermi level is pinned by 1D topological states at edges of surface terraces in SnTe class of crystalline topological insulators. Under these conditions, correlation effects in the 1D flat bands drive carriers to a collective state at low temperatures with a Su-Schrieffer-Heeger (SSH)-type of zero-energy excitations at domain walls formed spontaneously in 1D case. The BCS-type of criticality is then expected within the mean field approximation.

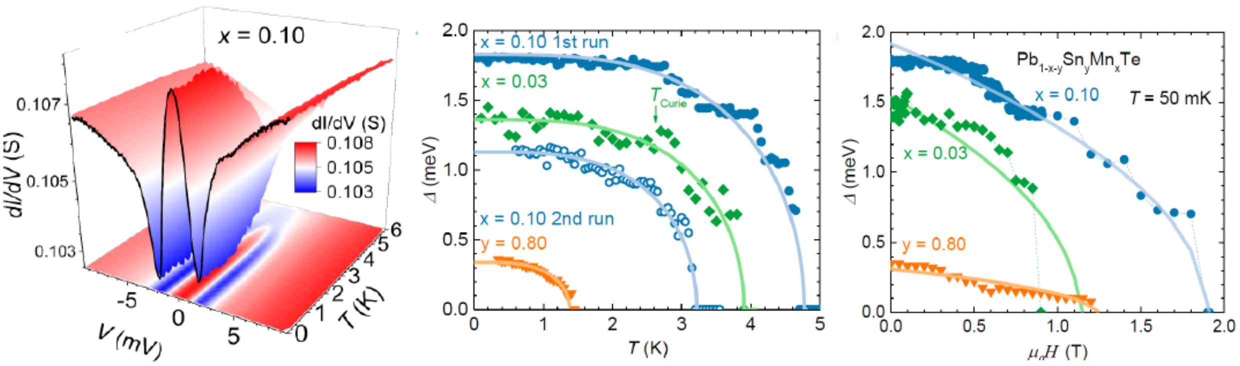


Fig. 10 Differential conductance as a function of bias voltage and temperature for soft junctions Ag/$Pb_{0.16}Sn_{0.74}Mn_{0.1}$Te (left panel). The width of the conductance features as a function of temperature (middle panel) and the magnetic field (right panel) for various Ag/$Pb_{1-y-x}Sn_yMn_x$Te samples [after Mazur et al. Phys. Rev. B 100, 041408(R) (2019)]

Further research in this field is underway making use of additional relevant experimental methods, also within the international collaboration, involving multiprobe scanning tunneling microscopy and scanning point-contact spectroscopy.

(v) Interfacing amorphous Se with topological and non-topological $Pb_{1-x}Sn_xSe$

Quantization of geometrical phases accounts for phenomena, such as the Aharonov-Bohm effect and Bohr-Sommerfeld quantization of energy levels, which are hallmarks of quantum physics. It has more recently been realized that the quantized value of the Berry phase $\varphi = \pi$, if evaluated over a proper trajectory in the Brillouin zone, points to the presence of topological surface states. Similarly, positive magnetoresistance, resulting from weak antilocalization (WAL) when the spin-orbit diffusion length is much shorter than the phase coherence length, is taken as evidence for the topological phase, as the Berry phase evaluated along the Fermi cross section of the Dirac cones is quantized $\varphi = \pi$. In MagTop, W. Brzezicki and T. Hyart [Majorana Group] with an input of T. Dietl [Theory Group] have considered the case of cubic lead-tin monochalcogenides and demonstrated theoretically that the quantization of φ results from the crystalline mirror and time-reversal symmetries rather than from non-trivial topology. This has been verified experimentally: A. Kazakov and V. Volobuev [MBE Group] studied 50-nm thick layers of $Pb_{1-x}Sn_xSe$ grown by MBE and characterized by ARPES in BESSY II lab in Berlin. The magnetoresistance behaviour follows the theory prediction that the Berry phase is quantized to $\varphi = \pi$ for both topologically trivial and non-trivial materials. However, the quantization is lost by intentionally breaking the mirror symmetry with an additional amorphous layer of Se:

A. Kazakov, W. Brzezicki, T. Hyart, B. Turowski, J. Polaczyński, Z. Adamus, M. Aleszkiewicz, T. Wojciechowski, J. Domagała, A. Varykhalov, G. Springholz, T. Wojtowicz, V. V. Volobuev, T. Dietl, ***Mirror-symmetry protected quantization of Berry phases and resulting magnetoresistance across the topological transition in*** $Pb_{1-x}Sn_xSe$, arXiv:2002.07622

Examples of magnetoconductance behaviour as a function of temperature and the determined values the phase coherence length are shown in Fig. 11. The low temperature l_φ saturation in Se covered samples, and its absence in bare epilayers, point to the crucial role of the mirror symmetry for the magnetoresistance behaviour.

Such an effect of the top interface, revealed by the data in Fig. 11, finds an elegant explanation by our theory. At high temperature, WAL is still governed by the thermally suppressed l_φ. In bare epilayers, WAL is protected by the quantized Berry phase $\varphi = \pi$ due to the mirror symmetry, thus l_φ continues to increase with cooling down. By contrast, long interference paths in Se capped epilayers, which are relevant for large values of l_φ, do not contribute to WAL, since scattering between states at the Fermi level, allowed by mirror symmetry breaking, randomizes the wave function phase φ and average it to zero. Thus, there is a new length scale, which limits an increase of WAL MR with lowering the temperature, similarly to the effect of time reversal breaking by spin-disorder scattering or spin splitting considered previously.

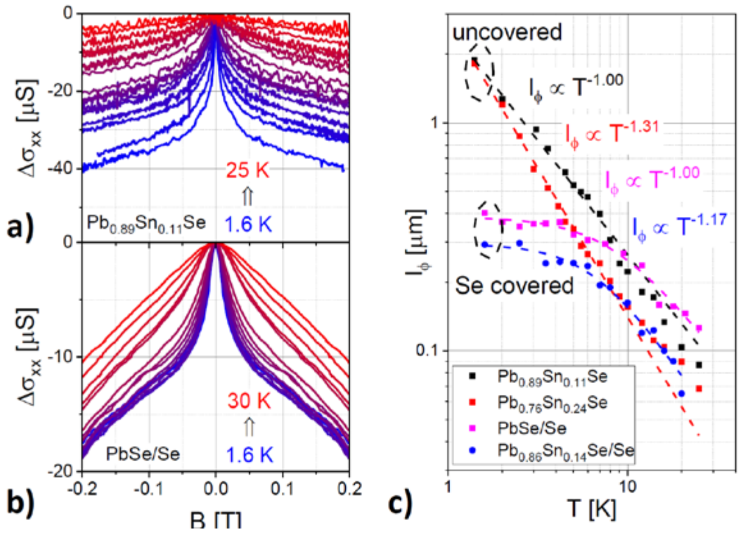


Fig. 11 Magnetoconductance and the determined phase coherence length $l_\varphi(T)$ for $Pb_{1-x}Sn_xSe$ showing low temperature saturation of $l_\varphi(T)$ in epilayers covered by an amorphous. Se layer [after Kazakov et al. arXiv:2002.07622]

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

I. (Cd,Zn,Mg,Mn)Te/GaAs compliant substrates for MBE and MOCVD technologies

MBE group has developed the technology of semiconductor II-VI compliant substrates composed of GaAs wafers and special II-VI buffer layers. This is a versatile solution to the market need for II-VI substrate crystals with required parameters. Our substrates have been successfully tested in many MBE laboratories. Improved quality (Cd,Zn,Mg,Mn)Te/GaAs compliant substrates (removal of hillocks) should open the way to commercial applications, e.g. in manufacturing infrared detectors by our partner VIGO SYSTEM and other optoelectronic companies as well as research institutions using MBE or MOCVD II-VI technologies.

II. Sputtering sources for ferromagnetic metals deposition systems

MagTop, in collaboration with PREVAC company, works on improved design of sputtering sources and targets for deposition of ferromagnetic metals. Such improved magnetrons will find their commercial application in sputtering systems produced by PREVAC and other ultra-high vacuum companies.

III. SQUID with Weyl semimetals

Results of our studies of conductance spectra of (Nb, Pb, In)/NbP superconductor/Weyl semimetal junctions indicate that this material system can be used to test the recent idea of electrically modulated SQUID consisting of a single Josephson junction coupled by Weyl semimetal. Such SQUID may have applications in superconducting electronics.

IV. Metrological applications of topological heterostructures

Results of our experimental and theoretical studies of electron transport and magnetic properties of 1D electronic edge states present in topological heterostructures exhibiting quantum spin Hall effect or quantum anomalous Hall effect revealed the physical and technological obstacles encountered in achieving robust conductance quantization needed for newly developed metrological standards.

2. INFORMATION ABOUT SENIOR POST DOCS(independent researchers), VISITING SCIENTISTS AND TECHNICIANS and their contribution to the implementation 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 contribute to the overall goals of the project.)

Senior postdocs

Except for Dr. Aleksei Shorokhov, who was employed by MagTop over 6 months only, the remaining eight senior postdocs have been instrumental for MagTop’s accomplishments presented above, and have been co-authors, often leading, of relevant publications. According to IFPAN rules, they are assigned to particular groups, but their expertise, activities, contacts with entrepreneurs, and co-supervision of younger colleagues are vital for the whole unit.

1. Prof. **Andrzej Wiśniewski** – Expert in magnetism and superconductivity (from 3.03.2017, ½ of full-time job)
Research tasks: the growth of bulk Weyl semimetals, their structural characterization, interfacing with superconductors, and doping with magnetic impurities; submitting applications to synchrotron centers and ARPES studies.
Additional responsibilities: contacts with companies; MagTop promotion.

2. Dr. **Tomasz Wojciechowski** – Expert in the fabrication of nanostructures (from 20.03.2017 to 31.05.2018, ½ of full-time job, from 1.06.2018 to 30.09.2019 and from 1.12.2019, ¾ of full-time job)
Research tasks: Nanostructurization of topological materials; research collaboration with Vigo System 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 MBE growth of IV-VI compounds (topological crystalline insulators - TCIs) and their physical properties (from 4.12.2017)
Research tasks: Making new MBE chamber for growth of IV-VI compounds and metal overlayers operating; growth of IV-VI compounds and their structural characterization; applications to synchrotron centers and ARPES studies. Timely submission of the habilitation thesis expected.
Additional responsibilities: training newcomers in MBE growth technology; co-supervisor of a PhD student; handling collaboration with Johannes Kepler University in Linz.

4. Dr. **Carmine Autieri** – Expert in *ab-initio* studies using fully relativistic codes suitable for topological materials (from 1.06.2018)
Research tasks: In collaboration with other groups carrying on *ab initio* studies of relevant systems stimulating and interpreting experimental results and theoretical findings within effective Hamiltonian methods. Habilitation thesis, containing also publications done at MagTop, submitted. While at MagTop, Carmine has co-authored nine published or submitted papers.
Additional responsibilities: co-supervision of two PhD students; handling collaboration with the University of Salerno; maintaining numerical codes; applying for computer time.

5. Dr. **Krzysztof Dybko** – Expert in the low-temperature transport measurements of topological matter (from 17.12.2018, ½ of full-time job)
Research tasks: Developing thermal conductivity experimental set up; carrying out magnetotransport studies and point contact spectroscopy of topological crystalline insulators. Habilitation thesis expected to be approved by the Scientific Council of IFPAN on February 27, 2020.
Additional responsibilities: applying to the Ministry for funds to purchase a new dilution refrigerator to Ministry; participating in the preparation of a suitable laboratory; maintaining collaboration with the University of Tokyo concerning four microprobe measurements of atomic step conductance.

6. Prof. **Tomasz Story** – Expert in IV-VI topological materials (from 1.04.2019 ½ of full-time job)
Research tasks: the growth of bulk TCIs and assisting in the development of new MBE chamber for TCIs, their structural characterization, and doping with magnetic impurities; research contact with Helioenergy company concerning thermoelectricity of topological materials.

Additional responsibilities: contacts with companies; MagTop promotion.

7. Dr. **Aleksei Shorokhov** – Expert in non-equilibrium topological phenomena and mathematical physics (from 5.06 to 4.12.2019)
Research task: Determination of the energy spectrum, wave functions, and local density of states associated with the presence of a magnetic impurity in a 2D superconductor with the Rashba spin-orbit interaction.

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 senior postdoc 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)
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.

Visiting scientists

- PhD student, **Yosuke Satake** from Tohoku University, spent 3 months in 2018 (3.07-3.09.2018) at MagTop as a visitor supported by his home institution. He defended his doctoral thesis in March 2019 at Tohoku University. A Tohoku/MagTop paper has been submitted.
- PhD student **Giuseppe Cuono** from the University of Salerno spent 5 months in 2019 (22.02 to 22.07.2019) at MagTop as a visitor supported by his home institution. He defended his PhD thesis "New features exhibited by transition metal pnictides" at the University of Salerno in January 2020 (evaluation "Great" and the distinction "Doctor Europaeus" owing to his stay at MagTop; Three publications MagTop/Salerno have been published. Recently, Dr. Cuono has succeeded in obtaining the "Della Riccia" Fellowship with MagTop as a hosting institution, so he will join MagTop as a postdoc, presumably in March 2020.
- Dr. **Aleksei Shorokhov** – Expert in non-equilibrium topological phenomena and mathematical physics spent 6 months at MagTop (from 5.06 to 4.12.2019) - he was employed as a senior postdoc.

Technical Staff

All eight technical staff members, who are (or soon will be) a part-time employees of MagTop, are indispensable for the successful realization of the project's goals as they give an important contribution to the materials development and experimental activities of the IRA unit. Apart from providing technical support of various apparatus being at the disposal of MagTop and without which MagTop could not function, they participated in various types of research in the area of their particular expertise.

1. Dr. Przemysław Iwanowski - *specialist in the growth of bulk crystals of topological materials* (from 19.04.2017 to 31.10.2017, ¼ of full-time job, from 1.11.2017 to 31.05.2018, ½ of full-time job, from 1.06.2018, ¾ of full-time job).

   Tasks: (i) Conducting research related to the growth of bulk crystals of topological materials, especially Weyl semimetals, as well as MBE growth of topological nanostructures; (ii) Studies of the basic properties of grown topological materials.

   Bulk Weyl semimetal crystals grown by Dr. Iwanowski have been already used in the studies of *superconductor/Weyl semimetal junctions and results have been published in one paper and presented at one conference.*

2. MSc Wojciech Zaleszczyk – *a 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)

   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. Without him, successful launching of the new MBE system could not have been possible (see report).

3. Paweł Ungier - *electronic specialist* (from 18.09.2018, ½ of full-time job)

   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.

   Apart from solving everyday electronic problems, Mr. Ungier has made an important contribution to the launching of the new MBE system. He has also designed and built some electronic devices allowing better control of the technological processes of the growth of topological materials.

4. MSc Maciej Wiater – *a specialist in MBE growth of topological materials* (from 18.09.2018 to 30.04.2019, ½ of full-time job) – *already retired*

   Task until 30.04.2019: Carrying out technological processes of the growth of nanostructures made of II-VI and IV-VI materials with topological properties using the method of molecular beam epitaxy (MBE) and studying their properties with the use of photoluminescence technique.

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

   Task: 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.

   MSc Korczak has already grown a number of TCI bulk crystals and wires (together dr hab. Andrzej Szczerbakow and MSc Jakub Polaczyński) that had been used in a number of experiments, which resulted in one publication and 3 conference presentations. He has also synthesized binary source materials (polycrystals of SnTe, PbSe, SnTe and PbSe) that are used in the new IV-VI MBE chambers (see results on MBE growth).

6. Dr. Krzysztof Fronc – *a 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)

   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.

7. Dr. Dawid Jarosz – *a specialist in the area of molecular beam epitaxy of II-VI compounds* (just chosen in an open competition, will be hired from 2.03.2020, 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 Cr.

8. MSc Jakub Grendysa – *a specialist in the area of molecular beam epitaxy of mercury chalcogenides* (just chosen in an open competition, will be hired from 2.03.2020, 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 mercury chalcogenides containing Mn and Cr.

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: group 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)

Position type	*Total number of researchers*	*Number of International researchers*	*Number of Returning researchers*
Group Leaders	**5**	**3**	**0**
Post docs	**8**	**6**	**2**
PhD students	**12**	**7**	**0**
Students	**0**		
Senior Post-docs	**8**	**3**	**1**
Visiting scientists	**0**		
Technicians	**5**	**0**	**0**

MagTop researchers and PhD students originate from **twelve countries**: China, Colombia, Finland, Germany, India, Italy, Pakistan, Poland, Romania, Russia, Ukraine, and Vietnam. Furthermore, they carried out at least one year research in many other countries: Austria, Belgium, France, Japan, Netherlands, South Korea, Switzerland, UK, and USA. The recruitment is performed *via* international open calls, and the procedure is supervised by the Foundation for Polish Science. The International Scientific Committee selects group leaders. There is a shortlist of candidates for the leader of the last 6th group. The selection procedure should be concluded in March 2020. There are **two female PhD students** and **one female postdoc** at MagTop. MagTop PIs are committed to helping with a **double carrier scheme** – there are three international MagTop members whose partners are employed by Warsaw's scientific institutions.

4. INFORMATION ABOUT SCIENTIFIC PARTNERS

4.1. Please provide a short overview of cooperation with foreign partners

MagTop PIs and other group leaders cooperate with the **International Scientific Committee** (ISC) and with the **strategic partner unit - Julius-Maximilians-Universität (JMU) in Würzburg** as well as with **Tohoku University's World Premier Institute (AIMR)** concerning the implementation in MagTop **best practices**. Furthermore, particular groups and researchers carry on extensive **research collaboration** documented by MagTop joint **publications and preprints with 17 foreign partners in the year 2019**. Most of the collaborations have been brought by newly employed internationally established group leaders and senior postdocs.

Cooperation between MagTop, its ISC, and JMU - the strategic partner unit

In agreement with MagTop's mission of adopting and implementing good practices (in research, research ethic, recruitment strategy, technology transfer, intellectual property rights, internationalization, equal opportunities, data management, …), all MagTop's group leaders take part in the meetings of the ISC in Warsaw. During the previous meetings, the ISC members interviewed and selected group leaders, presented suggestions concerning MagTop's research directions and cooperation with industrial partners as well as discussed and adopted the Recruitment Rules (in 2017) and Data Management Plan (in 2019).

Furthermore, all group leaders visited on 21-22 January 2020, MagTop's strategic partner unit JMU in Würzburg. The program of the visit included:

- Comprehensive interactive tutorial given by Prof. Lukas Worschech, a head of the JMU Technology Transfer Unit on spreading invention spirit among students and researchers, nucleating inventions and supporting inventors, intellectual property rights, opening and assisting start-ups, the role of the campus science park.
- Lunch with Professor Laurens Molenkamp, chair of MagTop's ISC on recent developments in the field of topological matter as well as on the ways he raises on the campus, a new Institute for Topological Insulators, financed by the Bayern Government. This was followed by a meeting and a discussion with Dr. Johannes Kleinlein on practices implemented to develop this new institution.
- Meeting and a discussion with Ms. Ms. Heidi Köllmann MSc, Katharina Scheffner M.A., and Renata Shenkman M.Sc. from the International Relations Office as well as with Professor Charles Gould from the Faculty of Physics and Astronomy concerning support for international researchers and students provided by the Office and the ways to organize an

exchange of PhD students within the Erasmus programme. The text of the corresponding Agreement is now discussed between IFPAN and JMU.

- Discussion with Prof. Ewelina Hankiewicz, previous IFPAN's PhD student, on her recent research accomplishments concerning topological matter at LMU and at Harvard, where she spent a sabbatical leave; exchange of information on gender, diversity, and equal opportunity practices at these institutions.
- Seminar on "*Correlated states in flat-band systems*" was delivered by Dr. Timo Hyart, a leader of MagTop's Majorana Group.

Cooperation between MagTop and WPI-AIMR

The Advanced Institute for Materials Research (AIMR) at Tohoku University was launched as one of the centers established by the World Premier International Research Centres Initiative (WPI) with the support of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), aimed at developing world-class research bases in Japan. It is therefore clear that the goals of WPI and IRAP are similar. Tomasz Dietl, appointed as a Professor and PI at AIMR in 2012, has since been spending one month a year at Tohoku University taking part in activities aiming at internationalization of research and establishing a new world-class research center. This experience is vital for the MagTop development.

Research collaborations with foreign scientific partners documented by publications in the 3rd year of MagTop activity

I. Collaboration with Advanced Institute for Material Research, **Tohoku University**: Prof. Tomasz Dietl has participated in the research activities of Advanced Institute for Materials Research (WPI-AIMR) and Institute for Materials Research (IMR) [group of Profs. T. Sato and A. Tsukazaki, respectively] and in teaching activities of the Graduate Program in Spintronics (GP-Spin) at Tohoku University as well as in research collaboration with Prof. Hideo Ohno, President of the Tohoku University and the former Director of the Research Institute of Electrical Communication (RIEC), which resulted in signing of the **Collaboration Agreement** between RIEC and IFPAN (attached). PhD student of IMR Yosuke Satake spent 3 months at MagTop within a grant from Tohoku University.

1/ T. Dietl, A. Bonanni, and H. Ohno, *Families of magnetic semiconductors — an overview*, arXiv:1909.02999, J. Semicond. **40**, 080301 (2019) [invited review]

2/ Y. Satake, J. Shiogai, G. P. Mazur, S. Kimura, S. Awaji, K. Fujiwara, T. Nojima, K. Nomura, S. Souma, T. Sato, T. Dietl, and A. Tsukazaki, *Magnetic-field-induced topological phase transition in Fe-doped* $(Bi,Sb)_2Se_3$ *heterostructures*, arXiv:2002.09292.

II. Tomasz Dietl initiated a collaboration with the **Institute of Physics, Chinese Academy of Sciences** (with a head of High Pressure group, Prof. Changqing Jin) formalized by signing the **Collaboration Agreement** IFPAN/IoPChAS in October 2019 (attached). Growth under high pressure allows to obtain unique magnetic systems, which will be overgrown by topological epilayers at MagTop.

III. Collaboration with **University of Nottingham** has been concluded by one joint publication: M. J. Grzybowski, P. Wadley, K. W. Edmonds, R. P. Campion, K. Dybko, M. Majewicz, B. L. Gallagher, M. Sawicki, and T. Dietl, *Gating effects in antiferromagnetic CuMnAs*, arXiv:1908.03521, AIP Advances **9**, 115101 (2019). PhD student Michał Grzybowski was a frequent visitor at UoN and carried out his research in MagTop on CuMnAs epilayers grown there.

IV. Collaboration of MagTop's senior postdocs Carmine Autieri and Wojciech Brzezicki with **University of Salerno** (US) and the 5 months' stay of US PhD student Giuseppe Cuono (supervisor – Dr. Carmine Autieri) within a grant from US. Dr. Couno has received the "Della Riccia" Fellowship with MagTop as a hosting institution, so he will join MagTop as a postdoc, presumably in March 2020.This collaboration in 2019 resulted in six joint publications and two preprints:

1/ G. Cuono, C. Autieri, F. Forte, M. T. Mercaldo, A. Romano, A. Avella, and C. Noce, *A minimal tight-binding model for the quasi-one-dimensional superconductor $K_2Cr_3As_3$*, arXiv:1812.01457, New J. Phys. **21**, 063027 (2019)

2/ M. Asa, C. Autieri, C. Barone, C. Mauro, S. Picozzi, S. Pagano, and M. Cantoni, *Detecting antiferromagnetism in tetragonal Cr_2O_3 by electrical measurements*, arXiv:1911.02596, Phys. Rev. B **100**, 174423 (2019)

3/ A. Nigro, P. Marra, C. Autieri, W. Wu, J. G. Cheng, J. Luo, and C. Noce, *Resistivity measurements unveil microscopic properties of CrAs*, arXiv:1812.09957, EPL **125**, 57002 (2019)

4/ G. Cuono, C. Autieri, G. Guarnaccia, A. Avella, M. Cuoco, F. Forte, C. Noce, *Spin-orbit coupling effects on the electronic properties of the pressure-induced superconductor CrAs*, arXiv:1910.02407, Eur. Phys. J. Special Topics **228**, 631–641 (2019)

5/ G. Cuono, F. Forte, M. Cuoco, R. Islam, J. Luo, C. Noce, and C. Autieri, *Multiple band-crossings and Fermi surface topology: role of double nonsymmorphic symmetries in MnP-type crystal structures*, arXiv:1905.04675, Phys. Rev. Materials **3**, 095004 (2019)

6/ R. Islam, G. Cuono, N. Minh Nguyen, C. Noce and C. Autieri, *Topological transition in $Pb_{1-x}Sn_xSe$ using Meta-GGA Exchange-Correlation Functional,* Acta Phys. Polon. A **136**, 667 (2019)

7/ M. Asa, C. Autieri, R. Pazzocco, C. Rinaldi, W. Brzezicki, A. Stroppa, M. Cuoco, S. Picozzi, M. Cantoni, *Anomalous Hall effect in antiferromagnetic/non-magnetic interfaces,* arXiv:1904.03541

8/ W. Brzezicki, F. Forte, C. Noce, M. Cuoco, A. M. Oleś, *Tuning Crystal Field Potential by Orbital Dilution in d^4 Oxides*, arXiv:1912.07975

V. Collaboration with **University of North Texas** has been concluded by one joint publication: C. Autieri, P. Barone, J. Sławińska, S. Picozzi, *Persistent spin helix in Rashba-Dresselhaus ferroelectric $CsBiNb_2O_7$*, arXiv:1905.07744, Phys. Rev. Materials 3, 084416 (2019). Dr. Jagoda Sławińska has payed short visits at MagTop.

VI. New collaboration with **Guilin University of Technology** (China): Xing Ming, C. Autieri, Huanfu Zhou, Jiafeng Ma, Xin Tang, Xiaojun Zheng, *In-gap states with nearly free electron characteristics in layered structure trivalent iridates*, arXiv:1909.04562.

VII. There is a decades long collaboration between IFPAN and **Johannes Kepler University in Linz**, which is continued by MagTop, whose Theory and MBE Groups collaborate with Prof. Alberta Bonanni's group T. Dietl, A. Bonanni, and H. Ohno, *Families of magnetic semiconductors — an overview*, arXiv:1909.02999, J. Semicond. **40**, 080301 (2019) and with the group of Prof. Gunther Springholz, which specializes in MBE of IV-VI compounds. MagTop's senior postdoc Dr. Valentine Volubuev, responsible for MBE of these semiconductors at MagTop originates from this group. Thus, the collaboration continues, also in ARPES studies of IV-VI compounds in Bessy II in Berlin and Solaris in Kraków, on samples grown in Linz or in Warsaw:

1/ R. Adhikari, V.V. Volobuev, B. Faina, G. Springholz, A. Bonanni, *Ferromagnetic phase transition in topological crystalline insulator thin films: Interplay of anomalous Hall angle and magnetic anisotropy*, Phys. Rev. B **100**, 134422 (2019)

2/ J. Krempasky, M. Fanciulli, L. Nicolai, J. Minar, H. Volfova, O. Caha, V. V. Volobuev, J. Sanchez-Barriga, M. Gmitra, K. Yaji, K. Kuroda, Shik Shin, F. Komori, G. Springholz, and J. H. Dil, *Fully spin polarised bulk states in ferroelectric GeTe*, Phys. Rev. Research **2**, 013107 (2020)

3/ A. Kazakov, W. Brzezicki, T. Hyart, B. Turowski, J. Polaczyński, Z. Adamus, M. Aleszkiewicz, T. Wojciechowski, J. Domagała, A. Varykhalov, G. Springholz, T. Wojtowicz, V. V. Volobuev, T. Dietl, *Mirror-symmetry protected quantization of Berry phases and resulting magnetoresistance across the topological transition in* $Pb_{1-x}Sn_xSe$, arXiv:2002.07622.

VIII. Collaboration of the MBE Group leader Tomasz Wojtowicz with the foreign strategic partner **Julius-Maximilians-Universität Würzburg** in the area of topological insulators consisted of joint experiments on the MBE growth and studies of (Pb,Cd)Se mixed crystal layers, which could be the basis of (Pb,Sn,Cd)Se crystalline topological insulator with much reduced bulk conductivity. One paper describing results has been published:

S. Chusnutdinow, M. Szot, S. Schreyeck, M. Aleszkiewicz, I.V. Kucherenko, A.V. Muratov, V.A. Yakovlev, T. Wojtowicz, and G. Karczewski, *Ternary* $Pb_{1-x}Cd_xSe$ *films grown by molecular beam epitaxy on GaAs/ZnTe hybrid substrates* J. Cryst. Growth **507**, 10 (2019).

IX. Collaboration with the **Technische Universität Dortmund** has been concluded by three joint publications:

1/ V. L. Korenev, I. V. Kalitukha, I. A. Akimov, V. F. Sapega, E. A. Zhukov, E. Kirstein, O. S. Ken, D. Kudlacik, G. Karczewski, M. Wiater, T. Wojtowicz, N. D. Ilyinskaya, N. M. Lebedeva, T. A. Komissarova, Yu. G. Kusrayev, D. R. Yakovlev, and M. Bayer, *Low voltage control of exchange coupling in a ferromagnet-semiconductor quantum well hybrid structure*, Nat. Commun. **10**, 2899 (2019) 24

2/ S. V. Poltavtsev, Y. Kapitonov, I. A. Yugova, I. A. Akimov, D. R. Yakovlev, G. Karczewski, M. Wiater, T. Wojtowicz, M. Bayer, *Polarimetry of photon echo on charged and neutral excitons in semiconductor quantum wells*, Sci. Rep. **9**, 5666 (2019)

3/ A. N. Kosarev, S. V. Poltavtsev, L. E. Golub, M. M. Glazov, M. Salewski, N. V. Kozyrev, E. A. Zhukov, D. R. Yakovlev, G. Karczewski, S. Chusnutdinow, T. Wojtowicz, I. A. Akimov, and M. Bayer, *Microscopic dynamics of electron hopping in a semiconductor quantum well probed by spin-dependent photon echoes*, arXiv:1907.12811, Phys. Rev. B **100**, 121401(R) (2019)

X/XI. Collaboration of Majorana Group leader Timo Hyart with **Microsoft Station Q** and **College of William and Mary** has been concluded by one joint publication: Xiang Hu, T. Hyart, D. I. Pikulin, E. Rossi, *Geometric and Conventional Contribution to the Superfluid Weight in Twisted Bilayer Graphene*, Phys. Rev. Lett. **123**, 237002 (2019).

XII. Collaboration with the **University of Jyväskylä** has resulted in a feature article: T. T. Heikkila, T. Hyart, *Moiré with flat bands is different*, Europhysics News 50/3, 24 (2019).

XIII. Collaboration with the **University of Cambridge** has been concluded by one preprint: Y. Li, M. Amado, T. Hyart, G. P. Mazur, V. Risinggård, T. Wagner, L. McKenzie Sell, G. Kimbell, J. Wunderlich, J. Linder, J. W. A. Robinson, *Competition between canted antiferromagnetic and spin-polarized quantum Hall states at ν = 0 in graphene on a ferrimagnetic insulator*, arXiv:1905.06866.

XIV. Dirac Group leader Mircea Trif has collaboration with the LPS group at the **University of Paris-Sud**:

1/ M. Trif and P. Simon, *Braiding of Majorana fermions in a cavity*, Phys. Rev. Lett. **122**, 236803 (2019).

2/ M. Trif and P. Simon, *Dynamics of a Majorana Trijunction in a Microwave Cavity*, Adv. Quantum Technol. 1900091, **1** (2019).
3/ A. Mishra, S. Hoffman, P. Simon, and M. Trif, *Dynamical torques from Shiba states in s-wave superconductors*, to appear (see http://www.magtop.ifpan.edu.pl/accomplishments/publications/).

XV. The collaboration with the group of Silas Hoffman (**University of Florida**) and PhD student Peixin Shen (**Tsinghua University**): Pei-Xin Shen, S. Hoffman, and M. Trif, *Theory of topological spin Josephson junctions*, arXiv:1912.11458.

XVI Collaboration of young doctor Dr. Archana Mishra with **KAIST**:
1/ GiBaik Sim, A. Mishra, Moon Jip Park, Yong Baek Kim, Gil Young Cho, SungBin Lee, *Multipolar superconductivity in Luttinger semimetals*, arXiv:1911.13224.
2/ Hee Seung Kim, A. Mishra, SungBin Lee, *Emergent chiral spin ordering and anomalous Hall effect of kagome lattice at 1/3 filling*, arXiv:1912.12621.
XVII The collaboration of Characterization Group leader Vinayak Bhat with Prof. Dirk Grundler from **EPFL, Lausanne** has resulted in a preprint: V.S. Bhat, S. Watanabe. K. Baumgaertl, and D. Grundler, *Direct Observation of Magnon Modes in Kagome Artificial Spin Ice with Topological Defects*, arXiv:1910.00874.

4.2. Please provide a short overview of cooperation with Polish partners

I. There is an extensive and natural collaboration with other divisions of the **Institute of Physics, Polish Academy of Sciences** (IFPAN), where MagTop is located and is a part of. Also, there is a continuous support of IFPAN's management board to MagTop development.

II. Collaboration – rather extensive and developing – in the field of HgTe-based topological materials with the **IRA unit "the Center for Terahertz Technology Research and Applications (CENTERA)"** (PI – Prof. Wojciech Knap) at the Institute of High Pressure Physics, Polish Academy of Sciences: I. Yahniuk, S. S. Krishtopenko, G. Grabecki, B. Jouault, C. Consejo, W. Desrat, M. Majewicz, A. M. Kadykov, K. E. Spirin, V. I. Gavrilenko, N. N. Mikhailov, S. A. Dvoretsky, D. B. But, F. Teppe, J. Wróbel, G. Cywiński, S. Kret, T. Dietl, W. Knap, *Magneto-transport in inverted HgTe quantum wells*, arXiv:1810.07449, npj Quantum Materials **4**, 13 (2019)

III. There have been a less systematic collaboration with a metal spintronic group from **AGH University** in Kraków: P. Ogrodnik, J. Kanak, M. Czapkiewicz, S. Ziętek, A. Pietruczik, K. Morawiec, P. Dłużewski, K. Dybko, A. Wawro, and T. Stobiecki, Structural, magnetostatic, and magnetodynamic studies of Co/Mo-based uncompensated synthetic antiferromagnets, arXiv:1907.00592, Phys. Rev. Materials 3, 124401 (2019)

IV. MagTop researchers are active users of the ARPES beamline at **SOLARIS in Kraków**
G. Grabecki, A. Dąbrowski, P. Iwanowski, A. Hruban, B.J. Kowalski, N. Olszowska, J. Kołodziej, M. Chojnacki, K. Dybko, A. Łusakowski, T. Wojtowicz, T. Wojciechowski, A. Wiśniewski, *Interface transmission of (Nb, Pb, In)/NbP – superconductor/Weyl semimetal junctions*, arXiv:1908.07359, Phys. Rev. B 101, 085113 (2020)

V. Collaboration with **University of Rzeszów**, initiated by Tomasz Dietl and Tomasz Wojtowicz, and formalized by a **Collaboration Agreement** IFPAN/URz (attached) concerning primarily the growth of HgTe-based topological materials by MBE dedicated to mercury/cadmium tellurides operating at the University of Rzeszów. There has been a joint publication: E. Bobko, D. Płoch, D. Śnieżek, M. Majewicz, M. Fołtyn, T. Wojciechowski, S. Chusnutdinow, T. Wojtowicz, J. Wróbel, *Conductance resonances and crossing of the edge channels in the quantum Hall ferromagnetic state of Cd(Mn)Te microstructures*, Phys. Rev. B **99**, 195446 (2019)

VI. Collaboration with the **University of Warsaw** has been concluded by one publication: D. Yavorskiy, M. Szoła, K. Karpierz, I. Własny, D. Śnieżek, P. Nowicki, J. Wróbel, S. Chusnutdinow, G. Karczewski, T. Wojtowicz, J. Łusakowski, *Terahertz Spectroscopy of Double CdTe/CdMgTe Quantum Wells*, Acta Phys. Polon. A **136**, 617-619 (2019)

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

5.1. Description of the strategy and steps taken to establish collaborations with entrepreneurial partners.

Following the *Letter of Intent* previously signed with the VIGO System S.A. and PUREMAT Technologies Sp. z o.o., "*Agreement on collaboration*" was signed with both companies (attached). Bilateral consultations with PREVAC were undertaken in order to specify the area of possible joint research more precisely. PREVAC is in particular interested in application of ferromagnetic targets designed at the Institute of Physics, as well as, in working jointly on improved design of magnetrons, which would highly increase the efficiency of sputtering of ferromagnetic materials. The collaboration agreement stating these activities and other area of joint research was prepared, approved by the Director of IFPAN and send to PREVAC for acceptance.

5.2. Description of steps taken to develop skills of IRAP unit researchers necessary to collaborate with entrepreneurs

1. Organization of the Workshop "Topological matter meets entrepreneurs"

During the Workshop MagTop's employees have delivered three lectures:

a/ Tomasz Dietl "*Introduction to topological materials*",

b/ Tomasz Story "*Topological insulators, semimetals and superconductors – materials for new electronics*?",

c/ Tomasz Wojtowicz "*Capabilities of the Institute of Physics in the area of growth, nanostructurization and characterization of topological materials*".

The lectures were recorded and are available at: www.magtop.ifpan.edu.pl/workshop

In the second part of the Workshop lectures of entrepreneurs and representative of FNP were delivered:
a/ Marek Dudyński (Modern Technologies and Filtration) "*The nanoparticles in charcoal and wood burning*",
b/ Artur Trajnerowicz (VIGO System) "*VIGO System – production capabilities and development of semiconductor IR detectors*",

c/ Olgierd Jeremiasz (Helioenergia) „*Helioenergia - R&D efforts in electrical power engineering and electronics*”,
d/ Andrzej Mycielski (PUREMAT Technologies) „*Puremat Technologies as a partner of MagTop*”,
e/ Kinga Słominska (FNP) „*Science- Industry cooperation in IRAP projects*”.

After the lectures entrepreneurs visited Institute of Physics’ labs.

Fig. 12 Lecture of Prof. Dietl during the Workshop.

Fig. 13 Lecture of Dr. Trajnerowicz from VIGO System during the Workshop.

2. Research visit of MagTop’s employees to VIGO System S.A.

On January 30, 2020 group of 18 employees of MagTop have visited VIGO’s premises and met with VIGO’s employees. After short description of the profile of VIGO System company by Dr.

Trajnerowicz, prof. Dietl introduced MagTop as a whole and next introduced the members of his group (specifying field of their expertise) present at the meeting. Next similar introductions were done by the other group leaders. After this introduction the employees of VIGO gave 6 presentations concerning:

- Technological problems connected with the grown of semiconducting materials and structures (general overview)
- MBE technology and detectors based on III-V materials
- MOVPE technology for HgCdTe
- Single element detectors
- Multi element detectors
- Characterization of parameters of detectors

The MagTop's employees were also given about 1 hour long tour in VIGO's labs and production hall. During the presentations and tour MagTop's employees asked several detailed questions about current most pressing problems of VIGO that could be the subjects of joint research and made some comments and propositions.

Fig. 14 Production hall tour of Polish and English speaking MagTop's employees.

During the meeting it became quite clear that collaboration in some fields may start immediately. It may concern numerical calculations and modelling of nanostructures that grown by VIGO, analysis of the noise of detectors, as well as, joint experimental research performed with use of electron beam lithography apparatus available at IFPAN. On the other hand the meeting also served as a kind of preliminary "brain storming" on how topological materials, with their specific transport and thermoelectric properties, may become the basis of new devices, which could be jointly designed by VIGO and MagTop.

5.3. Description of cooperation with business partners, including names of the research groups involved in the collaboration.

Collaboration with VIGO System, the Group of Theory of Topological Matter ON-6.1 involved.
Collaboration mainly concerns studies of optoelectronic properties of topological materials grown by MBE at MagTop. In particular, possibility of application of these materials in the infrared detection will be evaluated. Additionally joint research on technological steps that are required in order to produce both current and future detectors will be pursued. Detailed scope of the cooperation is specified in the **Agreement** (attached).

Collaboration with PUREMAT, the Molecular Beam Epitaxy ON-6.2 Group involved.
Collaboration concerns studies of innovative structures grown by MBE technology, containing Mn or Mg ions, and exhibiting topological properties. The studies are expected to indicate new directions of investigation of topological materials, as well as, to indicate new fields of applications of ultra-pure Mn and Mg. Detailed scope of the cooperation is specified in the **Agreement** (attached).

Collaboration with PREVAC, the Group of Characterization and Processing ON-6.3 involved.

Collaboration will concern mainly studies of possibility of application of ferromagnetic targets designed at the Institute of Physics, as well as, in joint research on improved design of magnetrons, which would highly increase the efficiency of sputtering of ferromagnetic materials.

5.4. Please summarize the results of the co-operation with business partners

I. Collaboration with VIGO SYSTEM S.A.

In the frame of collaboration with VIGO System, various joint experiments interesting for both parties were performed. They included:

1. SEM and stylus profilometry analysis of profiles of microlenses etched in GaAs substrates that are used for the growth of nanostructures both by VIGO and MagTop (see exemplary results below). The obtained data are to be used for optimization of parameters of lenses' formation process. Measured profiles were compared with the modelled, desired profiles. Optimized procedure will be used for making microlenses for increasing sensitivity of current as well as future detectors.

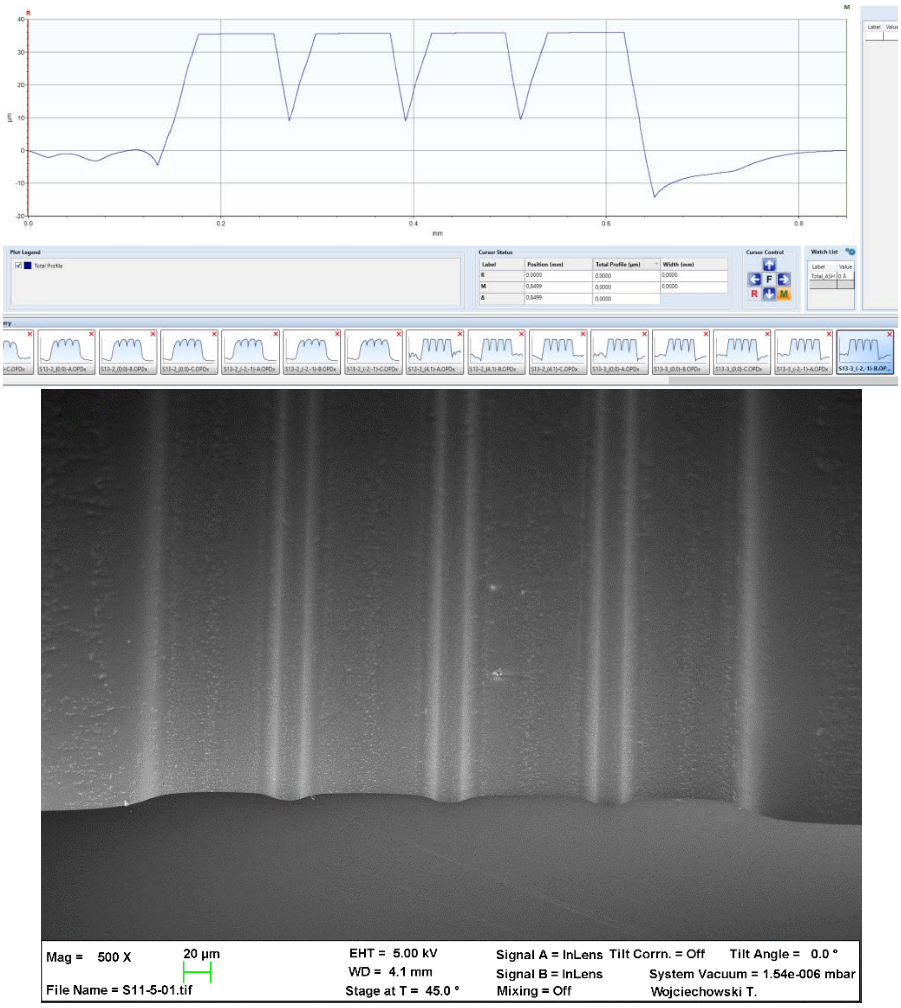


Fig. 15 Profilometry and SEM analysis of profiles of the microlenses etched in GaAs substrates.

2. Development and optimization of etching processes of various semiconductor structures via Inductively Coupled Plasma Reactive Ion Etching method (ICP RIE). SEM analysis of etching profiles was used as a test for the proper parameters of processes. The results served both for adjustment of technological parameters of Oxford ICP RIE at the MagTop and for optimization of ICP RIE etching process of InAlAs/InAs detector mesa structures produced at VIGO (see Figs. below).

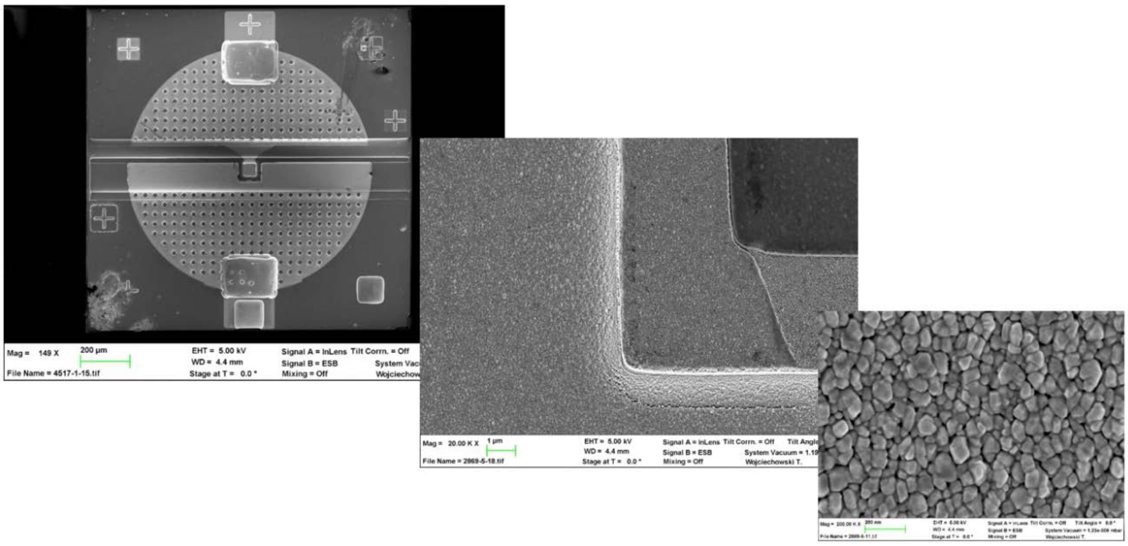


Fig. 16 SEM analysis of the RIE etching profiles and of the quality of gold layer deposition.

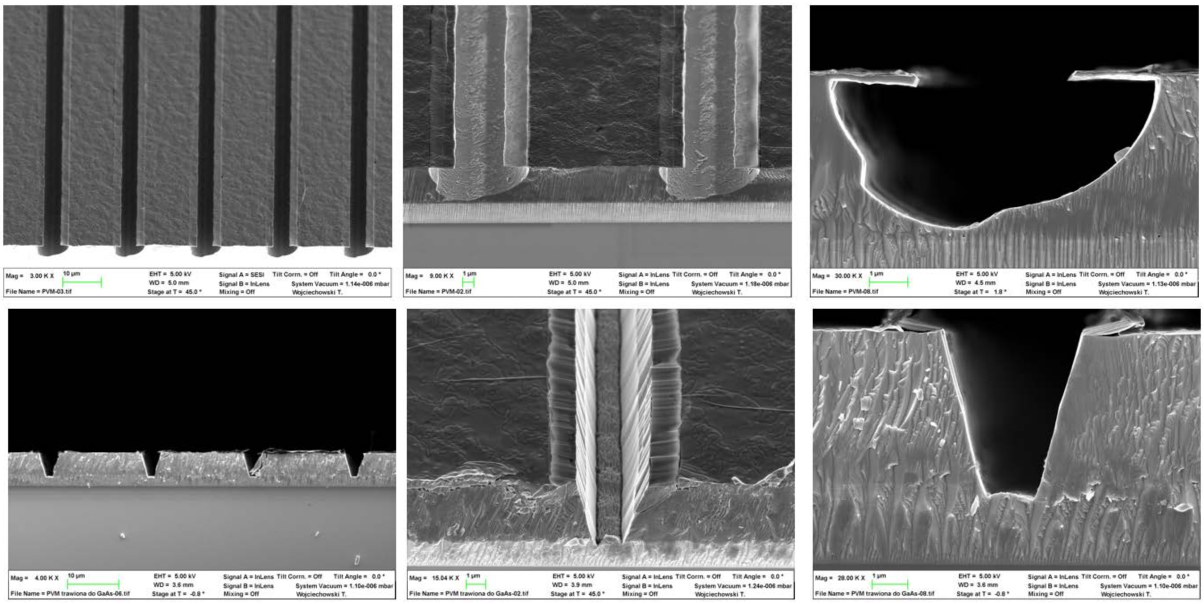
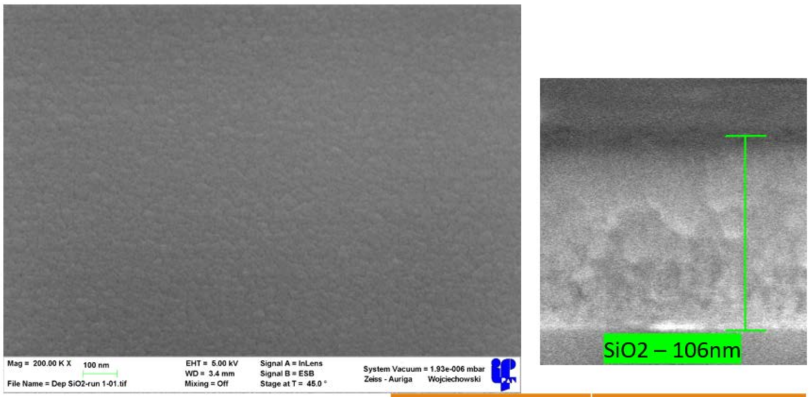


Fig. 17 SEM analysis of the FIB produced cross-section of PVM (multiple junction photovoltaic) detectors performed to estimate the depth of ion beam etching used for a conductivity type conversion

3. Studies of various methods of passivation and protection of sensitive semiconductor structures and devices. An example of such activities was deposition in MagTop of 106 nm SiO_2 passivation layer on test detector structures. This was the first attempt of passivation of III-V detectors with foreign layer via plasma enhanced chemical vapor deposition (ICP PECVD) at MagTop.



Material /Process gases	Deposition rate (nm/min)
SiO2 / SiH4 + N2O	8,7

Fig. 18 SEM analysis of the quality of SiO_2 layer deposited by PE CVD.

4. Studies of various methods of making good electrical contacts to HgTe- and CdTe-based nanostructures. Low resistive, linear (ohmic) and stable contacts are crucial for both two dimensional topological insulator structures (2D TI) based on HgTe studied by MagTop and for HgCdTe (MCT) based detectors produced by VIGO. Cross sections of various contacts were produced by FIB (Focused Ion Beam) in MagTop, including contact layers in MCT detectors (see Fig. below). SEM analysis of the cross-sections was then used in search of micro-cracks which could be created by high frequency vibrations, being the test of contacts stability.

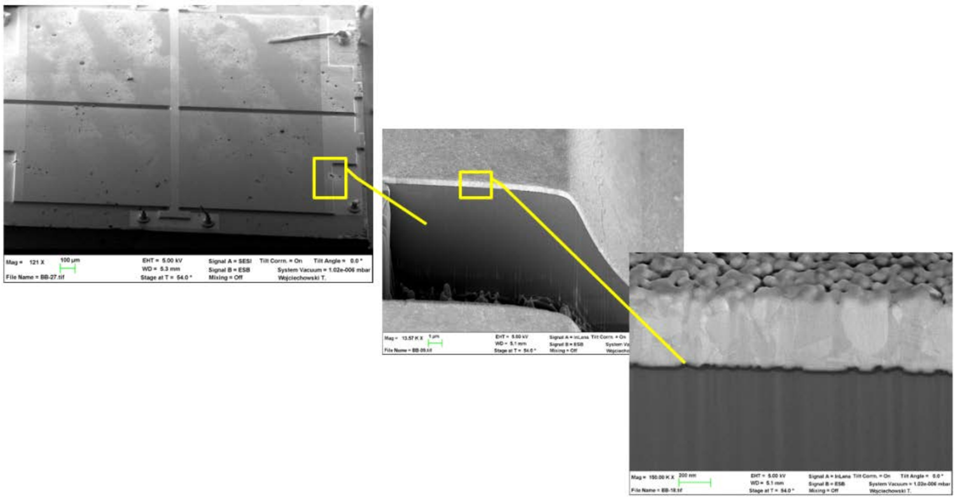


Fig. 19 SEM analysis of the FIB produced cross-section of ohmic contacts to MCT.

II. Collaboration with PUREMAT Technologies Sp. z o.o.

In the frame of collaboration with PUREMAT three directions of joint research has been undertaken. The first concerned the experiments on the MBE growth of 2DEG structures performed with the use of Mg and Mn produced by PUREMAT and aiming at improving the 2D carrier mobility.

The second direction concerned development of procedures for low temperature deposition of SiO_2 and $SiON_x$ layers by ICP-PECVD. Experience with such a low temperature deposition of insulating layers is vital both for MagTop, for making gated 2D topological insulator structures based on the strongly temperature sensitive HgTe, and for PUREMAT's x-ray CdTe-based detector, for which SiO_2 could serve as a passivation layer. Studies of the synthesis of thin films of silicon dioxide (SiO_2) was performed both on CdTe-based detectors and HgTe-based nanostructures using ICP-PECVD at temperature as low as 50 ^{o}C with silane (SiH_4) and nitrous oxide (N_2O) as precursor gases. For HgTe-based structures the studies of low-T (50 ^{o}C) deposition of $SiON_x$ layers (from SiH_4 + N_2O + N_2) was also performed.

The third direction of common interest was development of optical lithography as well as both wet and dry etching procedures for telluride-based device structures.

III. Collaboration with PREVAC Sp. z o.o.

Collaboration with PREVAC has been initiated with the aim of optimization of the construction of magnetrons and the shape of source charges made from ferromagnetic materials. If successful it will help MagTop in making high quality hybrid TI/ferromagnet structures, and PREVAC in improving their products.

5.5. Please complete the table *CO-OPERATION WITH ENTREPRENEURS and attach it to this report*

6. INFORMATION ON MASTERS' THESES AND DEGREES OR TITLES EARNED BY RESEARCHERS INVOLVED IN THE PROJECT AS A RESULT OF THE IMPLEMENTATION OF THE PROJECT

- Theory Group PhD student **Michał Grzybowski** defended his doctoral thesis "Electrical manipulation of the domain structure of antiferromagnetic CuMnAs" at IFAN with distinctions on Sept. 23rd, 2019; he is now a postdoc researcher in Henk Swagten's group in Eindhoven.
- Majorana Group PhD student **Grzegorz Mazur** defended his doctoral thesis "Zero-energy modes in ferromagnetic topological crystalline insulators" at IFPAN with distinctions on Sept. 24rd, 2019; he is now a postdoc researcher in Leo Kouwenhoven's group in Delft.
- Dr. **Krzysztof Dybko** (a senior postdoc) has submitted the habilitation dissertation "Impact of spin and spin-orbit interaction on transport properties of strongly correlated complex oxides and topological crystalline insulators", expected to be approved by Scientific Council of IFPAN on February 27, 2020.
- Dr. **Carmine Autieri** (a senior postdoc) has submitted the habilitation dissertation "New phases of the transition metal oxides"

- PhD student **Yosuke Satake** from Tohoku University, who spent 3 months in 2018 at MagTop as a visitor supported by his home institution, defended his doctoral thesis in March 2019 at Tohoku University (a Tohoku/MagTop paper has been submitted).
- PhD student **Giuseppe Cuono** from University of Salerno, who spent 5 months in 2019 at MagTop as a visitor supported by his home institution, defended his PhD thesis "New features exhibited by transition metal pnictides" at the University of Salerno in January 2020 (evaluation "Great" and the distinction "Doctor Europaeus" owing to his stay at MagTop; three publications MagTop/Salerno have been published). Recently, Dr. Cuono has succeed in obtaining the "Della Riccia" Fellowship with MagTop as a hosting institution, so he will join MagTop as a postdoc, presumably in March 2020.

7. AWARDS AND DISTINCTIONS AWARDED TO EMPLOYEES/STUDENTS OF THE UNIT

- MagTop researchers have been invited to present talks at 40 international meetings (2017-2019)

- Prof. Tomasz Dietl was selected by:
  1/ American Physical Society as an Outstanding Referee (2019),
  2/ Japan Society of Applied Physics as an International Fellow (2019).

- Dr. hab. Wojciech Brzezicki received:
  1/ Stipend for Outstanding Young Researcher subsidized by Polish Minister of Science and Higher Education (2017)
  2/ the Award of the Prime Minister of Poland for Outstanding Habilitation (2019)
  3/ the Young Researcher Award of the Visegrád Group Academies (2019)

- Dr. Marcin M. Wysokiński was granted with Stipend for Outstanding Young Researcher funded by Polish Minister of Science and Higher Education (2019)

- PhD student Grzegorz Mazur received best poster awards at:
  1/ 47th International School & Conference on the Physics of Semiconductors "Jaszowiec", Szczyrk, Poland 16-22.06.2018
  2/ Quantum Complex Matter - International Conference and School, June 10-15, 2018, Rome, Italy

- MagTop PhD students Michał Grzybowski and Grzegorz Mazur obtained PhD degrees at IFPAN with distinctions (2019)

8. 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)

Steps taken by MagTop's PIs towards securing sustainability and development of MagTop

- **Transfer of the IRA project from a research foundation to the Institute of Physics, Polish Academy of Sciences** (in June 2018) in order secure MagTop's sustainability after the termination of the IRA programme

- Cooperation with the ISC, IFPAN, and FNP to insure the highest possible scientific standing of newly employed young group leaders and postdocs, which allows **filling up IFPAN's generation gap,** and making the MagTop indispensable for the IFPAN future

- Activity towards fulfilment of **preconditions for successful applications** for national and international third party funding, including:

  - Persistent effort to promote MagTop's **national and international recognition and visibility**, in particular, by (i) rising research level and dissemination skills; (ii) appearing at national and international meetings, preferably as invited speakers; (iii) writing feature and review articles; (iv) accepting invitations to meeting committees and organize international events.

  - Insuring innovating research by **internationalization and brain circulation**, i.e., by (i) employing international scientists; (ii) maintaining and expanding international collaborations (also involving agreements concerning exchange of PhD students), and (iii) securing postdoc positions for former PhD students in high profile groups abroad. Commitment to **diversity and equal opportunity** principles and added value associated with their implementation.

  - Cooperating with the strategic partner units (*via* ISC recommendations and by onsite visits of JMU Wuerzburg) as well as with Tohoku University's AIMR (organized within World Premiere Institute Programme – similar to IRAP) to learn about and to implement **best practices** in research, research organization, recruitments of talents, research ethic, development of inventory spirit, technology transfer, intellectual property rights, data handling and shearing, and outreach activities.

  - Building **ties with entrepreneurs** and arranging **collaboration agreements with high profile companies,** which is going to allow for joint applications for national and European funding; stimulations of MagTop members to participate in workshops and seminars on relevant topics, also organized by MagTop in collaboration with entrepreneurs; joint PhD theses MagTop/high-tech companies.

  - Developing **soft skills**, including project preparation and writing as well as building of national and international networks; stimulating attendance of MagTop members in training events.

- **Applications for international and national projects.** So far, MagTop members have applied to:

  - Foundation for Polish Science (FNP): Competition for Funding the Purchase of a **Specialist Equipment** under the IRA Programme

  - MBE Group (Prof. Tomasz Wojtowicz) – successful (2019) - **4 351 250 PLN**
  - Theory Group – unsuccessful
  - Characterization Group (Dr. Vinayak Bhat) – successful (2019) - **3 850 000 PLN**

- ERC Starting Grant – unsuccessful
- ERC Consolidator Grant – pending
- Marie Skłodowska Curie Actions - Widening Fellowships (MagTop as a host institution) – unsuccessful
- Marie Skłodowska Curie Actions - Training Networks (MagTop as one of partners) – pending
- National Science Centre (NCN) Poland – SONATA BIS (for group building 2020-2023) – successful (Dr. hab. Wojciech Brzezicki) - **1 899 940 PLN**
- FWF/NCN – MOZART - Polish-Austrian Joint Projects – pending
- Ministry of Science and Higher Education for supporting a purchase a dilution refrigerator equipped with 16 T superconducting coil – pending
- "Della Riccia" Postdoc Fellowship (MagTop as a host institution) – successful (Dr. Giuseppe Cuono) – **8 000 EUR**

Furthermore, MagTop members have been regularly applying for **ARPES beamtimes** in SOLARIS (Kraków) and BESSY II (Berlin) in order study band structure of Weyl semimetals and topological crystalline insulators, particularly effects of metal deposition and magnetic impurities on topological surface states. So far, six one-week slots in SOLARIS, and two in BESSY II have been allocated to MagTop researchers, among those eight, five in collaboration with Johannes Kepler University in Linz. 36

Ab initio experts have been systematically applying for grants securing **computer time** at the Interdisciplinary Center of Modeling at the University of Warsaw.

9. IS THE PROJECT IMPLEMENTED ACCORDING TO THE SCHEDULE ATTACHED TO THE AGREEMENT ?

YES X **NO ☐**

If the answer is no, please provide an explanation

10. ADDITIONAL INFORMATION

Other important information relevant to the project

Summary statement

According to the mission of the IRA Programme, MagTop members are committed to establishing a research unit, whose trademark is the excellence in research and research applications, accomplished by the implementation of best practices and internationalization. Actually, MagTop – as a pioneer of the IRA Programme – has been serving as a testbed for indicating how the Programme rules should be adjusted to better fulfil the IRAP ambitious goal. Despite some initial shortcomings the pioneers are usually faced with, as this report demonstrates, MagTop researchers are proud of their research achievements and the progress they have made in the unit development over the last three years as well as about the steps they have already undertaken to insure MagTop's sustainability. It is, however, clear that an abrupt halting of MagTop support by FNP after five years of MagTop's existence will preclude to take full advantage of the human capital and equipment potential being already accumulated at MagTop. Undertaken collaboration with companies, a crucial aspect of activity, also requires a long-term stability of MagTop.

Outreach activities

- Organization of scientific meetings: MagTop members have organized or co-organized four workshops, two sessions at Warsaw's E-MRS Fall Meetings, participated in scientific committees of eleven established international conferences (ICPS, ICM, LT, EP2DS/MSS, PASPS, SPINTECH, …)
- Warsaw PhD School in Natural and BioMedical Sciences – participation in the recruitment process (Dr Carmine Autieri), Dr. Marcin Wysokiński prepared and delivered one semester course on condensed matter theory for PhD students
- Activities for high school students: Within the program "National Children Fund" (**https://fundusz.org/warsztaty-badawcze-insytut-fizyki-pan-warszawie-styczen/**) M. Płodzień, W. Brzezicki and T. Hyart took a part in organizing a one-week workshop for high-school students at IF PAN, and took care abound a monthly internship 1-31.07.2019 of Jakub Pilimon in agreement with the Fund. Jakub made very impressive progress during this period. Under the supervision of W. Brzezicki, he calculated the phase-diagram and properties of the edge modes for non-Hermitian version of Bernevig-Hughes-Zhang (BHZ) model.

11. CHANGES TO THE PROJECT PROPOSED BY THE LAUREATE – *if applicable*

(each proposed change should be complemented by an explanation why it is necessary and how it will be beneficial for the project)

no changes are proposed

12. PROPOSED BUDGET ADJUSTMENTS – *if applicable*

(Please, provide justification for each proposed modification explaining why the modification is necessary and how it will be beneficial for the project. If an increase of funding is requested detailed information about how the currently available budget will be spent is required.)

no adjustments are proposed

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.

Attachments to the project:

- ATTACHMENT 1 *CO-OPERATION WITH ENTREPRENEURS*
- ATTACHMENT 2 Documents regulating the terms of cooperation with business (e.g. Collaboration Agreement/ Letter of Intent etc.)

Date: 25 Feb 2020

Signature of the Laureate [signature] Tomasz Wojtowicz

Stamp of the Unit ....

Instytut Fizyki
Polskiej Akademii Nauk
02-668 Warszawa, al. Lotników 32/46
tel. (+48 22) 843 53 24
NIP: 525-000-92-75