SECOND MIDTERM 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**	
Agreement no.:	**MAB/2017/1**	**Reporting period from Feb. 1, 2018 to Jan. 31, 2019**
Project leader:	**Prof. dr hab. Tomasz Dietl**	

NB: The information below should reflect the status of the whole institution

1. Summary of the most important achievements and activities in the unit in the given reporting period (max. 1500 words – please refrain from excessive technical details)

Objectives

MagTop researchers in collaboration with the Institute of Physics, Polish Academy of Sciences (IFPAN) as well as with numerous foreign institutions, are currently carrying on research aiming at resolving major challenges of non-magnetic, magnetic, and superconductive topological materials:

(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? 1

(2) Can quantized topological Hall effects be observed in topological crystalline insulators?

(3) What is the origin of zero-bias conductance peaks in point-contact spectroscopy of topological surfaces? Is topological superconductivity involved?

(4) Are there new functional platforms for hosting quasiparticles with non-Abelian statistics?

(5) Which spin-spin coupling mechanisms account for magnetic properties of topological materials doped with transition metals?

(6) Are there new effects by incorporating magnetism and superconductivity to Weyl semimetals?

(7) What are effects of interplay between strong correlation and topological properties?

(8) 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

Studied materials and structures

The above agenda is accomplished by a considerable growth, processing, and characterization effort by the experimental teams. During the reported period extensive growth and structural characterization of topological crystalline insulators (TCI) [(Pb,Sn)Te, (Pb,Sn,Mn)Te] and Weyl semimetal (WSM) [NbP, (Nb,Mn)P] **bulk single crystals** has been performed, chiefly by present members of MagTop's technical staff and of Prof. Tomasz Story' Division at IFPAN [Dr. Andrzej Szczerbakow, MSc Eng. Jędrzej Korczak – TCI – the quality beyond the state of the art (Objective #3); Dr. Przemysław Iwanowski – WSM (Objective #6)]. In parallel, the MBE Group under the leadership of Prof. Tomasz Wojtowicz has carried on a strong epitaxy program on fabrication of **multilayers and nanowires** of TCI's (mainly lead-tin selenides - Objectives #2 - 4) and of non-magnetic and magnetic II-VI semiconductor compounds [mainly cadmium-zinc-magnesium-manganese tellurides – the quality beyond the state of the art (Objective #4)]. The material base has been enlarged by collaboration with: (i) T. Story's MBE group (TCI's - mainly lead-tin tellurides - Objective #2-4); (ii) Novosibirsk's researchers, who provide topological HgTe quantum wells (Objective #1) and (iii) Helmholtz-Zentrum (Dresden-Rossendorf) that supplied thin recrystallized films of (In,Fe)As. Some ARPES studies of TCI quantum structures are performed at large facilities by MagTop's Dr. Valentine Volobuiev on MBE TCI structures grown by him at Johannes Kepler University in Linz, the group of Prof. Gunther Springholz (Objectives #2-4).

Characterization, processing and experimental tools

MagTop/IFPAN collaboration has access to a number of in-house the state-of-the art equipment (SIMS, TEM, EELS, EDX, XRD, AFM, e-beam lithography, FIB, RIE, ALD, dilution fridge, …) and to the beyond state of the art SQUID magnetometry (Prof. Maciej Sawicki). Large facilities, particularly ARPES at SOLARIS and BESSY are exploited by MagTop researches, too, via applications for beam times.

Theoretical methods

As accomplishments discussed below demonstrate, Dr. Wojciech Brzezicki and Prof. Timo Hyart have mastered the determination of topological indexes beyond the state of the art. Due to Dr. Carmine Autieri, MagTop has access to the state of the art fully relativistic ab initio and tight binding approaches.

Experiment/theory collaboration

Remarkably, these two kinds of activities have been successfully combined already in two endeavours: (i) We have submitted jointly experimental and theoretical publications on the point contact spectroscopy in topological crystalline insulators [*arXiv:*1709.04000v2 (2018), *arXiv*:1812.02168 – Objective #2]. These two manuscripts were reviewed by the same referees and we are in the process of the resubmission of the revised versions. A similar approach is underway concerning Objective #1].

Selection of accomplishments addressing directly the above objectives, either published in a journal over the reported period or submitted to a journal and posted in arXiv in this period

(i) **The quantum Hall effect in 2D topological materials: prospects for application as a resistance standard** [T. Dietl – Objective #1)]

It was found that HgTe/(Cd,Hg)Te quantum wells (QWs) of the thickness corresponding to the vicinity of the normal-topological phase transition constitutes a competitive system (compared to n-GaAs and graphene) for fabrication of a novel resistance standard working at relatively low magnetic fields, achievable with permanent magnets. The samples were grown in Novosibirsk, and the work was done in collaboration with IFPAN, Montpellier University and Unipress in Warsaw [*arXiv*:1810.07449].

(ii) **The origin and theory of zero-energy excitations in low-temperature point contact spectroscopy of topological materials** [G. Mazur, D. Dybko, A. Szczerbakow, J. Korczak, T. Dietl, W. Brzezicki, T. Hyart, M. M. Wysokiński – Objective #3]

Experimental search for the origin of zero-energy excitations found by us in topological crystalline insulators has been continued leading to the conclusion about the absence of any global superconductivity [*arXiv:*1709.04000v2 (2018)]. This conclusion stimulated theoretical work at MagTop (Majorana and Theory Groups), within which the excitations are explained without invoking superconductivity but in terms of the appropriately modified Su-Schrieffer-Heeger model within which zero-energy excitation are associated with electronic topological states at the domain walls of a one dimensional collective phase. According to our model, this collective phase appears below a critical temperature T_c and is built of electrons occupying 1D topological states at surface atomic steps [*arXiv*:1812.02168]. This combined experimental and theoretical effort is MagTop's highlight.

(iii) **The origin of magnetism in transition-metal-doped topological matter** [T. Dietl – Objective #5]

In order to understand the origin of spin-spin interactions in topological materials, we advanced the determination of the Landau free energy by the perturbation theory and employed the formalism to develop an approach describing exchange interactions between spins of Anderson's magnetic impurities. Our theory provides a unified basis on which a single formula including the Ruderman-Kittel-Kasuya-Yosida, Bloembergen-Rowland, superexchange, and two-electron exchange integrals at nonzero temperature was derived [*Phys. Rev. B* **98**, 035105 (2018)].

(iv) **Quantum Hall ferromagnets as a host of impurity-generated non-Abelions** [A. Kazakov, T. Wojtowicz, T. Wojciechowski – Objective #4]

Experimental results obtained by MagTop researchers and co-workers [A. Kazakov *et al.*, *Phys. Rev. Lett.* **119**, 046803 (2017), also E. Bobko *et al. arXiv:*1804.03386v2], have demonstrated that helical domain walls in the quantum Hall ferromagnet of modulation-doped (Cd,Mn)Te quantum wells, if proximatized by a superconductor, may constitute a perspective system for searching for quasiparticles with non-Abelian statistics. These experimental results prompted theoretical investigations by the Purdue/MagTop team, showing that the impurity-induced Majorana modes emerge in the spin-orbit gap at the domain wall due to proximity to an s-type superconductor. Importantly, electrostatic control of domain walls in an integer quantum Hall ferromagnet allows manipulation of Majorana fermions. Ferromagnetic transitions in the fractional quantum Hall regime may lead to the formation and electrostatic control of higher order non-Abelian excitations [G. Simion *et al.*, *Phys. Rev. B* **97**, 245107 (2018)].

(v) **Experimental probing of spatial extend of topological surface states** [K. Dybko, G.P. Mazur, T. Wojtowicz – Objective #2]

Spatial penetration λ of surface topological wave function into the bulk is a key parameter of topological materials but it is not easy available experimentally. MagTop researches have employed weak antilocalization magnetoresistance, measured for various orientations of the magnetic field in respect to the thin film plane, for the quantitative determination of λ in topological crystalline insulator SnTe. T. Story's group together with the MBE Group fabricated SnTe layers with different thickness *t*, and hence different overlap of top and bottom topological surface states allowing the determination of λ as a function of *t* [K. Dybko *et al., arXiv*:1812.08711].

(vi) **Berry curvatures and the *ab initio* determination of parameters characterizing highly correlated and topological iridium and ruthenium oxides** [W. Brzezicki, C. Autieri – Objective #7]

Our theoretical studies confirmed that iridium and related oxides form a class of strongly correlated materials, in which relativistic effects (such as spin-orbit interaction and inverted band ordering) play a crucial role. By interpreting experimental results obtained at the Delft Technical University, we demonstrated theoretically (in collaboration with Salerno University) that the topological Chern numbers and the resulting Berry curvature and topological indexes can be manipulated by interface engineering of magnetic systems with large spin orbit. We showed that the tunability of the anomalous Hall effect at the interfaces arises from the competition between two topologically non-trivial bands in $SrRuO_3/SrIrO_3/SrTiO_3$ interfaces. This theoretical analysis required the determination of band structure parameters obtained within the team by *ab initio* methods [*Phys. Rev. B* **98**, 245123 (2018); *arXiv:*1807.01807; *arXiv:*1810.05619].

(vii) **Machine learning assisted determination of topological invariants** [T. Hyart – Objective #8]

In collaboration with the Leiden group we proposed a non-invasive method, which can be used for experimental determination of topological invariants. Namely, we showed that an artificial neural network can learn to approximate a topological invariant from the experimentally accessible local density of states. Our method can be used for analysing systems where direct transport measurements are not available and it can be applied also for characterization of systems consisting of regions of different topological phases [M.D. Caio *et al.*, *arXiv*:1901.03346v1].

In the reported period MagTop researchers co-authored 15 publications and submitted 11 manuscripts available in arXiv as well as presented 13 invited talks.

2. INFORMATION CONCERNING THE PROGRESS OF THE RESEARCH (1000 to 5000 words) (please, describe the progress in all research groups and doctors with advanced R&D experience)

Theory Team [including doctors with advanced research and development experience: Prof. A. Wiśniewski, Dr. C. Autieri and Dr. K. Dybko]

Magnetotransport studies of microstructures of HgTe quantum wells

Comprehensive studies of 2D topological insulators have been carried out for multilayer structures containing **HgTe quantum wells**, grown by MBE in Novosibirsk (Fig. 1) and provided by Prof. Wojciech Knap [Montpellier University and Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw (Unipress)]. Magnetotransport investigations have been performed in IFPAN by two PhD students, Magdalena Majewicz (supervised by Tomasz Dietl) and

Ivan Yahniuk (supervised by Wojciech Knap). Ms. Majewicz is in the final stage of thesis writing and should defend it by June 2019, whereas Mr. Yahniuk will defend his thesis presumably by the end of 2019.

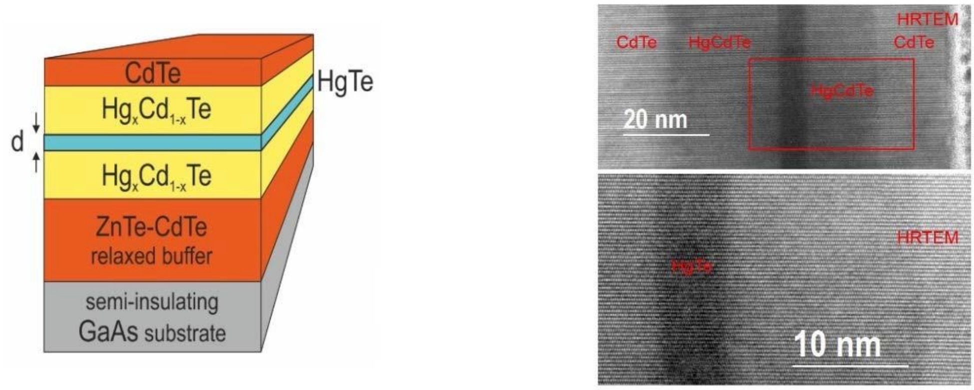

Fig. 1. *Layout of studied HgTe-CdTe multilayers obtained by MBE [S.A. Dvoretsky et al. – Novosibirsk] and their visualization by high-resolution electron microscopy [S. Kret et al., IF PAN]*

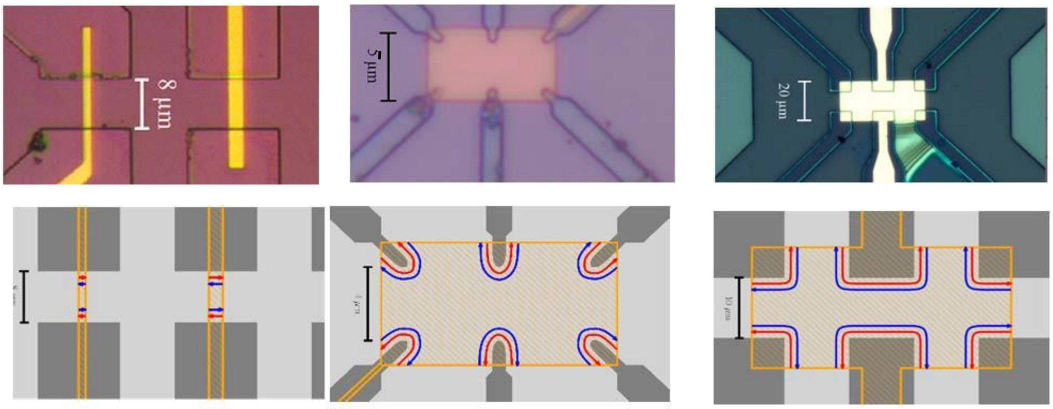

Fig. 2. *SEM visualization (upper panels) and schematic layout (lower panels) of microstructures for charge transport measurements obtained by electron beam lithography and wet etching [M. Majewicz et al. – IFPAN/MagTop]. Bright regions correspond to metal gate electrodes, either finger-like (left panels) 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.*

PhD student Magdalena Majewicz mastered a complex low-temperature processing of Hg-based multilayers and fabricated by electron beam lithography a series of gated microstructures (Fig. 2) 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. 3, is of the order of 2 μm.

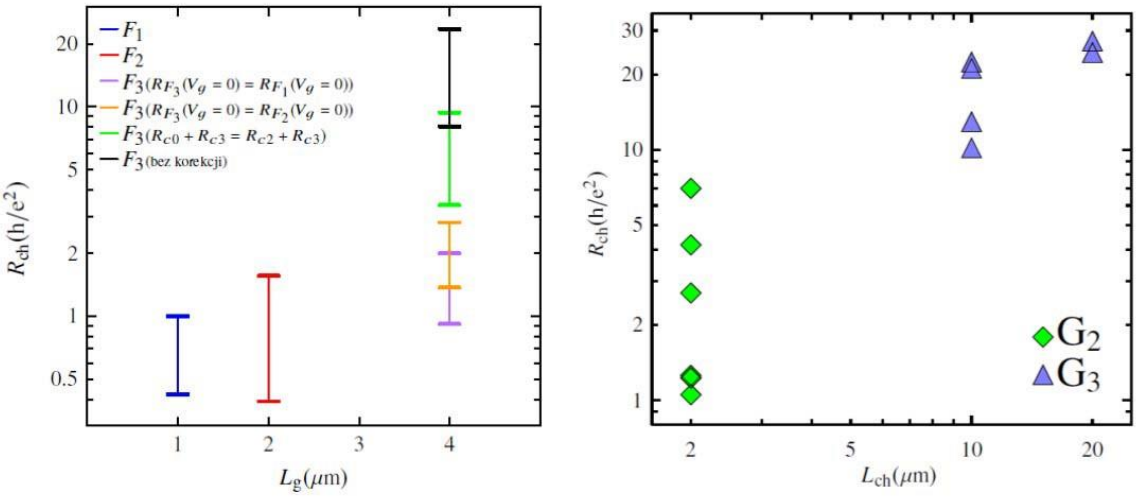

Fig. 3. *Single edge channel resistance as a function of the finger gate length (left panel) and channel length for devices with global gates (right panel). The results indicate that channel of the length up to 2 μm show an approximately quantized value of h/e*^{2} *[M. Majewicz et al., in preparation]*

Our 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. Actually, these data have stimulated a theoretical effort undertaken by the Majorana Group, as described in the corresponding report.

PhD student Ivan Yahniuk has carried out resistance and Hall effect measurements on a series of Hall bars with various HgTe quantum well width *d* in a wide range of magnetic fields, gate voltages, and hydrostatic pressures. His studies provide information on favourite conditions for the observation of the accurate Hall resistance quantization in a magnetic field [I. Yahniuk *et al., arXiv*:1810.07449]. As shown in that work, in the topological regime $d > d_c$, the coexistence of the topological and field-induced edge channels deteriorates the quantization precision. In contrast, for $d \leq d_c$ and for holes (see Fig. 4), $\sigma_{xy} = e^2/h$ to an accuracy better than 10^{-4}. The reason for such a broad hole plateau width and its appearance at lower magnetic fields than in the case of electrons is under theoretical investigations.

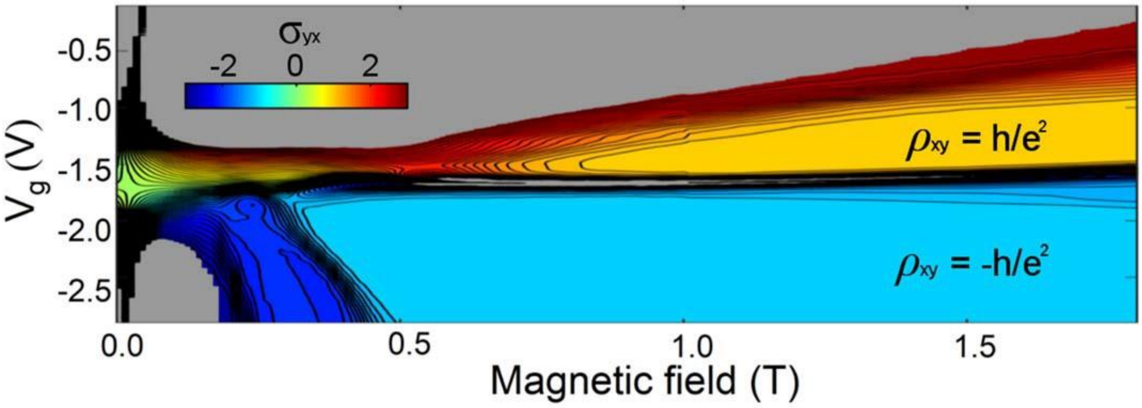

Fig. 4. *Hall conductivity σ_{xy} map as a function of the magnetic field for different Fermi level positions controlled by the gate voltage. QHE plateaus at $v = 1$ corresponding to electrons and holes are shown by yellow and cyan areas, respectively [I. Yahniuk et al. arXiv:1810.07449].*

Figure 5 shows the determined boundary between topological and normal phase in the plane magnetic field/hydrostatic pressure at $d_c < d = 8$ nm. This boundary coincidences with the computed crossing of the uppermost Landau level derived from the Γ_6 band with the lowest Landau level of the Γ_8 origin.

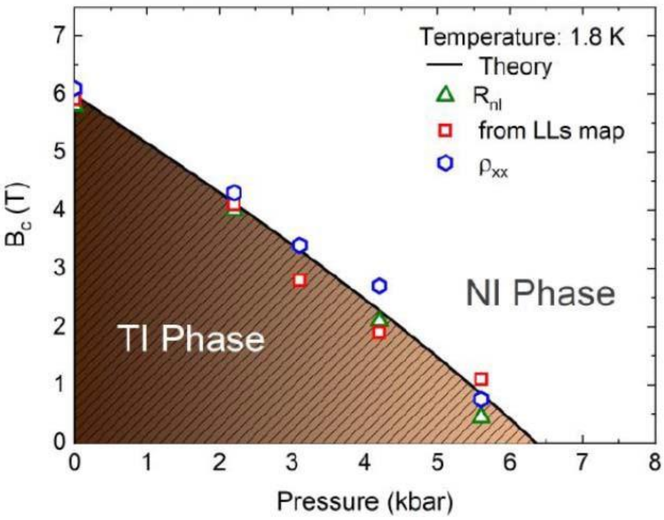

Fig. 5. *Experimental (points) and theoretical (solid line) boundary between the topological and normal insulator phases in a HgTe quantum well [I. Yahniuk et al., in preparation].*

Point-contact spectroscopy of topological surfaces in (Pb,Sn,Mn)Te

Studies of topological crystalline insulators by soft point-contact spectroscopy, began in 2017 by MagTop's Grzegorz Mazur (PhD student) and Krzysztof Dybko (experienced doctor), have revealed the presence of a low temperature phase at topological surfaces of diamagnetic $Pb_{1-y}Sn_yTe$ as well as paramagnetic and ferromagnetic $Pb_{1-y-x}Sn_yMn_xTe$ (see, Figs. 6 and 7).

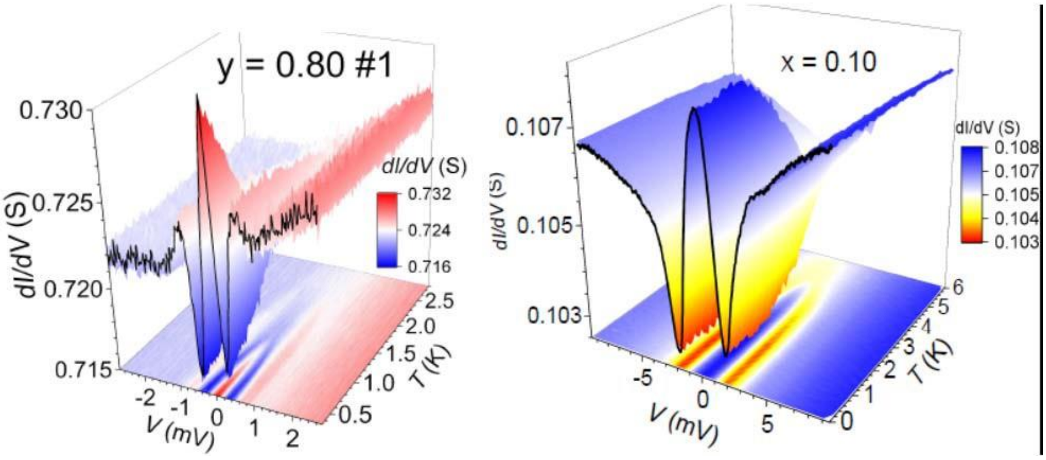

Fig. 6. Bias voltage and temperature dependence of differential conductance by silver paste contacts to the topological surface of (001) $Pb_{0.2}Sn_{0.8}Te$ and (011) $Pb_{0.16}Sn_{0.74}Mn_{0.1}Te$. Zero-bias conductance peak superimposed on a gap spectrum is visible in both cases [G. P. Mazur et al., arXiv:1709.04000v2 (2018) and v3 (2019), in preparation].

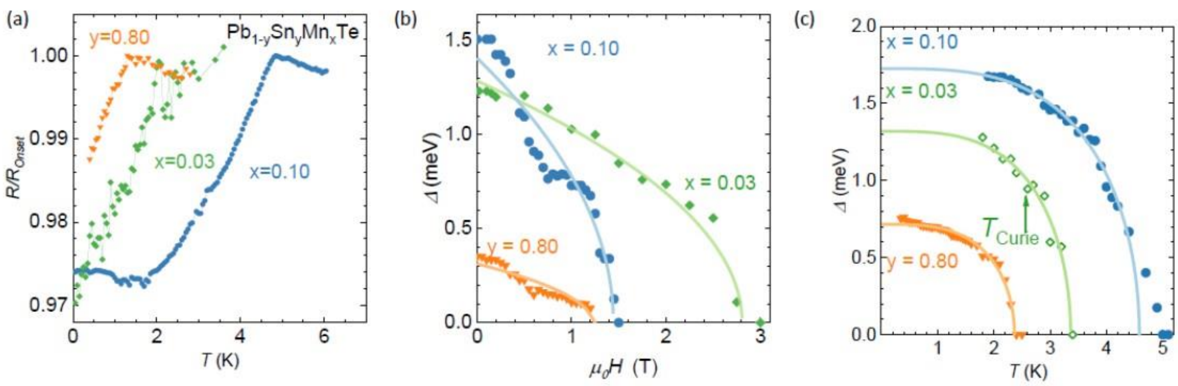

Fig. 7. (a) Temperature dependence of the point contact resistance in the limit of zero bias pointing to a phase transition. (b) Electron-hole gap Δ evaluated from the differential conductance spectra for $Pb_{1-y-x}Sn_yMn_xTe$ corresponding to the topological crystalline insulator phase vs. magnetic field perpendicular to the surface. (c) Temperature dependence of Δ;. Solid lines in (b) are fits of the formula $\Delta(T;H) = \Delta(T;H = 0)(1-H/H_c)^{1/2}$. Solid lines in (c) are fits of the BCS formula for $\Delta(T)$ to the experimental points treating T_c and C as adjustable parameters (C = 4.4, 4.5, and 3.5 from top to bottom respectively; C = 1.76 in the BCS theory). [G. P. Mazur et al., arXiv:1709.04000v2 (2018) and v3 (2019), in preparation].

8

Neither high-resolution SQUID magnetometry and resistance measurements nor careful structural and chemical characterization by x-rays and electron microscopy give indications for the presence of global or metal-inclusion driven superconductivity in the studied high quality single crystals [G. P. Mazur *et al., arXiv*:1709.04000v2 (2018)]. Together with MagTop's Majorana Group, results presented in Figs. 6 and 7 have been explained without invoking superconductivity but in terms of the appropriately modified Su-Schrieffer-Heeger model within which zero-energy excitation are associated with electronic topological states at the domain walls of one dimensional collective phase. According to the proposed model, this collective phase appears below a critical temperature T_c and is built of electrons occupying 1D topological states at surface atomic steps [W. Brzezicki *et al.*, *arXiv*:1812.02168]. Our experimental and theoretical results [*arXiv*:1709.04000v2 and *arXiv*:1812.02168, respectively] were jointly submitted and were referred by the same referees. Now, we are in the process of resubmitting the modified versions according to referees' suggestions. There is a timely question that we are addressing now on whether MagTop's novel model applies to other topological materials in which differential conductance show a similar phenomenology as that presented in Figs. 6 and 7.

Theoretical studies of mechanisms accounting for spin-spin interactions in topological materials

Following the influential paper of the Beijing/Stanford groups (R. Yu *et al*. *Quantized anomalous Hall effect in magnetic topological insulators*, *Science* **329**, 61 (2010)], it is believed that spin-spin coupling in intrinsic topological materials is chiefly mediated by interband quantum hopping [see, e.g., Y. Tokura, *Magnetic topological insulators*, *Nat. Rev. Phys*. 2019 (doi:10.1038/s42254-018-0011-5)], the mechanism improperly referred to as the van Vleck paramagnetism instead of using the well-established term, i.e., the Bloembergen-Rowland coupling.

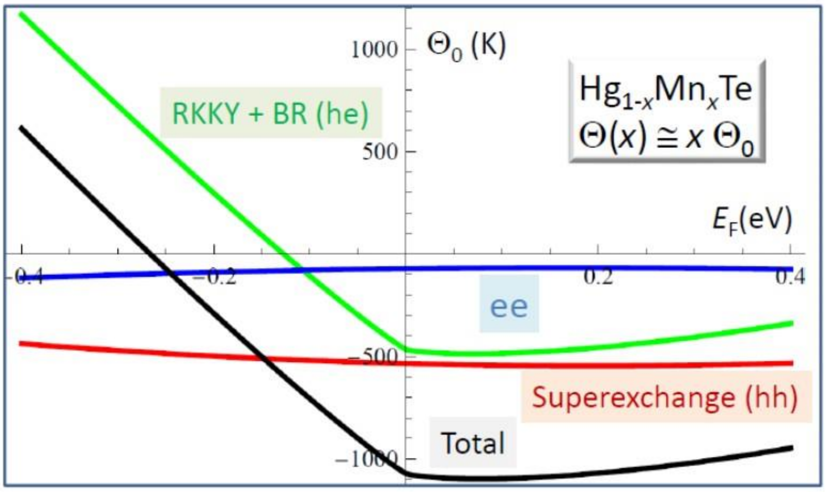

Fig. 8. Curie-Weiss temperature in $Hg_{1-x}Mn_xTe$, $\Theta(x) = x\Theta_0$, computed by empirical tight approximation for HgTe band structure parameters as a function of the Fermi level position (black line). The value of Θ_0 is obtained by summing up pairwise exchange energies between two Mn impurities at subsequent neighbour cation positions in the fcc lattice. Contributions from intra-band (RKKY) and inter-band (BR) excitations as well as superexchange and ee contributions are also shown [C. Sliwa, T. Dietl, in preparation].

Together with Dr Cezary Śliwa at IFPAN and MagTop's experienced doctor Carmine Autieri, we carry on a comprehensive program aiming at establishing the magnitudes of relevant mechanisms in topological materials doped with various transition metal impurities employing tight-binding and *ab initio* approaches. Figure 8 illustrates contributions of various mechanisms to the total mean-field Curie Weiss temperature Θ_0, evaluated within the empirical tight-binding approximation for a semiconductor of the HgTe band structure as a function of the Fermi level position (doping). As seen, without hole doping ($E_F \geq 0$) antiferromagnetic superexchange dominates in this topological zero-gap semiconductors and together with also large and antiferromagnetic Bloembergen-Rowland mechanisms leads to $\Theta_0 \cong 10^3$ K, which favourably compares with empirical value for slightly *p*-type (Hg,Mn)Te, $\Theta_0 = -660 \pm 80$ K [A. Lewicki *et al., Phys. Rev*. B **37**, 1860 (1988)].

Growth and studies of Weyl semimetals and their coupling to superconductors

As described in the 1st year report, MagTop's Dr. Przemysław Iwanowski and Prof. Andrzej Wiśniewski have successfully grown NbP single crystals, the program now extended towards the development of materials co-doped with transition metal impurities, such Mn. This undertaken requires a control over the distribution of magnetic impurities, depending on the growth conditions and magnetic ion content.

At the same time, in collaboration with other groups at IFPAN, comprehensive investigations of this Weyl semimetal (WSM) have been initiated. In particular, ARPES experiments were carried out with the use of the UARPES beamline at the National Synchrotron Radiation Centre SOLARIS in Krakow (Poland). Elliptically polarizing quasiperiodic undulator of APPLE II type was used as the source of the radiation in the energy range of 8–100 eV. The end-station was equipped with the SCIENTA OMICRON DA30L photoelectron spectrometer. A good energy (1.8 meV) and angular (0.1°) resolutions of the spectrometer enabled us the band mapping with a precision sufficient for observations of the features of the band structure characteristic of Weyl semimetals. As shown in Fig. 9, the Fermi surface pockets and arches, the fingerprints of the Weyl semimetal character of the investigated system, were found. They manifest themselves clearly in the vicinity of the Γ point (the "spoon-like" ones) or close to the Xpoint (the "bowtie-like" ones).

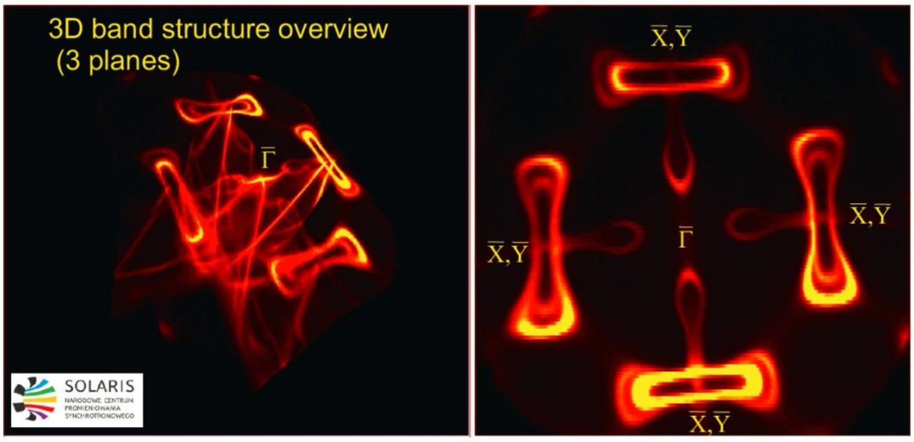

Fig. 9. *Results of angular-resolved photoemission studies of MagTop's NbP single crystals – 3D overview and band structure cross-section showing pockets and arches specific to Weyl semimetals [A. Wisniewski et al., in preparation]*

The superconductor–Weyl semimetal (WSM) interface conductance was studied for three different metals (Nb, Pb, In) deposited on NbP. The measurements were carried out as a function of temperature and the magnetic field, and the results were interpreted in terms of the Blonder-Klapwijk-Tingham (BTK) theory. For each of the three metals, qualitatively different behaviors were found.

In the case of Nb-NbP, the interface conductance as a function of the bias voltage exhibited well defined increase by factor about of two in the subgap region. This is consistent with dominant conductance mechanism by Andreev reflection and fitting the BTK theory gives high interface transmission with a small value of the barrier parameter Z = 0.15 (see Fig. 10). However, the theory cannot explain an abrupt vanishing of the subgap conductance, occurring at voltages significantly smaller than the half of the superconducting energy gap Δ. This can be interpreted in terms of current-induced superconductor-normal transition in the thin metal layer.

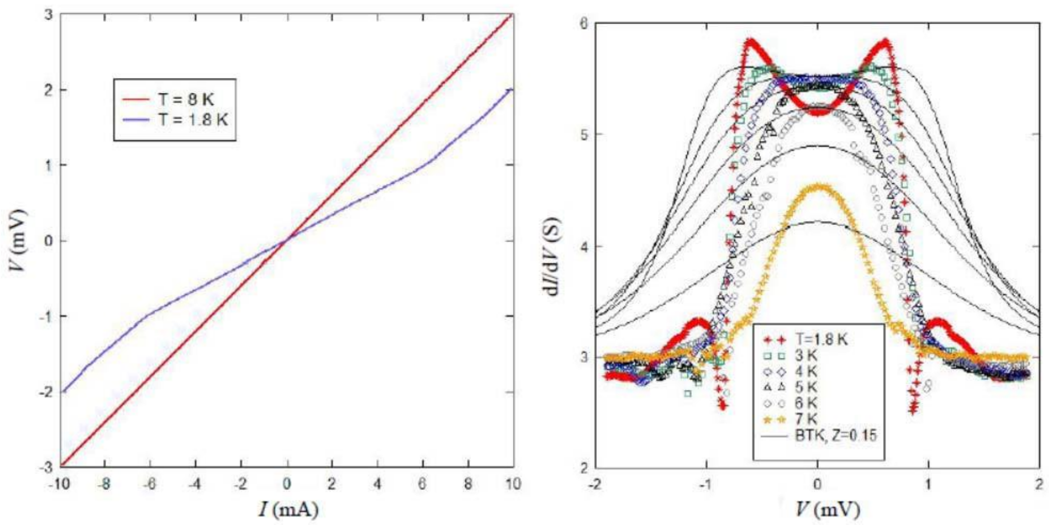

__Fig. 10.__ Current voltage characteristics and differential conductance of Nb|NbP junction showing Andreev reflection (points). Solid line are theoretical [A. Wisniewski et al., in preparation]

For Pb-NbP interface the subgap transmission (BTK gives Z = 0.5) is somehow smaller than in Nb-NbP case, but from the three metals, this spectrum is best described by the BTK theory. Some deviations are visible only at the lowest temperatures.

In the case of In-NbP structures the interface resistance dropped down as much as 20 times in comparison with the normal state. We interpret this in terms of interface alloying and formation of some mixed superconducting phase within NbP substrate. Such semiconductor is rather not suitable for further studies of the proximity effects. BTK theory is unable to describe the junction conductance.

The results show that both Nb and Pb are suitable for inducing superconductivity in NbP by the proximity effect. Our results show prospects for the exploration of superconductor-WSM low-dimensional structures aiming at search for Majorana anyons.

Theoretical studies of Interplay between strong correlation and topological properties
This important and intricate topic is carrying on by Theory Group's experience doctor Carmine Autieri and Majorana Group's young doctor Wojciech Brzezicki, primary in collaboration with Salerno University teams. The key result is the demonstration that the anomalous Hall effect in multilayers of $SrRuO_3/SrIrO_3/SrTiO_3$ results from topological properties of the band structure and not from topological effects in the real space (such as formation of skyrmions). The obtained results are also summarized below.

MBE Team [including doctors with advanced research and development experience: Dr. V. Volobuev and Dr. T. Wojciechowski]

During the second year of the Project's realization the MBE team continued to be working on various aspects of development of "technology of growth and nanostructurization of topological matter". Different types of topological matter were grown with the use of molecular beam epitaxy technique: (i) IV-VI topological crystalline insulators ((Pb,Sn,Mn)(Te,Se) in the form of both thick and thin layers, quantum wells, and nanowires) and II-VI nanostructures (high mobility (Cd,Mn)Te two dimensional gas structures nominally undoped or doped with either In or I, and (Zn,Cd,Mn)Te nanowire nanostructures). Also various types of hybrid devices have been produced, including semiconductor-ferromagnet, semiconductor-superconductor and devices with gates made of normal metal. The produced structures were used by other MagTop's team members and other employees as well as MagTop's collaborators in various types of experiments. The MBE Team was very closely collaborating with four doctors with advanced R&D experience, MagTop's experts in related fields, and was supported by three members of technical staff. The MBE team was also supported by the theoreticians employed by MagTop in the area of theoretical aspects of topological materials that are produced. Below is the more detailed description of the performed research and main results.

Development of MBE growth technology and studies of II-VI based structures - towards topological nanostructures.
An important part of the MBE group's effort was devoted to continuation of a development of growth technology of II-VI nanostructures in the still quite new MBE chamber GENXplor from VEECO. Here the main activities concentrated on (i) growth of high quality hybrid CdTe/GaAs substrates with oxide removed from GaAs in the preparation chamber, which is not equipped with RHHED; (ii) improving the quality of QW structures; (iii) doping of layers and modulation doping of QWs with indium (instead of iodine).
Ad. (i) – After finding a proper sequence of temperature steps at which GaAs substrate is annealed the growth of a number of hybrid CdTe/GaAs substrates was performed. One of methods used for the evaluation of substrates quality was the simultaneous growth of test QW in the EPI-620 chamber on pieces from two wafers, one that was grown in the old EPI-620 chamber and one grown in the new VEECO-GENXplor chamber. It has been found that PL linewidth of QWs from two wafers is very similar (see Fig. 11), proving that both deoxidation and growth procedures in the new chamber have been optimized. Grown hybrid substrates were than used for many successive growth of both II-VI and IV-VI tellurides structures.
Ad. (ii) – Quality of QW structures similar to that of structures grown in EPI 620 was achieved.

Ad. (iii) – While doping of CdTe layers with In was successful, so far the progress in the case of modulation doping of QWs was mediocre, in spite of the fact that 28 structures has been grown with different substrate temperature, spacer and doped layer thickness, and In flux. It has been found that only small number of structures had 2DEG and with poor mobility, even after low temperature illumniation. Therefore further optimization of the growth process is required.

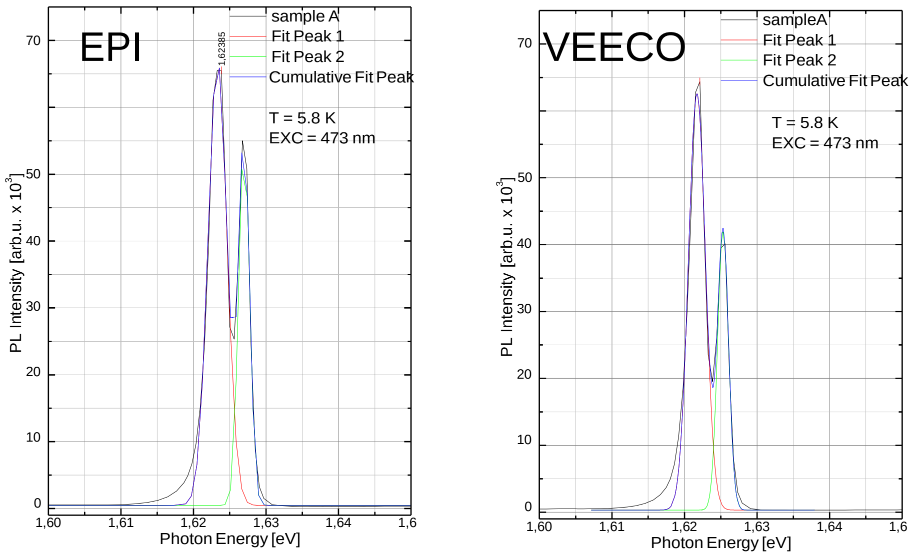

***Fig. 11**. On the left sample grown on reference (EPI) buffer, on the right sample grown on examined (VEECO) buffer.*

One of the important accomplishments of the second year in the area of II-VI based structures was in providing theoretical foundation for earlier proposition of the scalable semiconductor platform that could support Majorana and other non-Abelian excitations [G. Simion *et al., Phys. Rev. B* **97**, 245107 (2018)]. This research has been done in the collaboration with Purdue University in USA. Various devices based on local electrostatic gate control of helical domain walls (h-DWs) in quantum Hall ferromagnet have been proposed. If only superconducting contacts to the h-DWs could be produced (which is still an experimental challenge), these devices would allow performing basic operations on Majorana pairs, such as their creation, fusion, movement, exchange and braiding, simply by applying voltage sequentially to various gates.

Another important result [F. Spitzer *et al.*, *Nat. Phys*. **14,** 1043 (2018)] that was based on topological character of evanescent optical modes [see K.Y. Bliokh *et al.*, *Science* **348**, 1448 (2015); M. Stone, *Science* **348**, 1432 (2015)] was proposition and experimental demonstration of a new class of optical phenomena where directionality of light emission is established perpendicular to the externally applied magnetic field for light sources located in the vicinity of a surface. As a proof of principle for this effect, named transverse magnetic routing of light emission (TMRLE), the routing of emission for excitons in a diluted-magnetic-semiconductor (DMS) quantum well (QW) in hybrid plasmonic semiconductor structures was shown. Taking advantage of both a strong enhancement of spin splitting characteristic of DMS and spin-locking

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of light in plasmonic structures (analogous to carrier spin-locking in topological insulators) directionality of up to 60% was achieved.

Other already published papers reported extensive studies of various CdTe-based nanostructures, either nominally undoped or modulation doped, and thus containing ultra-high mobility two dimensional electron gas of different concentrations (being one of the focuses of MagTop), including as grown nanostructures [O. Borovkova *et al.*, *Nanophotonics* **8**, 287 (2019)], patterned nanostructures with dual-grating-gates [F. Passmann *et al.*, *Phys. Rev. B* **97**, 201413 (2018)] ferromagnet-semiconductor hybrid nanostructures [J. Płachta *et al.*, *Nanotechnology* **29**, 205205 (2018)] and (Cd, Mn)Te/(Cd, Mg)Te core/shell nanowires [P. Faltermeier *et al., Physica E* **101**, 178 (2018)].

During the reporting period a collaboration of the MBE group with the group of Prof. Wojciech Knap from the Institute of High Pressure Physics, Polish Academy of Sciences in Warsaw, in the area of HgTe-based topological structures was initiated. This is the continuation of previous collaboration between Prof. Dietl and Prof. Knap. Currently this collaboration covers studies of quantum structures grown in Novosibirsk. Building on expertise of Dr. Kazakov and on previous experience in this area existing in IFPAN (PhD student Magda Majewicz and Prof. Jerzy Wróbel), a know-how of producing microstructures containing HgTe QWs was developed also in the MBE group. The characteristic of HgTe QW structures is that they require very low temperatures during processing procedures. However, conventional semiconductor processing technologies are done at the temperatures above those, which are required for safe HgTe processing. Thus, processing technologies were adjusted so that they would not alter properties of as-grown HgTe QWs. As a result, field-effect transistor microstructures with sizes of 1-100 µm were produced in the MBE group.

Experiments, which are to be performed on these microstructures by our collaborators, are aimed to clarify boundaries of the topological phase transition in "temperature – magnetic field – pressure" coordinates. Phase boundaries are to be determined from measuring Landau level fan chart diagram with transport measurements. Until now however, with newly prepared devices only experiments as a function of gate voltage and magnetic field for various temperatures have been performed. A clear shift of the critical field with changing temperature was observed (see Fig. 12).

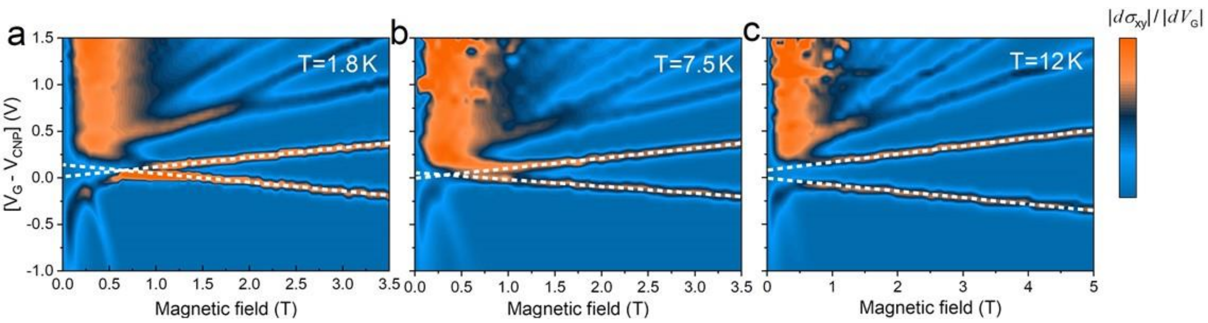

***Fig. 12**. Evolution of the experimentally obtained Landau level fan charts as a function of gate voltage and magnetic field at different temperatures (a-c). Dashed dot lines correspond to zero- mode Landau levels, which intercept at the point that gives value of the critical field.*

Development of MBE growth technology and studies of IV-VI based crystalline topological insulator (TCI) structures.

Various types of TCI structures have been grown during reporting period, both in the PREVAC 190 system being at MagTop's disposal (IV-Se structures), and in collaboration with group of Prof. Tomasz Story (ON1.2) in IFPAN (IV-Te structures), and in collaboration with Prof. Gunther Springholz from Johannes Kepler Universität in Linz, Austria (quantum well structures).

Layers and QW structures

The growths of $Pb_{1-x}Sn_xSe$ layers having thicknesses from 50 nm up to 1μm have been continued. The growths were performed on (111) oriented BaF_2 substrates in PREVAC 190 MBE system at IFPAN. High quality of the layers was proved by XRD, AFM, SEM and RHEED. The composition was determined by EDX. Example of structural characterization of epilayers is presented in Fig. 13.

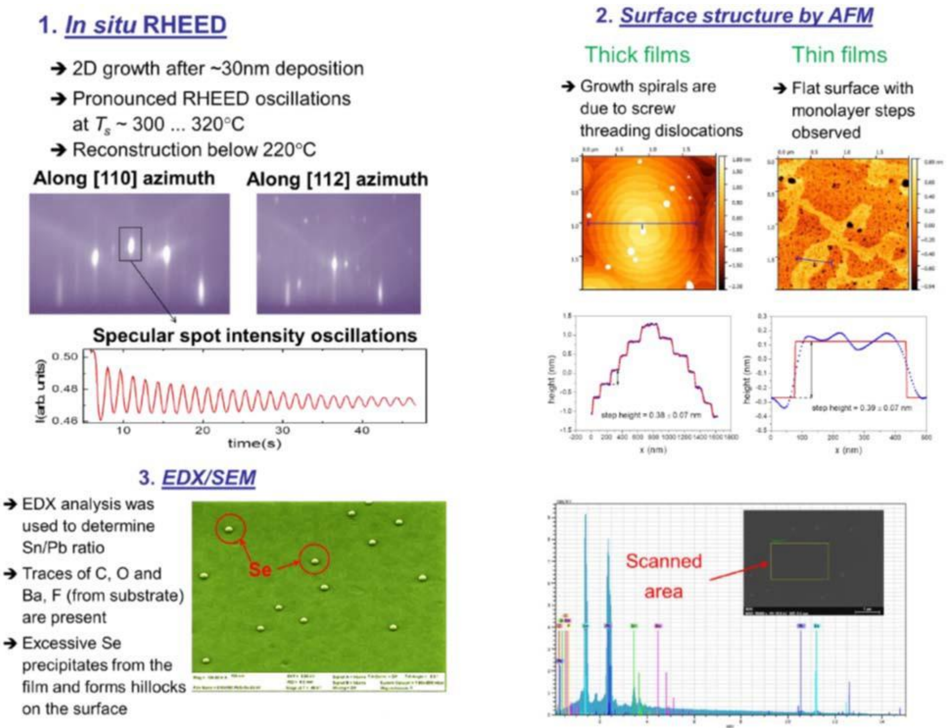

***Fig. 13**. Structural attestation of $Pb_{1-x}Sn_xSe$ epilayers by RHEED, AFM and EDX/SEM.*

Electrical transport studies of $Pb_{1-x}Sn_xSe$ epilayers was performed in order to determine carrier type, concentration and mobility, as well as to search for signatures of topological surface states. Carrier density and mobility in thick epilayers were found to be ~10^{17} cm^{-3} and 10^3 – 10^4 cm^2/V s, respectively. Magnetoresistance (MR) in thick epilayers was probed in two orientations of magnetic field: perpendicular and parallel to the film plane (see Fig. 14). In the literature, it is stated that the topological phase is characterized by a different behavior of MR in parallel and perpendicular fields. Sn content, $0 \leq x_{Sn} \leq 0.38$, in grown epilayers covers both trivial and topological phases. Thus, the difference in MR behavior on two sides of the composition range should reflect topological surface transport contribution. In the perpendicular field, high values of MR (up to ~300 %) are observed in epilayers with low tin content. If an applied field is parallel to the film plane, we observe negative MR for trivial compositions and positive MR for topological compositions, which is in contradiction with published results. Thus, an alternative explanation of the observed behavior should be developed.

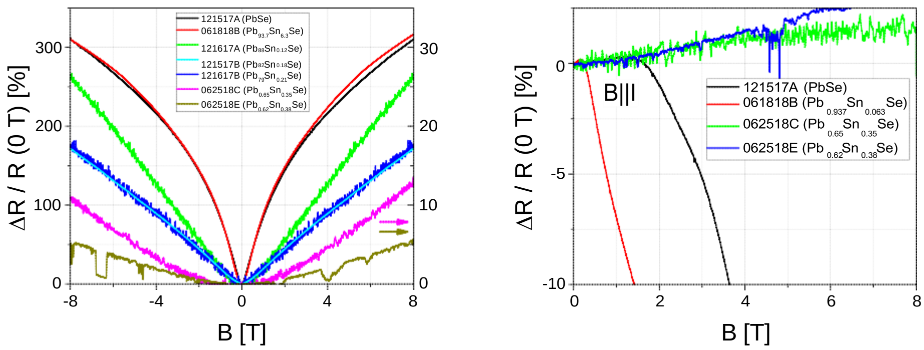

***Fig. 14**. Magnetoresistance observed in thick $Pb_{1-x}Sn_xSe$ epilayers in perpendicular magnetic field (left) and in parallel field (right).*

Thin $Pb_{1-x}Sn_xSe$ epilayers are characterized by high carrier concentration (~10^{19} cm^{-3}) and low mobility (~100 cm^2/V s). Carrier density is extracted from Hall slope, and mobility is calculated from zero-field resistance. These values are pointing to a presence of considerable disorder in the grown epilayers. Weak anti-localization (WAL) feature is well seen in these epilayers due to the relatively low conductivity of films (see Fig. 15). WAL is usually interpreted as a signature of the presence of the topological surface states. However, in studied films for the entire range of variation of x_{Sn}, WAL is observed in both trivial and topological compositions. Resulting curves are fitted with Hikami-Larkin-Nagaoka formula and corresponding values of α and phase coherence length l_ϕ are extracted. Parameter α is usually interpreted as a number of conducting channels, which take part in a quantum interference. In our case α was found to be -0.5 for all studied epilayers, which means that only one conducting channel takes part in the interference. This may be explained by the scattering between valleys, and between the top and the bottom surface states with the help of the bulk reservoir. l_ϕ was found to reach high values of 1-2 μm at 1 K. Temperature dependence of l_ϕ is following T^{-p} law, but p did not correlate with an epilayer composition. Thus, we haven't found yet correlation between observation of WAL and topological surface state transport in the studied epilayers. Measurements of WAL effect in tilted fields may clarify the picture.

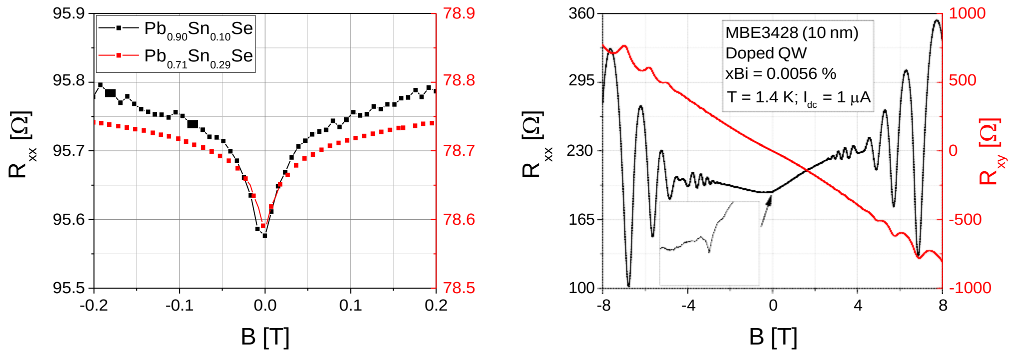

***Fig. 15**. WAL in thin $Pb_{1-x}Sn_xSe$ epilayers with trivial and topological compositions (left). Example of observed SdH oscillations found in QW heterostructures (right).*

Studies of WAL was also used by Dr. Dybko and MSc. Mazur (both of MagTop) to probe spatial extent of topological surface states in SnTe, prototypical TCI [K. Dybko *et al.*, *arXiv*:1812.08711]. MBE group contributed to the growth of SnTe layers with different thickness, and hence different overlap of top and bottom topological surface states. The structures were grown on CdTe hybrid substrates and capped by the CdTe protective layers for the studies.

Because of the lack of a possibility to grow doped heretostructures in the Institute's MBE systems high quality $Pb_{1-x}Sn_xSe$ quantum well structures with thickness in 5-50 nm range, separated by $Pb_{1-y}Eu_ySe$ barrier were grown in Linz by Dr. Volobuev, MagTop's doctor with advance R&D experience. The quantum wells or barrier were doped with small amount (less than 0.05%) of Bi. Magnetotransport studies performed by the MBE group demonstrate pronounced SdH oscillations.
$Pb_{1-x}Sn_xSe$:Bi (x_{Sn} = 0.25) QW had low carrier density, 3 – 7 10^{12} cm^{-2}, and mobility, 10^3 – 10^4 cm^2/V s. Different series of QWs with varied thickness (5-50 nm) and Bi doping were characterized. In all studied QWs we observed quantum oscillations in magnetoresistance. Carrier density extracted from the period of SdH oscillations corresponded to that extracted from Hall slope if an assumption of highly degenerate Landau levels is made. For thin (≤ 10 nm) QW WAL-like feature in the vicinity of 0 T is observed, which may be caused by scattering on the interface with PbEuSe barriers. Fitting of Shubnikov – de Haas oscillations gave value for the phase shift of these oscillations to be 2π/8 for 10 nm QW, which did not change with a tilt angle of an applied field. Experiments in tilted fields showed that phase of Shubnikov – de Haas oscillations is gradually changing to the value of -2π/8 for 20 nm QW. Origin of these phase shifts is unclear at the moment.

In order to perform further transport experiments, e.g. aiming at observation of quantum spin Hall effect, the structures require further processing and electrical gating. These works are currently being performed by Dr. Kazakov, MBE group's member.

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 creation of new topological phases. Following recent theoretical proposals predicting certain change of band structure, we were intended to study magnetically-doped surface of topological crystalline insulator (TCI) $Pb_{1-x}Sn_xSe$ epilayers in (001) and (111) orientation 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. The samples were covered in-situ in the MBE by amorphous Se and then were decapped in the ARPES preparation chamber by Se reevaporation.

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

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After each deposition ARPES spectra were recorded (see Fig. 1 6). In contrast to theoretical prediction it was observed that submonolayer deposition of either Mn or Fe on PbSnSe (111) and (001) did not open the band gap. On the other hand, we found that deposition of either Mn or Fe on PbSnSe (111) resulted in band bending bringing chemical potential upward into 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

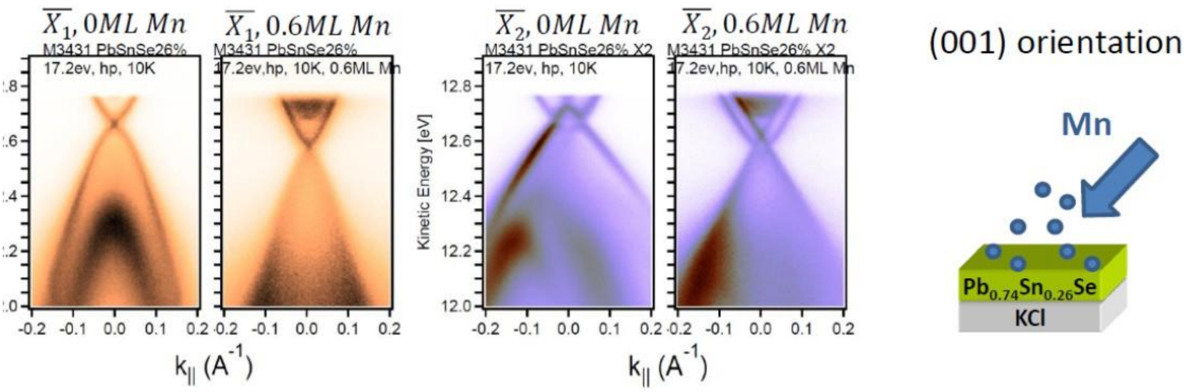

***Fig. 16**. ARPES spectra of $Pb_{1-x}Sn_xSe$ (001) $Pb_{1-x}Sn_xSe$ epilayers before and after Mn deposition.*

compensated polar (111) surface creates classical Rashba splitting which increases with increasing of transition metal thickness and finally saturates. However, Rashba effect was absent for (001) oriented films since this plane contains both metal and chalcogen atoms. Furthermore, deposition of Mn with submonolayer thickness on PbSnSe (001) decreases a distance in k space between Dirac points of the double Dirac cone. This apparently is connected with diminishing of hybridization between the cones due to presence of strong potential gradient introduced by surface doping. These spectra provide novel information about sensitivity of TSS to magnetic impurities and can be useful for implementation of topological crystalline insulator in spintronic devices.

Novel effects of coupling 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 about 2 eV·$Å^{-1}$ (typical value for other giant Rashba splitted materials) making this system perspective for spin torque devices.

MBE group contributed also to the MBE growth of SnTe/CdTe and $Pb_{1-x}Sn_xTe$/CdTe TCI layers and to the growth of $Sn_{1-x}Mn_xTe$, which were both done within the collaboration with Story's group at IFPAN (ON1.2). XPS studies of Te-protected surface of $Sn_{1-x}Mn_xTe$ have been performed in order to answer the question whether Te capping can be as effective in protecting of group IV telluride structures as the Se is for group IV sellenide structures [I.V. Kalitukha *et al.*, Phys. Solid State 60, 1578 (2018)].

Nanowires

Three different strategies were explored for the growth of IV-VI nanowires (NWs): (i) NWs growth on templates made of ZnTe NWs grown first with the use of VLS mechanism; (ii) Vapour-

Liquid-Solid (VLS) growth mechanism with the use of Au/Ga eutectic balls; (iii) self-catalytic growth. The morphology of grown samples was assessed with the scanning electron microscopy.
Ad. (i) – The idea behind this method was that growing at the tip of already existing quasi-one-dimensional object and with the use of previously formed Au/Ga eutectic balls should allow easier way of finding proper growth conditions for IV-VI NWs. Preparation of ZnTe pedestals samples was done with relative ease, as growth process was previously quite well developed at IFPAN. Although several attempts were made in order to define proper growth conditions for IV-VI nanowires, father experiments are needed.
Ad. (ii) – The same method of producing nano-catalyst was applied as the one previously used for the growth of II-VI NWs, namely through thermal procerssing of thin Au layer deposited on (111)-GaAs substrate. Initial results show beginning of the formation of nanowires, which gives hopes for obtaining (Pb, Sn)Se nanowires by Vapour-Liquid-Solid mechanism in MBE apparatus (see Fig. 17). Similarly as in the case (ii) further refining of growth conditions is necessary.
Ad. (iii) – So far this method resulted in the growth of cubical nanoobjects, which were interestingly aligned along some steps at the cleaved surface of (111)-BaF_2 substrate.

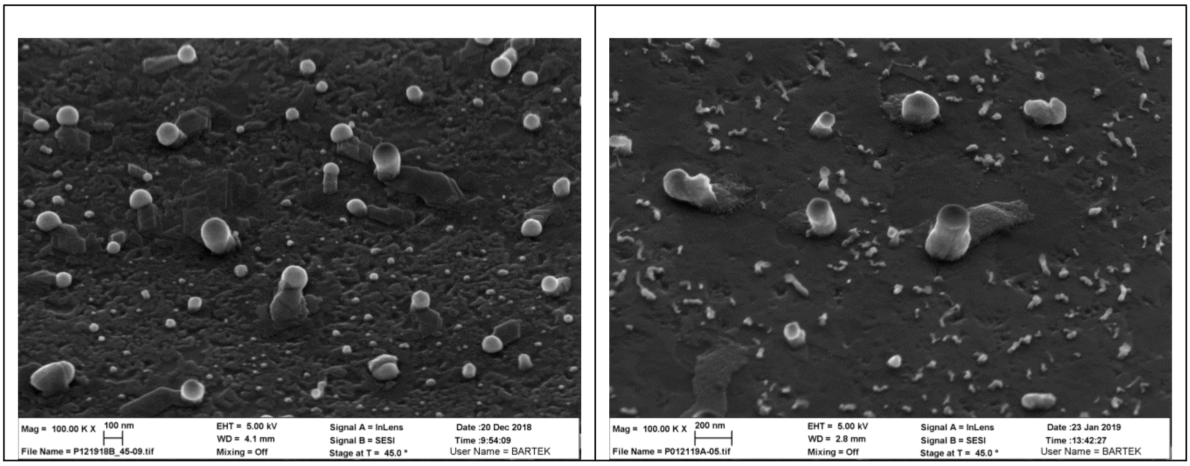

***Fig. 17**. Exemplary SEM image of initial growth of PbSe (left) and SnSe (right) nanowires by VLS mechanism directly on GaAs/Au substrates.*

In parallel to the growth of NWs the MBE Group was working on technology of making electrical connection to NWs and nanoplates (NPs) thus far produced in the Story's group. Several test samples were fabricated with the use of electron beam lithography in order to establish the best conditions in which electric contacts should be fabricated, including dose check for different thicknesses of resist, various contacts configuration and different methods of metallisation. A template substrate with a grid of markers, which enables the exact determination of NW's position and precise design of contacts was also developed. While for SnTe NPs one can work with contacts of the width of 200 nm, irradiated with the dose of 380 μC/cm^2, for NWs narrower contacts are required (this is due to the length of NWs, which is currently of the order of 1 μm for SnTe NWs). This turned out to be more difficult task, since on the one hand narrower structures require higher dose, while on the other, due to the proximity effect, higher dose leads to the coalescence of contacts. We have eventually established the proper dose to be around 450 μC/cm^2 and we are now going to fabricate first nanowire-based nanodevices. Nevertheless, first nanoplates-based devices were already produced and their electrical properties were tested. We found out that they are very sensitive to electrical discharge and we are now trying to improve measurement system to ensure better grounding of our samples. Fig. 18 presents SnTe NP with electric contacts.

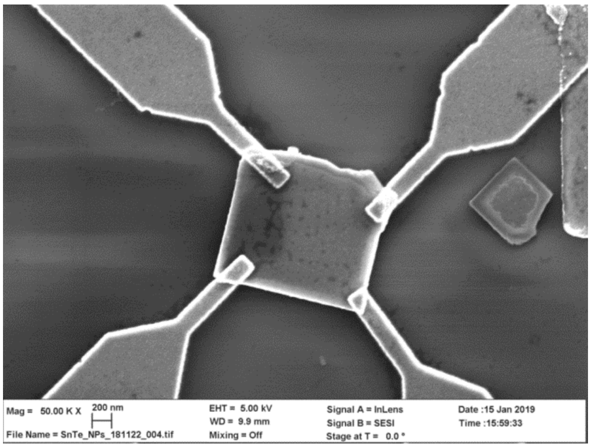

***Fig. 18**. SEM image of electric contacts to the SnTe nanoplate, fabricated by subsequent e-beam lithography, thermal evaporation of Ti/Au and lift-off.*

Majorana Team

Investigation of the zero-energy excitations in topological materials

Recent experiments performed in different topological semiconductors and semimetals indicate an emergence of order parameter, opening of an energy gap and appearance of a robust zero-bias peak in the tunneling conductance at low temperatures [G. P. Mazur *et al.*, *arXiv*:1709.04000; S. Das *et al., Appl. Phys. Lett.* **109**, 132601 (2016); H. Wang *et al.*, *Nat. Mater.* **15**, 38 (2016); L. Aggarwal *et al.*, *Nat. Mater.* **15**, 32 (2016)]. These observations have been interpreted as evidence of unconventional superconductivity and Majorana modes, but there exists no theoretical model, which could be used for describing the observed phenomenology and for making new predictions.

The SnTe material class allows the most detailed experimental study of this effect as shown by the research group's PhD student Grzegorz Mazur and his collaborators [G. P. Mazur *et al.*, *arXiv*:1709.04000]. In these experiments it was shown that the zero-bias anomaly develops only in topologically nontrivial materials. Moreover, no signs of superconductivity were found and surprisingly the increase of the concentration of magnetic dopants enhances the effect. This could be interpreted as indication of magnetic instability instead of superconductivity. A viable theoretical explanation should also be consistent with all the parametric dependencies of the zero-bias conductance peak reported in the experimental paper.

The team leader Timo Hyart and the research group's young doctor Wojciech Brzezicki in collaboration with the theory team's Marcin Wysokiński at MagTop approached this critical outstanding problem from a new perspective. Our theory [W. Brzezicki *et al.*, *arXiv*:1812.02168v1]

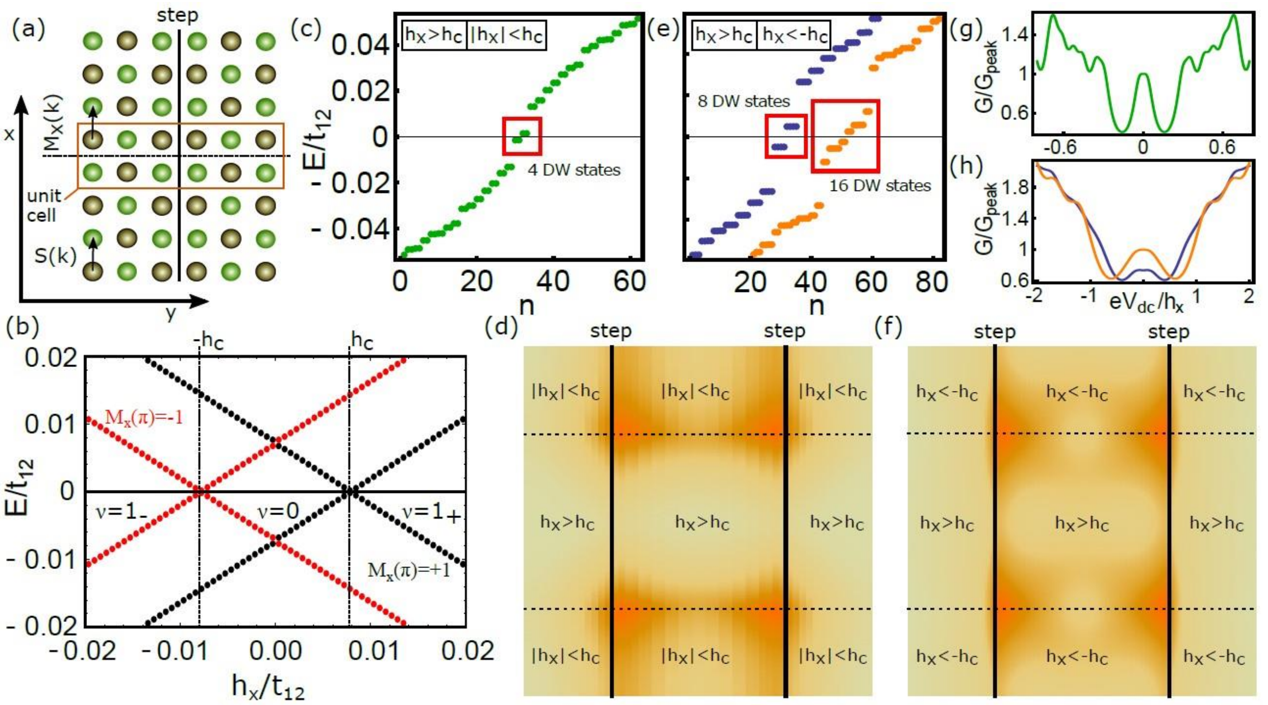

Fig. 19. *(a) Schematic top view of a surface of $Sn_{1-x}PbxTe_{1-y}Se_y$ multilayer system with a surface atomic step. (b) Spectrum at k=0 at a step in presence of magnetic field. Energy gap closings separate different topological phases. (c-d) Spectrum for a magnetic domain wall between magnetic and non-magnetic region with emergent topological in-gap states and their local density of states. (e-f) The same for domain wall separating opposite magnetization regions and with two domain walls. (g-h) Corresponding tunneling conductance demonstrating the zero-bias pea [W. Brzezicki et al., arXiv:1812.02168].*

focuses on surfaces of multilayer semiconductors that have regions of atomically flat terraces separated by atom-high steps [Fig. 19(a)]. We identified the important symmetries and used them to construct topological invariants, which describe low-energy states localized at the step defects. Moreover, we discussed possible instabilities for the appearance of correlated states and considered an easy-axis magnetization as one realistic possibility. Finally, the magnetic domain walls were shown to support low-energy topological bound states [Fig. 19(c-f)] because the regions with opposite magnetization are topologically distinct [Fig. 19(b)] in the presence of non-symmorphic chiral and mirror symmetries, providing a possible explanation for the zero-bias conductance peak observed in the recent experiment [Fig. 19 (g), (h)]. Remarkably, our theory explains all the experimentally observed phenomenology without requiring the existence of superconductivity.

These theoretical investigations will be continued. The research group's PhD student Nguyen Minh Nguyen, who started to work at the MagTop in November, has already started to learn the theoretical methods that are needed for investigating the topological properties of these materials. Our aim is to obtain a comprehensive understanding of the possible instabilities for the appearance of correlated states and to investigate which of them are consistent with the experimental observations. We also plan to develop a better general understanding of the topological phases of the theoretical model describing the SnTe material class and to study whether the zero-bias anomalies observed in the different topological semimetals and semiconductors could have a common origin.

Anomalous Hall effect in thin-film oxide interfaces

Research group's young doctor Wojciech Brzezicki in collaboration with MagTop's expert in ab-initio calculations Dr Carmine Autieri, Dr Mario Cuoco from CNR-SPIN Institute Salerno and Andrea Caviglia's experimental group in Delft has investigated the anomalous Hall effect at the interface of Ru- and Ir-oxide multilayers [D. J. Groenendijk *et al.*, *arXiv*:1810.05619 (2018)].

In the experiment it was surprisingly observed that the Hall conductivity in the thin-film multilayers of Ti/Ru/Ir oxides changes sign at some temperature. The MagTop's researchers provided theoretical support to explain this finding by performing DFT calculations and constructing a minimal model with desired symmetries. The essential component was the next nearest-neighbor orbital-mixing hopping [Fig. 20(a)] that leads to an avoided crossing of bands [Fig. 20(b)] in the subspace of fixed spin-orbital parity. This avoided bands crossing produced peaks in the Berry curvatures [Fig. 20(c)] and spin textures [Fig. 20(d)] while the spin-orbit coupling assured non-vanishing Chern numbers of two bands shown in Fig. 20(b). In the case of zero magnetization the contributions of Hall conductivity coming from the two different parity sectors are exactly opposite so that the total Hall conductivity vanishes. In presence of magnetization there is a non-vanishing signal whose dependence on temperature and magnetic profile is show in Fig. 20(e-f). These results are in qualitative agreement with experimental findings.

Wojciech Brzezicki studied also a similar layered oxide system in another project [F. Forte *et al.*, *arXiv*:1807.11301 (2018)]. The work focused on semimetal phases protected by mirror reflection symmetry with respect to the central layer of the system. Various types of topological nodal loops were found. It was shown that both the atomic spin-orbit coupling and the removal of local orbital degeneracy can lead to different types of electronic transitions with nodal lines that undergo a changeover from a loop structure enclosing the center of the Brillouin zone to pockets winding around multiple high symmetry points.

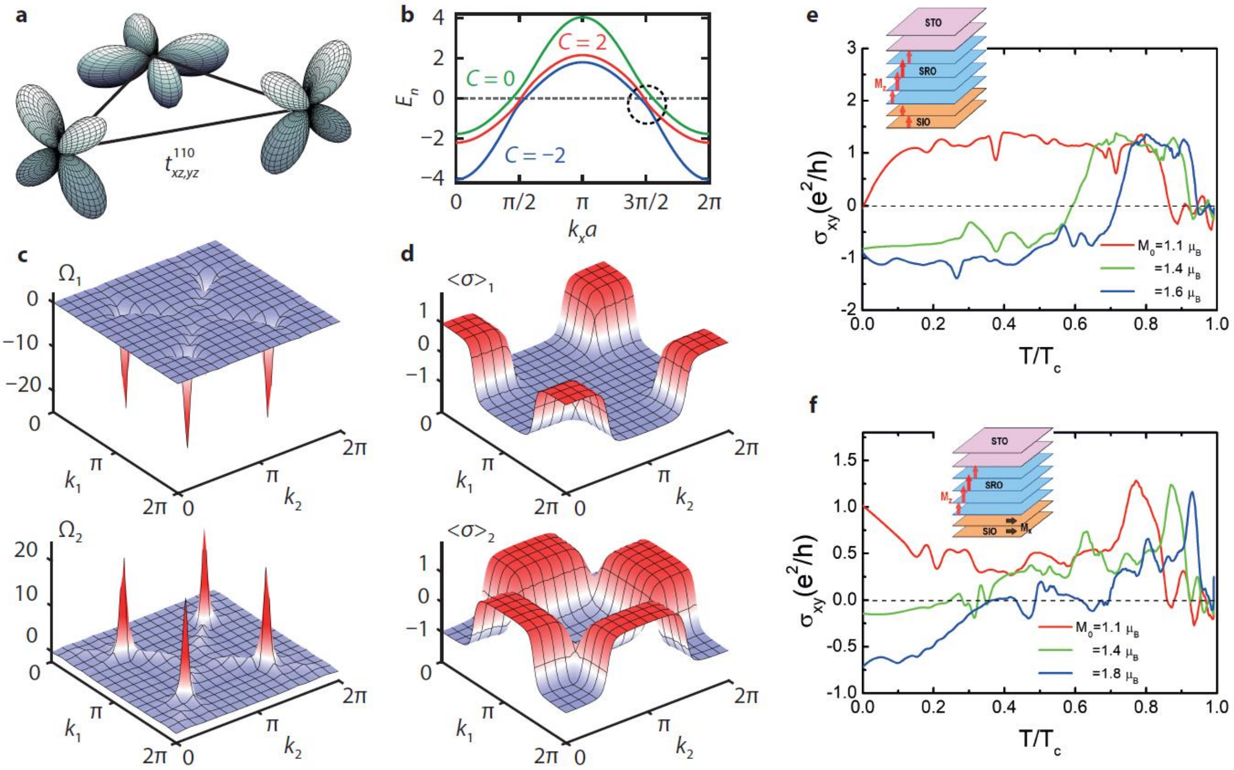

Fig. 20. (a) Schematic view of next nearest-neighbor orbital-mixing hopping. (b) Bands of the fixed parity block of the Hamiltonian having non-zero Chern numbers. (c-d) Berry curvatures and spin textures for the non-trivial bands. (e-f) Simulated Hall conductivity as a function of temperature for different magnetic profile of the multilayers systems of Ti/Ru/Ir oxides and different zero- temperature magnetizations M_0 [D.J. Groenendijk et al., arXiv:1810.05619].

Machine learning assisted determination of topological invariants

The team leader Timo Hyart in collaboration with the Leiden group proposed a non-invasive method, which can be used for experimental determination of topological invariants [M.D. Caio *et al.***,** *arXiv*:1901.03346v1]. Namely, we showed that an artificial neural network can learn to approximate a topological invariant from the experimentally accessible local density of states. Our method can be used for analyzing systems where direct transport measurements are not available and it can be applied also for characterization of systems consisting of regions of different topological phases.

Weak antilocalization experiments in thin films of SnTe

The research group's PhD student Grzegorz Mazur and his collaborators investigated magneto-transport in thin films of SnTe as a function of sample thickness and magnetic field direction, and evidence of antilocalization was observed [K. Dybko *et al., arXiv*:1812.08711]. The main motivation in these experiments is to understand how the surface and bulk states contribute to the transport. The observation of weak antilocalization in topological materials is often interpreted as evidence of surface states. However, weak anti-localization effect also occurs in a system with strong spin-orbit coupling which causes a spin rotation whenever an electron is scattered off an impurity [Y. Ando, *J. Phys. Soc. Jpn*. **82**, 102001 (2013)], so that the attribution of the weak anti-localization effect to the surface states is not straightforward. After more control experiments have been performed (including magnetotransport experiments for materials on the topologically trivial side of the SnTe material class) we will evaluate the need for developing transport theory for these materials.

Correlated phases in topological semimetals

The team leader Timo Hyart in collaboration with T. Heikkilä (University of Jyväskylä), D. Pikulin (Microsoft Station Q) and E. Rossi (College of William and Mary, United States) has developed theory for description of correlated states on topological semimetals. We have considered the possibility of high-temperature superconducting, magnetic and exciton condensate states due to surface flat bands appearing in topological semimetals. In particular we obtained preliminary results for the superfluid stiffness in such kind of systems and how it depends on the geometric phases. These studies will be continued and the insights obtained from these theoretical studies are expected to be useful for developing better understanding of the possible correlated phases appearing at the surface atomic steps in the SnTe material class.

Non-equilibrium topological phenomena

Research group's young doctor Marcin Płodzień, who has worked at the MagTop since October, has started to learn the theoretical methods used for description of periodically driven quantum systems. So far Dr. Płodzień has concentrated on developing a numerical library for simulation of these systems and he has tested the numerical methods using known model systems. Our aim is predict novel topological phases in periodically driven systems and to propose new experiments.

Topological phases in superconductors in the presence of impurity lattices

The team leader Timo Hyart in collaboration with the research group's young doctors M. Płodzień, W. Brzezicki, theory team's young doctor M. Wysokiński at MagTop and the group of B. Rosenow in Leipzig has been developing theory for impurity states in superconductors.

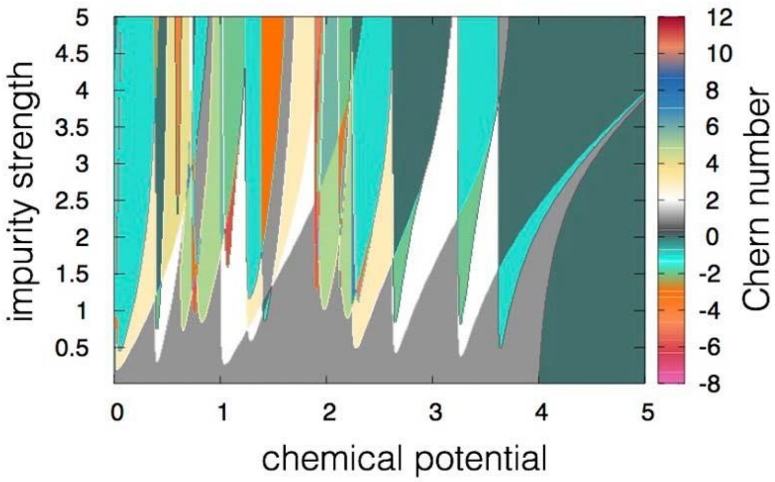

Fig. 21. *An example of a phase diagram for superconductors in the presence of an impurity lattice.*

We developed an efficient method for calculation of topological phase diagrams for superconductors in the presence of impurity lattice. Next this method will be applied to various systems and preliminary results have already been obtained. The impurity lattices can lead to very rich topological phase diagrams as illustrated in Fig. 21. This project looks very promising and it will be continued. It is relevant to experimental studies carried out by the Purdue/MagTop collaboration [[A. Kazakov *et al.*, *Phys. Rev. Lett.* **119**, 046803 (2017), also G. Simion *et al.*, *Phys. Rev. B* **97**, 245107 (2018), E. Bobko *et al., arXiv:*1804.03386v2].

Unexpected topological edge excitations in HgTe/CdTe quantum wells

Research group's young doctor Wojciech Brzezicki has obtained preliminary results indicating that in addition to the usual quantum spin Hall edge states HgTe/CdTe quantum wells can support a large number of additional edge modes. The working hypothesis is that they originate from a topological invariant, which exists due to a hidden approximate symmetry of the system. These preliminary results are very interesting and the project will be continued. In particular, we are interested how these additional edge modes contribute to the transport and could they lead to a breakdown of the topological protection of quantum spin Hall edge modes experimentally studied at IFPAN/Novosibirsk/Unipress/MagTop under leadership of Prof. T. Dietl.

Dissemination of research results

Publications in reviewed journals from the ISI list

[1] G. Simion, A. Kazakov, L.P. Rokhinson, T. Wojtowicz, Y.B. Lyanda-Geller, "Impurity-generated non-Abelions", Phys. Rev. B **97**, 245107 (2018).

[2] F. Spitzer, A.N. Poddubny, I.A. Akimov, V.F. Sapega, L. Klompmaker, L.E. Kreilkamp, L.V. Litvin, R. Jede, G. Karczewski, M. Wiater, T. Wojtowicz, D.R. Yakovlev, M. Bayer, "Routing the emission of a near-surface light source by a magnetic field", Nat. Phys. **14**, 1043 (2018), corrections, doi:10.1038/s41567-018-0291-9.

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Invited talks at international conferences, workshops and schools

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[29] T. Dietl, "Nematicity of spin systems driven by anisotropic chemical phase separation", 8th JSPS Core-to-Core Workshop on 'New-Concept Spintronic Devices', 11-12 January 2019, Sendai, Japan

[30] T. Dietl, "International Research Agenda Programme", Regional Meeting of Academia Europae Members, 15-16 October 2018, Wrocław, Poland.

[31] T. Dietl, "Topological phase transitions and quantum Hall effects in 2D topological systems", 13th International School on Theoretical Physics, Symmetry and Structural Properties of Condensed Matter, 10-15 September 2018, Rzeszów, Poland.

[32] T. Dietl, "Topological Crystalline Insulators: Role of Superconductivity and Magnetism", Erice Workshop 2018: Majorana Fermions and Topological Materials Science, 21 - 27 July 2018, Erice, Sicily, Italy.

[33] T. Dietl, "Electrical spin orientation", 50 Years of Optical Orientation in Semiconductors, 18-19 June, 2018, Paris, France.

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[35] T. Dietl, "Topological Crystalline Insulators: Role of 1D Topological States", Exotic Interactions in Quantum Correlated Materials, 10-14 June, 2018, Cracow, Poland.

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[38] M.M. Wysokiński, "Mechanisms of phase transitions between ferro- and antiferro- magnetic orderings in itinerant d and f electron materials", Fundamental Aspects of Superconductivity: 3rd International Conference on Superconductivity and Magnetism in Selected Systems, September 16-21 2018, Zakopane, Poland.

[39] W. Brzezicki, "Exotic Topological States in Hybrid Transition Metal Oxides", Workshop on Exotic Interactions in Quantum Correlated Materials, June 10-14 , 2018, Kraków, Poland.

[40] T. Hyart, "Interplay of spontaneous symmetry breaking and topology in condensed matter systems", The 9th International Conference New Generation in Strongly Correlated Electron Systems (NGSCES 2018), September 3-7, 2018, San Sebastian, Spain.

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[41] A. Kazakov, G. Simion, V. Kolkovsky, Z. Adamus, G. Karczewski, T. Wojtowicz, Y. Lyanda-Geller, L.P. Rokhinson, "Formation of helical channels in quantum Hall effect regime", 47th "Jaszowiec" International School and Conference on the Physics of Semiconductors, June 16-22, 2018, Szczyrk, Polska (abstract of Rokhinson's invited talk).

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[45] W. Wołkanowicz, P. Dziawa, B. Taliashvili, M. Zięba, A. Sulich, J.Z. Domagała, R. Minikayev, E. Łusakowska, A. Reszka, K. Dybko, M. Wiater, T. Wojtowicz, T. Story, "Epitaxial Growth, Structural and Electric Properties of SnTe/CdTe and Pb1-xSnxTe/CdTe Topological Layers ", X Anniversary Symposium of PhD Students, 04-06 June 2018, Białobrzegi, Poland - oral.

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[51] J. Sadowski, S. Kret, A. Kaleta, B. Kurowska, K. Morawiec, T. Wojciechowski, W. Knoff, A. Reszka, R. Mathieu, M. Sawicki, "MBE-grown III-V semiconductor nanowires with ferromagnetic shells", 47th "Jaszowiec" International School and Conference on the Physics of Semiconductors, June 16-22, 2018, Szczyrk, Polska – oral.

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[58] C. Autieri, "Low-connectivity in spin-orbit coupled iridium oxides", The 9th International Conference New Generations in Strongly Correlated Electron Systems Conference, 3-7 September 2018, San Sebastian, Spain – oral.

[59] C. Autieri, "Spin-orbit semimetal SrIrO3 in the two-dimensional limit", SuperFox Conference on Superconductivity and Functional Oxides, 13-15 September 2018, Salerno, Italy – oral.

[60] M.M. Wysokiński and M. Fabrizio, "Efficient variational approach to strongly correlated fermions at and far from equilibrium", The 9th International Conference New Generations in Strongly Correlated Electron Systems Conference, 3-7 September 2018, San Sebastian, Spain – oral.

[61] W. Brzezicki, "Orbital Majorana modes in a hybrid oxide system", TO-BE Spring Meeting (MP1308 COST Action TO-BE Towards Oxide-Based Electronics), March 12-14 2018, Sant Feliu de Guíxols, Spain – oral.

[62] W. Brzezicki, "Orbital Majorana modes in a hybrid oxide system", Oxide Superconducting Spintronics Workshop 2018, 11-13.04.2018 Amalfi, Italy – oral.

Poster presentations at international conferences, workshops and schools

[63] W. Wołkanowicz, B. Taliashvili, P. Dziawa, M. Zięba, A. Sulich, J.Z. Domagała, R. Minikayev, E. Łusakowska, A. Reszka, K. Dybko, M. Wiater, T. Wojtowicz, T. Story, "MBE growth and structural properties of SnTe/CdTe and Pb1-xSnxTe/CdTe topological layers", 47th "Jaszowiec" International School and Conference on the Physics of Semiconductors, June 16-22, 2018, Szczyrk, Polska - poster.

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[69] R. Rudniewski, W. Zaleszczyk, M. Wiater, Z. Adamus, T. Wojciechowski, T. Wojtowicz, "Towards high mobility 2DEG in CdTe quantum wells doped with Indium", 47th "Jaszowiec" International School and Conference on the Physics of Semiconductors, June 16-22, 2018, Szczyrk, Polska - poster.

[70] M. Szot, S. Chusnutdinow, K. Dybko, B. Turowski, L. Kowalczyk, M. Wiater, T. Wojtowicz, T. Story, G. Karczewski, "Photoluminescence studies of single PbSe/CdSe quantum well", 34th International Conference on the Physics of Semiconductors, 29th July - 3rd August 2018, Montpellier, France - poster.

[71] I. Tanveer, B.D. McCombe, Z. Adamus, M. Wiater, G. Karczewski, T. Wojtowicz, "THz magneto-spectroscopy of diluted-magnetic-semiconductor Quantum Wells: spin-orbit coupling, many electron effects and resonant magneto-polaron coupling", 34th International Conference on the Physics of Semiconductors, 29th July - 3rd August 2018, Montpellier, France - poster.

[72] Y. Imanaka, G. Karczewski, T. Wojtowicz, "Charged exciton in CdTe wide quantum well at high magnetic field", 34th International Conference on the Physics of Semiconductors, 29th July - 3rd August 2018, Montpellier, France - poster.

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[74] K. Sawicki, J.G. Rousset, R. Rudniewski, M. Ściesiek, T. Kazimierczuk, W. Pacuski, M. Nawrocki, J. Suffczyński, "Lasing from a CdSe/(Cd, Mg)Se quantum well embedded into a microcavity in a strong and weak coupling regime", 34th International Conference on the Physics of Semiconductors, 29th July - 3rd August 2018, Montpellier, France – poster

[75] J. Polaczyński, "Fabrication of electric contacts to nanoobjects by e-beam lithography ", European School on Nanosciences & Nanotechnologies ESONN 2018, August 26- September 15, 2018, Grenoble, France – poster.

[76] A. Borodziuk, Ł. Kłopotowski, D. Elbaum, J. Mikulski, P. Kowalik, K. Fronc, I. Kamińska, R. Minikayev, T. Wojciechowski, A. Sienkiewicz, M. Łapiński, B. Sikora, "Modified upconverting $NaYF_4$ nanoparticles for photodynamic therapy ", 2nd Conference and Spring School on Properties, Design and Applications of Upconversion Nanomaterials, 2 - 6 April 2018, Valencia, Spain – poster.

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[78] A. Kazakov, V.V. Volobuev, Z. Adamus, M. Aleszkiewicz, T. Wojciechowski, B. Turowski, T. Wojtowicz, T. Dietl, "Magnetotransport of (111) Pb1-xSnxSe topological crystalline insulator epilayers", 10th International School and Conference on Physics and Applications of Spin Phenomena in Solids, August 05-09, 2018, Linz, Austria - poster.

[79] G. Grabecki, K. Grasza, W. Paszkowicz, M. Szot, M. Wołcyrz, P. Dąbrowski, S. Chusnutdinow, P. Skupiński, A. Avdonin, I. Yahniuk, E. Łusakowska, R. Jakieła, A. Barcz, A. Reszka, M. Majewicz, K. Dybko, A. Łusakowski, T. Dietl, "Model for anomalous electron transport in $(Cd_{0.38}Zn_{0.62})_3As_2$", 47^{th} "Jaszowiec" International School and Conference on the Physics of Semiconductors, June 16-22, 2018, Szczyrk, Polska – poster.

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[81] M.J. Grzybowski, M. Majewicz, P. Wadley, K.W. Edmonds, R. Campion, B.L. Gallagher, T. Dietl, M. Sawicki, "Achieving electric field influence on thin films of antiferromagetic CuMnAs", 47^{th} "Jaszowiec" International School and Conference on the Physics of Semiconductors, June 16-22, 2018, Szczyrk, Polska – poster.

[82] M.J. Grzybowski, M. Majewicz, P. Wadley, K.W. Edmonds, R. Campion, B.L. Gallagher, T. Dietl, M. Sawicki, "Achieving electric field influence on thin films of antiferromagetic CuMnAs", 10th International School and Conference on Physics and Applications of Spin Phenomena in Solids, August 05-09, 2018, Linz, Austria – poster.

[83] A. Navarro-Quezada, M. Aiglinger, M. Sawicki, K. Gas, B. Faina, M. Matzer, T. Li, R. Jakieła, P. Dłużewski, T. Dietl, A. Bonanni, "Magnetoresistance of phase separated (Ga,Fe)N containing $Ga_yFe_{4-y}N$

embedded nanocrystals", 10th International School and Conference on Physics and Applications of Spin Phenomena in Solids, August 05-09, 2018, Linz, Austria – poster.

[84] G.P. Mazur, K. Dybko, A. Szczerbakow, M. Zgirski, E. Łusakowska, S. Kret, J. Korczak, T. Story, M. Sawicki, T. Dietl, "Majorana-like excitations in a ferromagnetic topological crystalline insulator", 10th International School and Conference on Physics and Applications of Spin Phenomena in Solids, August 05-09, 2018, Linz, Austria – poster.

[85] M. Sawicki, O. Proselkov, C. Śliwa, P. Aleshkevych, J.Z. Domagała, J. Sadowski, T. Dietl, "Cubic anisotropy rotations in (Ga,Mn)As layers: Experiment and theory", 10th International School and Conference on Physics and Applications of Spin Phenomena in Solids, August 05-09, 2018, Linz, Austria – poster.

[86] M.J. Grzybowski, P. Wadley, K.W. Edmonds, K. Dybko, M. Majewicz, R. Campion, B.L. Gallagher, T. Dietl, M. Sawicki, "Achieving electric field influence on thin films of antiferromagetic CuMnAs", Quantum Complex Matter - International Conference and School, June 10-15, 2018, Rome, Italy – poster.

[87] G.P. Mazur, K. Dybko, A. Szczerbakow, M. Zgirski, E. Łusakowska, S. Kret, J. Korczak, T. Story, M. Sawicki, T. Dietl, "Majorana-like excitations in a ferromagnetic topological crystalline insulator", Quantum Complex Matter - International Conference and School, June 10-15, 2018, Rome, Italy – poster.

Seminars in Poland and abroad

[88] T. Dietl, "Anomalous Hall effect in collinear and non-collinear spin systems", 22 January 2019 at Laboratory for Nanoelectronics and Spintronics, Katahira Campus, Tohoku University, Sendai, Japan.

[89] T. Dietl, "Magnetoresistance and magnetization anisotropies violating crystal symmetry", 16 January 16 2019 at Laboratory for Nanoelectronics and Spintronics, Katahira Campus, Tohoku University, Sendai, Japan.

[90] T. Dietl, "Search for the origin of zero-energy modes in topological materials", 12 December 2018 at AGH University of Science and Technology, Academic Centre for Materials and Nanotechnology, Kraków, Poland.

[91] M.J. Grzybowski, "Antyferromagnetic spintronics – switching CuMnAs with electrical current ", 6 November 2018 at the Faculty of Physics, University of Bialystok, Poland.

[92] M.M. Wysokiński, "Numerically efficient variational methods to strongly correlated fermion systems at and out of equilibrium", 10 October 2018 at the Faculty of Physics, University of Warsaw, Poland.

[93] M. Płodzień, "Few-fermion thermometry: using ultra-cold atoms for measuring ultra-low temperatures", 4 October 2018 at the Faculty of Physics, University of Warsaw, Poland.

[94] T. Hyart, "Majorana fermions", 10 July 2018 at the University of Antwerp, Belgium.

[95] T. Hyart, "Transport phenomena in double-layer exciton condensates", 9 July 2018 at the University of Antwerp, Belgium.

[96] T. Hyart, "Majorana fermions and topological quantum computing: An overview", 5 June 2018 at the Institute of Physics PAS, Warsaw, Poland.

[97] M.M. Wysokiński, "Efficient variational approach to strongly correlated fermions at and far from equilibrium", 21 May 2018 at the Faculty of Physics, Astronomy and Applied Computer Science, Faculty of Physics, Jagiellonian University, Poland.

[98] T. Hyart, "Interplay of spontaneous symmetry breaking and topology in condensed matter systems", 27 April 2018 at the Faculty of Physics, University of Warsaw, Poland.

[99] T. Dietl, "Topological insulators of narrow-gap semiconductors", 16 March, 2018 at Laboratory for Nanoelectronics and Spintronics, RIEC Katahira Campus, Tohoku University, Sendai, Japan.

[100] T. Dietl, "Central spin problem – a confined electron spin coupled to surrounding nuclear or magnetic spins", 8 March 2018 at Graduate School of Science, Kita-Aobayama Campus, Tohoku University, Sendai, Japan.

3. INFORMATION ABOUT THE TASKS PERFORMED BY TECHNICAL AND RESEARCH STAFF

(please provide a list of technical/research staff with a few words of description about their tasks, as well as the title of the project on which each person is working on (including students).

Team 1 Theory:

1. Prof. dr hab. Tomasz Dietl – Team leader (from 2.02.2017, unpaid leave from 16.02 to 19.03.2018 and from 27.12.2018 to 28.01.2019) – EPC = 0,8281
   Title of the project: "Interplay between magnetism and superconductivity in topological matter and the origin of magnetism in transition-metal-doped topological materials".

2. Dr. Wojciech Brzezicki – Young doctor (from 2.10.2017 to 31.05.2018) – EPC = 0,3333
   Title of the project: "Interplay between magnetism and superconductivity in topological matter and the origin of magnetism in transition-metal-doped topological materials".

3. Dr. Marcin Wysokiński – Young doctor (from 2.11.2017) – EPC = 1
   Title of the project: "Interplay between magnetism and superconductivity in topological matter and the origin of magnetism in transition-metal-doped topological materials".

4. MSc Grzegorz Mazur – PhD student (from 1.07.2017 to 31.12.2018) – EPC = 0,9167
   Title of the project: "Interplay between magnetism and superconductivity in topological matter and the origin of magnetism in transition-metal-doped topological materials".

5. MSc Michał Grzybowski – PhD student (from 1.07.2018) – EPC = 0,5833
   Title of the project: "Interplay between magnetism and superconductivity in topological matter and the origin of magnetism in transition-metal-doped topological materials".

6. MSc Ashutosh Wadge – PhD student (from 1.10.2018) – EPC = 0,3333
   Title of the project: "Interplay between magnetism and superconductivity in topological matter and the origin of magnetism in transition-metal-doped topological materials".

7. MSc Rajibul Islam – PhD student (from 1.11.2018) – EPC = 0,25
   Title of the project: "Interplay between magnetism and superconductivity in topological matter and the origin of magnetism in transition-metal-doped topological materials".

Team 2 MBE:

1. Prof. dr hab. Tomasz Wojtowicz – Team leader (from 1.02.2017) – EPC = 1
   Title of the project: "Technology of growth and nanostructurization of topological matter"

2. Dr. Aleksandr Kazakov – Young doctor (from 19.10.2017) – EPC = 1
   Title of the project: "Technology of growth and nanostructurization of topological matter".

3. MSc Rafał Rudniewski – PhD student (from 1.07.2017) – EPC = 1
   Title of the project: "Technology of growth and nanostructurization of topological matter"

4. MSc Jakub Polaczyński – PhD student (from 1.10.2017) – EPC = 1
   Title of the project: "Technology of growth and nanostructurization of topological matter".

5. MSc Bartłomiej Turowski – PhD student (from 1.10.2017) – EPC = 1
   Title of the project: "Technology of growth and nanostructurization of topological matter".

Team 5 Majorana:

1. Dr. Timo Hyart – Team leader (from 1.04.2018) – EPC = 0,8333
   Title of the project: "Theoretical investigation of topological invariants and transport effects in topological materials"

2. Dr. Wojciech Brzezicki – Young doctor (from 1.06.2018) – EPC = 0,6667
   Title of the project: "Theoretical investigation of topological invariants and transport effects in topological materials"

3. Dr. Marcin Płodzień – Young doctor (from 2.10.2018) – EPC = 0,3297
   Title of the project: "Theoretical investigation of topological invariants and transport effects in topological materials"

4. Dr. Victor Fernandez Becerra – Young doctor (from 11.01.2019) – EPC = 0,0568
   Title of the project: "Theoretical investigation of topological invariants and transport effects in topological materials"

5. MSc Nguyen Minh Nguyen – PhD student (from 1.11.2018) – EPC = 0,25
   Title of the project: "Theoretical investigation of topological invariants and transport effects in topological materials"

6. MSc Grzegorz Mazur – PhD student (from 1.01.2019) – EPC = 0,0833
   Title of the project: "Theoretical investigation of topological invariants and transport effects in topological materials"

Doctors with advanced R&D experience

1. Prof. dr hab. Andrzej Wiśniewski – Expert in magnetism and superconductivity (from 3.03.2017, ½ of full time job) – EPC = 0.5
   Title of the project "Experimental studies of superconductivity in single crystal of topological insulators".

2. Dr. Tomasz Wojciechowski – Expert in fabrication of nanostructures (from 20.03.2017 to 31.05.2018, ½ of full time job, from 1.06.2018, ¾ of full time job) – EPC = 0,6667
   Title of the project: "Technology of growth and nanostructurization of topological matter".

3. Dr. Valentine Volobuev – Expert in the MBE growth of topological matter (from 4.12.2017) – EPC = 1
   Title of the project: "Technology of growth and nanostructurization of topological matter".

4. Dr. Carmine Autieri – Expert in *ab-initio* (from 1.06.2018) – EPC = 0,6667
   Title of the project: "Interface topological effects"

5. Dr. Krzysztof Dybko – Expert in the low-temperature transport measurements of topological matter (from 17.12.2018, ½ of full time job) – EPC = 0,0614
   Title of the project: "Interplay between magnetism and superconductivity in topological matter and the origin of magnetism in transition-metal-doped topological materials".

Technical Staff

1. Dr. Przemysław Iwanowski (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) – EPC = 0,6667

2. MSc Wojciech Zaleszczyk (from 19.04.2017 to 31.05.2018, ½ of full time job, from 1.06.2018, ¾ of full time job) – EPC = 0,6667

3. Paweł Ungier (from 18.09.2018, ½ of full time job) – EPC = 0,1854

4. MSc Maciej Wiater (from 18.09.2018, ½ of full time job) – EPC = 0,1854

5. MSc Eng. Andrzej Szczerbakow (from 1.11.2018, 1/6 of full time job) – EPC = 0,0417

6. MSc Eng. Jędrzej Korczak (from 10.01.2019, ½ of full time job) – EPC = 0,0303

4. INFORMATION ABOUT SCIENTIFIC PARTNERS

4.1. Description of cooperation with foreign partners

I. Collaboration with the foreign strategic partner **Julius-Maximilians-Universität Würzburg** (Würzburg, Germany) in the area of topological insulators has been continued. Further joint experiments on the MBE growth and studies of PbCdSe mixed crystal layers, which could be the basis of PbSnCdSe crystalline topological insulator with much reduced bulk conductivity, have been performed. The manuscript describing results: S. Chusnutdinow, M. Szot, S. Schreyeck, M. Aleszkiewicz, I.V. Kucherenko, A.V. Muratov, V.A. Yakovlev, T. Wojtowicz, and G. Karczewski, “Ternary Pb1−xCdxSe films grown by molecular beam epitaxy on GaAs/ZnTe hybrid substrates” has been accepted to J. Cryst. Growth.

II. Collaboration with **Advanced Institute for Material Research, Tohoku University** (Tohoku, Japan): Prof. Tomasz Dietl participated in the research activities of Advanced Institute for Materials Research (WPI-AIMR) and in teaching activities of the Graduate Program in Spintronics (GP-Spin) at Tohoku University.

III. Timo Hyart, leader of the Group of Physics of Majoranas, has continued the collaboration with the groups of B. Rosenow (**Leipzig University**, Germany), E. Rossi (**The College of William and Mary in Virginia**, Williamsburg, United States), D.I. Pikulin (**Microsoft Station Q, University of California**, Santa Barbara, United States), and T. Heikkilä (**University of Jyväskylä**, Finland).

IV. Collaboration with **Purdue University** (Purdue, USA) has been concluded by one joint publication: G. Simion, A. Kazakov, L.P. Rokhinson, T. Wojtowicz, Y.B. Lyanda-Geller, "Impurity-generated non-Abelions", Phys. Rev. B **97**, 245107 (2018).

V. Collaboration with **Technische Universität Dortmund** (Dortmund, Germany) has been concluded by five joint publications:

(i) F. Spitzer, A.N. Poddubny, I.A. Akimov, V.F. Sapega, L. Klompmaker, L.E. Kreilkamp, L.V. Litvin, R. Jede, G. Karczewski, M. Wiater, T. Wojtowicz, D.R. Yakovlev, M. Bayer, "Routing the emission of a near-surface light source by a magnetic field", Nat. Phys. **14**, 1043 (2018), corrections, doi:10.1038/s41567-018-0291-9;

(ii) F. Saeed, M. Kuhnert, I.A. Akimov, V.L. Korenev, G. Karczewski, M. Wiater, T. Wojtowicz, A. Ali, A.S. Bhatti, D.R. Yakovlev, M. Bayer, "Single-beam optical measurement of spin dynamics in CdTe/(Cd,Mg)Te quantum wells", Phys. Rev. B **98**, 075308 (2018);

(iii) F. Passmann, S. Anghel, T. Tischler, A.V. Poshakinskiy, S.A. Tarasenko, G. Karczewski, T. Wojtowicz, A.D. Bristow, M. Betz, "Persistent spin helix manipulation by optical doping of a CdTe quantum well", Phys. Rev. B **97**, 201413 (2018);

(iv) I.V. Kalitukha, M. Salewski, I.A. Akimov, V.L. Korenev, V.F. Sapega, D.R. Yakovlev, G. Karczewski, M. Wiater, T. Wojtowicz, Y.G. Kusrayev, M. Bayer, "Interfacial Ferromagnetism in a Co/CdTe Ferromagnet/Semiconductor Quantum Well Hybrid Structure", Physics of the Solid State **60**, 1578 (2018);

(v) O. Borovkova, V, F. Spitzer, V. Belotelov, I, I.A. Akimov, A.N. Poddubny, G. Karczewski, M. Wiater, T. Wojtowicz, A.K. Zvezdin, D.R. Yakovlev, M. Bayer, "Transverse magneto-optical Kerr effect at narrow optical resonances", Nanophotonics **8**, 287 (2019);

and one conference proceedings paper: A.V. Akimov, S.V. Poltavtsev, M. Salewski, O.A. Yugov, G. Karczewski, M. Wiater, T. Wojtowicz, M. Reichelt, T. Meier, D.R. Yakovlev, M.

Bayer, "Coherent optical spectroscopy of charged exciton complexes in semiconductor nanostructures", Proc. SPIE Proceedings, Ultrafast Phenomena and Nanophotonics XXII, 10530, (2018), ed.: M. Betz, A.Y. Elezzabi , p.105300G;

and one arXiv preprint: 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, "Voltage control of the long-range p-d exchange coupling in a ferromagnet-semiconductor quantum well hybrid structure", arXiv:1812.09680v1 [cond-mat.mes-hall], (2018).

VI. Collaboration with **University of Regensburg** (Regensburg, Germany) has been concluded by one joint publication: P. Faltermeier, G.V. Budkin, S. Hubmann, V.V. Bel'kov, L.E. Golub, E.L. Ivchenko, Z. Adamus, G. Karczewski, T. Wojtowicz, D.A. Kozlov, D. Weiss, S.D. Ganichev, "Circular and linear magnetic quantum ratchet effects in dual-grating-gate CdTe-based nanostructures", Phys. E **101**, 178 (2018).

VII. Collaboration with **Helmholtz-Zentrum Dresden-Rossendorf**, Institute of Ion Beam Physics and Materials Research has been concluded by one joint publication: Y. Yuan, R. Hübner, M. Birowska, C. Xu, M. Wang, S. Prucnal, R. Jakieła, K. Potzger, R. Böttger, S. Facsko, J.A. Majewski, M. Helm, M. Sawicki, S. Zhou, T. Dietl, "Nematicity of correlated systems driven by anisotropic chemical phase separation", Phys. Rev. Materials **2**, 114601 (2018).

VIII. Collaboration with **Universiteit Leiden** (Leiden, The Netherlands) has resulted in a preprint: M.D. Caio, M. Caccin, P. Baireuther, T. Hyart, M. Fruchart, "Machine learning assisted measurement of local topological invariants", arXiv:1901.03346v1 [cond-mat.dis-nn], (2019).

IX. Collaboration with the group of A. Caviglia in Delft (**Technische Universiteit Delft**, The Netherlands) and M. Cuoco in Salerno (**Università degli Studi di Salerno**, Fisciano, Italy) has resulted in preprint: D. J. Groenendijk, C. Autieri, T. C. van Thiel, W. Brzezicki, N. Gauquelin, P. Barone, K. H. W. van den Bos, S. van Aert, J. Verbeeck, A. Filippetti, S. Picozzi, M. Cuoco, and A. D. Caviglia, "Berry phase engineering at oxide interfaces", arXiv:1810.05619 [cond-mat.str-el], (2018).

X. Collaboration with **Università degli Studi di Salerno** (Fisciano, Italy) has been concluded by four joint publications:
(i) Wojciech Brzezicki and Mario Cuoco, "Nodal S-wave Superconductivity in Antiferromagnetic Semimetals", Physical Review B **97**, 064513 (2018);
(ii) G. Cuono, C. Autieri, F. Forte, M.T. Mercaldo, A. Romano, A. Avella, C. Noce, "A minimal tight-binding model for the quasi-one-dimensional superconductor $K_2Cr_3As_3$", arXiv:1812.01457v1 [cond-mat.supr-con], (2018);
(iii) A. Nigro, P. Marra, C. Autieri, W. Wu, J. G. Cheng, J. Luo, C. Noce, "Resistivity measurements unveil microscopic properties of CrAs", arxiv.org:1812.09957 [cond-mat.str-el], (2018);
(iv) F. Forte, D. Guerra, C. Noce, W. Brzezicki, M. Cuoco, "Tuning nodal line semimetals in trilayered systems", arXiv:1807.11301 [cond-mat.mes-hall], (2018).

XI. Collaboration with **Guilin University of Technology** (Guilin, China) has been concluded by one joint publication: Xing Ming, Xiangang Wan, Carmine Autieri, Jianfeng Wen, Xiaojun Zheng, “Spin-orbit driven insulating state in hexagonal iridates Sr3MIrO6 (M = Sr, Na and Li)”, Phys. Rev. B **98**, 245123 (2018).

XII. Collaboration with **University of Montpellier** (Montpellier, France) has been concluded by one joint publication: I. Yahniuk, S.S. Krishtopenko, G. Grabecki, B. Jouault, Ch. 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, “Perspectives of HgTe Topological Insulators for Quantum Hall Metrology”, arXiv:1810.07449v1 [cond-mat.mes-hall], (2018).

XIII. Collaboration with **Johannes Kepler University Linz** (Linz, Austria): Dr. Valentine Volobuev conducted the growth of topological crystalline insulator thin film for ARPES measurements at SOLARIS (Cracow) and **BESSY (Berlin)** and the growth of (Pb,Sn)Se quantum wells for magnetotransport experiments.

XIV. PhD student Grzegorz Mazur (the Group of Physics of Majoranas) completed his half-year training period at the **University of Cambridge**, Department of Materials Science and Metallurgy, UK.

XV. PhD student Jakub Polaczyński participated in the European School on Nanosciences and Nanotechnologies ESONN 2018 (**Université Grenoble-Alpes**, Grenoble, France) and in optical measurements in magnetic field using FT-IR spectroscopy (**Laboratoire National des Champs Magnétiques Intenses** LNCMI (Grenoble, France).

4.2. Description of cooperation with Polish partners

All MagTop’s group collaborate tightly with **IFPAN** researchers, particularly with the **Laboratory of Cryogenic and Spintronic Research** – SL2 (headed by Prof. Maciej Sawicki) and with the **Laboratory of X-Ray and Electron Microscopy Research** – SL1 (headed by Prof. Krystyna Jabłońska). The MBE Team has a very close collaboration with the **Laboratory of Growth and Physics of Low Dimensional Crystals** – SL3 (headed by Prof. Jacek Kossut) where practically all growth processes (of II-VIs and IV-Se structures) are jointly performed. Also very strong collaboration with the **Group of Physics and Technology of Epitaxial layers** – ON1.2, headed by Prof. Tomasz Story, expert in IV-VI TCIs, in the area of the growth and studies of TCIs exists. These collaborations are reflected in the fact that practically all publications coauthored by MBE Team’s members are joint publications with the Institute.

Successful ARPES measurements of TCIs and WSM were carried out at **SOLARIS (Cracow).**

5. INFORMATION ABOUT BUSINESS PARTNERS

5.1. Description of cooperation with foreign business partners

None

5.2. Description of cooperation with Polish business partners

Three letters of intent for cooperation were formulated based on the discussion about mutual points of interest. These letters have been signed by appropriate representatives of Puremat Technologies, PREVAC, and Modern Technologies and Filtration SA and by the Director of the Institute, Prof. Roman Puźniak.

- PUREMAT Technologies (Warsaw) is a spin-off company that raised from the Institute of Physics. The company sells ultrapure materials, Mg and Mn, for MBE and other semiconductor technologies. The materials are prepared using a new method of purification and preparation. This new method is particularly effective for removal of oxygen, carbon, sulfur and metallic contaminants. The letter of intent specifies that the cooperation will consist in testing by the MagTop thin films and nanostructures, grown by MBE, containing ultrapure Mn and Mg. Studies of mobility of carriers and of Fractional Quantum Hall Effect - an extreme test of element purity – are performed and will be continued by groups of Prof. Dietl and Wojtowicz with PUREMAT.
- PREVAC (Rogów, Poland) is one of the world's leading manufacturers of research equipment for analysis of high and ultra-high vacuum applications including MBE and sputtering nanotechnology systems. The PREVAC products are fully designed, manufactured and tested in Poland and they are currently working successfully all over the world. According to the letter of intent collaboration will consist in joint realization of research tasks under the project, including the MBE growth and studies of physical properties of thin films and nanostructures exhibiting properties of topological matter
- Modern Technologies and Filtration S. A. (Warsaw). The fields of expertise of the company are: industrial gas and liquid purification, and thermal processes (especially gasification) enabling conversion of biomass and waste into thermal and electrical power. The company is interested in finding solutions to the production of heat and electricity using renewable/alternative energy sources. Hence, in an agreement with the letter of intent, joint research tasks concerning search for efficient thermoelectric materials as well as detectors and sensors that may be used for harvesting of thermal and vibration energies in engines are planned.

The areas of possible cooperation with Vigo System are under discussion and to this end some preliminary joint experiments concerning electrical contacts have been already performed.

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

Dr. Wojciech Brzezicki has completed habilitation thesis.

MagTop's PhD students Grzegorz Mazur and Michał Grzybowski are in a final stage of theses writing and should defend them in 2019.

7. INFORMATION ABOUT THE ORGANIZATIONAL STRUCTURE OF THE UNIT AND HOW ITS DEVELOPMENT ALIGNS WITH THE SUBMITTED PROPOSAL

During the reporting period a major change in the organization structure took place: the MagTop Project was transferred from the Research Foundation MagTop to a newly created dedicated unit at IFPAN: Scientific Division ON6: International Centre for Interfacing Magnetism and Superconductivity with Topological Matter –MagTop. This move required preparing a number of new legal documents (e.g. its statue of the unit, recruitment rules, etc.) as well as modification of the grant agreement and the agreement with the foreign strategic partner unit. We managed to organize the process in the way that the shift of all employees to the new institution occurred without a discontinuity in the payment of salary.

We regard this move, carried on with a support of all concerned parties (Foundation for Polish Science, MagTop Foundation Management, MagTop Foundation Board, International Scientific Committee (ISC), IFPAN Director and Scientific Council), as an important step helping MagTop to accomplish successfully the IRA Programme goals.

At the same time we have kept unchanged the internal structure of MagTop, which aligns with the submitted proposal. We anticipate, however, that the employment of three new team leaders (as envisaged for 2019) may result in some modifications of the MagTop internal organization structure. These changes may be prompted by new team leaders but also by the ISC and/or the IRA competition Laureates.

Within the organization structure of the original proposal the Majorana Team (No 5) was formed under the leadership of Dr. Timo Hyart.

8. INFORMATION ABOUT RECRUITEMENTS IN PROCESS AS WELL AS COMPLETED RECRUITEMENT PROCEDURES AND CURRENT RECRUITEMENT PLANS (RESEARCH STAFF ONLY - EXCLUDING STUDENTS). ADDITIONALLY PLEASE ELABORATE ON THE GOOD HR PRACTICES THAT HAVE BEEN IMPLEMENTED.

The international recruitment process is carried out according to the Recruitment Rules elaborated under the supervision of MagTop's International Scientific Committee (ISC) and Foundation for Polish Science. Under these rules, the team leaders are selected by the ISC, whereas other MagTop's employees by recruitment committees appointed for each employment category by the IRA Laureates, according to the IRA programme rules. A person representing IFPAN director is participating in the process. Minutes of ISC and committees meetings, and the corresponding recruitment recommendations have to be accepted by the Foundation for Polish Science prior to submitting offers to the successful applicants.

The list of researchers employed in the reported period

Dr. Timo Hyart – team leader of the Majorana team (from 1.04. 2018 – full time)

Dr. Carmine Autieri – Expert in *ab-initio* (from 1.06.2018 – full time)

Dr. Marcin Płodzień – Young doctor (from 2.10.2018 – full time)

Dr. Krzysztof Dybko – Expert in the low-temperature transport measurements of topological matter (from 17.12.2018 – half time)

Dr. Victor Fernandez Becerra – Young doctor (from 11.01.2019 – full time)

The list of researchers to whom offers have been presented

Dr. Mircea Trif – new team leader, full time – offer accepted, starting date: March 2019

Dr. Vinayak Bhat – new team leader, full time – offer accepted, starting date: May 2019

Dr. Sergey Medvedev – new team leader, full time – offer accepted, starting date not yet decided

The recruitment plan

There are two calls under way:

(1) For young doctors and PhD students – deadline passed 31.01.2019, the Recruitment Committee meeting to decide about the final ranking is expected to be organized by March 8th.
(2) For six months' visitors – the call text is in the hands of IFPAN Director for acceptance.

After employment of the new team leaders new call for their teams will be announced.

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

Professor Tomasz Dietl was honored by the American Physical Society with a title of Distinguished Referee.

Stipends:

Wojciech Brzezicki - Stipend for Outstanding Young Researchers funded by Polish Ministry of Sciences and Higher Education [yearly only 180 laureates in all research fields].

Invited talks at International Conferences:

13 invited talks (listed in the chapter on dessimination of the results)

Best poster awards:

Grzegorz Mazur - Best poster award - 47th International School & Conference on the Physics of Semiconductors ”Jaszowiec”, Szczyrk, Poland 16-22.06.2018.

Grzegorz Mazur - Best poster award - Quantum Complex Matter, Rome, Italy 10-15.06.2018.

Chairing sessions at International Conferences:

T. Wojtowicz

Session: Quantum transport in heterostructures – 2, at 34th International Conference on the Physics of Semiconductors, 29th July - 3rd August 2018, Montpellier, France.

T. Dietl

Erice Workshop 2018: Majorana Fermions and Topological Materials Science, Erice, Italy, 21st – 27th July, 2018

Quantum Complex Matter - International Conference and School, June 10-15, 2018, Rome, Italy.

Participation in scientific committees of international conferences:

T. Dietl:

(1) ICM2018 International Conference on Magnetism (IUPAP) San Francisco, 2018
(2) 34th International Conference on Physics of Semiconductors (IUPAP), Montpellier, France, 2018
(3) 28th International Conference on Low Temperature Physics (IUPAP), Goteborg, 2018
(4) 10th International Conference on Physics and Applications of Spin-related Phenomena in Solids, Linz, Austria, 2018
(5) 20th International Conference on Superlattices, Nanostructures and Nanodevices, Madrid, Spain, 2018

W. Brzezicki:

9th International Conference New Generation in Strongly Correlated Electron Systems (NGSCES 2018), September 3-7, 2018, San Sebastian, Spain

10. IS THE PROJECT BEING IMPLEMENTED ACCORDING TO THE SCHEDULE ATTACHED TO THE AGREEMENT?

YES X **NO ☐**

If the answer is no, please provide an explanation :

11. ADITIONAL INFORMATION

Other important information relevant to the project

During reporting period a lot of effort was devoted to transferring of the MagTop Project from the Research Foundation MagTop to the new division of the Institute: International Centre for Interfacing Magnetism and Superconductivity with Topological Matter -MagTop (ON6). These included creating of this new division, which required preparing many legal documents (e.g. its statue of the unit, recruitment rules, etc.) and transferring of employees (signing new contracts).

After transferring the Project to the Institute of Physics an important part of ON6 activities was dedicated to designing a new, state of the art MBE system for the growth of chalcogenide topological thin films and heterostructures, as well as for interfacing them with magnetic and superconducting layers. This system will be based on the GENXplor MBE chamber that is in possession of the Institute of Physics and will be Institute's contribution to the project.

In order to build such a state of the art system two steps are required. First the purchase of a number of low-cost research equipment has to be done from the funds that have already been granted to MagTop in the category 4.1a of the budget. Second additional apparatus would need to be purchased from the money to be obtained through Equipment Grant from the Foundation for Polish Science. To this end MagTop was preparing such a grant application that soon will be submitted.

The MagTop was also preparing a public tender for the above mentioned low-cost research equipment, which is to be purchased from money in 4.1a category. These activities consisted of: (i) discussions with members of all groups to decide the growth of what kind of IV-VI based crystalline topological insulators nanostructures would be the most interesting and perspective; (ii) a number of meetings with potential suppliers of the equipment in order to discuss available options; (iii) preparing actual documents for a public tender. The tender was finally announced on Feb. 14-th, 2019.

In the reporting period also one application for the Equipment grant was prepared and submitted to the Foundation for Polish Sciences. This application concerns funds for purchasing of an integrated set of equipment that will allow to design and to characterize new topological materials and then to search for their hitherto unknown properties and functionalities. The set will constitute of a distinctive setup for charge and entropy transport measurements at ultra-low temperatures (down to around 10 mK) and in high magnetic fields (at least 14 T) as well as of a workstation for beyond-the-state-of-the art numerical and theoretical predictions and interpretation of experimental results.

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

We anticipate that the employment of three new team leaders (as envisaged for 2019) may result in some modifications of the MagTop Project. These changes may be prompted by new team leaders but also by the ISC and/or the IRA competition Laureates.

13. PROPOSED BUDGET ADJUSTMENTS – *if applicable*

To update the budget, according to actual costs incurred in recent periods and the necessity to transfer computer equipment from category 4.4 (Other direct costs, subcategory – worksite's equipment for R&D staff) to category 4.1 (low-cost research equipment), and also due to delays in employing new leaders and members of their groups as well as other changes in the employment-structure - the following changes of budget have been made:

Remuneration:

Unused funds of existing groups and unused funds of general budget (from periods 4, 5 and 6) have been moved to later periods.
Unused funds of non-created groups (from periods 4, 5 and 6) have been directed to finance Group 5 which employed 2 post-doctoral researchers more than originally planned.

Stipends:

The funds for stipends that have not been spent in existing groups have been moved to later periods. Non-created groups' stipends have been divided into Group 1 and Group 5. It is expected that the number of PhD students in these groups will soon be increased or has already increased.

Other direct costs:

In existing groups: most unspent funds in 4.4b from the periods 4, 5 and 6, have been moved to later reporting periods. Non-existing groups' funds have been moved to the category 4.1b "Low-cost research equipment - research groups" for Groups 1, 2, 5 (due to the necessity of changing cost category for the computer equipment). Additionally in Group 5 in order to compensate for insufficient funds in 4.1b category some founds from category 4.4b from later periods have been moved to category 4.1b (The amount of funds in 4.4b has been thus reduced)

In general budget: due to the necessity of changing the computer equipment category, part of the funds in 4.4a1 has been moved to 4.1a category.

Low-cost research equipment:

The budget in category (4.1a) has been increased from 2 600 000 PLN to 2 863 000 PLN and the budget in category 4.1b was increased to 337 000 PLN (the total budget in category 4.1 is now 3 200 000 PLN). That is because of expected higher prices of low-cost research equipment for MBE technology (for which a European tender was announced) and due to the necessity of buying computer equipment according to the following list:

7 workstations for advanced numerical calculations
4 computers for controlling experiments and for collecting data
31 computers for R+D staff

49 monitors
1 network server
3 multi-function printers (MFP)

I hereby confirm that the information contained in the 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.

Date: 25. II. 2019

Signature of the Laureate Tomasz Dietl

Stamp of the Unit Instytut Fizyki Polskiej Akademii Nauk w Warszawie Międzynarodowe Centrum Sprzężenia Magnetyzmu i Nadprzewodnictwa z Materią Topologiczną - MagTop (ON-6)

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