Summary of Professional Accomplishments

1. Name

Maciej Roman Molas

2. Diplomas, degrees conferred in specific areas of science or arts, including the name of the institution which conferred the degree, year of degree conferment, title of the PhD dissertation

2014 - ***PhD in Physics***, University of Warsaw, Faculty of Physics, Poland; and ***PhD of University of Grenoble***, France, specialisation: physics of condensed matter and radiation. PhD studies were carried out within the joint supervision (co-tutelle) between University of Warsaw and University of Grenoble. PhD thesis: "*Multiexcitons in semiconductor quantum dots*". Supervisors: dr hab. Adam Babiński and dr M. Potemski.

2010 - ***MSc in Physics***, University of Warsaw, Faculty of Physics. Specialisation: solid state physics. Master thesis: "*Influence of condition growth on the optical properties of quantum dots*". Supervisor: dr hab. Adam Babiński.

3. Information on employment in research institutes or faculties/departments or school of arts

03.2020 – present - ***adiunkt*** (research and teaching position) at the Faculty of Physics, University of Warsaw, Poland.

11.2017 – 02.2020 - ***adiunkt*** (research position) at the Faculty of Physics, University of Warsaw, Poland. The position was a part of the project "*Exciton-phonon interaction in thin layers of transition metal monochalcogenides*" (SONATINA project), funded by the National Science Centre, Poland.

12.2014 – 10.2017 - ***postdoctoral fellow*** at the National High Magnetic Field Laboratory in Grenoble, France. The position was a part of the project "*Magneto-optics of layered materials: exploring many-body physics in electronic systems with unconventional bands*" (MOMB project), funded by the European Research Council.

4. Description of the achievements, set out in art. 219 para 1 point 2 of the Act

The achievement described here is a series of publications on ***the excitonic complexes in thin layers of semiconducting transition metal dichalcogenides***.

4.1 Series of publications forming the scientific achievements

[MM1]**M. R. Molas**, K. Nogajewski, A. O. Slobodeniuk, J. Binder, M. Bartos, M. Potemski, *The optical response of monolayer, few-layer and bulk tungsten disulfide*, Nanoscale **9**, 13128 (2017).
I planned and performed all measurements presented in the work. I analysed the experimental data, actively participated in discussions and in writing of the publication.

[MM2] D. Vaclavkova, J. Wyzula, K. Nogajewski, M. Bartos, A. O. Slobodeniuk, C. Faugeras, M. Potemski, **M. R. Molas**, *Singlet and triplet trions in WS_2 monolayer encapsulated in hexagonal boron nitride*, Nanotechnology **29**, 325705 (2018).
I planned and performed all measurements presented in the work. I analysed the experimental data, actively participated in discussions and in writing of the publication.

[MM3] **M. R. Molas**, K. Nogajewski, M. Potemski, A. Babiński, *Raman scattering excitation spectroscopy of monolayer WS_2*, Scientific Reports **7**, 5036 (2017).
I planned and performed all measurements presented in the work. I analysed the experimental data, actively participated in discussions and in writing of the publication.

[MM4] **M. R. Molas**, C. Faugeras, A. O. Slobodeniuk, K. Nogajewski, M. Bartos, D. M. Basko, M. Potemski, *Brightening of dark excitons in monolayers of semiconducting transition metal dichalcogenides*, 2D Materials **4**, 021003 (2017).
I performed all measurements presented in the work. I analysed the experimental data, actively participated in discussions and in writing of the publication.

[MM5] **M. R. Molas**, A. O. Slobodeniuk, T. Kazimierczuk, K. Nogajewski, M. Bartos, P. Kapuściński, K. Oreszczuk, K. Watanabe, T. Taniguchi, C. Faugeras, P. Kossacki, D. M. Basko, M. Potemski, *Probing and Manipulating Valley Coherence of Dark Excitons in Monolayer WSe_2*, Physical Review Letters **123**, 096803 (2019).
I performed measurements in magnetic fields up to 14 T at the National High Magnetic Field Laboratory in Grenoble, France. I analysed the experimental data, actively participated in discussions and in writing of the publication.

[MM6] **M. R. Molas**, A. O. Slobodeniuk, K. Nogajewski, M. Bartos, Ł. Bala, A. Babiński, K. Watanabe, T. Taniguchi, C. Faugeras, M. Potemski, *Energy spectrum of two-dimensional excitons in a nonuniform dielectric medium*, Physical Review Letters **123**, 136801 (2019).
I planned and performed all measurements presented in the work. I analysed the experimental data, actively participated in discussions and in writing of the publication.

[MM7]**M. R. Molas**, K. Gołasa, Ł. Bala, K. Nogajewski, M. Bartos, M. Potemski, A. Babiński, *Tuning carrier concentration in a superacid treated MoS_2 monolayer*, Scientific Reports **9**, 1989 (2019).
I participated in measurements presented in the work. I analysed the experimental data, actively participated in discussions and in writing of the publication.

4.2 Description of the scientific achievements

Excitons in semiconductors are bound states of negatively charged electrons and positively charged holes, which are attracted to each other by the electrostatic Coulomb force. Excitonic complexes can be divided into several types, including *e.g.* a neutral exciton comprising an electron-hole (*e*-*h*) pair or a trion made of two particles of the same charge and one particle of the opposite charge. Excitons are responsible for electronic and optical response of many semiconductors. They are important for Bose-Einstein condensation, superfluidity, dissipationless current flow and the light-induced excitonic spin Hall effect, just to name a few examples of phenomena which occur in semiconductors. Semiconducting transition metal dichalcogenides (S-TMDs) with formula MX_2, where M=Mo or W and X=S, Se or Te, are the most intensively investigated group of two-dimensional (2D) layered materials, which have recently attracted considerable scientific attention, primary in the area of semiconductor physics and nanoscience as well as optoelectronic applications. The most known property of these materials is transition from an indirect to a direct band gap semiconductor as the number of layers is reduced from the bulk form to the monolayer (ML) limit [1,2]. The MLs exhibit a number of appealing optical phenomena related, among others, to valley-selective circular dichroism [3-5] and non-trivial effects of Coulomb interaction in the 2D geometry [6-8]. Furthermore, the optical response of thin layers of S-TMDs is dominated by excitonic effects [9,10], which opens up the possibility to investigate the properties of excitons in atomically thin materials.

In my work, I have focused on the properties of excitonic complexes observed in thin layers of S-TMDs, such as MoS_2, $MoSe_2$, WS_2, and WSe_2. I have investigated the interactions of excitons with phonons, modifications of their properties due to different types of surrounding environment and chemical treatment, as well as the evolution of their optical response as a function of temperature and electric and magnetic fields. Below I grouped the obtained results into five subjects:

- *Excitonic complexes in thin layers of WS_2* **[MM1, MM2]**, which have been investigated using photoluminescence (PL), photoluminescence excitation (PLE) and reflectance contrast (RC) experiments carried out as a function of the number of layers and temperature.
- *Exciton-phonon interaction in monolayer WS_2* **[MM3]**, which has been determined with the aid of an unconventional spectroscopy scheme, referred to as the Raman scattering excitation (RSE).
- *Dark excitons in S-TMD monolayers* **[MM4, MM5]**, which emissions have been observed due to application of the in-plane magnetic field partially mixing the neutral bright and dark exciton states.
- *Excitonic ladder in S-TMD monolayers* **[MM6]**, which has been investigated in four high quality S-TMD MLs encapsulated in hexagonal boron nitride (hBN) using low-temperature PL experiment performed in the out-of-plane magnetic field.
- *Tuning carrier concentration in monolayer MoS_2* **[MM7]**, which has been achieved in the MLs subjected to four-fold bis(trifluoromethane) sulfonimide (TFSI) treatment and investigated using PL, RC and Raman scattering techniques.

Excitonic complexes in thin layers of WS_2

Monolayers of **tungsten disulphide (WS_2)**, like other materials belonging to S-TMDs, are direct band gap semiconductors with the minima (maxima) of the conduction (valence) band located at the inequivalent K^+ and K^- points of their hexagonal Brillouin zone (BZ) [11]. Above the ML limit, WS_2 layers are characterized by an indirect band gap involving the Λ and Γ points of the conduction band (CB) and the valence band (VB), respectively.

A comprehensive optical study of thin flakes of WS_2 is presented in **[MM1]**. The investigations of structures with thickness ranging from mono- to octalayer and of a 32 nm thick bulk-like flake, have been carried out in a wide temperature range (5-300 K) using PL, PLE and RC spectroscopy techniques. The investigated samples comprising flakes of different thickness were obtained on a Si/SiO_2 substrate by polydimethylsiloxane (PDMS)-based exfoliation [12] of bulk WS_2 crystals (2H phase). The presented results can be divided into three subjects devoted to: (1) the optical response of the WS_2 ML; (2) the indirect emission of thicker layers (>ML); (3) the RC spectra of thin-layer WS_2.

The characterization of the optical response of ML WS_2 and the nature of various excitonic resonances (due to neutral, charged, and localized *e-h* complexes) determining the absorption-like (RC and PLE) and PL spectra of this system is discussed. The measured low-temperature (T=5 K) RC and PLE spectra show to three absorption-type resonances, which are assigned to **one neutral and two negatively charged excitons** (negative trions). These complex are formed in the vicinity of the optical band gap (the so-called A exciton), which is reduced with respect to the electronic band gap (a band-to-band transition) by the amount of the binding energy of excitons. The assignment of the neutral exciton is straightforward and stays in accordance with previous works [13,14], while the origin of the charged excitons required confirmation by measurements of RC spectra on a back-gated WS_2 monolayer structure. On the other hand, the low-temperature PL spectrum measured on the WS_2 ML consists, apart from the aforementioned excitons, of several emission lines and a broad emission band, which are assigned to the radiative recombination of **localized-excitons** and to the recombination spectrum of **donor-acceptor pairs**, respectively.

The evolution of the low temperature PL spectra of thin layers WS_2 as a function of the number of layers has also been studied. The measured PL spectra of thicker layers (>ML) are dominated by two well-defined emission peaks, which are assigned to **the Λ-Γ transitions** (Λ-Γ indirect excitons). As their energy separation does not depend on the layers number, it is supposed that these recombination processes involve two different phonons characterized by energies that differ by 30 meV and the same *k*-vector corresponding to the Λ point of the BZ (to match the wave vector difference of the recombining Λ electrons and Γ holes). Moreover, it has been found that the evolution of the indirect Λ–Γ emission energy can be well reproduced with a rather simple formula which applies to **the description of the energy evolution of the 2D confined electronic states in a rectangular well with infinite barriers**.

An important insight into the structure of higher lying bands of WS_2 can be provided by the low temperature RC spectroscopy. A strong spin-orbit (SO) coupling in S-TMDs, inherited from heavy metal atoms, leads to spin-split and spin-polarized subbands in both the VB and the CB at the K points of the BZ. The amplitude of the spin-orbit splitting (SOS) at the top of the VB is large as it reaches ∼400 meV, while for the CB states, its magnitude is estimated to be of ∼30 meV in the ML WS_2 [11]. The transitions between these SOS subbands are the so-called A and B excitons. The measured RC spectra display a group of resonances (A-exciton region) in the vicinity of the optical band gap, as well as features at higher energies that arise from the B-exciton resonance at the K-point of the BZ and from the so-called C exciton which is possibly related to a direct optical transition that takes place apart from the K points. **The energies of resonances related to the A and B excitons exhibit rather weak dependence on the layers number**, which indicates a strong intralayer character of these complexes. **For the C exciton, however, its red shift with increasing number of layers is observed**, which indicates pronounced changes in the electronic bands associated with this transition. Moreover, the

measured multiple-resonance character of the A-exciton feature, revealed in most of the studied thicker flakes >ML, is identified as arising due to **a specific hybridization scheme of electronic states at the K points** of the Brillouin zone of 2H-stacked S-TMD layers.

The investigation of charged excitons has also been conducted in an improved-quality WS_2 ML encapsulated in hBN flakes **[MM2]**. As it was demonstrated in [15], the hBN encapsulation permits to significantly reduce the inhomogeneous broadening of spectral lines. It allowed us to resolve and study the PL due to both **singlet (intravalley)** and **triplet (intervalley) states of negatively charged excitons in this material**. The found energy separation between these two lines is of about 7 meV, which reflects rather weak effects of the electron-electron exchange interaction. The polarization-resolved experiments have demonstrated that the helicity of the excitation light is better preserved in the emission spectrum of the triplet trion than in that of the singlet trion. Moreover, it has been found that the singlet charged exciton can be observed at ambient conditions (even at room temperature) whereas the emission line due to the triplet complex is only apparent at low temperatures.

Exciton-phonon interaction in monolayer WS_2

The next studied property of the excitonic complexes in S-TMDs is related to **the exciton-phonon interaction**. It has been addressed at low temperature (T=5 K) **in monolayer WS_2** exfoliated on a Si/SiO_2 substrate using the unconventional RSE spectroscopy **[MM3]**. That method relies on tracing the Raman scattering response when the detection energy of the outgoing photons is fixed and the laser energy is being swept. The technique is analogous to PLE, but the analysed signal is due to the Raman scattering process under resonant conditions of excitation.

The optical response of the WS_2 ML measured as a function of the excitation energy and detected at three selected energies: 2.061 eV (in resonance with the negatively charged exciton), 2.078 eV, and 2.093 eV (in resonance with the neutral exciton) was analysed. The excitation energy of the laser was tuned in the range allowing for the observation of the first order phonon modes in resonance energy with both the neutral and charged excitons. It has been demonstrated that the RSE spectrum strongly depends on the selected detection energy. **The resonance of the outgoing light with the neutral exciton leads to an extremely rich RSE spectrum**, which displays several Raman scattering features not reported so far, while no clear effect on the associated background photoluminescence is observed. The obtained Raman spectrum also includes second order Raman scattering processes, *e.g.* $2A_1'$, $E' + A_1'$. It is important to mention that the intensity of the out-of-plane A_1' mode is comparable with the intensity of emission lines due to both charged and neutral A excitons, when it is observed exactly at the energy of the neutral A exciton. **A strong enhancement of the negatively charged exciton occurs** instead, when **the outgoing photons resonate with the negative trion.**

Dark excitons in S-TMD monolayers

It has been noted above that the SO interaction leading to the spin-split and spin-polarized subbands in both the CB and VB is particularly important in the S-TMD MLs. The SOS in the valence band in MLs is as large as few hundreds of meV while its counterpart in the conduction band has been predicted to be of the order of few tens of meV only [11]. As the SOS in the CB can be positive or negative [11,16], two distinct ordering of the conduction subbands are possible. Because optical transitions in S-TMDs do conserve the spin, different orderings of electronic bands in the CB have profound consequences on their optical properties. Depending on the sign of the SOS in the CB, the excitonic ground state can be **bright** (parallel spin configuration for the top VB and the lowest CB subbands between which the optical transition

is allowed) or **dark** (anti-parallel spin configuration and optically forbidden ground-state interband transition). The ordering of the electronic bands allows to establish **two families of S-TMD MLs: bright** (the excitonic ground state is optically active or bright) and **darkish** (the excitonic ground state is optically inactive or dark). Theoretical studies [11] predicted indeed that $MoSe_2$ and $MoTe_2$ MLs should be bright while WSe_2 and WS_2 MLs are darkish. There was no general consensus however concerning the bright or darkish character of a MoS_2 ML before our study.

In order to determine the bright or dark character of excitonic ground states, direct measurements of the dark exciton emission in four S-TMD MLs, *i.e.* MoS_2, $MoSe_2$, WS_2, and WSe_2, exfoliated on Si/SiO_2 substrates were performed by mixing the spin states of bright and dark excitons with the aid of in-plane magnetic field **[MM4]**. It was predicted theoretically that the application of **the in-plane magnetic field leads to an admixture of the bright neutral exciton state to the dark neutral** exciton state making the latter resonance possibly observable in the PL spectra [17]. Consequently, the low temperature PL spectra of the MLs as a function of the in-plane magnetic field up to 14 T have been recorded. The obtained results permitted to establish **the WS_2, WSe_2 and MoS_2 MLs as darkish materials**, *i.e.* the direct band gap systems but with a dark excitonic ground state, and **the $MoSe_2$ ML as a direct-band-gap bright material** with a bright exciton ground state. The bright-dark exciton splitting has been found to be of about 50 meV in WS_2 and WSe_2 MLs in fair agreement with theoretical expectations, but its value of about 100 meV derived for the MoS_2 ML is surprisingly large.

The investigations of the properties of dark excitonic states were also continued in high-quality WSe_2 ML encapsulated in hBN flakes, using the low-temperature PL experiments performed in magnetic fields applied in-plane and/or out-of-plane **[MM5]**. It was predicted theoretically that the dark neutral excitons states in S-TMD MLs exhibit a fine double structure comprising the so-called **grey** and **dark** complexes, which are characterized, correspondingly, by **an out-of-plane and zero excitonic dipole momenta**. In contrast, the bright neutral excitons are described by an in-plane dipole momentum. The PL experiments were conducted in the configuration of normal incidence of the excitation and the collected beams in reference to ML's plane. Consequently, the grey exciton emission was observed in the spectra measured at zero magnetic field due to a relatively high numerical aperture of the used microscope objective. When the in-plane magnetic field was applied, both the grey and dark excitons were observed in the PL spectra. The main obtained results, which are in good agreement with previous reports [18,19], include the following observations: (i) the grey exciton line is red-shifted by 38 meV from the bright neutral exciton peak; (ii) the energy separation between the grey and dark excitons is found to be of about 660 μeV; (iii) the grey and dark excitons lines are much narrower (~0.6 meV) than the bright exciton line (~4 meV), which indicates significantly longer lifetimes of the dark and grey excitons as compared to the lifetime of the bright exciton.

The polarization properties of magnetically brightened dark and grey excitons at a magnetic field of 10 T were also analysed. The emission lines due to both **the dark and grey excitons were linearly polarized** with the transition dipoles are oriented along and perpendicular to the applied in-plane magnetic field, respectively. To probe and manipulate the valley degree of freedom of the dark excitons, PL experiments were performed in both orientations of the magnetic field, *i.e.* in-plane and out-of-plane. It has been determined that while the in-plane magnetic field gives rise to linear polarizations of the grey and dark excitons, the application of the out-of-plane magnetic field leads to **a subsequent transformation of their polarization**

into elliptical. It allowed to determine **the g-factor of the grey/dark exciton** to be of about **-9.6**.

Excitonic ladder in S-TMD monolayers

Excitons are typically divided into so-called Frenkel and Wannier-Mott, which correspond to excitons formed in structures characterized by small and large dielectric constants, respectively. In semiconductors, which is also the case of S-TMDs, dielectric constants are generally large, which results in formation of **Wannier-Mott excitons** with a radius larger than the lattice spacing. These excitons are characterized by a series of hydrogen-like excitonic states, the so-called excitonic Rydberg series, labelled, like in a hydrogen atom using main and angular quantum numbers, *i.e.* 1*s*, 2*s*, 2*p*, 3*s*, 3*p*, 3*d*, and so on, where 1*s* is a ground state and higher states are excited states. In typical semiconductor 2D systems, it is expected that the energy ladder of excitons is described by a hydrogenic Rydberg series. In a typical optical experiment (PL and/or RC), only **the *s*-type Rydberg series of excitonic states** is measurable due to symmetry and it should follow a simple energy ladder: $\epsilon_n = -Ry^*/(n-0.5)^2$, n=1, 2, 3…, where Ry^* is the effective Rydberg energy. In the case of S-TMD MLs, a pronounced deviation from the 2D Rydberg series of excitonic states was demonstrated [13]. The main reason for that is the dielectric inhomogeneity of the 2D S-TMD structures. At large *e-h* distances, the Coulomb interaction scales with the dielectric response of the surrounding medium, whereas it appears to be significantly weakened at short *e-h* distances by usually stronger dielectric screening in the 2D plane. A common approach to account this effect for the excitonic spectra of S-TMD MLs refers to solutions of the Schrödinger equation, in which the *e-h* attraction is approximated by the Rytova-Keldysh (RK) potential. The problem however, can be solved only numerically.

The ladders of excitonic states have been investigated in four high quality S-TMD MLs, *i.e.* MoS_2, $MoSe_2$, WS_2, and WSe_2 encapsulated in hBN, using low-temperature PL experiment performed in the presence of a magnetic field **[MM6]**. It has been demonstrated that the energy spectrum of **Rydberg series of s-type excitonic states in S-TMD MLs** follows an energy ladder: $\boldsymbol{\epsilon_n = -Ry^*/(n+\delta)^2}$. The values of $Ry^*$and δ have been established from magneto-optical investigations for all the studied materials. In particular, the close to zero values of $\delta = -0.083$ for a WSe_2 ML and $\delta = -0.095$ for a MoS_2 ML have been found. Those make the ϵ_n spectrum for both materials very similar to that of a 3D hydrogen atom (δ=0). Moreover, the $\epsilon_n = -Ry^*/(n+\delta)^2$ ansatz has been well reproduced with an analytical approach in which the *e-h* potential was assumed to have the form of **a modified Kratzer potential**. It has been found that the effective $Ry^* = Ry(\mu/\varepsilon^2 m_0)$ energy is scaled by the dielectric constant ε of the surrounding hBN medium and by the reduced *e-h* mass μ, where $Ry = 13.6$ eV and m_0 is the free electron mass. The found Ry^* and δ parameters has allowed to estimate the excitonic binding energies (E_b) and reduced *e-h* masses in all these ML structures. The obtained E_b are around 170 meV and 220 meV for W- and Mo-based materials, respectively. Note that the proposed model may be applicable to other Coulomb bound states (*e.g.* donor and/or acceptor states), and also to other systems, such as colloidal platelets and 2D perovskites.

Tuning carrier concentration in monolayer MoS_2

The following aspect of my study was related to the influence of the quality of ML's surface on its properties. As it was discussed above, the encapsulation of S-TMD MLs in hBN flakes leads to the suppression of the inhomogeneous contribution to the linewidths of excitonic resonances. Another approach to modify the surface of S-TMDs thin layers is to subject them to a specific chemical treatment. Notably, it was demonstrated that treating MoS_2 MLs with

TFSI, referred to as a superacid, results in a considerable increase of the related PL intensity [20].

In order to deepen the understanding of the superacid effect on S-TMD MLs, **the optical properties of MoS_2 ML** exfoliated on Si/SiO_2 substrate and subjected to four-fold **superacid treatment** have been investigated using PL, RC, and Raman scattering techniques **[MM7]**. The effect of superacid treatment on the PL and RC spectra measured at T=5 K and 300 K has been found to be the most prominent after the first round. For room-temperature experiments, there are apparent significant shifts of about 20-30 meV of the observed emission lines and absorption dips in the vicinity of the A and B excitons after the first passivation process. It is ascribed to the vanishing of the resonances of charged excitonic complexes due to the superacid treatment. The influence of successive passivation steps (starting from the second one) on the PL and RC spectra is less pronounced and mostly appears as monotonic redshifts of both the A and B resonances (the total shift amounts to about 10 meV after the fourth passivation round). In the case of low temperature measurements, the superacid effect is more distinct due to smaller linewidths of excitonic resonances. Well-resolved features are observed for both the neutral and charged exciton in the vicinity of the A exciton. Similarly to the room-temperature behaviour, the PL signal coming from the charged exciton complex is quenched as a result of the superacid treatment leaving the neutral-exciton emission as a main feature of the spectrum. These **two observations** have been explained in terms of significant decrease of **high non-intentional doping of the as-exfoliated MoS_2 ML** (untreated by superacid) combined with a reduced influence of **the quantum-confined Stark effect** reflecting the modification of the built-in vertical electric field in the structure due to passivation of defects on the sample surface.

The superacid influence on the resonant conditions of Raman scattering has been also investigated. After four superacid treatment rounds, the energy of the neutral A exciton cumulatively downshifted by about 30 meV and became comparable to the energy of the charged A exciton in the as-exfoliated MoS_2 ML. An enhancement of Raman scattering at resonant excitation in the vicinity of the neutral A exciton was clearly observed for both the out-of-plane A_1' and in-plane E' modes. On the contrary, when the excitation was in resonance with a corresponding trion, the Raman scattering features became hardly visible. Note that this result is similar to the one observed for the RSE experiment performed on WS_2 ML and discussed above.

In conclusion, the presented achievement has provided several new results, which broaden our understanding of elementary interactions between charge carriers in S-TMDs. The most important, in the author's own opinion, are investigations of dark excitonic states and the proposed model of excitonic ladder in the S-TMD MLs, which are crucial for potential future opto-electronic applications.

Moreover, it is demonstrated that the presented scientific achievement provides a significant contribution to the development of solid state physics. That statement is supported by numerous citations of the works comprising the achievement, *i.e.* the total number of citations of works [MM1]-[MM7] without self-citations equal to 256 (07.10.2021).

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5. Presentation of significant scientific or artistic activity carried out at more than one university, scientific or cultural institution, especially at foreign institutions

Internship in Grenoble (35 months)

After obtaining a PhD degree, I accepted a postdoctoral fellowship in the group of dr Marek Potemski at the National Laboratory of High Magnetic Fields in Grenoble, France. The decision to continue my work in that group was related to a complete change in the research subject of the postdoctoral fellowship in relation to doctoral studies. I was employed as a researcher for 35 months in the project entitled "*Magneto-optics of layered materials: exploring many-body physics in electronic systems with unconventional bands*" financed by the European Research Council under the Advanced Grant program.

My research tasks during the internship in Grenoble were related to the study of optical properties of 2D layered materials, in particular thin layers of S-TMDs. I was employing a wide spectrum of experimental techniques, including measurements of photoluminescence,

photoluminescence excitation, reflection contrast and Raman scattering spectra with spatial resolution of the order of a few micrometers. Moreover, these experiments were carried out under various external conditions, *e.g.* as a function of temperature (4.2 K - 300 K), in an external magnetic field (up to 14 T with the use of a superconducting coil and up to 30 T with the use of a resistive magnet) in two configurations: Faraday and Voigt and as a function of the applied electric field in the case of gated structures.

My experimental results obtained during the postdoctoral fellowship (as a main or a participating investigator) contributed to the publication of over 24 articles devoted to properties of 2D materials, which were published in 2015-2019 in such journals as: *Nature Communications, Nano Letters, 2D Materials, Nanoscale, and Nanophotonics*.

Internship in Manchester (6 months)

After returning to Poland, my employment at the Faculty of Physics, University of Warsaw was associated with realization of my project "*Exciton-phonon interaction in thin layers of transition metal monochalcogenides*" financed by the National Science Centre under the Sonatina program. The project was carried out in cooperation with prof. Amalia Patane from the University of Nothingham and dr Roman Gorbachev from the University of Manchester.

The main part of that project was a 6-month scientific internship in the group of dr Roman Gorbachev at the National Graphene Institute (NGI), the University of Manchester, United Kingdom. The aim of the internship was to learn the exfoliation and deterministic transfer of samples containing thin layers of selected metal monochalcogenides under controlled conditions using a glove box equipped with a system for deterministic transfer of thin flakes of layered materials. As a result of that work, I created a number of samples containing GaSe and InSe thin layers enclosed in hexagonal BN flakes. The investigations of these samples contributed to the publication of an article in *Faraday Discussions*.

Moreover, during this internship, I constructed at the NGI a system for measurements of second harmonic generation on thin flakes of layered materials. This technique allows to determine the twist angles between crystallographic axes of the thin layers stacked on top of each other to create a more complex van der Waals structure. With the aid of this system, I determined the twist angles between $MoSe_2$ and WS_2 monolayers in a series of artificial bilayers. The study of the optical properties of these samples was published in *Nature*.

6. Presentation of teaching and organizational achievements as well as achievements in popularization of science or art

Supervision over diploma theses

Msc theses:

- Supervision of a MSc work of Ms Dorota Staszczuk entitled "*Raman spectroscopy of gallium monochalcogenides*" (2018, Faculty of Physics, University of Warsaw).
- Supervision of a MSc work of Mr Marcin Osiekowicz entitled "*Raman spectroscopy of indium selenide*" (2019, Faculty of Physics, University of Warsaw).
- Supervision of an on-going work of Ms Łucja Kipczak entitled "*Optical spectroscopy of thin layers of rhenium diselenide ($ReSe_2$)*" (2021, Faculty of Physics, University of Warsaw).

PhD theses:

- Co-supervision (promotor pomocniczy) of a PhD work of dr Magdalena Grzeszczyk entitled "*Raman scattering in thin layers of molybdenum ditelluride ($MoTe_2$)*" (2020, Faculty of Physics, University of Warsaw).
- Co-supervision (promotor pomocniczy) of an on-going PhD work of Ms Małgorzata Zinkiewicz entitled "*Excitonic complexes in monolayers of transition metal dichalcogenides*".
- Co-supervision (promotor pomocniczy) of an on-going PhD work of Ms Katarzyna Olkowska-Pucko.
- Co-supervision (promotor pomocniczy) of an on-going PhD work of Ms Łucja Kipczak.

Teaching

Teaching before obtaining PhD degree

- Laboratory of measurement techniques (laboratory),
- Physical and electronic laboratory (laboratory),
- Physics II (electricity and magnetism) (demonstrations for the lecture).

Teaching after obtaining PhD degree

- Fundamentals of physics II (electricity and magnetism) (class exercises),
- Fundamentals of electromagnetism (class exercises),
- Introduction to optics and condensed matter physics (class exercises),
- Modern methods of experimental condensed matter physics and optics (class exercises),
- Laboratory of measurement techniques for astronomy students (laboratory).
- B. Sc. degree student seminar

Popularization of science

I was involved in popularizing activities, which include:

- participation in the committee of the 6th (2012) and 7th (2013) editions of the National Physical Competition "*Poszukiwanie talentów*".
- organization of workshops entitled "*From macro- to nano- in three simple steps*" as part of the 23rd Science Festival, September 25th – 27th, 2019.
- organization of workshops entitled "*From macro- to nano- in three simple steps*" as part of the 24th Science Festival, online, September 22nd, 2020.

Organization contribution

- member of the Scientific Council of Physical Sciences Discipline at University of Warsaw (2019-present).
- member of organizing committee of the scientific workshop entitled *Joint annual meeting International Research Projects, CNRS "2DM" and "TeraMIR"*, online, November 30th – December 1st, 2020.

7. Apart from information set out in 1-6 above, the applicant may include other information about his/her professional career, which he/she deems important.

Scholarships

- 2010 – 2014 – **PhD scholarship** within the European Union project "*International PhD studies at the Faculty of Physics UW*" founded by the Foundation for Polish Science.
- 2018 – 2021 – **scholarship for outstanding young scientists** of Minister of Science and Higher Education, Poland.

Awards

- 2019 – **The Rector Prize** (II degree) of University of Warsaw.
- 2020 – **The IOP Outstanding Reviewer** award for 2D Materials for 2019.
- 2021 – **The Rector Team Prize** of University of Warsaw (part 1/3).

Podpisany elektronicznie przez
Maciej Molas; Uniwersytet Warszawski
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(Applicant's signature)