30 December 2016

Summary of professional accomplishments

1. First and last name: **Wojciech Pacuski**

2. Academic degrees:

y. 2003 - Master of Science, University of Warsaw, Faculty of Physics,; master thesis: „Magnetospectroscopy of doped quantum wells".
Supervisor: prof. dr hab. Piotr Kossacki.

y. 2007, PhD, University of Warsaw, Faculty of Physics and Université Joseph Fourier (Grenoble 1), double PhD in frame of cotutelle programme.

Thesis: „Optical spectroscopy of wide gap diluted magnetic semiconductors based on ZnO and GaN"

Supervisors: prof. Joel Cibert and prof. dr hab. Piotr Kossacki.

3. Employment:

2008-2009 post-doc in group of Prof. Detlef Hommel, at University of Bremen. Scholarships of DAAD, Humboldt Foundation, and Marie Curie program, 20 moths in Germany

since **2009** – Assistant Professor (adjunct) at Faculty of Physics, University of Warsaw

4. Scientific achievement as defined by the Act "Ustawa o stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki (Dz. U. nr 65, poz. 595 ze zm.)"

a) Title of the achievement
(series of thematically related publications):

Design, fabrication and optical study of new microcavities and quantum structures incorporating magnetic ions

b) List of publications constituting scientific achievement:

H1. **W. Pacuski**, C. Kruse, S. Figge, and D. Hommel,

"High-reflectivity broadband distributed Bragg reflector lattice matched to ZnTe",

Applied Physics Letters 94, 191108 (2009).

H2. C. Kruse, **W. Pacuski**, T. Jakubczyk, J. Kobak, J. A. Gaj, K. Frank, M. Schowalter, A. Rosenauer, M. Florian, F. Jahnke, and D. Hommel,

"Monolithic ZnTe-based pillar microcavities containing CdTe quantum dots",

Nanotechnology 22, 285204 (2011).

H3. **W. Pacuski**, T. Jakubczyk, C. Kruse, J. Kobak, T. Kazimierczuk, M. Goryca, A. Golnik, P. Kossacki, M. Wiater, P. Wojnar, G. Karczewski, T. Wojtowicz, D. Hommel,

"Micropillar cavity containing a CdTe quantum dot with a single manganese ion",

Crystal Growth & Design 14, 988 (2014).

H4. J. Kobak, T. Smoleński, M. Goryca, M. Papaj, K. Gietka, A. Bogucki, M. Koperski, J.-G. Rousset, J. Suffczyński, E. Janik, M. Nawrocki, A. Golnik, P. Kossacki, **W. Pacuski**,

"Designing quantum dots for solotronics",

Nature Communications 5, 3191 (2014).

H5. **W. Pacuski**,

"Individual cobalt and manganese ions in semiconductor quantum dots and photonic structures",

Proc. SPIE 9167, Spintronics VII, 91670K (2014); doi:10.1117/12.2063774.

H6. T. Smoleński, **W. Pacuski**, M. Goryca, M. Nawrocki, A. Golnik, and P. Kossacki,

"Optical spin orientation of an individual Mn^{2+} ion in a CdSe/ZnSe quantum dot",

Physical Review B 91, 045306 (2015).

H7. J.-G. Rousset, B. Piętka, M. Król, R. Mirek, K. Lekenta, J. Szczytko, J. Borysiuk, J. Suffczyński, T. Kazimierczuk, M. Goryca, T. Smoleński, P. Kossacki, M. Nawrocki, **W. Pacuski**,

"Strong coupling and polariton lasing in Te based microcavities embedding (Cd,Zn)Te quantum wells",

Applied Physics Letters 107, 201109 (2015).

H8. T. Smoleński, T. Kazimierczuk, J. Kobak, M. Goryca, A. Golnik, P. Kossacki, **W. Pacuski**,

"Magnetic Ground State of an Individual Fe^{2+} Ion in Strained Semiconductor Nanostructure"

Nature Communications 7, 10484 (2016).

H9. J.-G. Rousset, J. Kobak, E. Janik, M. Parlinska-Wojtan, T. Slupinski, A. Golnik, P. Kossacki, M. Nawrocki, **W. Pacuski**,

"Distributed Bragg reflectors obtained by combining Se and Te compounds: Influence on the luminescence from CdTe quantum dots",

Journal of Applied Physics 119, 183105 (2016).

c) Objectives and results

Key to references:

- Works with a letter H, e.g. [H1], [H2], are publications constituting the scientific achievement.
- Works with a letter S, e.g. [S1], [S2], are supplementary publications related to the scientific achievement, but not constituting scientific achievement. They are listed in section „Description of other scientific achievements".
- Works [1], [2], are other references, listed at the end.

1.0 Introdcution

1.1 Introduction on designing distributed Bragg reflectors, microcavities, and photonic structures

Distributed Bragg reflectors (DBRs) are structures with very high reflection, made out of alternating layers with low and high refractive index. Condition for constructive interference of the reflected light with wavelength λ (in air) requires $\lambda/4n$ thickness of each layer in the DBR, where n is the refractive index. Two DBRs placed close to each other (e.g. $\lambda/4n$) form a microcavity that can be used to enhance and to guide emission of low dimensional structures such as quantum dots (QDs) and quantum wells (QWs). However, the practical combination of microcavities with low-dimensional semiconductor structures requires facing several technical problems. Firstly, achieving high quality quantum structures exhibiting narrow spectral lines is possible only if they are grown on lattice-matched substrates or buffers. Therefore lattice constant of DBRs should be matched to quantum structures. Secondly, to avoid relaxation, high refractive index layer should be lattice matched to low refractive index layer and both layers should be transparent in the spectral region of low dimensional structures emission. Finally, combination of very different materials in DBRs and quantum structures can be limited due to accessibility of elements which can be introduced to one growth chamber or due to danger of cross contamination.

1.2 Reported microcavity systems and this work's objectives

Aim of series of publications presented here was understanding effects of exchange interactions in low dimensional and photonic structures. More precisely, the aim was to develop technology of new photonic and low dimensional structures doped with magnetic ions and to apply new structures to magneto-optical study of effect of exchange interaction between magnetic ions and confined carriers. The most interesting was fabrication of systems where exchange interaction can be observed for single particles: single electrons, single holes and single magnetic ions. The first milestone, defined in introduction of work [H1], was to produce the first microcavity with QDs doped with single magnetic ions. Although before my works there were several reports about good material systems for fabrication of microcavities with QWs [1,2,3,4,5] and QDs [6,7,8,9], but their application to spintronics and magneto-optical investigations of quantum structures exhibiting *s,p-d* exchange interaction were limited. Most of investigations on semiconductor photonic structures is based on arsenides, so on microcavities made out of Ga, Al, In, and As. In arsenides, magnetic field induced splitting is relatively small and cannot be enhanced by *s,p-d* exchange interaction with transition metal ions because doping arsenides with group II elements leads to increase of carrier concentration and to general degradation of optical properties: broadening of spectral lines and quenching of excitonic luminescence [10,11]. Therefore assumed objectives (understanding effects of exchange interactions in low dimensional and photonic structures) can be rather reached with II-VI semiconductor systems, where at least some magnetic ions (e.g. Mn) does not induce significant optical degradation. Also in II-VI semiconductors doped with magnetic ions some broadening of spectral lines is observed, but typically this effect is not hindering exchange splittings. However any of former II-VI microcavity systems was optimized to magneto-optical investigations. The highest quality factor Q was obtained for microcavities made out of Zn(S,Se) (high refractive index layer) and lattice matched superlattice MgS/(Zn,Cd)Se (low refractive index layer) [7,12]. Inside such a microcavity one can effectively place (Zn,Cd)Se/ZnSe QWs or CdSe/ZnSe QDs. However, the only lab which was producing such structures (MBE lab at University of Bremen) had no Mn source in II-VI growth chamber, and it was not clear if it is reasonable to replace one of molecular sources by Mn source, because before my research, luminescence of Mn doped (Zn,Cd)Se/ZnSe and CdSe/ZnSe structures was considered as effectively quenched due to nonradiative intraionic transitions of Mn. Other high quality II-VI microcavity system was based on alternating layers of (Cd,Mg)Te and (Cd,Mn)Te [3,13,14,15,16,17,18,19]. Inside such microcavities, one can place CdTe and even (Cd,Mn)Te QWs, what opens possibility of using *s,p-d* exchange interaction for enhancing Zeeman splitting and for photon exciton tuning. However, such structure is not yet optimal for magneto-optical investigations, because manganese is present in both QWs and in the DBR layers, so it is difficult to distinguish various Mn-related magneto-optical effects. So there was no good microcavity for (Cd,Mn)Te QWs. And for other interesting quantum system: CdTe/ZnTe QDs with a single Mn [20] ion (many years the only system of a QD with a single magnetic ion), there was no appropriate microcavity system. Therefore, I started presented here series of works by developing building blocks of microcavities, which can include QDs CdTe/ZnTe, and in the next steps I extended number of quantum dot systems which can be used for studying exchange interaction with various kinds of individual magnetic ions.

2.0 Results

2.1 Invention of Distributed Bragg reflector lattice matched to ZnTe [H1]

Construction of microcavity with CdTe/ZnTe QDs requires distributed Bragg reflector, which consist of layers lattice matched to ZnTe. Such layers should exhibit energy gap greater or equal to ZnTe and their refractive index should be significant. Natural candidate for high refractive index (low band gap) material is just ZnTe, but challenging was designing II-VI semiconductor with significantly lower refractive index and lattice parameter of ZnTe. It cannot be binary or even ternary compound, eventually quaternary (Zn,Mg)(Te,Se) could be in principle fitted to the lattice parameter of ZnTe, but growth of thick structures with such a complex compound is impractical [21], what was verified at University of Bremen before my research stage there. After analysis of reported ZnSe-based Bragg reflectors [8], I was convinced that I should seriously consider short period superlattices and digital alloys as candidates for low refractive index material lattice matched to ZnTe. Morover, I realized that my new superlattice should consist of more than two components (used before). I proposed a short period superlattice ZnTe/MgSe/MgTe/ZnTe with layer thickness in range of a few monolayers [H1]. From a practical point of view, invented superlattice is a new material with several advantages [comparing to e.g. (Zn,Mg)(Te,Se)] : (i) it consist of binary compounds, (ii) its lattice parameter can be easily adjusted by setting ratio of MgSe and MgTe layer thickness, (iii) its energy gap can be tuned in wide range from energy gap of ZnTe in green spectral range to near UV, and finally (iv), its refractive index can be even 20% lower than refractive index of ZnTe, (v) it can be stable in air for years.

I evidenced good properties of the new ZnTe/MgSe/MgTe/ZnTe superlattice by using it to molecular beam epitaxy (MBE) growth of DBR. Only 15 DBR pairs exhibited over 99% of reflection and reflection spectrum was in agreement with simulation assuming previously determined refractive indices. Apart from publication in APL [H1], the invention was submitted to European Patent Office (№ EP 2211431 A1). The idea was also appreciated by the Humboldt Foundation, which awarded me a grant (Humboldt Research Fellowship) for realization of proposed DBRs. Nowadays, three MBE laboratories are using the invented superlattice either as a material with low refractive index [H2,H3,H9, S1,S2,S3,S7] either as a barrier material for CdTe QDs [22].

2.2 Fabrication of microcavity with CdTe QDs [H2]

To evidence functionality of new DBR, I grew series of microcavities consisting of 20 bottom DBR pairs, λ/n long cavity including CdTe/ZnTe QDs in the middle, and finally 18 DBR pairs on top [H2]. Reflection spectrum of new microcavities was in almost perfect agreement with a simulation, quality factor of the cavity exceeded 3000 and there was spectral matching of cavity mode with emission energy of CdTe/ZnTe QDs. Next, using focused ion beam (FIB) we etched a series of micropillars, which are photonic structures with interesting optical properties. In work [H2] we presented experimental and theoretical energy structure of three dimensional cavity modes. In next works basing on this structures we presented spatial distribution of cavity modes [S3] and the Purcell effect [S2] – shortening of emission decay time from QDs. The most spectacular application of our micropillars was fabrication of cavity with radial distributed Bragg reflectors. Such reflectors stop leaky modes – emission perpendicular to pillar axis. Thanks to this effect, we reached elongation of emission decay time of QDs

[S1]. In future, our development could be helpful in reaching near 100% of efficiency for photon extraction from semiconductor structures.

2.3 Micropillar cavity with a QD containing a single Mn ion [H3]

Development of ZnTe-based DBR [H1] opened possibility of introduction of a QD with a single Mn ion to the microcavity. However, at University of Bremen where I was working that time, there was missing Mn source in II-VI MBE growth chamber. Therefore I needed to develop procedure of multistep microcavity growth. After analysis of simulations I decided to grow first bottom DBR and ¼ of the cavity. This was covered by amorphous tellurium to protect the surface. Structure was transported to Institute of Physics PAN, where was performed growth of next ¼ of the cavity, CdTe/ZnTe QDs contacting Mn ions, and once more about ¼ of the cavity. Once more structure was covered by amorphous tellurium and transported back to Bremen. Critical point of the next step was precise growth of remaining part of the cavity. Thanks to simulation prepared in advance, I knew how to recognize actual thickness of the last layer by observation of in-situ reflectivity. Consequently, the cavity was closed at correct thickness and top DBR was properly gown. Further, the structure was used to etched micropillars with diameters of a few micrometers, and larger square mesas with about 20 micrometer long sides. Using low temperature microphotoluminescence I checked that there is no QD with a single Mn ion in micropillars, but I found such a QD in large mesa. I determined precisely position of the QD and using two more steps of etching I fabricated a square micropillar cavity with side equal to 4 micrometers and I verified that a QD with a single Mn is still there, unaffected.

Application of microcavity structures with QDs containing individual Mn ion can be resonance spectroscopy or four wave mixing [23]. Potentially, such structures could be used for controlling occupancy and energy structure of individual dopants due to control of lifetime excitons coupled to various dopant states. In the more distant future such structures could be used for controlled interaction of spatially separated magnetic ions in different quantum dots, but one microcavity [24]. Therefore studied system would be a good candidate for qubits of future quantum computers

Side, but significant effect of labor-intensive fabrication of a pillar cavity with a QD and a single Mn ion was gaining knowledge about designing optimal MBE machines for this kind of projects. This was a basis of later achievements presented in this work.

2.4 Establishment of MBE laboratory at University of Warsaw

Establishment of the first, and so far the only one, MBE laboratory at University of Warsaw was preceded by a few years preparation. I and dr. Tomasz Słupiński, who is now head of III-V part of the laboratory, were trained in foreign MBE laboratories. We visited MBE labs with interesting for us technologies, we consulted our plans with experienced researchers and with companies producing MBE machines. Finally we decided to order double chamber MBE, the first chamber for II-VI semiconductors, the second one for III-V semiconductors. In each growth chamber there are 10 ports for molecular sources. The first sample in II-VI part of the lab (which is under my supervision) was grown in January 2012, 5 years after preparation started. Establishment of new laboratory and reception of grant Lider from NCBR were a good opportunity to form a new scientific team, including in the first place two PhD students working under my co-supervision. PhD student working on QDs is mgr Jakub Kobak, and his main supervisor is prof. Andrzej Golnik, PhD student working on microcavities is mgr Jean-Guy Rousset, and his main supervisor is prof. Michał Nawrocki. We started growth from semiconductor layers: ZnSe, ZnTe, CdTe on GaAs substrates. After growing just a few layers of each binary semiconductor we reached reasonable optical quality, e.g. sharp spectral lines of excitonic transitions. Therefore after a few weeks we started growth of low-dimensional structures, such as quantum wells [S10] and quantum dots [S4,S5,S6,S9], and diluted magnetic semiconductors with Mn and Co [S8]. For such structures we also obtained reasonable results in a few weeks, and we were ready to start growth of novel structures which are part of achievement presented in this work.

2.5 Novel systems of QDs with individual magnetic ions [H4, H6, H8]

Before we started growth of QDs with individual magnetic ions, there were only two systems of this kind: QDs CdTe/ZnTe [**Błąd! Nie zdefiniowano zakładki.**] and InAs/GaAs [25], both with individual Mn. Development of new systems was discouraged by experience of bad optical properties of semiconductor systems doped with other ions than Mn: broadening of spectral lines, formation of precipitates, and quenching of excitonic emission due by nonradiative recombination introduced by intraionic transitions of magnetic ions. Only Mn exhibit intraionic levels energy high enough (about 2.1 eV) to block energy relaxation of excitons in semiconductors with relatively low energy gap such as CdTe and InAs. However, for wide band gap semiconductors such as ZnSe or ZnO, transfer of energy from excitons to magnetic ions is observed for all transition metals, even for Mn [26,27,28,29,30,31,32,33]. Therefore I made quite risky decision to work on QDs doped with cobalt and to dop with Mn QDs CdSe/ZnSe.

However, quenching appeared to be not so important in case of single dopants in QDs and already in the first sample with QDs CdTe:Co/ZnTe I found bright QDs with individual cobalt ions. Thank to this discovery, in work [H4] we were able to report spectrum of a QD with a single cobalt ion. In such a QD, exciton line is split to four components due to four possible spin projections of Co^{2+} ($S = 3/2$) ion on growth axis (being quantization axis of excitons). Intensity of out and inner lines is different due to different energy and occupancy of Co^{2+} spin states. It appears that levels with spin projection $\pm 3/2$ are at lower energy than states with spin projection $\pm 1/2$, so outer lines are more intense than inner lines. Identification of spectral lines of QDs with a single Co^{2+} ion has been confirmed by magneto-photoluminescence measurements and by the model which is similar to the model of exciton–Mn system, but it includes additionally complex anisotropy of Co^{2+} ion.

To quantify actual strength of photoluminescence quenching in QDs doped with a single cobalt ions, we measured and compared exciton decay time of QD with and without single cobalt ion. We didn't find significant differences, therefore we concluded that if there is a quenching, it is weak, at present stage - negligible [H4]. Similarly we concluded optical study of our second novel system : QD CdSe/ZnSe with a single Mn ion [H4], where also photoluminescence quenching was negligible.

Despite system of a CdSe/ZnSe QD with a single Mn is quite similar to well known system of CdTe/ZnTe QD with a single Mn, we observed a few interesting and new properties. Firstly, optical orientation of Mn spin is here relatively simple – it is enough to excited sample nonresonantly with polarized light [H6]. Secondly, relaxation time of Mn is about order of magnitude longer in selenide QD [H4] than in telluride QD [34]. Since spin-orbit interaction is in general responsible for relaxation, we interpret this as consequence of weaker spin-orbit interaction in selenides than in tellurides (selenium is lighter element than tellurium). This effect inspired us to one more idea [published in H4] related to another effect which shorten relaxation time (T_2) - interaction of electronic and nuclear spin. Since photoluminescence quenching is not a problem, we can seriously consider introduction to QD individual ion of transition metal without nuclear spin [H4]. For Mn and Co all accessible isotopes exhibit nonzero nuclear spin, but e.g. for Fe 98% of atoms (natural abundance) exhibit zero nuclear spin. One could argue that for coherent relaxation time (T_1) nuclear spin is so slowly changing that relaxation should be not affected, but in such approach nuclear spin is anyhow an obstacle, because we do not have optical control over nuclear spin of transition metal ions in QDs.

Therefore I decided to fabricate and study one more novel system - CdSe/ZnSe QD with a single iron ion [H8]. It would be interesting to observe Fe^{3+} ion in our QD, so ion with the same electronic configuration (d^5) as Mn^{2+}. Due to half filed *d*-shell, such a configuration exhibits zero orbital momentum what results in the longest accessible relaxation time [35]. Also, for odd number (5) of *d*-shell electrons degenerate (therefore magnetic) ground state is protected by symmetry. However, in II-VI semiconductors the most probable electronic configuration of iron is Fe^{2+}(d^6). Such a configuration enhances effects related to spin-orbit interaction, e.g. sensitivity to strain. Moreover, even number of electrons cannot guarantee degenerate ground state. Single, nondegenerate ground state exhibit zero spin so it is nonmagnetic [36,37,38,39,40,41,42,43,44,45]. Such a spin configuration is observed for Fe^{2+} in all zinc blende and wurtzite semiconductors. Higher energy states are 2 meV from the ground state, so at least in superfluid helium temperatures they contribution to spin effects is negligible. Therefore one can expect that single Fe^{2+} will not affect excitonic spectrum of a QD. However our experimental ad theoretical study negatively verified this hypothesis. Due to epitaxial strain of a QD (lattice mismatch of CdSe and ZnSe) spin configuration of Fe^{2+} is modified and as a consequence, ground state is doubly degenerate and it consist of states with spin projection ± 2 [H8]. In agreement with theoretical considerations we observe small splitting of such ground state, but this splitting is much smaller than e.g. energy of exchange interaction with carriers, so it is only weakly affecting excitonic spectrum of a QD with a single iron ion. One could doubt if such state can be optically oriented, but our experiment shows that although at zero field optical orientation is not possible, it is enough to apply B = 0.2 T to realize efficient optical orientation of single Fe^{2+} spin, what make a QD with a single iron ion almost a perfect, nuclear spin free, two level system for coherent optical manipulation [H8].

2.6 Novel microcavities for investigation of quantum wells and quantum dots containing magnetic ions [H5,H7,H9]

During preparation of the work [H3] about microcavity with a QD and single Mn ion we considered that the most difficult technological challenge was related to the transportation of DBRs between MBE machines with appropriate molecular sources. Therefore we expected that similar projects will be much simpler in new MBE at University of Warsaw, where all needed sources can be installed in one growth chamber. That was over-optimistic, many different molecular sources in a growth chamber increases risk of cross contamination. In particular it appeared that combination of ZnTe/MgSe/ZnTe/MgTe-based DBRs with CdTe/ZnTe QDs leads to such a broadening of QDs lines that it is not possible to resolve lines of a QD with a single Mn ion [H9]. After chemical analysis of cross-sectional image and after technological experiments we attributed this broadening to preferential incorporation of Se instead of Te in CdTe QDs [H9,S6], even if Se source is in principle closed. We found that this can be eliminated by delaying growth of QDs after finishing bottom DBR. 24 h after Se source is cooled down growth chamber is clean enough to grow Se-free CdTe QDs [H9]. Structure prepared with this method exhibits excellent optical properties including sharp spectral lines which allow us to resolve lines of a QD with single Mn ion [H9]. However, many-hours-long break in epitaxial growth is impractical and lead to similar technical challenges to reported in work [H3]. Therefore I proposed to mgr. Jean-Guy Rousse development of one more microcavity system, based on tellurium only, which avoids selenium.

When we were considering various materials for construction of new microcavities, we realized that there is very promising set of materials lattice matched to MgTe. If we choose Cd and Zn concentration of (Cd,Zn)Te in such a way that this compound is lattice matched to MgTe, then adding Mg will not change lattice parameter of (Cd,Zn,Mg)Te, only energy gap and refractive index. Using this method we obtain three materials with the same lattice parameter: (Cd,Zn)Te QW, (Cd,Zn,Mg)Te with low Mg content Mg (about 10%) – high refractive index layer and barrier for QW, (Cd,Zn,Mg)Te with high Mg content Mg (about 50%) – low refractive index layer of the DBR. Comparing to previous solutions, in our structure we avoided also Mn, which was used previously for high refractive index layers [3,13] and which is affecting magneto-optical spectra, so it sometimes difficult to distinguish between magneto-optical effect related to QWs and to photonic structures. Good optical properties of our novel system has been proved in work [H7] where we have shown strong coupling and polariton lasing from microcavity based on (Cd,Zn,Mg)Te and containing Mn ions only in QWs. There is also a simple method to extend our system to spectroscopy of QDs, because instead of CdTe or (Cd,Zn)Te QW, we can grow very thin (about 1 nm) layer of CdTe, which lead to formation of CdTe QDs. Since such QDs can exhibit emission in spectral range of Al_2O_3:Te laser, our system is very promising for coherent and resonant spectroscopy of QDs with single magnetic ions [23]. Proposal of this idea and critical analysis of other ideas for photonic structures with individual magnetic ions are summarized in a review paper [H5].

3.0 Summary of scientific achievement presented in this work

Design and fabrication of novel semiconductor structures:

- Distributed Bragg Reflector lattice matched to ZnTe [H1]
- Distributed Bragg Reflector lattice matched to MgTe [H7]
- Microcavities with CdTe QDs [H2], including the first microcavity with QDs containing single magnetic ions [H3,H5,H9]
- The first QDs with individual cobalt [H4] and iron [H8]
- The first QDs with individual magnetic ions with zero nuclear spin [H8]
- The first QDs based on selenides and containing individual magnetic ions [H4]

Novel structures allowed us to obtain high degree of control over individual dopants, confined carriers and interference effects. Thanks to preparation of above structures we understand and solved several technical issues related to combination of various semiconductor layers.

Optical spectroscopy of novel structures resulted in following discoveries:

- Negligible effect of quenching of excitonic photoluminescence in QDs doped with single magnetic ions [H4].
- Good optical properties, including polariton lasing, for microcavities with QWs containing magnetic ions [H7]
- Complex anisotropy of Co^{2+} induced by epitaxial strain [H4].

- Elongation of relaxation time of individual magnetic ions in semiconductors with weak spin-orbit interaction [H4].
- Inducing magnetic properties of Fe^{2+} due to strain of nanostructures [H8]
- Simple method for optical orientation of individual magnetic ions in QDs CdSe/ZnSe [H6,H8]

3.1 The importance of presented scientific achievement for the field of solotronics and photonics

- Opening of new possibilities of designing, fabrication and study of QDs with individual magnetic ions: my pioneering works motivated researchers from other groups to work on wide gap QDs with individual magnetic ions [46] and to continue search of nuclear spin free systems of a QD with single magnetic ion [47,48].
- Development of technologies and fabrication of structures beyond the presented achievement: for semimagnetic polaritons, coupled microcavities, Purcell effect, anisotropy of zero-dimensional confined carriers, four wave mixing on individual QDs and dopants [S1-S10,23,49,50].

Description of other scientific achievements

Other scientific achievements can be dived into three groups: a) related to structures presented in main scientific achievement, b) related to subject of PhD thesis c) related to subject of master thesis

a) Selected works based on technologies and structures presented in main scientific achievement:

[S1] T. Jakubczyk, H. Franke, T. Smoleński, M. Ściesiek, **W. Pacuski**, A. Golnik, R. Schmidt-Grund, M. Grundmann, C. Kruse, D. Hommel, P. Kossacki, "Inhibition and Enhancement of the Spontaneous Emission of Quantum Dots in Micropillar Cavities with Radial Distributed Bragg Reflectors", **ACS Nano** 8, 9970 (2014).

[S2] T. Jakubczyk, **W. Pacuski**, T. Smoleński, A. Golnik, M. Florian, F. Jahnke, C. Kruse, D. Hommel, P. Kossacki, "Pronounced Purcell enhancement of spontaneous emission in CdTe/ZnTe quantum dots embedded in micropillar cavities", **Applied Physics Letters** 101, 132105 (2012).

[S3] T. Jakubczyk, **W. Pacuski**, T. Smoleński, A. Golnik, M. Florian, F. Jahnke, C. Kruse, D. Hommel, P. Kossacki, "Light-matter coupling in ZnTe-based micropillar cavities containing CdTe quantum dots", **Journal of Applied Physics** 113, 136504 (2013).

[S4] K. Sawicki, F. K. Malinowski, K. Gałkowski, T. Jakubczyk, P. Kossacki, **W. Pacuski**, J. Suffczyński, "Single-color, in situ photolithography marking of individual CdTe/ZnTe quantum dots containing a single Mn^{2+} ion", **Applied Physics Letters** 106, 012101 (2015).

[S5] A. Bogucki, T. Smoleński, M. Goryca, T. Kazimierczuk, J. Kobak, **W. Pacuski**, P. Wojnar, and P. Kossacki, "Anisotropy of in-plane hole g factor in CdTe/ZnTe quantum dots", **Physical Review B** 93, 235410 (2016).

[S6] M. Ściesiek, J. Suffczyński, **W. Pacuski**, M. Parlińska-Wojtan, T. Smoleński, P. Kossacki, A. Golnik, "Effect of electron-hole separation on optical properties of individual Cd(Se,Te) quantum dots", **Physical Review B** 93, 195313 (2016).

[S7] J.-G. Rousset, J. Kobak, E. Janik, T. Jakubczyk, R. Rudniewski, P. Piotrowski, M. Ściesiek, J. Borysiuk, T. Slupinski, A. Golnik, P. Kossacki, M. Nawrocki, **W. Pacuski**, "MBE grown microcavities based on selenium and tellurium compounds", **Journal of Crystal Growth** 401, 499 (2014).

[S8]. K. Gietka, J. Kobak, E. Janik, J.G. Rousset, J. Borysiuk, M. Nawrocki, A. Golnik, P. Kossacki, **W. Pacuski**, "The impact of position of Mn delta-doping on the formation of CdTe/ZnTe quantum dots with single magnetic ions", **Journal of Crystal Growth** 401, 640 (2014).

[S8]. M. Papaj, J. Kobak, J.G. Rousset, E. Janik, M. Nawrocki, P. Kossacki, A. Golnik, **W. Pacuski**, "Photoluminescence studies of giant Zeeman effect in MBE-grown cobalt-based dilute magnetic semiconductors", **Journal of Crystal Growth** 401, 644 (2014).

[S9]. J. Kobak, J.-G. Rousset, R. Rudniewski, E. Janik, T. Słupiński, P. Kossacki, A. Golnik, **W. Pacuski**, "Ultra low density of CdTe quantum dots grown by MBE", **Journal of Crystal Growth** 378, 274 (2013).

[S10]. J.-G. Rousset, J. Kobak, T. Slupinski, T. Jakubczyk, P. Stawicki, E. Janik, M. Tokarczyk, G. Kowalski, M. Nawrocki, **W. Pacuski**, "MBE growth and characterization of a II-VI distributed Bragg reflector and microcavity lattice-matched to MgTe", **Journal of Crystal Growth** 378, 266 (2013).

Above works are based on fabricated by me microcavities [S1,S2,S3] and quantum dots [S3,S4,S5], while works [S7,S8,S9,S10] describe early stage development of our epitaxial technology. Probably the most significant result based on my samples is fabrication of new kind of photonic structure – micropillar covered by radial distributed Bragg reflector [S1]. We present evidence that depending on resonance conditions such a structure exhibit both shortening and elongation of exciton lifetime due to Purcell effect. In future, such structures could reaching near 100% of efficiency for photon extraction from semiconductor structures.

b) Selected works on magneto-spectroscopy of wide gap diluted magnetic semiconductors, including works related to PhD thesis:

[WGDMS1] **W. Pacuski,** "Optical Spectroscopy of Wide-Gap Diluted Magnetic Semiconductors", Rozdział w pracy książce „Introduction to the Physics of Diluted Magnetic Semiconductors" pod redakcją Jana A. Gaja i Jacka Kossuta, **Springer Series in Materials Science** Vol. 144, Pp. 37-63 (2010).

[WGDMS2] **W. Pacuski**, P. Kossacki, D. Ferrand, A. Golnik, J. Cibert, M. Wegscheider, A. Navarro-Quezada, A. Bonanni, M. Kiecana, M. Sawicki, T. Dietl, "Observation of strong-coupling effects in a diluted magnetic semiconductor $Ga_{1-x}Fe_xN$", **Physical Review Letters** 100, 037204 (2008),

[WGDMS3] **W. Pacuski**, D. Ferrand, J. Cibert, C. Deparis, J. A. Gaj, P. Kossacki, C. Morhain, "Effect of the s ,p-d exchange interaction on the excitons in (Zn,Co)O epilayers", **Physical Review B** 73, 035214 (2006).

[DMS4] **W. Pacuski**, J. Suffczynski, P. Osewski, P. Kossacki, A. Golnik, J. A. Gaj, C. Deparis, C. Morhain, E. Chikoidze, Y. Dumont, D. Ferrand, J. Cibert, T. Dietl, "Influence of s,p-d and s-p exchange couplings on exciton splitting in (Zn,Mn)O", **Physical Review B** 84, 035214 (2011).

[WGDMS5] **W. Pacuski**, D. Ferrand, J. Cibert, J. A. Gaj, A. Golnik, P. Kossacki, S. Marcet, E. Sarigiannidou, H. Mariette, "Excitonic giant Zeeman effect in GaN:Mn^{3+}", **Physical Review B** 76, 165304 (2007).

[WGDMS6] J. Suffczyński, A. Grois, **W. Pacuski**, A. Golnik, J. A. Gaj, A. Navarro-Quezada, B. Faina, T. Devillers, A. Bonanni, "Effects of s,p-d and s-p exchange interactions probed by exciton magnetospectroscopy in (Ga,Mn)N", **Physical Review B** 83, 094421 (2011).

[WGDMS7] J.-G. Rousset, J. Papierska, **W. Pacuski**, A. Golnik, M. Nawrocki, W. Stefanowicz, S. Stefanowicz, M. Sawicki, R. Jakieła, T. Dietl, A. Navarro-Quezada, B. Faina, T. Li, A. Bonanni, J. Suffczyński, "Relation between exciton splittings, magnetic circular dichroism, and magnetization in wurtzite (Ga,Fe)N", **Physical Review B** 88, 115208 (2013).

[WGDMS8]. E. Przeździecka, E. Kamińska, M. Kiecana, M. Sawicki, Ł. Kłopotowski, **W. Pacuski**, J. Kossut, "Magneto-optical properties of the diluted magnetic semiconductor p-type ZnMnO", **Solid State Communications** 139, 541 (2006).

[WGDMS9]. "Effect of magnetic field on intraionic photoluminescence of (Zn,Co)Se", M.J. Grzybowski, A. Golnik, M. Sawicki, **W. Pacuski, Solid State Communications** 208, 7 (2015).

[WGDMS10] J. Papierska, A. Ciechan, P. Bogusławski, M. Boshta, M. M. Gomaa, E. Chikoidze, Y. Dumont, A. Drabińska, H. Przybylińska, A. Gardias, J. Szczytko, A. Twardowski, M. Tokarczyk, G. Kowalski, B. Witkowski, K. Sawicki, **W. Pacuski**, M. Nawrocki, J. Suffczyński, **Physical Review B** 94, 224414 (2016).

Above works describe influence of magnetic ions on optical properties of new class of diluted magnetic semiconductors: wide gap DMSs [e.g. (Zn,Co)O, (Zn,Mn)O, (Ga,Mn)N, (Ga,Fe)N, (Zn,Fe)O, (Zn,Co)Se]. The most important discovery was the observation that in contrary to general trend of increasing strength of *p-d* exchange integral $N_0\beta$ with decrease of lattice constant, in case of semiconductors with very small lattice constant, effective exchange integral is small and has opposite sign to usually observed. It is due to effect of strong *p-d* coupling and creation of bound states. Such conclusions are explicitly described in works [WGDMS1, WGDMS2], but it is documented by almost all listed works.

c) Selected works on magneto-optical properties of (Cd,Mn)Te QWs, including works related to master thesis:

[QW1]. M. Goryca, D. Ferrand, P. Kossacki, M. Nawrocki, **W. Pacuski**, W. Maślana, J. A. Gaj, S. Tatarenko, J. Cibert, T. Wojtowicz, G. Karczewski, "Magnetization Dynamics Down to a Zero Field in Dilute (Cd,Mn)Te Quantum Wells", **Physical Review Letters** 102, 046408 (2009),

[QW2]. C. Aku-Leh, F. Perez, B. Jusserand, D. Richards, **W. Pacuski**, P.Kossacki, M. Menant, G. Karczewski, "Measuring the spin polarization and Zeeman energy of a spin-polarized electron gas: Comparison between Raman scattering and photoluminescence", **Physical Review B** 76, 155416 (2007).

[QW3] P. Kossacki, **W. Pacuski**, W. Maślana, J.A. Gaj, M. Bertolini, D. Ferrand, J. Bleuse, S.Tatarenko, J. Cibert, "Spin engineering of carrier-induced magnetic ordering in (Cd,Mn)Te quantum wells", **Physica E** 21, 943-946 (2004).

In above works we analysed impact of strain and band structure on spin properties of system of holes and Mn ions in (Cd,Mn)Te QWs. I was doing magneto-optical measurements and, to identify origin of observed magnetic properties, I was performing **k·p** simulations of the valance band.

Summary of all research activities (full list is in attachment) :

- My main three experimental techniques:
  - Molecular Beam Epitaxy
  - Magneto-optical spectroscopy

  - Modelling optical properties of semiconductor structures
- 62 articles published in journals from ISI Master Journal List, including 2 articles in Nature Communications, 1 in ACS Nano, 2 in Physical Review Letters, 11 in Physical Review B, 4 in Applied Physics Letters, 2 articles in following journals: Journal of Applied Physics, Journal of Physics: Condensed Matter, Solid State Communications and Physica E, 1 articles in following journals: Crystal Growth & Design, Nanotechnlogy, Superlattices and Microstructures, 5 articles in Journal of Crystal Growth.
- 10 invited talks on international conferences including The International Conference on II-VI Compounds, and on big conferences of American and European scientific societies: American Physical Society March Meeting, The international society for optics and photonics (SPIE), European Materials Research Society Fall Meeting.
- 16 oral talks on international conferences including two talks on ICPS, two talks on International Conference on II-VI compounds, one talk on The international conference on Molecular Beam Epitaxy.
- Heading 4 research projects: Lider NCBR, Sonata Bis NCN, two projects Iuventus Plus MNiSW
- Establishment of MBE laboratory and leading the lab what resulted in 23 articles during first 4 years.
- Co-supervision of two PhD students, who are just finishing their works. Both achieved significant scientific results.
- Supervision of 5 master thesis and 5 bachelor thesis. All my students continue their research career. One of my students, Michał Papaj, received Golden Medal of Chemistry for the best Bachelor thesis in chemistry in year 2014 (the thesis was prepared under my supervision).
- Initialization of new lecture on Faculty of Physics UW : "Technology and structuration of semiconductor materials (y. 2011 and continuation in years 2012-2016).
- Program committee member for International Conference on Molecular Beam Epitaxy 2016.
- Foreign research stages: in France – 3 months during master study and 15 months during PhD study, and 20 months in Germany on post-doctoral stage.
- Personal collaboration with researchers from Institut NÉEL, CEA Gronoble, CRHEA Valbonne, Institut des NanoSciences de Paris, University of Versailles, University of Bremen, University of Linz, Institute of Physics PAN.
- 42 manuscripts reviewed for renowned scientific journals.
- Popularization of science: broadcasts, lectures and for school students, press releases.

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