1. Name:

Barbara Julia Piętka

2. Degrees and diplomas

2007 **Doctor of Physics, *Warsaw University, Warsaw, Poland***
2007 **Doctor of Physics*, Université Joseph Fourier, Grenoble, Francja***
Double degree within the Polish – French co-tutelle convention.

Thesis subject: Excitonic Complexes in Natural Quantum Dots Formed in Type II GaAs/AlAs Structures.
Degree cum laude.
Supervisor: prof. dr hab. Roman Stępniewski, Uniwersytet Warszawski and prof. dr hab. Marek Potemski, National High Magnetic Field Laboratory, CNRS-UGA-UPS-INSA-EMFL, Grenoble, France.

2003 ***Master of Science, Department of Physics, University of Warsaw***

Subject: The influence of localization on the radiative recombination in semiconductor structures with reduced dimensionality.
Graduated cum laude.
Supervisor: prof. dr hab. Andrzej Wysmołek, Uniwersytet Warszawski.

3. Employment in scientific institutions

since **2010** **Assistant Professor at the University of Warsaw, Faculty of Physics, Department of Solid State Physics, Warsaw, Poland**

2007 – 2010 **Post-doctoral internship at the Ecole Polytechnique Fédérale de Lausanne, Quantum Optoelectronics Laboratory, Lausanne, Switzerland**
Scientific supervisor prof. Benoit Deveaud, EPFL, Lausanne, Switzerland

Other short-term scientific internships:
- July/August 2016, research internship funded by Ambassade de France en Pologne, National High Magnetic Field Laboratory, CNRS, Grenoble, France
- March 2014, October 2015, April 2016 experiment at Helmholtz-Zentrum Dresden-Rossendorf, HZDR, Dresden, Germany
- six-month stay within the Socrates - Erasmus program, National High Magnetic Field Laboratory, CNRS, Grenoble, France.
- three two-month internships in a chemical laboratory from 1999 to 2002, Solvay Fluor und Derivate GmbH, Hannover, Germany

4. Scientific achievements * resulting from art. 16 sec. 2 of the Act of 14 March 2003 on academic degrees and academic title and on degrees and title in the field of art (Journal of Laws No. 65, item 595, as amended):

a) title of scientific achievement

Coherent phenomena in exciton-polariton gases in semiconductor microcavities.

b) List of publications constituting a scientific achievement (ordered from the newest to the oldest)

[H1] **B. Piętka**, N. Bobrovska, D. Stephan, M. Teich, M. Król, S. Winnerl, A. Pashkin, R. Mirek, K. Lekenta, F. Morier-Genoud, H. Schneider, B. Deveaud, M. Helm, M. Matuszewski, J. Szczytko, Doubly dressed bosons: exciton polaritons in a strong terahertz field.
Phys. Rev. Lett. 119, 077403 (2017) **IF 8.462**

[H2] **B. Piętka**, M. R. Molas, N. Bobrovska, M. Król, R. Mirek, K. Lekenta, P. Stępnicki, F. Morier-Genoud, J. Szczytko, B. Deveaud, M. Matuszewski, M. Potemski, 2s exciton polariton revealed in external magnetic field.
Phys. Rev. B. 96, 081402(R) (2017) **IF 3.836**

[H3] R. Mirek, M. Król, K. Lekenta, J.-G. Rousset, M. Nawrocki, M. Kulczykowski, M. Matuszewski, J. Szczytko, W. Pacuski, **B. Piętka**, Angular dependence of giant Zeeman effect for semi-magnetic cavity polaritons.
Phys. Rev. B 95, 085429 (2017) **IF 3.836**

[H4] 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.
Appl. Phys. Lett. 107, 201109 (2015) **IF 3.142**

[H5] **B. Piętka**, D. Zygmunt, M. Król, M. R. Molas, A. A. L. Nicolet, F. Morier-Genoud, J. Szczytko, J. Łusakowski, P. Zięba, I. Tralle, P. Stępnicki, M. Matuszewski, M. Potemski, B. Deveaud, Magnetic field tuning of exciton-polaritons in a semiconductor microcavity.
Phys. Rev. B 91, 075309 (2015) **IF 3.718**

[H6] F. Manni, K. G. Lagoudakis, **B. Pietka**, L. Fontanesi, M. Wouters, V. Savona, R. André, B. Deveaud-Plédran, Polariton condensation in a one-dimensional disordered potential.
Phys. Rev. Lett. 106, 176401 (2011) **IF 7.370**

[H7] G. Nardin, G. Grosso, Y. Léger, **B. Pietka**, F. Morier-Genoud, B. Deveaud-Plédran, Hydrodynamic nucleation of quantized vortex pairs in a polariton quantum fluid.
Nature Physics 7, 635 (2011) **IF 18,967**

[H8] K. G. Lagoudakis, F. Manni, **B. Pietka**, M. Wouters, T. C. H. Liew, V. Savona, A. V. Kavokin, R. André, B. Deveaud-Plédran, Probing the dynamics of spontaneous quantum vortices in polariton superfluids.
Phys. Rev. Lett. 106, 115301 (2011) **IF 7.370**

[H9] K. G. Lagoudakis, **B. Pietka**, M. Wouters, R. Andre, B. Deveaud-Plédran, Coherent oscillations in an exciton-polariton Josephson junction.
Phys. Rev. Lett. 105, 120403 (2010) **IF 7.622**

[H10] G. Nardin, K. G. Lagoudakis, M. Wouters, M. Richard, A. Baas, R. André, Le Si Dang, **B. Pietka**, B. Deveaud-Plédran, Dynamics of long-range ordering in an exciton-polariton condensate.
Phys. Rev. Lett. 103, 256402 (2009) **IF 7.328**

The following cycle of literature designations has been adopted:
- own works constituting a scientific achievement are marked with the letter H, e.g. [H1]
- own works directly related to the subject of scientific achievement are marked with the letter B, e.g. [B1]
- own work other, not related to the subject of scientific achievement, are marked with the letter I, e.g. [I1]
- quoted works of other authors are marked without the use of letters, e.g. [1].

c) *Description of a scientific goal of aforementioned works and the results achieved including a discussion of their potential applications.*

Abstract

The publication record discusses the properties of exciton-polaritons in semiconductor microcavities. I focus my research on phenomena that occur in the gas of exciton-polaritons, when this system is excited by a strong non-resonant or resonant laser. Non-resonant excitation leads to the creation of an exciton reservoir (excitons with high values of the wave vector) that, while relaxing, feed the polariton state. As a result, high polariton densities can be achieved in one of the ground states and the polariton gas can be driven through the phase transition to the Bose-Einstein non-equilibrium condensate. Such a state shows very interesting properties, which until now have been observed mainly in the gases of ultra-cold atoms. I showed that in polariton system such coherent phenomena as long-range correlations [H10], quantum vortices [H8], or Josephson's oscillations [H9] can be observed. In the case of resonant excitation with a coherent laser, a superfluid behaviour can be induced and phenomena from the quantum hydrodynamic regime, with propagating quantum vortices can be investigated [H7]. I also showed that properly designed resonant excitation with two coherent laser beams with energy tuned to the excited states [H2] leads to the creation from exciton-polaritons, new quasiparticles, excitons strongly coupled to two photons of different wavelengths while maintaining their bosonic properties [H1]. In addition, exciton-polaritons inherit some of the characteristics from excitons, namely a spin. The spin properties of polaritonic condensates are not widely studied due to the small polariton Zeeman splitting [H5]. I showed that the use of semi-magnetic semiconductors to modify the excitonic part of the polariton, leads to the observation of the giant Zeeman effect [H3] and the non-equilibrium condensate of semi-magnetic polaritons can still be formed [H4]. My research on a new type of polaritons with strong magnetic properties opens the way to study the spinor properties of polariton condensates, unique among bosonic gases.

State of knowledge before the beginning of the studies and discussion of the scientific purpose of the research.

Exciton-polaritons (hereinafter referred to as polaritons) are quasiparticles formed as a result of strong coupling of photons with excitons [1]. Strong coupling is achieved by placing a semiconductor quantum well at the maximum of the electric field distribution in the semiconductor micro-cavity. For this purpose, semiconductor microcavities are designed to obtain a large wave amplitude in a precisely defined spatial position. Most often the structure is composed of two Bragg mirrors separated by a layer constituting a cavity with the resonant photon energy tuned to the frequency of the exciton transition in the quantum well. As a result of coupling (so-called Rabbi oscillations) instead of a bare photon mode and an exciton resonance, two new modes are obtained: upper and lower polariton, with the properties shared between both of its components [1]. Polaritons inherit a small effective mass from the photon part (nine orders of magnitude smaller than the mass of atoms) and the possibility to interact from the excitonic component.

In 2006, J. Kasprzak, M. Richard at al. [2] showed that polaritons in the high density regime undergo a transition to a new quantum state: the Bose-Einstein condensate (BEC) [3]. This particular quantum state was predicted by Albert Einstein in 1924-25 inspired by the work of Satyender Natah Bose working on statistical properties of photons. Einstein extended Bose's work to all bosons and showed that it is possible to macroscopically populate a single quantum state with the total indistinguishability of the particles at low temperatures. Further, in 1938, using these works, Fritz London proved that the phenomenon of helium superfluity observed at that time was directly related to the Bose-Einstein condensation. The experimental confirmation of the existence of the phase transition at low temperature of a boson gas was possible in 1995, when Carl Wieman and Eric Cornell and independently Wolfgang Ketterle, using laser cooling techniques, demonstrated the atom velocity redistribution and the macroscopic occupation of a single quantum state. For a very long time the observation of this quantum degeneracy was reserved only for atomic gases at very low temperatures (on the order of nano-kelvins).

The condensation of the exciton-polaritons, which is now also observed at room temperature [4, 5], has opened new possibilities for studying this particular quantum state. The study of fundamental quantum phenomena, such as the determination of the type of long-range correlation [6] or the nature of phase transition (BEC - BKT) [7] become possible. In 2009, A. Amo et al. [8] showed that polaritons exhibit superfluidity, together with the appearance of quantum vortices and half-quantum vortices [9, 10], or as shown later, also dark and light solitons [11, 12]. I started my research in this field when the phenomenon of non-equilibrium condensation of polaritons, the existence of long-range correlation and superfluidity were demonstrated, but the time of phase coherence build-up, the mechanisms governing the propagation of quantum vortices or other coherent phenomena such as Josephson's oscillations were unknown. Also the spinor part of the polariton wave function and their magnetic properties have not been analysed at all. The existence of excited states of polaritons and the potential for manipulating these states were not even considered.

Achieved scientific results being the subject of habilitation and prospects for their possible use.

The observed quantum degeneracy in the gas of exciton-polaritons [2, 13 - 16] is a direct consequence of their bosonic character and appears for large concentration, in the non-linear polariton-polariton interaction regime, where the boson stimulation to the final state dominates over the losses of particles resulting from their radiative recombination. The non-equilibrium nature of polariton condensate distinguishes it from the stable nature of atomic condensates. Also the type of the phase transition itself is not the same as in the case of the ideal Bose-Einstein condensate due to its finite size and the fact that long-range correlations disappear with distance. Despite this, the term "condensate" in relation to the phase transition of polaritons gas has been accepted in the literature, as it is described by the same theoretical models (eg. the Gross-Pitaevskii equation) taking into account losses and external pumping.

The ideal Bose-Einstein condensate is determined by the existence of a macroscopic wave function [17]. It is defined by the appearance of a long-range order (OLDRO) that extends over the entire system. This concept was introduced by Penrose and Onsager in

1956, who also demonstrated that the correlation function plays the role of the order parameter in the case of atomic condensates. The appearance of a non-zero value of the spatial correlation function is therefore the most important proof of the observation of a phase transition. The first question I asked myself when I started the research on polariton condensates was: how fast long-range correlations are built-up during a phase transition? It should also be noted that research into the dynamics of phase coherence formation is extremely difficult to carry out in the gases of cold atoms, where this problem was addressed in 2007 [18, 19]. In my work [H10] I showed that the onset of establishing the phase correlation between condensate points separated by 8.5 μm occurs within a few pico-seconds, much faster than expected, simultaneously with the beginning of stimulated scattering. The dynamics of the entire process depends on the density of the particles. In the low density regime, i.e. at the threshold densities, the phase coherence build-up is slow, adiabatically follows the build-up of the population. When the system is quickly driven through a phase transition, long-range coherence is established much slower than the population is built. This shows that the system needs some time, a few picoseconds in our case, for a long-range order to occur. I showed that the speed of phase formation in the polaritonic condensate is just as fast or faster than the propagation of interactions, given by the speed of sound in this system. This means that it is a much faster process than in the case of cold atoms.

The problem of the build-up of long-range correlations is also interesting in the case of systems characterized by a large spatial disorder. It was predicted that in the case of a system with an inhomogeneous distribution of the potential, the final state of the phase transition is not the condensate, but the insulator, the so-called Bose-Glass (BG) [20 - 22]. BG is characterized by a vanishing superfluid phase and exponential decay of long-range correlations with distance. Therefore, it was expected that in this case the defragmentation of condensate into smaller, unconnected condensates will occur. In [H6] I studied spatial correlations in a one-dimensional, non-homogeneous polariton condensate. I showed that despite the strong localization of particles in the potential minima, the correlation function extends over all condensate. The decrease of the correlations with the distance is not monotonic, and its value is closely related to the density and density fluctuation of polaritons in a given potential minimum. These results confirmed once more the non-equilibrium nature of polaritonic condensates.

Therefore, knowing that the highly spatial inhomogeneous polariton condensate may sustain high values of the long-range correlation function, and that it is possible to obtain many different coexisting condensates [B4], I have reduced the system to even simpler one. I studied the condensate located in only two potential minima. The barrier separating the two condensates and the density of polaritons in each minima established an effective value of the coupling constant between them. I created, therefore, the polaritonic equivalent of a bosonic Josephson junction. The Josephson effect is one of the most surprising manifestations of the quantum collective effects of matter, because it allows the current to flow through the junction without dissipation, which is impossible in the classical regime. The traditional Josephson junction is created by separating two superconductors from each other by a thin layer of an insulator. The bosonic Josephson junction is a system of two bosonic condensates separated by a potential barrier. Such a junction was realized in the condensates of cold atoms [23, 24]. In [H9] I showed that the Josephson effect can be observed also in the case of polariton condensates. By studying the time distribution of polariton densities in both traps and the mutual phase relations between them, I showed the existence of coherent and periodic density oscillations between the potential minima. The accompanying oscillations of the phase modulo 2π show that this is the AC Josephson process.

At the time when I was performing the above mentioned research, a lot of discussion was carried out on the nature of the phase transition observed in the polariton gas. Geometry itself forbade the existence of Bose-Einstein ideal condensate. Polaritons are created in a two-dimensional system, because they are formed in a plane determined by a semiconductor quantum well, moreover, they have finite dimensions due to the size of the excitation laser spot. It was therefore expected that the phase transition in this system is of the Berezinski-Kosterlitz-Thoules (BKT) type to the superfluid phase. In the case of the interacting two-dimensional Bose gas, the superfluid phase is formed by the creation of pairs of vortices with opposite charges. In [H8] I investigated the dynamics of spontaneous formation of quantum vortices during the phase transition in the polariton gas. So far, the vorticity in polariton gas has been confirmed only in the case of vortices located in the potential disorder [25] or forced by external excitation [26, 27]. The dynamics of spontaneously created vortices remained unknown. By investigating temporally separated interferograms with high spatial resolution I showed in [H8] that spontaneously created vortices always follow the same path determined by the disorder. This vortex creation scheme suggested that the Kibble-Zurek mechanism [28 - 30] in non-equilibrium systems is responsible for the formation of the order parameter locally, in a form of domains. The phase coherence would be built by combining domains with different phases, so in the final state, with a coherence extending over the entire system, there numerous topological defects could be formed. This theory, however, has not been confirmed [31].

Vortices may appear in the polariton system also in another, quite unique way: when gas passes from a superfluid state to a classical one, on the superfluity breakdown. In the case of superfluid helium and cold atomic gases, they have been identified as the quantum equivalent of turbulence in classical fluids. In [H7] I showed that when polaritons in a superfluid state collide with an obstacle, the quantum vortices are nucleated in the wake of an obstacle, and are further released by the flowing liquid. It was a very special experiment because, for the first time, it allowed for the discussion on the quantum hydrodynamic properties of a degenerate polariton gas. Polaritons in a superfluid state were made in this experiment by excitation with a resonant laser beam, similar to the work of A. Amo et al. [8], and were further propagating freely to encounter a defect in their path. Depending on the speed of the polariton superfluid, v, (given by the angle of incidence of the pumping laser) relative to the sound velocity in this system, c_s (set by polariton - polariton interaction strength and by polariton density), I showed a typically superfluid regime - when the defect is bypassed, a classical gas regime - where numerous scattering effects are observed on the defect, and a limit situation when excitations in the form of quantum vortices are generated in the liquid. This situation is achieved for $v/c_s \approx 1$, when the liquid speed reaches the speed of sound. The research presented here shown the enormous potential of exciton-polaritons in the research on the formation of turbulence in quantum gases.

Until now, in my research, I did not take into account the spin properties of polaritons. Optically active excitons, with ± 1 spin degeneracy, are coupled with light to form polaritons with two spin orientations. From the point of view of the spin structure, polaritons are, therefore, complex bosons with a spinor character [32], which is unusual among the bosonic gases. In the literature, the polariton spin has not been widely considered because of the experimental difficulties and the expected low values of polariton Zeeman splitting. Having experience in experimental techniques used in strong magnetic fields [I16 - I18, I24], I decided to deal with this issue. The prospects were very interesting. In the theoretical work Y. G. Rubo et al. [33] showed the similarity of polaritonic condensates to superconductors, because he predicted the screening of the external magnetic field from the material interior (Meissner effect) and the suppression of superfluidity by the magnetic field. Examining these issues has become one of the goals of my further work.

First of all, the value of Zeeman splitting of polaritons should have been examined and it should be shown whether the magnetic field can be used to energetically separate both spin components. I investigated III-V based semiconductors, mainly GaInAs, due to the fact that polariton condensates in these materials have the longest lifetimes [34], are the most homogeneous [35] and show superfluid propagation at record distances of 150 μm [36]. In [H5] I studied in detail the behavior of polaritons in a linear regime (without condensate) in an external magnetic field up to 14 T. I showed how the polariton energies change and how this change affects the excitonic component (responsible for the Zeeman effect and polariton - polariton interaction strength). In addition, I showed an increase in the coupling energy (Rabi energy) between the exciton and the photon modes in the magnetic field. The Zeeman effect of the polaritons turned out to be very small, in the order of 100 μeV, which was comparable to the polariton linewidth up to 14 T.

It became clear that to observe all interesting collective effects associated with the spin in the degenerated polariton gas another semiconductor material should be considered, where the spin effects are more significant. At the same time at the Faculty of Physics of the University of Warsaw dr hab. Wojciech Pacuski and his team began to produce high quality semiconductor microcavity structures by introducing manganese ions into quantum wells. A novel approach was to create a new type of exciton-polaritons (the so-called semi-magnetic polaritons) by introducing into the system magnetic interactions through the *s,p-d* exchange interaction between the excitonic component in the polariton state and magnetic moments of atoms located inside quantum wells. The structure of the cavity and Bragg's mirror did not contain magnetic ions. Therefore, the exchange interaction affects polaritons only by their excitonic component, whereas neither the Mn ions nor the external magnetic field affect the cavity photons. In [H3] I showed the giant Zeeman effect occurring in such structures. Already at the magnetic field of 5 T I observed the separation of both spin components of the lower polariton.

The next breakthrough came when in the semi-magnetic cavities I observed the non-equilibrium condensation of polaritons. In [H4] I showed that under conditions of strong, pulsed, non-resonant excitation, polaritons macroscopically populate a single quantum state. The influence of polariton - polariton and polariton - excitonic reservoir interactions were visible in the energy shift of polaritons with the increase of the population.

Physics in the case of semi-magnetic polariton condensate is much richer and differs from the case of spin-less bosons. Interactions between polaritons, responsible for a series of non-linear effects (condensation, superfluidity), depend on spin [32, 36 - 38]. This is due to the fact that polaritons with parallel spins repel each other, and polaritons with anti-parallel spins attract. My research now focused on the study of spin effects in semi-magnetic condensates of polaritons opens the way to many interesting phenomena. The magnetic field introduces an imbalance between the states with both spin orientations by the tendency to orient the spins. In addition, the magnetic field affects the critical conditions to achieve condensation, as I shown in [B1]. It is worth mentioning that for a long time the lack of mechanism that would allow to influence the interaction strength was considered to be the main disadvantage of polaritonic condensates compared to atomic condensates, where a change in the interaction constant allows for tuning the degenerate atomic gases through many regimes. Now I would like to show that this is also possible in polariton condensates. I am close to [B0] demonstrate and understand the spin-Meissner effect of polaritons introduced in Ref. [33]. In addition, polaritons may have paramagnetic, ferromagnetic or diamagnetic properties depending on external conditions [37, 39], which I am currently working on. In my laboratory, together with my team, we have built an interferometer, which coupled to a system operating in a strong magnetic field, will allow us to explore the rich physics of quantum vortices in these spinor fluids and half-quantum vortices with different orientation of charge and polarization [9, 10, 40], a phenomenon that does not occur in the gases of cold atoms.

It is also worth mentioning that in addition to interesting spin properties, polaritons have a rich structure of excited states. Because part of the wave function is inherited from exciton, it is expected that polaritons should have identical excited state ladder. In a quantum well, the structure of energy states of excitons is analogous to a two-dimensional hydrogen atom with successive states as 1*s*, 2*s*, 2*p*, 3*s*, 3*p*, 3*d*, ... Optically active states are excitons with an *s*-type symmetry of the wave function in the plane of the quantum well. In [H2] I showed that in addition to the ground 1*s* exciton, the exciton - photon strong coupling can also be observed in the excited 2*s* (and 3*s*) state. I carried out the experiment in a strong magnetic field, and I separated the 2*s* exciton state from energetically close [B2, B3] 2*p* states, which allowed for the observation of the splitting of a photon line into two polariton components. In the same work I also showed that the exciton - photon coupling energy (Rabi energy) in the 1*s* and 2*s* state significantly increases in magnetic field, which is directly related to the increase of the exciton oscillator strength in magnetic field [B2, B3].

Showing the existence of a ladder of excited states of exciton-polaritons allowed me to design a much more complicated experiment. In the work [H2] I determined the energy difference between the 1*s* and 2*p* states of an exciton to 6.5 ± 0.5 meV, which corresponds to the wavelength of the photon in the THz radiation range, 191 μm. The new experiment consisted of a simultaneous creation of exciton-polaritons in the ground state, i.e. 1*s* exciton strongly coupled to photons in a cavity (in the NIR range) and additional illumination of the system with a strong and coherent THz radiation beam with energy tuned to the 1*s* - 2*p* exciton energy difference. Such resonant THz radiation will lead to a strong coupling of THz photons with 1*s* - 2*p* exciton resonance. I performed this experiment in the Helmholtz-Zentrum Dresden-Rossendorf laboratory, HZDR, in Dresden, Germany, where a free electron laser (FEL) with a strong (several hundred mW) and narrow spectral (0.03 meV) radiation beam was available. In [H1] I showed that indeed, an exciton can be strongly coupled to two photons of different energies, NIR and THz. The nature of this coupling is different, for polaritons it is the vacuum field Rabi coupling, for coupling with THz radiation, the usual Rabi-type coupling to free radiation field. I therefore showed the existence of double-dressed quantum states. Further, I showed that these states retain their boson properties. The condensation of double-cladded polaritons will therefore be particularly interesting, because these states are characterized by a high dipole moment (due to the admixture of 2p states). This can lead to completely new phenomena, such as a supersolidity [41].

With regard to future possible applications, the ability to create the condensate in semiconductor structures opens the way to the construction of new optoelectronic devices in a rapidly growing field combining optoelectronic with polaritons, the so-called "polarytronics" [42]. The basic physical aspects associated with the physics of polaritons and their potential application give this semiconductor physics a unique meaning as well as an interdisciplinary character, combining the interests of scientific communities dealing with semiconductors, atomic gases and quantum optics.

Summary of the achievements

I showed that the exciton-polaritons, being the boson quasiparticles, show the class of physical quantum phenomena reserved so far mainly for Bose-Einstein's condensates of cold atomic gases. I demonstrated:

- The dynamics of the formation of a phase coherence in the non-equilibrium Bose-Einstein condensate of polaritons [H10] and the dynamics of formation and propagation of quantum vortices [H8].
- The existence and operation principle of the bosonic Josephson junction with the oscillating current between two localized polariton condensates [H9].
- In a hydrodynamic regime of superfluid polaritons I showed how quantum vortices are formed when the polariton fluid flows through the defect [H7].
- In the one-dimensional condensate of polaritons I showed the existence of long-range correlation despite the existence of strong spatial inhomogeneities [H6].

I also demonstrated how exciton-polaritons and their condensates behave under the influence of external fields.

- Under the influence of a strong magnetic field I showed an increase in the exciton - photon coupling strength [H5], and I demonstrated that polaritons have a well-defined excited state ladder [H2].
- I demonstrated that in the semi-magnetic exciton-polaritons system it is possible to create a non-equilibrium polariton condensate [H4], and the spin of condensed polaritons strongly depend on the external magnetic field [H3].
- Designing appropriately the experiment, I created a new type of exciton-polaritons with bosonic properties under the influence of a strong and coherent THz radiation: an exciton strongly coupled to two photons of different wavelengths (NIR and THz) [H1].

5. Discussion of other scientific achievements

Scientific achievements that do not directly constitute the habilitation achievement and are obtained after doctoral thesis can be divided into three groups: a) studies of localized quantum states in photonic zero-dimensional systems; b) study of the properties of two-dimensional electrons modulated by external radiation; and c) continuation of the PhD studies on single quantum dots in GaAs/AlAs heterostructures with an indirect energy gap.

In parallel with the research on the coherent properties of exciton-polariton gases, I was investigating the properties of zero-dimensional exciton-polaritons, i.e. polaritons in photonic traps. Due to the low effective mass of polaritons, of the order of 10^{-4}-10^{-5} of free electron mass, the in-plane confining potential is achieved in the area of the size of few micrometers [43 - 45]. This allows to relatively easy create structures of any shape and size (eg. by lithographic techniques). My research was focused on oval mesas with sizes from 3 to 20 micrometers. The micrometer size of these objects allows observation of the entire wave function of bound states (amplitude and phase) by means of standard optical systems in the range of visible light.

I demonstrated among other:

- the amplitude distribution and the full three-dimensional tomography (two spatial directions and energy) of states confined in photonic traps [I10], [I7];

- the method for determining the phase of polariton states confined in photonic traps [I7], [I5];
- the increase in the relaxation rate due to the spatial confinement of the wave function [I9];
- a method of controlling the wave function of localized polaritons by an external laser resonantly tuned to a given localized mode [I8];
- dynamics of amplitude oscillations of resonantly excited polariton states due to non-linear effects [I4];
- the method of generation and properties of quantum vortices in localized states [I3], [I2];
- the influence of magnetic field on the wave function of bound states and a redistribution of the occupancy on subsequent states under the magnetic field [I1].

An interesting issue, which I investigated after the doctoral thesis, was to determine how the external radiation from the far-infrared and visible radiation affect the properties of two-dimensional electron gas. I became interested in the properties of a two-dimensional electron gas during my doctoral thesis when I participated in the studies that showed the existence of composite fermions (electrons with two magnetic fluxes attached) in the fractional Hall effect regime [I16]. The present work aimed to determine the spectrum of plasmonic excitations in a two-dimensional electron gas with extremely high electron mobility, taking into account the effect of periodic electrostatic potentials generated by visible light [I11] or generated by metallic periodic structures deposited on the sample surface [I12], [I14], [I15]. An interesting achievement of these studies was the demonstration of the THz scanner based on field-effect transistors with two-dimensional electron gas [I13].

I also continued to study single quantum dots in GaAlAs heterostructures, the investigation that started during my PhD thesis. The heterostructure based on GaAs/AlAs double quantum wells surrounded by the GaAlAs barriers were designed so that the X-band in the AlAs quantum well lies below the Γ band in the quantum GaAs well. On the GaAs/AlAs interface, quantum dots with a direct energy gap (Γ-Γ) are formed, which I demonstrated in [I24]. Such a band arrangement created an interesting system in which excitons located in quantum dots constituted an effective radiation recombination channel for long-lived indirect excitons created in the immediate vicinity of quantum dots. The dynamics of formation of excitons and higher excitonic complexes I described in [I20] and [I22]. Additionally, in [I23], [I21], [18] and [I17] I demonstrated the existence of a family of excitonic complexes, from single neutral excitons, through biexcitons to more complex structures, such as singlet and triplet trion states. The properties of quantum dots as emitters of individual photons I showed in [I19], in which I also demonstrated that different exciton complexes are formed by three families of excitonic states: neutral, positively or negatively charged.

Currently, together with dr. hab. Jacek Szczytko, I built a new Laboratory of Optics on Polariton Structures at the Faculty of Physics at the University of Warsaw, in which various experimental techniques in visible optical range are combined in a system with a strong magnetic field. With my co-participation new equipment was purchased (superconducting magnet operating up to 5 T, confocal microscope coupled with superconducting magnet operating up to 9 T, continuous laser with exceptional optical beam stability and pulsed laser, microscope and micro-translational stages, optical beam stabilization systems, advanced interferometer) and it is fully operational. Under my supervision (together with dr hab. Jacek Szczytko) three PhD students and a post-doc are currently working in the laboratory. Moreover, I supervise the work of students within the frame of different type of student laboratories. Our current laboratory allows on a world-wide scale to develop research in the field of non-linear spectroscopy in combination with strong magnetic fields. I collaborate closely with experimental and theoretical groups from Poland, France, Switzerland, Germany and England.

To summarize in brief my scientific achievements (the full list is included in the annex):

- I am a co-author of 52 peer-reviewed scientific papers in international journals (39 published after PhD), including two articles in Nature Physics, five articles in Physical Review Letters, twelve articles in Physical Review B, two articles in Applied Physics Letters and one article in Scientific Reports.
- The total number of citations of my works according to the Web of Science database (as of April 15, 2018) is: 670,
- The number of citations without self-citations is 604,
- The Hirsch index according to the Web of Science database (including articles published under the family name Chwalisz) is 13.
- I am doing reviews for international scientific journals, including Scientific Reports, Superlattices and Microstructures and Physical Review Letters.
- I participated in over 25 scientific conferences, I delivered 17 talks, including five invited oral presentations.
- I am a member of the Team of Experts of the National Science Center, the Scientific Council of the Institute of Experimental Physics at the University of Warsaw and the Polish Physical Society.
- I managed three research projects (two funded by the National Science Center, one by the Foundation for Polish Science), I was a scientific investigator in five other projects.
- I am the scientific supervisor of two "Diamond Grant" projects of the Ministry of Science and Higher Education.

List of publications (selection):

Own work directly (B) related to the subject of scientific achievement (obtained after the PhD thesis):

[B0] M. Król, R. Mirek, K. Lekenta, J.-G. Rousset, M. Nawrocki, M. Matuszewski, J. Szczytko, W. Pacuski, **B. Piętka**, Spin polarized semimagnetic exciton-polariton condensate in magnetic field, Scientific Reports 8, 6694 (2018) **IF: 4.847**

[B1] J.-G. Rousset, **B. Piętka**, M. Król, R. Mirek, K. Lekenta, J. Szczytko, W. Pacuski and M. Nawrocki, Magnetic field effect on the lasing threshold of a semimagnetic polariton condensate. Phys. Rev. B 96, 125403 (2017) **IF: 3.836**

[B2] P. Stępnicki, **B. Piętka**, F. Morier-Genoud, B. Deveaud, M. Matuszewski, Analytical method for determining quantum well excitons properties in a magnetic field, Phys. Rev. B 91, 195302 (2015) **IF: 3.781**

[B3] P. Zięba, **B. Piętka**, I. Tralle, J. Łusakowski, Exciton binding energy and oscillator strengh in a shallow QW in an external magnetic field, Acta Physica Polonica A 128, 237 (2015). **IF: 0.525**

[B4] D.N. Krizhanovskii, K.G. Lagoudakis, M. Wouters, **B. Pietka**, R. A. Bradley, K. Guda, D.M. Whittaker, M.S. Skolnick, B. Deveaud-Pledran, M. Richard, R. André, Le Si Dang, Coexisting Non-Equilibrium Condensates with Long-Range Spatial Coherence in Semiconductor Microcavities, Phys. Rev. B 80, 045317 (2009) **IF: 3.475**

Own other work (I), not related to the subject of scientific achievement (obtained after the PhD degree):

a) studies on exciton-polariton localized states

[I1] **B. Piętka,** J. Szczytko, J. Łusakowski, G. Nardin, Y. Léger, F. Morier-Genoud, and B. Deveaud – Plédran, Magnetic Field Induced Redistribution of Exciton-Polariton Density on Confined Modes, Acta Physica Polonica A, vol. 122, no. 6, p. 1093 (2012). **IF: 0.531**

[I2] G. Nardin, Y. Léger, **B. Pietka**, F. Morier-Genoud and B. Deveaud-Plédran, Coherent oscillations between orbital angular momentum polariton states in an elliptic resonator, Journal of Nanophotonics 5, 053517 (2011). **IF: 1.570**

[I3] G. Nardin, Y. Léger, **B. Pietka**, F. Morier-Genoud, and B. Deveaud-Plédran Coherent oscillations between polariton vortex and anti-vortex states in an elliptical resonator. Proc. SPIE 7937, 79371Y (2011); doi:10.1117/12.885513

[I4] T. K. Paraiso, R. Cerna, M. Wouters, Y. Léger, **B. Pietka**, F. Morier-Genoud, M. T. Portella-Oberli, and B. Deveaud-Plédran, Collisional damping of dipole oscillations in a trapped polariton gas, Phys. Rev. B 83, 155304 (2011) **IF: 3.691**

[I5] G. Nardin, Y. Léger, **B. Pietka**, F. Morier-Genoud and B. Deveaud-Plédran, Phase-resolved Imaging of Confined Exciton-Polariton Wavefunctions in Elliptical Traps, Phys. Rev. B. 82, 045304 (2010) **IF: 3.774**

[I6] G. Nardin, K. G. Lagoudakis, **B. Pietka**, F. Morier-Genoud, Y. Léger, and B. Deveaud-Plédran, Selective photoexcitation of confined exciton-polariton vortices, Phys. Rev. B 82, 073303 (2010) **IF: 3.774**

[I7] G. Nardin, T. K. Paraïso, R. Cerna, **B. Pietka**, Y. Léger, O. El Daif, F. Morier-Genoud, and B. Deveaud-Plédran, Probability density tomography of microcavity polaritons confined in cylindrical traps of various sizes, Superlattices and Microstructures 47, 207 (2010) **IF: 1.096**

[I8] R. Cerna, D. Sarchi, T. K. Paraıso, G. Nardin, Y. Leger, M. Richard, **B. Pietka**, O. El Daif, F. Morier-Genoud, V. Savona, M. T. Portella-Oberli, B. Deveaud-Pledran, Coherent optical control of the wave function of zero-dimensional exciton polaritons, Phys. Rev. B 80, 121309(R) (2009) **IF: 3.475**

[I9] T. K. Paraïso, D. Sarchi, G. Nardin, R. Cerna, Y. Leger, **B. Pietka**, M. Richard, O. El Daïf, F. Morier-Genoud, V. Savona, and B. Deveaud-Plédran, Enhancement of microcavity polariton relaxation under confinement, Phys. Rev. B 79, 045319 (2009) **IF: 3.475**

[I10] G. Nardin, T. K. Paraïso, R. Cerna, **B. Pietka**, Y. Léger, O. El Daif, F. Morier-Genoud, and B. Deveaud-Plédran, Probability density optical tomography of confined quasiparticles in a semiconductor microcavity, Appl. Phys. Lett. 94, 181103 (2009) **IF: 3.554**

b) works discussing the properties of two-dimensional electron gas under the influence of an external radiation:

[I11] P. Sznajder, **B. Piętka**, W. Bardyszewski, J. Szczytko, and J. Łusakowski, Resonant Plasmon Response of a Periodically Modulated Two-Dimensional Electron Gas, Acta Physica Polonica A, vol. 122, no. 6, p. 1090 (2012). **IF: 0.531**

[I12] M. Białek, K. Karpierz, **B. Piętka**, M. Grynberg, J. Łusakowski, M. Czapkiewicz, K. Fronc, J. Wróbel and V. Umansky, Magnetoplasmons in a High Electron Mobility GaAs/AlGaAs Heterostructure, Acta Physica Polonica A, vol. 122, no. 6, p. 1096 (2012). **IF: 0.531**

[I13] D. Yavorskiy, J. Marczewski, K. Kucharski, P. Kopyt, W. Gwarek, M. Ratajczyk, W. Knap, M. Ściesiek, **B. Piętka**, J. Łusakowski, THz Scanner Based on Silicon Metal-Oxide-Semiconductor Field-Effect Transistors, Photonics Letters of Poland, vol. 4, no. 3, pp. 100-102 (2012)

[I14] J. Szczytko, R. Adomavicius, E. Papis, A. Barańska, A. Wawro, A.Krotkus, **B. Piętka**, J. Łusakowski, THz Time Domain Spectroscopy of Thin Gold and Titanium Layers on GaAs, Acta Physica Polonica A, vol. 122, no. 6, p. 1118 (2012). **IF: 0.531**
[I15] J. Szczytko, M. Stolarek, **B. Piętka**, A. Wawro, A. Baraska, E. Papis, N. Pałka, P. Zagrajek, R. Adomavisius, A. Krotkus, J. Łusakowski, Terahertz Properties of Metallic Layers and Grids, 2012 19th International Conference on Microwave Radar and Wireless Communications (MIKON), vol. 1, page(s): 271 - 275
[I16] M. Byszewski, **B. Chwalisz (Piętka)**, D. K. Maude, M. L. Sadowski, M. Potemski, T. Saku, Y. Hirayama, S. Studenikin, D. G. Austing, A. S. Sachrajda, P. Hawrylak “Optical probing of composite fermions in a two-dimensional electron gas” Nature Physics 2, 239 (2006) **IF: 12.040**

c) studies on quantum dots in GaAs/AlAs indirect structures:
[I17] M. R. Molas, A. A. L. Nicolet, B. Piętka, A. Babiński, and M. Potemski, The excited spin-triplet state of a charged exciton in quantum dots, Int. Journal of Mod. Phys. 28, 365301 (2016) **IF: 2.209**
[I18] M. Molas, A. A. L. Nicolet, **B. Piętka**, A. Babiński, M. Potemski, Magnetic Field effect on the Excitation Spectrum of a Neutral Exciton in a Single Quantum Dot, Acta Physica Polonica A 124, 1066 (2014) **IF: 0.530**
[I19] **B. Piętka**, J. Suffczyński, M. Goryca, T. Kazimierczuk, A. Golnik, P. Kossacki, A. Wysmolek, J. A. Gaj, R. Stępniewski, and M. Potemski, Photon correlation studies of charge variation in a single GaAlAs quantum dot, Phys. Rev. B 87, 035310 (2013) **IF: 3.664**
[I20] M. D. Martin, C. Anton, L. Vinia, **B. Pietka** and M. Potemski, Recombination dynamics of excitons and exciton complexes in single quantum dots, Europhysics Letters 100, 67006 (2012) **IF: 2.260**
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[I23] J. Suffczynski, A. Trajnerowicz, T. Kazimierczuk, **B. Pietka**, K. Kowalik, P. Kossacki, A. Golnik, M. Nawrocki, J. A. Gaj, A. Wysmolek, R. Stepniewski, M. Potemski, V. Thierry – Mieg, Control of Photon Polarization in GaAs/AlAs Single Quantum Dot Emission, Acta Physica Polonica A, 112, 461 (2007) **IF: 0.340**
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