Summary of professional accomplishments

Prepared for the purpose of habilitation procedure

1 Given names, surname, and contact information

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2 Academic degrees

2010 PhD in Theoretical Physics,
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Based on the PhD thesis entitled *Collective effects in spontaneous emission from double quantum dots*, supervised by Prof. Paweł Machnikowski.

2006 MSc in Physics, specialization: Solid State Physics,
Faculty of Fundamental Problems of Technology of the Wroclaw University of Science and Technology
Based on the MSc thesis entitled *Decoherence of carrier states localized in quantum dot systems*, supervised by Prof. Paweł Machnikowski.

3 Employment history

2014 – present Assistant professor at the Department of Theoretical Physics, Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, Wroclaw, Poland

2016 – 2018 Postdoctoral researcher at the School of Science and Engineering and Nanophysics Center, Reykjavik University, Reykjavik, Iceland

2014 – 2016 Postdoctoral researcher at the Science Institute, University of Iceland, Reykjavik, Iceland

2013 – 2014 Assistant professor at the Institute of Physics, Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, Wroclaw, Poland

2010 – 2013 Research and teaching assistant at the Institute of Physics, Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, Wroclaw, Poland

2008 – 2009 PhD student (DAAD scholarship holder) at the Institute of Theoretical Physics, Technical University of Berlin, Berlin, Germany

2006 – 2010 PhD student at the Institute of Physics, Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, Wroclaw, Poland

4 Scientific achievement constituting the basis of the habilitation procedure

4.1 Title of the scientific achievement

Geometry dependent properties of quantum dots, rings, and wires

4.2 List of publications constituting the scientific achievement:

H.1 Anna Sitek and Paweł Machnikowski, *Vacuum-induced coherence in quantum dot systems*, Phys. Rev. B **86**, 205315 (2012).

H.2 Anna Sitek and Andrei Manolescu, *Dicke states in multiple quantum dots*, Phys. Rev. A **88**, 043807 (2013).

H.3 Anna Sitek and Andrei Manolescu, *Spontaneous generation of entangled exciton in quantum dot systems*, Opt. Quant. Electron. **46**, 613 (2014).

H.4 Anna Sitek, Llorenç Serra, Vidar Gudmundsson, and Andrei Manolescu, *Electron localization and optical absorption of polygonal quantum rings*, Phys. Rev. B **91**, 235429 (2015).

H.5 Anna Sitek, Gunnar Thorgilsson, Vidar Gudmundsson, and Andrei Manolescu, *Multi-domain electromagnetic absorption of triangular quantum rings*, Nanotechnology **27**, 225202 (2016).

H.6 Anna Sitek, Mugurel Ţolea, Marian Niţă, Llorenç Serra, Vidar Gudmundsson, and Andrei Manolescu, *In-gap corner states in core-shell polygonal quantum rings*, Sci. Rep. **7**, 40197 (2017).

H.7 Anna Sitek, Miguel Urbaneja Torres, Kristinn Torfason, Vidar Gudmundsson, Andrea Bertoni, and Andrei Manolescu, *Excitons in core-shell nanowires with polygonal cross sections*, Nano Lett. **18**, 2581 (2018).

4.3 Description of the scientific goals of the articles H.1–H.7, obtained results and their possible applications

The purpose of the research presented in the articles H.1–H.7 was to determine the geometry-dependent properties of InAs quantum dots, rings and wires. We analyzed the shapes of individual structures as well as the arrangements of the system components and we specified their implications on absorption and emission processes. In particular, we defined conditions which allow for the formation of robust subradiant states, rapidly decaying superradiant states, and trapping of excitation in ensembles of nonidentical quantum dots. We also investigated how these conditions change with the distribution of emitters [H.1–H.3]. Moreover, we showed that the existence of corners induces the formation of corner- and side-localized states even for relatively thick quantum rings. The corner states can be separated from higher states by a large energy gap which, for triangular rings, may substantially exceed the room-temperature energy

[H.4, H.5]. The interplay of corner localization and Coulomb repulsion leads to the formation of in-gap states in the conduction band. These are purely corner-localized states of electron pairs shifted to energies that were forbidden for non-interacting electrons, but still below the energies of corner-side-localized states [H.5]. Similar in-gap states build up in the excitonic spectrum. Here they are associated with symmetrically distributed electrons which due to the spin singlet configuration acquire much larger contributions from Coulomb interaction than other states corresponding to the same particle distribution [H.7].

Motivation

Semiconductor nanostructures such as quantum dots, rings, dashes, and wires have been in the focus of theoretical and experimental research due to their promising application as building blocks of quantum nanodevices. The physical properties of single structures are very rich, still the features of systems composed of few elements are much more complex and allow for the phenomena which do not appear in one-component structures, and thus enable new applications.

The unique properties of systems consisting of only two quantum dots, double quantum dots or quantum dot molecules, allow for long-time storage of quantum information [1], conditional optical control of carrier states [2], implementation of a two-qubit quantum gate [3], optical writing of information on the spin state of the dopant Mn atom [4], and the construction of quantum nanoantennas due to collective phenomena [5]. The third dot in the system opens the possibility to entangle the same system in two inequivalent ways [6] and enables the control of spin blockades [7]. Moreover, three-quantum-dot systems allow to realize the teleportation scheme based on superradiance [8], controlled- NOT (CNOT) gates [9], and the collective transport effect (electronic Dicke or Kondo-Dicke effect) [10, 11].

Another example of structures composed of two or more elements are core-multishell nanowires. Such systems consist of a core which is surrounded by one or more shells of different material. The external layer changes considerably the physical properties of the system and allows for the control of many features. In particular, the band alignment may be modeled through the appropriate combination of the core and shell materials and also through the doping of the shells which considerably changes the electron and hole distribution within the sample [12, 13]. Electrons confined in such modulation-doped systems show high-mobilities [14], the effect attenuates with temperature but still the reported room-temperature values are high [15]. Moreover, the method allows for the enhancement of the photoconductivity and photoluminescence at room-temperature [15, 16]. Covering a single wire with shells may lead to the considerable increase of absorption [17, 18] with the reduction of the material used [19]. Finally, these structures allow to realize radial p-(i-)n junctions [20–22]. These properties of core-shell systems allow for the optimization of solar cells [19, 22–26] and antennas [27–29]. Other interesting devices based on such wires are lasers [30–33] and light emitting diodes [21,34,35]. The design and construction of such appliances require the understanding of the physical properties and processes taking place in individual nanostructures and the systems consisting of a few nanoscale elements.

Introduction

In my research I focused on the effects resulting from the collective coupling of quantum dots to an electromagnetic field and their dependence on the shape and arrangement of the emitters. In particular, I studied the formation of the Dicke states and vacuum-induced coherence. I also studied the impact of polygonal cross section on the properties of quantum rings and wires. Here I paid attention especially to the interplay of the Coulomb interaction and localization in corner

areas or along the edges.

Atoms or quantum dots interact collectively with a photon reservoir if the spatial dependence of the electromagnetic field may be neglected within the whole set of emitters. This occurs in closely spaced ensembles in which the distances between the systems are much smaller than the radiation wavelength they absorb (Dicke limit) [36, 37]. The collective interaction induces the formation of a rapidly decaying (superradiant) state, robust (subradiant) states (Dicke states), and consequently the vacuum-induced process which consists in excitation transfer between the dots and occupation trapping.

In general, the scientific interest of the collective effects was driven by the possibility of laser optimization shown by the short-living states [38], and until recently focused on the concept of a "superradiant laser" [39–41] which led to the technological realization of the device in 2012 [42]. Moreover, the superradiant states build up spontaneously in a cascade emission and manifest themselves as an outburst of radiation [37, 43, 44]. Because of that, it was much easier to obtain them experimentally than the subradiant ones. Still, the formation of the robust states was observed in atomic ensembles [45], more recently, the preparation of such states was reported in a system of superconducting qubits [46], and in a diatomic molecule in an optical lattice [47]. The subradiant states are resistant to radiative decoherence, and thus they may span decoherence-free subspaces [48, 49] which shows huge possibilities for quantum information processing [40,50–53], in particular, for noiseless encoding of quantum information [54,55]. Other potential implementations include a scalable quantum processor [56], quantum memories [57], nonlinear sign-shift gates [58], storage of time-bin qubits [59], and electromagnetically induced transparency scheme [60].

Superradiance of atomic ensembles was predicted over 60 years ago [36]. Since then the phenomenon has been well described [37, 61–63] and confirmed experimentally [43, 45]. Few years ago it again drawn attention due to the increased number of systems which allow for the effects to occur. The examples are: Bose-Einstein condensate [64], superconducting qubits [65,66], ionic Coulomb crystals [67], dipolaritons [68], ultracold atoms [69], and quantum dots [70]. Although the latter ones and atoms have many features in common, still they differ considerably. As a result the methods developed for ensembles of atoms could not have been applied directly to describe the collective effects in systems consisting of quantum dots.

The characteristic feature of core-shell nanowires is a polygonal cross section which usually appears naturally as a result of the crystallographic structure. The most common shape is a hexagon [71–73], but examples of square [74] and triangular [20, 34, 75–78] structures have already been obtained and their number is increasing. The prismatic geometry strongly affects particle distribution within the sample, especially in the shell areas where it induces the formation of quasi-one dimensional channels along the edges [12,13,79–83]. The edge or corner localization occurs due to the effective quantum wells appearing between the internal and external boundaries of the cross section. The effects of the same origin were observed for bent wires [84–91]. In particular, it was shown that the bent part of a single-mode wire acts as a square quantum well, whose properties are determined by the angle and radius of the circular bend [86]. A polygonal quantum ring may be considered as a closed nanowire with multiple bends, each effectively being a quantum well which attracts low-energy electrons. For the elongated systems, i.e., prismatic quantum wires, this results in the electron localization along the edges.

Quantum rings or prismatic tubes can be obtained in a few different ways, still most commonly these are specific areas within core-shell wires where electrons are accumulated. The possibility of growing a layer of a different material on the surface of a quantum wire allows for the

control of many physical properties, e.g., band alignment. For the appropriate combination of the materials used, core diameter and shell thickness it is possible to obtain the type II (staggering) band alignment at the heterojunction, and thus accumulate the electrons only in the shell area [71, 92, 93]. The energy structure of a core-shell wire may be strongly modified by doping. The additional atoms usually induce the V-type potentials and quantum wells at the heterojunction which localize particles in tubular volumes [12, 14]. Moreover, the present manufacturing technology allows for etching out the core parts, and thus producing nanotubes of finite thickness [72, 73]. Finally, in narrow-gap materials electrons may be accumulated close to the wire surface due to the Fermi-level pinning above the conduction-band edge, and also form conductive shells [94].

Although core-shell nanowires have been extensively studied experimentally, not much focus has been put on their specific geometry and its implications. The hexagonal cross section is usually seen as a natural outcome which does not affect the results, or as a curiosity when the shape is different. In fact, thick hexagonal shells do not differ much from circular tubes. For such shells the probability of finding low-energy electrons is only slightly higher in the corner areas than on the sides, i.e., electrons are distributed along the whole circumference of the cross section like in the case of circular structures. This may explain the lack of interest in the geometry-dependent properties. The difference between the probability of finding an electron in the corner or on the side increases with decreasing the side thickness but pronounced nonuniform particle distribution occurs only for very thin (with respect to the cross section diameter) hexagonal shells. The corner localization peaks sharpen also with decreasing the number of corners, as a result even for relatively thick triangular shells low-energy electrons are accumulated in small corner areas, i.e., depleted from the sides. Core-shell nanowires with 3 facets were obtained over 10 years ago and showed very interesting features such as a broad range of emitted radiation which was observed even at room temperature [95] and tunable to a high extent [34], emission in the infrared range [77, 78, 96] or clear diode characteristics [20]. Nonetheless, the features observed were not attributed to the shape or nonuniform particle distribution.

Results

Vacuum-induced coherence in double quantum dots

Self-organized semiconductor structures usually differ in size and shape which results in the inhomogeneity of their energy structure and interband dipole moments, both factors affect interaction of such nanostructures as quantum dots with light, especially, in the Dicke limit. Collective interaction with photon reservoir may as well lead to the outburst of radiation as inhibit the emission. The effects occur due to the formation of super- and subradiant states which for a pair of identical two-level systems are positive and negative superpositions of localized states corresponding to the excitation of one particular system. If the two-level systems are prepared initially in a superradiant state then the excitation decays with the twice larger rate compared to a single emitter. On the other hand, such a system in a subradiant state is perfectly resistant to radiative decoherence. The collective interaction is very sensitive to the homogeneity of emitters, in particular, fundamental transition energy. The mismatches of the order of one millionth of the excitation energy, considerably slow down the decay of the bright state and induce the emission from the subradiant state. The collective effects are destroyed in such systems because the localized eigenstates corresponding to different energies cannot form delocalized eigenstates.

Still, this effect may be considerably reduced by excitation transfer coupling between the emitters which delocalizes the system eigenstates. If it is sufficiently strong then it dominates the eigenstates such that they become very close to the Dicke states. This allows to restore the super-

radiance phenomena for double quantum dots even with realistic values of the energy mismatch [H.1, D.8]. If initially only one of the two-level systems is excited then the collective interaction redistributes the excitation between both systems in such a way that sub- and superradiant states are formed. The emission from the bright state results in the decay of the half of the excitation and trapping of the second half. This leads to the coherent excitation transfer from the initially excited system to the initially empty one which lasts until the occupations of both emitters reach the same level. The excitation transfer is accompanied by spontaneous build up of coherence, and thus the process is refereed to as vacuum-induced coherence [61]. Since the subradiant state looses its collective character in the presence of the energy mismatch, the excitation trapping does not take place in energetically inhomogeneous dots and the whole excitation is quenched. The decay of the half of the initial excitation may be considerably slowed down if the spatial separation of the two dots is so small that the coupling between them (Förster or tunneling) becomes effective. Still, the emission from double quantum dots which have different transition energies, but identical dipole moments cannot be perfectly blocked, even for strongly coupled systems.

In the article H.1 we studied pairs of vertically stacked semiconductor quantum dots obtained in a self-assembled two-layer process. Due to the strain changes induced by the lower quantum dots the upper structures are much bigger [97]. Although the present technology allows for the considerable reduction of this effect [98], the realistic structures slightly differ from each other. The geometry is reflected in the carrier wave functions, and thus also in the interband dipole moments which may differ in amplitude and, if the hole states have different light-hole admixtures, also in orientation. Since spontaneous decay rates are governed by dipole moments [99], excitons confined in dots which differ in size and shape recombine with different rates.

The vacuum-induced process in pairs of quantum dots with identical fundamental transition energies and parallel dipole moments but of different amplitudes resembles the evolution of identical systems. The interaction with the common photon reservoir induces excitation transfer from the initially occupied dot to the initially empty one which results in the excitation trapping. As in the case of identical two-level systems, the collective interaction redistributes the excitation between the sub- and superradiant states. However, contrary to the ideal case the Dicke states are not anymore symmetric and antisymmetric superpositions of the localized states, i.e., the weight factors of the contributing states depend on the single-dot decay rates, and thus on dipoles. In particular, $|\mathrm{super}\rangle = (\sqrt{\Gamma_{22}}|10\rangle + \sqrt{\Gamma_{11}}|01\rangle)/\sqrt{\Gamma_{11}+\Gamma_{22}}$ and $|\mathrm{sub}\rangle = (\sqrt{\Gamma_{11}}|10\rangle - \sqrt{\Gamma_{22}}|01\rangle)/\sqrt{\Gamma_{11}+\Gamma_{22}}$, where $\Gamma_{11,22}$ and $|10,01\rangle$ are spontaneous decay rates and the localized single-exciton states corresponding to the electron-hole pair residing in one of the dots. Consequently, the fraction of trapped excitation also depends on the decay rates, $\Gamma_{11}/(\Gamma_{11}+\Gamma_{22})$, as well as the levels at which the occupations of individual dots stabilize, $[\Gamma_{11}/(\Gamma_{11}+\Gamma_{22})]^2$ and $\Gamma_{11}\Gamma_{22}/(\Gamma_{11}+\Gamma_{22})^2$, for the initially occupied and empty dots, respectively. This means that different dipole moments allow a number of final situations. The fraction of trapped excitation may differ as well as the occupations of individual dots and the final occupation of the initially exited dot may be higher or lower than that of the initially empty one.

The two dots may also have different light-hole admixtures to the hole states. If so, then the dipole moments become nonparallel, and thus the off-diagonal decay rates depend on the angle between them. In this case the emission cannot be fully blocked, i.e., the occupation always decays. However, the quenching is very weak even for the angles which considerably exceed the realistic values. As a result, the impact of the hole-sub-band mixing on the vacuum-induced coherence process is negligible for the time scales of the order of exciton lifetimes.

The technologically realistic pairs of vertically stacked quantum dots are coupled via Förster

or tunneling coupling, the mismatches of their fundamental transition energies are of the order of mili-electron volts and their dipole moments differ slightly in amplitude and are tilted with respect to each other. Although the energy differences are large, the coupling between the dots strongly overcomes its impact, such that the decay of the final occupations is significantly slowed down. Contrary to the identical two-level systems, the interaction leads to fast oscillations of the single-dot occupations in the initial phase of the evolution. However, the final occupations of the dots are defined only by the decay rates corresponding to the two emitters. The coupling between the dots rebuilds collective effects, but for identical dipole moments the perfect trapping is possible only in the limit of infinite coupling. For systems with different dipole moments the same effect may be obtained in the presence of finite coupling, if the other parameters, like the energy mismatch and amplitudes of the dipole moments are adjusted in such a way that the system eigenstates correspond to sub- and superradiant states. In principle, this is possible only for parallel dipoles, but since the impact of the heavy-light hole mixing is negligible on the time scales of the order of nanoseconds, it should not affect experimental outcomes [H.1].

Collective effects in multiple quantum dots

In the two following articles, H.2 and H.3, we expanded the system under study to an arbitrary number of quantum dots and analyzed in detail systems consisting of 3 and 4 emitters situated in the corners of equilateral triangles and squares. First we studied the case of a single electron-hole pair confined in sets of dots which differ only in the amplitudes of their dipole moments (uncoupled systems with identical fundamental transition energies and parallel dipole moments). Contrary to the double quantum dots, systems built of 3 and more emitters allow for the realization of an arbitrary number of dark states, whereas for each number of dots there is only one superradiant combination. We showed that for such multidot systems any single-exciton state may be expressed as the superposition of the superradiant state and one particular subradiant state which enables excitation trapping. Since the short-living state is the superposition of all localized states, in the final state all quantum dots are partly occupied. The corresponding fractions of the initial excitation blocked in each dot are defined by the coefficients of the complimentary subradiant state, i.e., by single-dot decay rates. If initially the electron-hole pair is localized in the dot number i, then the total occupation stabilizes at the level $\Gamma_{ii}/\sum_j \Gamma_{jj}$, where the summation runs over all emitters. For a set of N identical two-level systems this means that $(N-1)/N$ of the initial excitation becomes trapped and also that the final occupation increases with the number of emitters. However, this does not hold for systems with different dipole moments. Here the fraction of excitation trapped in a system of 3 dots may be higher than the one blocked in a set of 4 dots.

Spontaneous trapping of excitation may also occur in highly inhomogeneous but coupled multiple quantum dots. The single-exciton eigenstates of technologically achievable systems are nonsymmetric superpositions of the localized states whose weight factors depend only on the energy mismatches and coupling. The Dicke states spanned in such systems are also nonsymmetric superpositions of localized states, but their contributions are defined solely by the spontaneous decay rates. If the energy mismatches, coupling between the dots and decay rates match, i.e., if the system eigenstates have sub- and superradiant character, then the multiple quantum dots are in the "collective regime" and in most cases behave like atomic ensembles. In fact, it is necessary to define only the superradiant eigenstate, because this will impose the subradiant condition on the other eigenstates.

As in the case of double quantum dots, also realistic multiple quantum dots driven into the "collective regime" allow for the trapping of the same fraction of excitation as the system of energetically identical two-level systems with the same decay rates. Also, the coupling induces

excitation transfer between the dots, and thus oscillations of the single-dot occupations. Contrary to the pairs of emitters, for systems consisting of 3 or more dots the oscillation amplitudes decay only partly, i.e., in the final state, when the total occupation of the system stabilizes, the occupations of individual dots still oscillate. For such systems there are at least two subradiant eigenstates and also many other dark superpositions may be defined. As a result, the final population number may be realized by different amplitude combinations. For a system of 3 dots the initial oscillations are governed by three energy gaps, i.e., between the superradiant and the two subradiant eigenstates and by the splitting between the two dark states. The oscillation pattern simplifies due to the emission from the superradiant component such that in the final state the occupations of individual dots show single-mode oscillations with the period defined by the subradiant eigenstates and amplitudes depending on the initial occupations. The number of dark eigenstates increases with the number of emitters. For a system of 4 quantum dots three states of this type coexist, and thus the steady state oscillations of individual dots show a more complicated pattern resulting from the overlap of the oscillations with periods given by the three energy splittings between all pairs of optically inactive states [H.2, H.3].

Multiple quantum dots allow for many different planar arrangements of the emitters. Since the excitation transfer coupling between quantum dots depends on the distances between pairs of the emitters, the system eigenstates, and thus also the decay rates which allow for the collective effects to occur are sensitive to the geometry of the multiple quantum dots. We studied a system of 3 dots initially distributed between the corners of an equilateral triangle and showed how the decay rates in the "collective regime" change with the distance between 2 dots (or the opposite angle). If the decay rate corresponding to one of the dots is assumed constant, then increasing the separation of the 2 other emitters leads to the similar decrease of their individual decay rates and a weak increase of the trapped excitation. On the contrary, reducing the spatial separation of the 2 dots leads to the increase of their coupling. In the limiting case of strongly coupled pair of dots accompanied by a distant one, only the 2 closeby dots collectively interact with the photon reservoir [H.2].

Systems consisting of 3 or more dots allow for the realization of delocalized biexcitonic states, and thus permit superradiance phenomena in the two-exciton subspace. However, their appearance is conditioned by the occurrence of collective effects also in the single-exciton subspace. This is a consequence of the restriction imposed by the interaction with the electromagnetic field which allows for the recombination of only one exciton at a time, and thus the total decay of 2 excitons requires the formation of single-exciton superradiant state. It is also possible to block a pair of excitons, i.e., to define biexcitonic subradiant states, but only in multiple quantum dots consisting of at least 4 emitters. Contrary to the single-exciton case, realistic quantum dots allow for the realization of either the superradiant or subradiant biexcitonic state, but never both at the same time. In each of these cases the basis is completed by a state which allows for the recombination of one exciton and trapping of the second one or for the decay of the whole excitation. The possibility to span single as well as biexcitonic optically inactive states in systems of 4 quantum dots enables the blocking of an arbitrary fraction of initial excitation. Interestingly, the initial biexcitonic state results in well-defined final single-exciton states, i.e., the oscillation amplitudes of individual dots are considerably reduced with respect to the single-exciton initial case [H.2].

Single-particle energy levels and electron localization in polygonal quantum rings

The quantum rings we describe are in fact short core-shell nanowires in which electrons are confined only in the shell area [71] or hollow systems obtained by etching out the core part [72, 73]. The sample length may be neglected if the wire is short enough to guarantee larger separation

between the two lowest longitudinal modes in the growth direction than the energy range due to the confinement in the radial direction. In this case all the electrons may be considered to be in the lowest longitudinal mode. We focus mostly on the electrons in the conduction band assuming that the valence band is fully occupied, but in the article H.7 we described also the valence band. In general, we focus on quantum rings but our results may as well be applied for electronic states with zero wavevector k in the infinite shells.

Symmetric polygonal rings, which are restricted internally and externally by regular polygons, have specific energy structure. In particular, energy states are arranged into groups consisting of $2p$ states, where p is the number of corners. For the rings with even number of corners the lowest and highest levels in each group are twofold (spin) degenerate while the states in between form fourfold (spin and orbital momentum) degenerate levels, two in the case of hexagonal and one for square rings, respectively. If the number of corners is odd then the degeneracy sequence, which is repeated in the spectrum, consists of two groups, i.e., of $4p$ states, and resembles the one corresponding to the ring with twice as many corners. The lowest group of $2p$ states may be separated from the higher ones by a gap which for triangular samples may considerably exceed the room-temperature energy. If the distance from the center of the ring to the external corners (external radius), and side thickness are kept constant then increasing the number of corners results in the considerable reduction of the gap which for most of the hexagonal rings becomes comparable to other energy splittings. At the same time ground state increases as well as the energy dispersion of each group of states.

Irrespective of the sample shape the lowest $2p$ states are always associated with probability distributions which form maxima only in the corner areas. On the contrary, the second group of $2p$ states is built of side-localized states for which the corresponding probability distributions form one maximum on each side. Following on the energy scale the number of localization peaks on each side increases by one between adjacent groups of $2p$ states. The groups are defined rather by the specific localization than degeneracy. All the $2p$ states forming a group are associated with the probability distributions of the same type, i.e., with the same number of maxima on each side. For the polygons with even number of corners the whole repeated degeneracy sequence is realized within one group, in the case of rings with odd number of corners, the repeated alignment of states is spread between two groups of different localization type. Consequently, the gap above the lowest $2p$ states separates corner from side states.

For the 5 nm thick triangular ring restricted by the external radius of 25 nm the probability distributions associated with both, the ground level (2 states) and the first excited level (4 states), form sharp and well separated peaks in the corner areas such that low-energy electrons are depleted from the sides. The side-localized maxima corresponding to the two following levels (four- and twofold degenerate) are spread along the whole sides, i.e., are relatively low and strongly elongated. If the external radius and side thickness do not change but the number of corners increases then the corner localization softens while the side maxima sharpen. This opposite evolution leads to the diminishing of the difference between the shape of corner and side maxima and to the reduction of the energy gap separating the two groups. Moreover, for the studied triangular rings the corner-localized probability distributions associated with the two lowest levels do not differ considerably from each other, this does not hold for square and hexagonal rings where the corner localization maxima sharpen with increasing energy [H.4].

Triangular quantum rings show the most pronounced effects. In particular, the corner localization is the strongest, the dispersion of corner states is the smallest while the separation between corner and side states is the largest. The last property is particularly interesting because such a large energy gap provides a good protection for the subspace of corner states which becomes

robust to many perturbations. These properties convinced us to focus particularly on triangular cross sections in the article H.5. The degeneracy of energy states is determined solely by the number of corners but splittings between consecutive levels depend on the aspect ratio between side thickness and the external radius and on the value of the latter parameter. If the external radius is assumed to be constant then the energy structure and particle localization depend only on the ring width. The increase of the side thickness results in the increase of the areas between internal and external boundaries where the effective quantum wells are formed and leads to the shift of the energy spectrum towards lower energies. The corner states may be considered sixfold degenerate or quasidegenerate for a wide range of samples, but their structure becomes relevant for wide rings. The corresponding probability distributions evolve from sharp and well-separated peaks to strongly overlapping maxima for very thick structures which should rather be considered priced triangles. Moreover, the difference between the probability distributions associated with the ground level and the first excited level increases with side thickness and in the case of the upper one the overlap of neighboring peaks is much smaller. Both these levels originate from the lowest states of a (full) triangle, here the ground state is associated with the probability distribution which forms a wide peak in the center of the sample while the electrons in the first excited state are distributed between three small areas. As a result the probability maxima corresponding to the second level of a thick ring are also much sharper. The maxima formed in the side areas change in the same way, i.e., they also sharpen with increasing the side thickness and for very thick samples they reach the height of the corner peaks. Moreover, these maxima may be accompanied by lower corner peaks. The gap that separates corner from side states is always substantially larger than the dispersion of the corner states and also than the other energy splittings. This property distinguishes triangular rings from square and hexagonal structures for which the separation of the lowest states may become comparable to the splittings within groups of the same localization type. Even more importantly, the gap rapidly increases with decreasing the ring width reaching values which considerably exceed the room-temperature energy [H.5]. In fact, the reduction of the side thickness has the same effect on the energy dispersion of the corner states and their separation from the side states as the decrease of the number of corners [H.4, H.5].

In spite of high-precision manufacturing technologies it is still impossible to obtain perfectly symmetric shells. The core-shell wires are grown in sets of closeby vertical samples, the screening of neighboring structures impedes the covering of the wires with homogeneous shells. As a result the side thickness varies along the sample circumference. To account for that we also modeled rings with sides of different width. The energy levels of such samples are only twofold (spin) degenerate, i.e., the degeneracies due to the orbital momentum are lifted. This leads to the increase of the energy dispersion of the corner states and reduction of the gap between corner and side states, but for triangular samples this gap remains considerably large. The electron localization, especially in the corner domain, is very sensitive to the ring symmetry but still there are $2p$ states of corner type. In the case of nonsymmetric rings the lowest states are localized around particular corners. The probability distribution corresponding to the ground state forms one peak around the largest corner (between the two widest sides), electrons exited to the second level are accumulated in the middle corner area, while the localization peak corresponding to the highest corner level is situated the smallest corner. The probability distributions associated with the side states of thinner rings form single maxima but with increasing the side thickness lower localization peaks on the other sides also build up [H.4, H.5]. Similar electron distributions may be obtained for geometrically symmetric samples exposed to an external electric fields but in this case the effect on the side states is weaker [H.4].

Interacting electrons in polygonal quantum rings

The energy levels of a few noninteracting electrons confined in a triangular ring form quaside-

generate levels consisting of states associated with the same localization type. In the case of two electrons, the lowest group of states is built of 15 corner states and is separated from the second quasidegenerate level by a gap which approximately equals to the splitting between single-particle corner and side states. The second group of many-body states contains contributions from both lowest single-particle groups, and thus the corresponding probability distributions consist of six maxima, one on each side and in every corner. Coulomb interaction between the particles shifts all the levels towards higher energies by an amount of energy which depends on spatial separation between the particles. The 12 lowest states correspond to electrons distributed between different corner areas which results in small contributions due electrostatic repulsion. Interestingly, the 3 remaining corner states are shifted to much higher energies, forbidden for noninteracting particles, i.e., to the gap between corner and mixed (corner-side) states, and thus refereed to as in-gap states. These 3 states correspond to at least one pair of electrons in a spin singlet configuration which occupies the same corner area. Due to the very small dimensions of the confining zone they acquired much larger contributions from the Coulomb interaction than other corner states. The in-gap states reproduce the degeneracy of single-particle corner states up to the spin factor of two, which suggests that they behave like single and spinless particles.

The third electron confined in the triangular ring increases the shift of the ground state and enables formation of 12 in-gap states. In this case the higher corner states refer to pairs of closeby electrons accumulated in one corner area which are accompanied by the third electron in the other corner. Because of this unpaired particle the in-gap states are spin-polarized, and thus two- and fourfold degenerate. When another electron enters the sample, then every corner-localized state corresponds to at least one pair of electrons occupying the same corner area which considerably increases the energy of the ground state. As in the case of 2 electrons, there are 3 in-gap states but this time they are associated with two corners doubly occupied. For the case of 5 electrons confined in a triangular ring there is only one way of distributing all the particles between the corner areas, i.e., 2 corners have to contain pairs of electrons while the fifth particle stays in the third corner. Here all states associated with purely corner-localized probability distributions form one quasidegenerate level. The in-gap states build up if the numbers of corners and electrons confined in the ring allow for the different arrangements of particles between corner areas, in particular, for the formation of different number of electron pairs accumulated in one corner.

Such states may be obtained in the case of most of square rings where they allow for the formation of two groups of in-gap states, corresponding to one or two corners doubly occupied. On the contrary, for hexagonal structures the gap that separates purely-corner localized many-body states from the ones that are associated with mixed corner-side-localized probability distributions is usually much smaller than the Coulomb interaction of closeby electron pairs, as a result such states are shifted above the gap and mix with corner-side localized states [H.6].

Absorption of polygonal quantum rings

The optical absorption of polygonal quantum rings is governed by the shape of the wave functions corresponding to the initial and final states, and thus strongly depends on the sample geometry. We studied the process in the presence of the external magnetic field perpendicular to the sample plane which lifts both degeneracies (due to spin and orbital momentum) and consequently allows to investigate particular transitions. We restricted the discussion to the excitations from the ground state induced by circularly polarized light. Since we did not include spin-orbit interaction the optically-induced transitions conserve spin. In principle, single electron confined in a symmetric ring with p sides should be excited to $p-1$ higher corner states and p side states. However, irrespective of the number of corners only one corner and one side state may be excited

in the presence of one polarization type, i.e., there are only two optically active states in each domain. In the absence of an external fields the two corner or side states are degenerate, the external magnetic field creates a splitting between states associated with clockwise and counter-clockwise rotations in the ring plane which can be compensated by photons of one or the other polarization type. For the triangular ring analyzed in H.4 the corner states are dispersed within an interval of the order of decimals of meV while the side states are separated by a 150 meV gap from the former ones. Therefore, the transitions to the corner states are induced by the microwave photons, while the excitation of electrons to the side domain requires absorption of electromagnetic radiation from the near-infrared range. This means that the same sample may absorb electromagnetic waves with wavelengths differing by orders of magnitude [H.4, H.5]. Similar effects, i.e., wide absorption range was observed experimentally for InGaN/GaN triangular core-shell nanowires [95]. The dispersion of corner and side states as well as the gap between them depend on the side thickness and the external radius. Accordingly, the energy range of absorbed photons in the corner domain may vary from fractions of meV to a few meV, at the same time the energy distance from the ground state to the side states may change by an order of magnitude. This allows for the control of absorption through the deposition time and provides a possibly to obtain samples with well-defined absorption properties. Moreover, the magnitude of the splitting between states of the same localization type which are exited by differently polarized photons may be precisely controlled with the external magnetic field [H.5]. Many optical transitions for square and hexagonal rings are blocked due to vanishing dipole moments. This changes in the presence of an external electric field which rearranges particle distribution within the sample, and thus breaks the symmetry of wave functions. This results in the opening of all spin-allowed transitions but with the different values of the absorption coefficients.

Due to vanishing dipole matrix elements between many pairs of single-particle states, most transitions of a few-electron systems are blocked. In the presence of each polarization type, a pair of Coulomb interacting electrons confined in a triangular ring may be excited from its ground state to one of the nearby corner states, to one of the in-gap states and finally to 3 states from the first group above the gap. However, the transition to the in-gap state, which is well-separated energetically from other corner states as well as from the higher mixed states, takes place only in presence of the very low or vanishing magnetic fields. With increasing the field the Zeeman splitting exceeds the energy separation between the two lowest states which interchange. Together with the ground state changes its spin configuration, while the 3 in-gap states stay in the singlet configuration. As a result, dipole matrix elements between the new ground state and the in-gap states vanish, and thus the excitation of the higher corner states is blocked [H.6]. On one hand, such optical experiments may be used to probe the sample geometry, on the other hand the sensitivity of absorption to the external fields allows for a contactless control of optical properties.

Excitons confined in prismatic shells

In the article H.7 we showed our results on a single exciton confined in prismatic shells. To do that we had to include the valence band. In the terms of degeneracy and localization its single-particle levels are the mirror reflection of those from the conduction band, i.e., the states that approach the semiconductor band gap are of corner type while the probability distributions associated with the $2p$ states below, where the p is the number of corners, form one maximum on each side. Due to larger effective mass, the splittings between consecutive levels are much smaller than in the upper band, e.g., for the studied triangle shell the separations between corner and side states equal to 47 and 2.7 meV for the conduction and valence bands, respectively. If the Coulomb interaction was neglected then the lowest excitonic states of a triangular shell would consist of two groups of states spread within very small energy intervals and separated by approximately the gap between corner and side states of the conduction band. The groups

are defined by the localization of the conduction electron, for the lower one it occupies corner areas while in the case of the upper one it stays on the sides. The Coulomb interaction depends on the distances between particles which for the polygonal rings means the dependence on particle distribution within the sample. The interaction rearranges the excitonic states into a few well-separated quasidegenerate levels consisting of states associated with similar localizations. In particular, the lowest 9 excitonic states are pulled down with respect to the noninteracting case. These states correspond to the symmetric particle distribution, i.e., the conduction electron and the vacancy are localized in the same corner area. Interestingly, there are 12 states of this localization type, but only the fraction of them with spin triplet configuration, forms the first level. The 3 remaining states are in the spin singlet configuration which allows the electrons to approach much closer to each other. This results in the large contributions due to the Coulomb repulsion which shift the states to the gap separating the excitons consisting of the conduction electron localized in the corner or on a side, i.e., in-gap states appear also in the excitonic spectrum of polygonal ring. As their conduction band counterparts [H.6], the excitonic in-gap states show unique optical properties. For the triangular ring studied in H.7, the two lower in-gap states are the only optically active states within the spectrum. Their lifetimes are of the order of decimals of nanoseconds and, because of the dependence on the inverse of the energy difference between the final and initial states, they increase with the ring width. The other transitions are blocked due to geometry, spin and chirality selection rules.

The second excitonic level corresponds to the conduction electron and the vacancy occupying different corner areas. In this case there are 3 electrons (2 in the valence and 1 in conduction band) accumulated in one corner. The contribution due to the Coulomb interaction to a system containing 3 closeby electrons considerably exceeds the one to the symmetrically distributed electrons with the spin triplet configuration and leads to the large separation between the two lowest levels. The energy splitting between the second and third levels is much smaller because it stems from the shift of the vacancy from the corner to the side area. The impact of the Coulomb interaction on higher (above the gap) levels is weaker than on the lower states, still it creates or increases energy separations between some levels. Similar effects, i.e., well-separated quasidegenerate levels and excitonic in-gap states appear only for very thin square shells. In the case of hexagonal cross sections, the in-gap states do not mix with higher states only for samples characterized by relatively small aspect ratios and very small diameters. Contrary to the triangular and square shells, it is difficult to obtain wires with hexagonal cross sections and nearly dispersionless levels. The reason is that this geometry induces larger dispersion of single-particle corner states, moreover, the six corner areas allow for many different electron arrangements, each associated with slightly different contribution due to Coulomb interaction [H.7].

Summary of the main scientific achievements

The results presented in the series of articles H.1–H.7 address the properties of InAs quantum dots, rings and wires. In particular, we focused on the geometry of the structures, i.e., on the shape of individual systems or the arrangement of those consisting of a few elements and its implications on the physical properties. To describe the superradiant phenomena in quantum dot systems we could approximate the emitters with two-levels systems. Whereas, to investigate the absorption and recombination processes taking place in prismatic structures first we had to determine and understand their energy spectra and particle localization, which themselves showed interesting features. The most interesting and relevant results are listed below:

- Vacuum-induced coherence process in multiple quantum dots is very sensitive to the mismatch of the fundamental transition energies. Still, its destructive effect may be considerably suppressed by coupling between the dots, but perfect trapping of excitation is possible

only in systems with different dipole moments.

- Polygonal geometry of quantum rings induces unique energy structure, consisting of two- and fourfold degenerate levels, and nonuniform particle distributions along the sample circumference. In particular, low-energy electrons are localized in corner areas while the particles excited to higher states occupy sides. The most pronounced effects occur for triangular rings. These are:
  - The largest energy gap between corner and side states,
  - Accumulation of low-energy electrons in small and well-separated corner areas,
  - Absorption of light from different regions of the electromagnetic spectrum within one sample.
- The lowest many-body states in the conduction band of quantum rings and of single excitons confined in polygonal shells may be arrange in well-separated quasidegenerate levels.
- The interplay of Coulomb interaction and corner localization leads to the formation of in-gap states. Such states may be created either in the conduction band or appear in the excitonic spectrum. The former ones are corner-localized states of electron pairs with the spin singlet configuration shifted to the energies forbidden for non-interacting electrons, i.e., to the gap between purely corner-localized states and corner-side-localized states. The excitonic in-gap states are associated with symmetrically distributed electrons, where the conduction electron and the vacancy occupy the same corner area. Due to the spin singlet configuration they acquire much larger contributions from the Coulomb interaction than other states of the same localization type, and thus are shifted to the gap between excitonic states corresponding to the conduction electron localized in a corner or on a side.
- Absorption of polygonal rings is very sensitive to the external (static) magnetic field which enables contactless control of optical properties.

Possible applications

In a few recent papers we addressed some of the possible applications of the results presented in the articles H.4–H.7. In particular, we showed how the corner localization and the large separation between corner and side states affects conductance of core-shell nanowires [R.1]. Moreover, we analyzed the possible formation of multiple Majorana states in prismatic shells [R.2, R.3]. The two probably most interesting applications of core-shell nanowires are solar cells and nanoantennas, the technological realization and optimization of such devices requires the understanding of their transport and optical properties. The goal of the ongoing project I have been working for the last two years is to predict whether and when core-shell nanowires can function as emitter and/or receiver nanoantennas.

The collective effects in the ensembles of quantum dots are especially important for the application of quantum computation, in particular, the possibility of obtaining decoherence resistant states. To take the advantage of the realistic structures and built quantum nanodevices, it is important to understand their limitations and develop control schemes which we tried to address in the articles the H.1–H.3. In the article H.2 we already mentioned that collective effects may be controlled if the dots are placed in the intrinsic region of a *p-i-n* junction.

5 Description of the other scientific achievements

The scientific works not included in the main achievement can be divided into 3 groups. The first one (R) consists of publications closely related to the main topic which show either particular examples or possible applications of the results shown in the set H.1–H.7. The second group (N) is formed of articles not related to the main achievement concerning the properties of quantum wires and lateral double quantum dots in an optical cavity. The last group (D) consists of articles published before obtaining the PhD degree.

R Publications related to the topic of the main scientific achievement published after obtaining the PhD degree

Refereed articles:

R.1 Miguel Urbaneja Torres, Anna Sitek, Sigurdur Ingi Erlingsson, Gunnar Thorgilsson, Vidar Gudmundsson, and Andrei Manolescu, *Conductance features of core-shell nanowires determined by the internal geometry*, Phys. Rev. B **98**, 085419 (2018).

R.2 Tudor D. Stanescu, Anna Sitek, and Andrei Manolescu, *Robust topological phase in proximitized core-shell nanowires coupled to multiple superconductors*, Beilstein J. Nanotechnol. **9**, 1512 (2018).

R.3 Andrei Manolescu, Anna Sitek, Javier Osca, Llorenç Serra, Vidar Gudmundsson, Tudor D. Stanescu, *Majorana states in prismatic core-shell nanowires*, Phys. Rev B **96**, 125435 (2017).

R.4 Andrei Manolescu, George Alexandru Nemnes, Anna Sitek, Tomas Orn Rosdahl, Sigurdur Ingi Erlingsson, and Vidar Gudmundsson, *Conductance oscillations of core-shell nanowires in transversal magnetic fields*, Phys. Rev. B **93**, 205445 (2016).

R.5 Paweł Karwat, Anna Sitek, Paweł Machnikowski, *Phonon effects on the radiative recombination of excitons in double quantum dots*, Phys. Rev. B **84**, 195315 (2011).

R.6 Anna Sitek, Paweł Machnikowski, *Self-induced coherence in a single pair of quantum dots*, Phys. Stat. Sol. B **248**, 847 (2011).

Conference proceedings:

R.7 Miguel Urbaneja Torres, Anna Sitek, Vidar Gudmundsson, and Andrei Manolescu, *Radiated fields by polygonal core-shell nanowires*, Proceedings of the 20th International Conference on Transparent Optical Networks (ICTON 2018).

R.8 Anna Sitek, Miguel Urbaneja Torres, Kristinn Torfason, Vidar Gudmundsson, and Andrei Manolescu, *Controlled Coulomb effects in core-shell quantum rings*, Proceedings of the 19th International Conference on Transparent Optical Networks (ICTON 2017).

R.9 Anna Sitek, Gunnar Thorgilsson, Vidar Gudmundsson, and Andrei Manolescu, *Electronic states in core-shell quantum rings*, Proceedings of the 18th International Conference on Transparent Optical Networks (ICTON 2016).

R.10 Anna Sitek, Vidar Gudmundsson, and Andrei Manolescu, *Symmetry dependent electron localization and optical absorption of polygonal quantum rings*, Proceedings of the 17th International Conference on Transparent Optical Networks (ICTON 2015).

Book chapter:

R.11 Paweł Karwat, Krzysztof Gawarecki, Katarzyna Roszak, Anna Sitek, and Paweł Machnikowski, *Phonon-assisted processes and spontaneous emission in double quantum dots*, in: *Quantum Dot Molecules* (eds: J. Wu, Z. M. Wang), Lecture Notes in Nanoscale Science and Technology, Vol. 14, Springer (2014), ISBN 978-1-4614-8129-4.

In addition to the research which results were presented in the series of articles constituting my main scientific achievement, I contributed to the other research on the properties of quantum dots and core-shell systems, and the possibilities of taking the technological advantage of them. In particular, we showed how the localization induced by a transversal magnetic field, i.e., the existence of sneaking states, affects transport through the wires [R.4]. In another article we combined the two localization mechanisms, i.e., due to the external magnetic field and prismatic geometry, and showed how the conductance depends on the electron localization in the wire cross section and to what extent it may be controlled with the external magnetic field [R.1]. Due to the electron localization along the edges the prismatic shells may be treated as bunches of a few wires. We studied the formation of Majorana states in such systems and we showed that they allow for the formation of either one zero-energy mode which may be accompanied by an even number of pseudo-Majorana states or an even number of pseudo-Majorana states. These are the states in the superconducting gap with very low but finite energies and, like Majorana states, well separated from the other states. The triangular shells provide a wide range of parameters for which the Majorana states are stable, i.e., for which the destructive orbital effects are strongly inhibited [R.3]. Moreover, covering the nanowires with different superconductors provides the possibility to obtain and control the relative phase between different corner areas, and thus stabilize Majorana states [R.2].

We also published a series of conference papers in which we studied particular examples of prismatic structures. We showed that two different angles of a diamond quantum ring split single-particle corner states into two quasidegenerate levels each associated with probability distributions forming two maxima in opposite corners [R.10]. We studied the many-body spectrum and absorption of the hexagonal ring for which the larges values of absorption coefficients are associated with transitions between corner-localized states [R.9]. The following paper was focused on the control of many-body properties of triangular rings with an external electric field in the ring's plane. We showed that the number of single-particle corner-localized maxima depends on the orientation of the field, that the in-gap states reproduce the degeneracy of single-particle levels, and that the optical excitation of these states is possible only in the absence of the external electric field [R.8]. In the last of these articles we studied the implications of polygonal cross sections on the electromagnetic field radiated by tubular nanowires. In the absence of perpendicular fields, when the carriers are symmetrically distributed between the corner areas, the radiated field resembles the one around a single nanowire. The picture considerably changes in the presence of a transverse magnetic field which induces longitudinal channels of electrons traveling in opposite directions. As for all studied cases, the strongest effects, i.e., the highly anisotropic radiated field, was obtained for triangular shells [R.7].

We also studied the recombination process of excitons confined in a system of two coupled quantum dots interacting with photon and phonon reservoirs. We showed that for the negative coupling (e.g. tunneling) the carrier lifetime increases with temperature which may result in the non-monotonic dependence of the exciton lifetime. Moreover, the coherent transfer of the biexcitonic interband polarization to excitonic one can increase the lifetime of the total coherent polarization [R.5]. In the article R.6 we analyzed the self-induced coherence process in a system of two coupled quantum dots with identical iterband dipole moments. We showed that the excitation trapping occurs either for perfectly identical dots (with the same fundamental transition energies) or for strongly coupled systems. Finally, in the book chapter R.11 we gathered together the results on the properties of double quantum dots obtained by the whole group.

N Publications not related to the topic of the main scientific achievement published after obtaining the PhD degree

Refereed articles:

N.1 Vidar Gudmundsson, Nzar Rauf Abdullah, Anna Sitek, Hsi-Sheng Goan, Chi-Shung Tang, Andrei Manolescu, *Current correlations for the transport of interacting electrons through parallel quantum dots in a photon cavity*, Phys. Lett. A **382**, 1672 (2018).

N.2 Vidar Gudmundsson, Nzar Rauf Abdullah, Anna Sitek, Hsi-Sheng Goan, Chi-Shung Tang, Andrei Manolescu, *Electroluminescence caused by the transport of interacting electrons through parallel quantum dots in a photon cavity*, Ann. Phys. **530**, 1700334 (2018).

N.3 Vidar Gudmundsson, Nzar Rauf Abdullah, Anna Sitek, Hsi-Sheng Goan, Chi-Shung Tang, Andrei Manolescu, *Time-dependent current into and through multilevel parallel quantum dots in a photon cavity*, Phys. Rev. B **95**, 195307 (2017).

N.4 Vidar Gudmundsson, Thorsteinn H. Jonsson, Maria Laura Bernodusson, Nzar Rauf Abdullah, Anna Sitek, Hsi-Sheng Goan, Chi-Shung Tang, and Andrei Manolescu, *Regimes of radiative and nonradiative transitions in transport through an electronic system in a photon cavity reaching a steady state*, Ann. Phys. **529**, 1600177 (2017).

N.5 Thorsteinn H. Jonsson, Andrei Manolescu, Hsi-Sheng Goan, Nzar Rauf Abdullah, Anna Sitek, Chi-Shung Tang, and Vidar Gudmundsson, *Efficient determination of the Markovian time-evolution towards a steady-state of a complex open quantum system*, Comput. Phys. Commun. **220**, 81 (2017).

N.6 Vidar Gudmundsson, Anna Sitek, Nzar Rauf Abdullah, Chi-Shung Tang, and Andrei Manolescu, *Cavity-photon contribution to the effective interaction of electrons in parallel quantum dots*, Ann. Phys. **528**, 394 (2016).

N.7 Vidar Gudmundsson, Anna Sitek, Pei-yi Lin, Nzar Rauf Abdullah, Chi-Shung Tang, and Andrei Manolescu, *Coupled collective and Rabi oscillations triggered by electron transport through a photon cavity*, ACS Photonics **2**, 930 (2015).

Besides the investigations of superradiance phenomena and localization-dependent effects I participated in the research on the transport through nanoscale systems placed in photon cavities. The central systems were either finite parabolic two-dimensional quantum wires [N.4, N.5] or such nanowires with two embedded parallel quantum dots [N.1, N.2, N.3, N.6, N.7]. In particular, we presented an efficient computational method for calculating a Markovian solution of a Nakajima–Zwanzig generalized master equation. The approach was based on the idea of mapping the equation from a many-body Fock space of states to a Liouville space of transitions [N.5]. Using this method we identified two regimes, radiative and nonradiative, in the evolution of a multilevel many-electron system towards the steady state [N.4]. In the group of 5 articles we focused on the transport through double quantum dots. The main obtained results include the demonstration that the currents through such systems are affected by the Rabi oscillations [N.7] and that the electron-electron repulsion is enhanced by the interaction with cavity photons [N.6]. We analyzed the structure of the final steady state for different initial conditions, i.e., we specified the many-body contributions. Moreover, we showed high tunability of the transport with the plunger gate voltage, the photon frequency, and the initial number of photons [N.3]. We studied the transport-induced electroluminescence and we showed that the choice of the cavity-photon polarization allows to select the Rabi-splitting caused either by the para- or the diamagnetic electron-photon interactions [N.2]. Finally, in the article N.1 we used the current–current correlation spectral density to identify radiative and non-radiative transitions active in the steady state.

D Articles published before obtaining the PhD degree

Refereed articles:

D.1 Marten Richter, Alexander Carmele, Anna Sitek, and Andreas Knorr, *Few-photon model of the optical emission of semiconductor quantum dots*, Phys. Rev. Lett. **103**, 087407 (2009).

D.2 Paweł Machnikowski, Katarzyna Roszak, and Anna Sitek, *Collective luminescence and phonon-induced processes in double quantum dots*, Acta Phys. Pol. A **116**, 818 (2009).

D.3 Anna Sitek and Paweł Machnikowski, *Interplay of coupling and superradiant emission in the optical response of a double quantum dot*, Phys. Rev. B **80**, 115319 (2009).

D.4 Anna Sitek and Paweł Machnikowski, *Theory of nonlinear optical response of ensembles of double quantum dots*, Phys. Rev. B **80**, 115301 (2009).

D.5 Anna Sitek and Paweł Machnikowski, *Collective optical response from quantum dot molecules*, Microelectronics J. **40**, 505 (2009).

D.6 Anna Sitek and Paweł Machnikowski, *Superradiance effects in the linear and nonlinear optical response of quantum dot molecules*, Acta Phys. Pol. A **114**, 1355 (2008).

D.7 Anna Sitek and Paweł Machnikowski, *Four-wave mixing spectroscopy of quantum dot molecules*, Acta Phys. Pol. A **112**, 167 (2007).

D.8 Anna Sitek and Paweł Machnikowski, *Collective fluorescence and decoherence of a few nearly identical quantum dots*, Phys. Rev. B **75**, 035328 (2007).

Conference proceedings:

D.9 Anna Sitek and Paweł Machnikowski, *Four-wave mixing optical response of an ensemble of quantum dot molecules*, Phys. Stat. Sol. C **6**, 492 (2009).

My Master thesis and PhD studies were focused on the collective optical effects in double quantum dots and quantum dot molecules. We studied the decay of sub- and superradiant excitonic states and we showed that their evolution is very sensitive to the homogeneity of the fundamental transition energies. Already for the energy mismatches of the order of μeV the exponential decay with a doubled rate (with respect to the decay of a single quantum dot) of the superradiant state and the horizontal line characterizing the robustness of the subradiant state to radiative decoherence are replaced by oscillations around the exponential decay of independent emitters. However, the collective evolution may be rebuilt in coupled systems [D.8, D.2]. We identified the traces of collective interaction in the time-resolved luminescence and absorption spectrum of a pair of coupled quantum dots. These are the enhanced decay of polarization and absorption line composed of two superimposed Lorentzians which have the same amplitudes but different widths and opposite signs [D.3]. Finally, we modeled a four-wave mixing response of an ensemble of double quantum dots. The signal is governed by two rates, initially the evolution is dominated by the superradiant decay, after a fast emission of a fraction of excitation the decay slows down due to the subradiant component. This shows that this experimental technique can be used to identify collective interaction of quantum dots with photon environment [D.4, D.5, D.6, D.7].

During the PhD studies I spend 9 months at the Technical University of Berlin in the group of prof. Andreas Knorr where I participated in the research on single-photon emitters, in particular, on the modifications of a cluster-expansion scheme which allowed to include few photons in the description of nanodevices based on quantum dots [D.1]

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