Warsaw, January 19th, 2017

dr Jan Suffczyński

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AUTOREFERAT

1. Name

Jan Suffczyński

2. Dyplomas and scientific degrees

1. Scientific degree: PhD in Physical Sciences

Institution: Faculty of Physics, University of Warsaw
Year: **2007** (with distinction)
Title of the PhD thesis: „Correlation between photons emitted from individual CdTe/ZnTe quantum dots"
Advisor: prof. dr hab. Michał Nawrocki

2. MSc Diploma

Institution: Faculty of Physics, University of Warsaw
Year: **2002** (with distinction)
Title of the MSc thesis: „Studies of exciton polarization in quantum wells coupled through a semimagnetic barrier"
Advisor: prof. dr hab. Michał Nawrocki

3. Information about emplyment in scientific institutions

1. Faculty of Physics, University of Warsaw

Adjunct (assistant professor), from 2009 r.

2. Laboratoire de Photonique et de Nanostructures, Centre National de la Recherche Scientifique (CNRS), Marcoussis (France)

Postdoctoral position, 2007-2009

4. Scientific accomplishment, in the sense of article 16, paragraph 2 of the Act on academic degrees and academic title and degrees and title in art (Dz. U. nr 65, poz. 595 ze zm.):

a) Title of the scientific accomplishment

Influence of interference and cavity effects on optical properties semiconductor structures

b) Publications included into the scientific accomplishment

[H1] J. Suffczyński, A. Grois, W. Pacuski, A. Golnik, J. A. Gaj, A. Navarro-Quezada, B. Faina, T. Devillers, and A. Bonanni, *Effects of s,p-d and s-p exchange interactions probed by exciton magnetospectroscopy in (Ga,Mn)N*, **Physical Review B 83, 094421 (2011).**

[H2] M. Koba, **J. Suffczyński**, *Magneto-optical effects enhancement in DMS layers utilizing 1-D photonic crystal*, **Journal of Electromagnetic Waves and Applications 27, 700 (2013).**

[H3] M. Koba, **J. Suffczyński**, *Angle dependence of the photonic enhancement of the magneto-optical Kerr effect in DMS layers*, **EPL (Europhysics Letters) 108, 27004 (2014).**

[H4] J. Suffczyński, A. Dousse, K. Gauthron, A. Lemaître, I. Sagnes, L. Lanco, J. Bloch, P. Voisin, and P. Senellart, *Origin of the Optical Emission within the Cavity Mode of Coupled Quantum Dot-Cavity Systems*, **Physical Review Letters 103, 027401 (2009).**

[H5] D. Valente, **J. Suffczyński**, T. Jakubczyk, A. Dousse, A. Lemaître, I. Sagnes, L. Lanco, P. Voisin, A. Auffeves, and P. Senellart, *Frequency cavity pulling induced by a single semiconductor quantum dot*, **Physical Review B 89, 041302(R) (2014).**

[H6] A. Dousse, **J. Suffczyński**, A. Beveratos, O. Krebs, A. Lemaître, I. Sagnes, J. Bloch, P. Voisin, and P. Senellart, *Ultrabright source of entangled photon pairs*, **Nature 466, 217 (2010).**

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

Abstract

In the set of works included into the presented scientific accomplishment I study the impact of interference and cavity effects on optical and magnetooptical properties of semiconductor structures.

In works **[H1-H3]** I show that interference effects and confinement of the light in one-dimensional optical cavity affect significantly the magnetooptical response of layers made of semimagnetic semiconductor. In works **[H4-H5]** I present results of my research conducted on structures, where a semiconductor quantum dots is coupled to a mode of three dimensional optical microcavity. I highlight a specificity of the optical response of structures of such type resulting from a presence of phonons in semiconductor. In work **[H6]** I demonstrate a quantum entanglement in emission of individual quantum dots embedded in optical micro-cavity in a form of a, so called, photonic molecule.

The most important results are:

- Elaboration of a model description of reflectivity spectra in magnetic field from structures involving a thin layer of semimagnetic semiconductor, which takes into account effects of the light interference. Measurements of reflectivity in magnetic field I performed on (Ga,Mn)N and their description using the above model allowed me for a precise determination of energies of optical transitions of *A*, *B* and *C* excitons in (Ga,Mn)N as a function of magnetic field. This led to determination of exchange interaction constants between Mn ion and band carrier in (Ga,Mn)N (work **[H1]**).
- Establishing through calculations performed in transfer matrix formalism that a significant enhancement of magnetooptical response of semimagnetic semiconductor is obtained thanks to its deposition on a Bragg mirror **[H2]**. Calculations carried out for polarizations of the light parallel and perpendicular to the incidence plane show that a maximum enhancement is obtained for the light polarized parallel incident on the structure under the Brewster angle **[H3]**.
- Establishing of the origin of an optical emission, which is observed at the wavelength of a resonant mode of a semiconductor optical microcavity **[H4]**. The emission origin was a subject a vivid controversies in the literature in years preceding the publication.
- Observation of a qualitatively new effect of a modification of energy of resonant mode of optical microcavity due to the interaction with an exciton confined in a quantum dot in *weak* coupling regime of the light-matter interaction, as well as elucidation of this phenomenon **[H5]**. The elucidation of the effects discussed in works **[H5]** and **[H4]** requires taking into transfer of energy from the exciton the mode involving phonons.
- Utilization of cavity effects for a fabrication of a highly efficient semiconductor source of entangled photon pairs. The source bases on a cascaded biexciton-exciton

emission from the semiconductor quantum dot coupled to optical modes of a microcavity formed in the photonic molecule **[H6]**.

The dissertation is organized as follows. In the part **A** I describe state of knowledge and the scientific aim of performed research. In part **B** I present obtained results highlighting their significance for a development of the domain. Concise conclusions and an outlook summarize the text.

A. State of knowledge and a description of the scientific aim of performed research

I will start a description of the state of knowledge by indicating difficulties resulting from a presence of the light interference for a description and interpretation of an optical response of structures involving thin semiconductor layers. Next, I will discuss new capabilities resulting from a deliberate use of cavity and interference effects. I will show that through the enhancement of the light-matter interaction, these effects allow one to widen substantially perspectives of the fundamental studies, as well as to enhance functionalities of semiconductor structures and nanostructures. It is relevant for the domains of, e. g., optoelectronics, spintronics or quantum optics.

Optical spectroscopy measurements allow one to determine several important parameters characterizing a semiconductor.[1,2] It has a particular meaning in the case of semimagnetic semiconductors (DMS), in which part of the cations is substituted by ions with non-vanishing spin moment.[3,4] One of the well-established methods of determination of exchange constants $N_0\alpha$ and $N_0\beta$ between magnetic ion and band carriers in DMS is measurement of reflectivity or absorption in magnetic field. Typically, as a result of measurement one determines energy of the excitonic transition as a function of magnetic field. Next, based on the obtained Zeeman splitting of bands, which is proportional to a magnetization one determines constants of exchange interaction. Studied structures are often composed of thin layers (thickness of the order of micron or hundreds of nanometers), which means that the wavelength of the incident light is comparable to the size of the layers. Reflectivity spectrum in the spectral region below the band gap is affected in this case by a large amplitude Fabry-Pérot interference. In sub-band gap spectral region the amplitude of interferences decreases, while their frequency increases due to a contribution to a dielectric function, and in consequence to a refractive index, coming from excitonic and interband optical transitions.

Superposition of excitonic transitions, typically of Lorentzian shape and quite often of small oscillator strength, on oscillations, which are strongly dependent on the wavelength is a significant difficulty for the determination of parameters of these transitions. This difficulty is additionally increased in the case of semimagnetic semiconductors based on wide-band-gap materials, like GaN or ZnO. In the case of these materials, due to the effects coming from the crystal field and spin-orbit interaction, the valence band is non-degenerate at $\mathbf{k} = 0$ and in optical spectrum there are optical transitions of three excitons, labelled usually as A, B and C.[5] Because of different symmetries of the valence subbands these excitons split in magnetic field in opposite directions on the energy scale. Moreover, linewidth of excitonic transitions, increased as a result of an increased disorder resulting from the doping of the crystal with magnetic ions becomes comparable with magnetic field dependent splittings of the exciton. In this case a proper description of the reflectivity spectra is difficult, while a presence of interference effect makes it even more intricate.

In the work **[H1]** described in part **B** of the dissertation I present results of reflectivity measurements on (Ga,Mn)N layers, along with a model, which served for a description of the spectra obtained as a function of magnetic field. Taking into account of the interference effects enabled me to describe correctly the spectra and to determine parameters of optical transitions in the material, and in consequence to determine constants of exchange interaction Mn ion-carrier in (Ga,Mn)N.

Effects of interference of the light make interpretation of optical spectra difficult in a substantial degree. At the same time, an intentional enhancement of these effects, e. g., through the use of an optical microcavity can be very useful in the context of fundamental studies and applications of semiconductors.[6,7] Optical microcavities are typically formed by a pair a Bragg reflectors embedding a layer of a thickness assuring a confinement of an optical resonant mode. The Bragg mirror is a set of alternating dielectric layers of a different refractive index. The thicknesses of the consecutive layers are $d_i = \lambda/4n_i$, where $n_{i(=1,2)}$ indicates the refractive index of the i-th layer. The intermediate case between a structure composed of a set of layers of random thicknesses and a regular optical microcavity is a *halfcavity*, that is a cavity without one of the mirrors. In such a case a role of a missing mirror is played by the semiconductor/air interface. For typical semiconductors refractive index is between 1.5 and 3.5, which gives a coefficient $R = (n-1)^2/(n+1)^2$ of reflectivity from the interface between 0.04 and 0.31. Despite it is much less than for a good quality Bragg reflector ($R > 0.99$) one should expect that the halfcavity structure will significantly affect optical properties of the active layer. Apart from a multiple passage of the light through the active layer and resulting increase of absorption, it will also direct the emission from the active layer. Advantages of the halfcavity structure include also a relative ease of its fabrication using epitaxial methods, since its small thickness and shorter growth time allows limiting of the role of growth fluctuations (e. g., random changes of the elements flow during the epitaxial growth). Application of the halfcavity structures seems promising in studies of the DMS layers through a magnetooptical Kerr effect (MOKE).[8] The MOKE is a widely used tool for a determination of the magnetization of a material. In the case of typical DMS, the MOKE magnitude scales typically linearly with the Zeeman splitting of excitonic levels, which, in turn, is linearly proportional to the magnetization. However, the MOKE magnitude drops strongly in a limit of a small content of magnetic dopant (due to the small Zeeman splitting), as well as in the limit of its high concentration (due to lowering of a crystal structure quality inducing weakening of the excitonic transitions). This imposes a need for possibly the easiest method of the MOKE enhancement. A contribution to MOKE magnitude comes from: (i) induced by the *s,p-d* interaction Zeeman splitting of excitonic levels, as well as from a polarization dependent (ii) change of spectral width and (iii) amplitude of excitonic transitions.[9] A presence of an optical resonator does not affect in the first approximation the splitting and the spectral width of the excitonic levels. It leads, however, through multiple passage of the light through the DMS layer, to an increase of the excitonic absorption, and in consequence, to the MOKE enhancement.

In works **[H2-H3]** described in a part **B** of the dissertation I present the results of calculations indicating the possibility of a significant enhancement of the MOKE coming from the layer of (Cd,Mn)Te, (Ga,Mn)N or (Ga,Fe)N thanks to the use of interference effects in the halfcavity structure.

The magnitude of the effects of the light-matter interaction obtained thanks to a confinement of a photon in a microcavity increases with a decrease of the confined mode volume and an increase of the cavity quality factor, as well as with the increase of the oscillator strength of optical transitions in the active material.[7] In the case of structures with planar microcavity a further increase of the confinement degree is obtained through microstructuralization of the microcavity. It could be achieved, e. g., by etching of the micropillars of a diameter of the order of a micron, so that comparable with a wavelength of the confined photon.[10] In such a case a confinement of the photon in one of the dimensions is ensured by the Bragg mirrors, and in two remaining ones – through a reflection on the micropillar sidewalls resulting from a contrast of refractive indices of the micropillar material and the air. It is particularly important, when the confined optical mode interacts with a single quantum emitter such as the exciton confined in low dimensional structure such as the quantum dot. In the following part I limit my discussion to this case and for the sake of simplicity I treat the quantum dot as a two level system. Three physical quantities play a crucial role in a description of a coupled quantum dot – optical microcavity system: coupling constant g defining a rate of energy exchange between the quantum dot and the microcavity resonant mode, a rate γ_M of dissipation of the energy of the mode to the outside of the cavity, and a rate γ_{QD}, at which the emitter transfers its energy to a surrounding (spontaneous emission rate in vacuum). In a frame of Jaynes-Cumming's model [11] the resonant frequencies $\Omega_\pm$ of the coupled system and spectral widths $\Gamma_\pm$ corresponding to them are defined by the equation:

$$\Omega_\pm + i\Gamma_\pm = \frac{\omega_M+\omega_{QD}}{2} - i\frac{\gamma_M+\gamma_{QD}}{4} \pm \sqrt{g^2 + \frac{1}{4}\left(\Delta\omega - i\frac{\gamma_{QD}-\gamma_M}{2}\right)^2},$$

where $\Delta\omega = \omega_M - \omega_{QD}$ is a detuning between exciton and the microcavity mode.

In the so called *weak coupling* regime (when g is smaller than $\gamma_M/4$ or $\gamma_{QD}/4$) in the resonance of the emitter and the cavity mode a single optical transition is visible in the emission spectrum. As a result of the coupling spontaneous emission rate increases (Purcell effect [12]) for a factor called Purcell factor. It is proportional to a ratio of the emitter emission rate into the cavity mode to the rate of emitter emission in the vacuum.

In the so called *strong coupling* regime (when g is greater then $\gamma_M/4$ and $\gamma_{QD}/4$) the photon remains in the cavity for the time long enough to be multiple times reabsorbed and reemitted by the emitter. As a result there emerge mixed states of the light and matter. Rabi oscillations with a frequency g occur between them. Wavefunctions of these states are symmetric and anti-symmetric combinations of wavefunctions in the form:

$$|emitter\ in\ a\ fundamental\ state\ , photon\ in\ the\ cavity\rangle$$

and

$$|emitter\ in\ an\ excited\ state\ , empty\ cavity\rangle$$

In this regime at resonance one observes two optical transitions of equal width $(\gamma_{QD} + \gamma_M)/2$ in the emission or reflectivity spectrum, corresponding to two mixed light-matter states.

An expected consequence of the contribution coming from the exciton to a wavefunction of a confined photon in the vicinity of the resonance in the *strong* coupling regime and for small emitter-cavity detunings is an emission taking place at the wavelength of the cavity mode.[13,14,15] The question, however, that from years have been present in the literature was why this emission is observed also outside the resonance region, that is for detunings larger than a few $(\gamma_{QD} + \gamma_M)/2$ widths, also in the *weak* coupling regime.[13,15,16,17] The presence of the emission at the wavelength of the resonant mode of microcavity is indeed surprising since *a priori* there is no oscillator, which could account for an optical transition at the wavelength corresponding to the cavity mode. The presence of the cavity mode means only that there is a locally increased, in the spectral and spatial domain, density of photon states. In the work **[H4]** presented in the part **B**, along with coworkers I confirm observation and put forward an explanation for the origin of the emission under question. The explanation requires taking into account transfer of energy between exciton and the mode mediated by the interaction with phonons in semiconductor. Their presence is specific for optical cavities made of semiconducting materials. On a significant role of phonons is photonic structures made of semiconducting materials I indicate also in the work **[H5]**. In this work, I describe the effect of an *apparent* modification of the resonant mode energy in the weak coupling regime as a result of interaction of a confined photon with a single exciton, which transition is broadened due to the interaction with phonons.

Application of cavity effects allows one to not only observe new phenomena, but also to enhance functionalities of semiconductor structures. As it has been proposed theoretically [18] and demonstrated experimentally,[19,20] a semiconductor quantum dot can act as a source of entangled photon pairs, produced in a cascaded radiative decay of a confined biexciton. According to a Pauli principle spin orientations of the two excitons forming the biexciton are orthogonal. So that, when one considers the emission detected in circular polarization basis and the case of the quantum dot, in which the neutral exciton state is spin degenerate, the decay of the exciton pair will result in the emission of two photons polarized orthogonally. Indistinguishability of two decay paths of the biexciton leads to a polarization entanglement of two photons emitted in the cascade. Most often, however, a potential confining the exciton in the quantum dot is anisotropic. A resulting anisotropic electron-hole exchange interaction lifts degeneracy of the two states of the exciton,[22] and results in a loosing of the indistinguishability of the two biexciton decay paths and, in consequence, in a loosing of the entanglement of the emitted photons. Methods applied so far aiming at decreasing of anisotropic exchange splitting of the exciton (FSS) relied mostly on recovering the symmetry of the wavefunctions of the electron and hole forming the confined exciton through application of an external electric field,[23] magnetic field,[24] strain[25] or increasing of the symmetry of the quantum dot confining potential through annealing [26]. In the work **[H6]**, along with coworkers, I applied a new method exploiting cavity effects. In this work I describe the idea and realization of a highly efficient source of entangled photon pairs in the biexciton-exciton cascade in GaAs/(Al,Ga)As quantum dot coupled to the modes of the photonic molecule [39] etched out of the planar microcavity. An obtained shortening of the lifetime of the exciton led to an increase of a homogenous linewidth of the excitonic level, so that its value overcame FSS. This enabled recovering of the indistinguishability of the two paths of the cascaded biexciton decay and an observation of the polarization entanglement of photons emitted in the cascade.

B. Obtained results and possible perspectives of their application

As I have shown in the previous part, for a proper description of the energy of excitonic transitions in a thin layer of wide band-gap semimagnetic semiconductor one needs taking into account effects of the light interference in that and other layers constituting the sample. In the case of the studies performed in the work **[H1]**, the sample contained a sapphire substrate, GaN layer of around 900 nm thickness and (Ga,Mn)N layer (molar Mn content from 0 % to 0.8 %) of thickness from 300 nm to 500 nm. In the experiment I measured reflectivity spectra as a function of the magnetic field applied in Faraday configuration. For a description of the spectra I adopted a model applied previously to (Ga,Fe)N.[27] In the model construction I took into account contributions to the (Ga,Mn)N and GaN dielectric function coming from excitons *A, B* and *C* characteristic for a wurtzite structure semiconductor, excited states of these excitons, as well as interband transitions involving undound carriers. I assumed a Lorentzian shape of excitonic lines and the shape of the absorption edge such as in the work [28]. Next, by calculations conducted in the transfer matrix formalism, after taking into account all layers constituting the sample, I calculated reflectivity spectra of the studied structures. In works published so far [4,27] only the dielectric function and resulting complex refractive index of the upper, active layer of the DMS layer have been taken into account. Interference effects were neglected,[4,27] which led to a decrease of the accuracy of the determination of the energy of the excitons. Reflectivity spectra determined by calculations in the work **[H1]** described the experimental ones with a high accuracy in both, excitonic, as well as above the band gap spectral region, where interband absorption saturates. A correct description extended also to a spectral region below the band gap of GaN, where the signal is strongly modulated due to Fabry-Pérot interferences. Fitting of the calculated spectra to experimental ones allowed for unequivocal determination of energy of the excitonic transitions as a function of the magnetic field. Next, in order to determine exchange constants between the Mn^{3+} ion and band carriers I fitted the dependences calculated in the frame of the model describing excitonic shifts in magnetic field to the excitonic energies obtained from the experiment.[27] Obtained *apparent* exchange constants ($N_0\alpha = 0.0 \pm 0.2$ eV and $N_0\beta = +0.8 \pm 0.2$ eV) confirm results of theoretical considerations, predicting a compensation of exchange interaction between the magnetic ion and the carrier in the wide band-gap DMS related to a heavy hole confined in a Coulomb potential of the magnetic ion.[29,30] The obtained result, apart from the determination of the exchange constants itself, is thus important for understanding of discrepancies between values of the exchange constants determined from chemical trends and magnetooptical measurements in the case of the wide band-gap DMS.

Interference effects complicate interpretation of the (magneto)optical spectra, however, when deliberately exploited, they can facilitate studies and applications of semiconducting materials. An example here is a halfcavity structure, in which a layer of the DMS (active layer) is deposited on the Bragg reflector, proposed by me and dr Marcin Koba in the work **[H2]**. In this work, through calculations conducted in the transfer matrix method formalism, we showed a desired influence of the light interference effects, namely enhancement of the MOKE thanks to a multiple passage of the light through the active layer for semiconductor layers doped with manganese: (Ga,Mn)N or (Cd,Mn)Te.

In order to asses a degree of the enhancement, we determined magnitude of the MOKE related to excitonic optical transitions in the structure involving the DMS layer of a thickness of around $d_{DMS} = 100$ nm deposited on the Bragg mirror. Next, we performed an analogous calculation for a reference structure, where the DMS layer was deposited on an (Al,Ga)N buffer layer and we compared the results obtained in both cases. We assumed a small, of the order of 5 % contrast of refractive indices of the layers constituting the Bragg mirror ($Al_{1-x}Ga_xN/Al_{1-y}Ga_yN$ or $Cd_{1-x}Mg_xTe/Cd_{1-y}Mg_yTe$ in the respective case of the III-V and II-VI sample), so that a small difference of a composition of these layers. In the case of practical realization of the structures it should suppress undesired effects of strain and decrease a density of dislocations arising due to the lattice mismatch.[31] Parameters of the optical transitions in the case of (Ga,Mn)N came from the work **[H1]**, and in the case of (Cd,Mn)Te from the literature [32]. Angle of the Kerr rotation after application of the magnetic field was calculated as:

$$\theta(\lambda) = \frac{1}{2} arg\left(\frac{r^{\sigma-}(\lambda)}{r^{\sigma+}(\lambda)}\right),$$

where $r^{\sigma-}(\lambda)$ and $r^{\sigma+}(\lambda)$ is a dependent on the wavelength λ amplitude of the reflected light in the polarization σ– or σ+, respectively.[33] The MOKE enhancement redicted by the calculations results from an increased rotation of the light polarization as a result of a multiple passage of the light through the magnetized material.

Calculations for a fixed nonzero magnetic field revealed a fast increase of the Kerr rotation angle (MOKE magnitude) with the increase of the number of pairs forming the Bragg mirror, with a saturation at the value as low as 4 pairs. The enhancement in the excitonic spectral region was, depending on the light wavelength, at least a few-fold.

It is worth to notice that the proposed structure differs from a standard one ("active layer + buffer layer") only by an additional, simple Bragg mirror. It is important from the point of view of possible sample production using epitaxial methods [34] and is favorable for a practical application of the structure. Moreover, the calculations carried out by us predict the MOKE enhancement for both, (Ga, Mn)N and for (Cd, Mn)Te, so that for a III–V semiconductor representing a wurtzite structure DMS, as well as for a II-VI semiconductor representing a zinc-blend structure DMS. This indicates a possibility of a wide application of the proposed method.

The work **[H2]** aimed at providing a proof of the effect of the photonic enhancement of the MOKE. The work **[H3]** broadens the previous study. The structure considered in **[H3]** was the same as in **[H2]**: a DMS layer, being the (Ga,Fe)N layer in this case, deposited on the top of a Bragg mirror. In this case, however, we determined the MOKE magnitude as a function of such parameters of the structure as the DMS layer thickness d_{DMS} and a wavelength, at which the Bragg mirror was centered. We performed calculations for the light incident along normal to the sample, and for selected parameters of the structure also as a function of the angle of the light incidence.

The calculations showed, that the magnitude of the MOKE increases with the d_{DMS} up to a saturation value, and exhibits a strong oscillations as a function of d_{DMS} below the saturation. The maxima of the MOKE for a fixed wavelength occurred for d_{DMS} approximately equal to a multiple of the half of the effective wavelength of the light in (Ga,Fe)N ($\lambda/2n_{(Ga,Fe)N}$). For such thicknesses partial reflections of the light in the cavity, which one border is the Bragg mirror and the second border is an interface (Ga,Fe)N/air, sum up in phase. It shows that oscillations as a function of the d_{DMS} result from the interference effects. Both, the MOKE magnitude and the amplitude of oscillations are a few times larger in the case of the structure with the Bragg mirror, when compared to the case of the reference structure. The effect of the MOKE enhancement is the strongest, when the central wavelength of the Bragg mirror

coincides with the spectral region of excitons in (Ga,Fe)N.
Calculations carried out as a function of the angle of the light incidence showed that a few-fold MOKE enhancement for the light polarized perpendicular to the incidence plane (TE) is maintained practically in the whole range of incidence angles. The calculations carried out for the parallel (TM) polarization reveal an additional, strong maximum (an order of magnitude of the MOKE enhancement) for the incidence angle equal to the Brewster angle in (Ga,Fe)N. The effect of the maximum MOKE for the Brewster angle has been observed so far only for the MOKE resulting from the interaction of the light with a magnetized metallic layer.[35]
The important conclusion from the work **[H3]** is that the MOKE magnitude in studies of the DMS layers does not depend solely on the concentration of the magnetic dopant, as it is commonly assumed. The correct interpretation of the MOKE requires taking into account the effect of the light interference in the set of the layers constituting the sample. Moreover, as results from the work **[H3]**, in the DMS materials it is possible to efficiently tune the MOKE magnitude by adjusting the angle of the light incidence and the polarization of the incident light.

As I mentioned in the introductory part **A** of the dissertation, the microstructuralization of the photonic structures leads to an additional increase the light-matter interaction related to the interference and cavity effects. The effect observed by several authors in the case of the system involving a quantum dot coupled with the mode of an optical microcavity in a micropillar, but so far unexplained was an emission taking place at the mode wavelength, even for a large detuning between the quantum dot state and the mode. [13,15,16,17] The mode emission is surprising, as the Jaynes-Cumming's model often applied for a description of experiments in the domain of Cavity Quantum Electrodynamics predicts that when the spectral width of the emitter is much smaller than the spectral width of the mode, the emission at the wavelength of the emitter dominates, independently of the detuning quantum dot-mode.[11] In particular, outside of the spectral region of the emitter-mode resonance the emission at the mode wavelength should be negligible.
In the work **[H4]** I explain the origin of the emission through the mode of the semiconductor microcavity by performing a time-resolved and time-integrated study on *weakly* coupled systems of GaAs/(Al,Ga)As quantum dot- micropillar microcavity. These systems were produced using a method of photolithographic coupling, in which elaboration I participated.[36] The method enables achieving of the optimal (spectrally and spatially) coupling between the exciton in a selected quantum dot and the mode of the micropillar. As a

result, the emission from the selected quantum dot couples to the mode much stronger than the emission coming from (many) other quantum dots. The suppression of the role of the background emitters has enabled us to perform observations that were not possible previously.

The time-resolved measurements that I carried out have shown that the decay of the emission at the wavelength of the mode exhibits the same constant as the emission decay of the closest spectrally exciton transition in the quantum dot coupled to the mode. If two excitonic transitions in the quantum dot coupled to the mode are characterized by different decay rates and are comparably detuned from the mode, the mode emission decay rate takes an intermediate value between them. Systematic studies performed on the statistics of a few tens of coupled systems have confirmed the above correlation between the decay rates of the exciton and mod emission. This result indicates that the same emitter (the quantum dot) is responsible for the emission not only at its own wavelength, but also for the emission at the wavelength of the mode.

The above result can be explained assuming an interaction of the confined exciton with acoustic phonons or free carriers in the vicinity of the quantum dot, which would lead to the emission also outside the zero-phonon line of the quantum dot. Due to a high density of the photon states at the mode wavelength, this emission would be efficiently grabbed by the mode. A confirmation for such a hypothesis is the work by Naesby and coworkers.[38] Through theoretical considerations, they show that the effects of dephasing, which broaden the optical transition of the quantum dot, lead to a much enhanced emission of the microcavity mode, to which the quantum dot is coupled. According to the prediction of Naesby *et al.* the emission at the mode wavelength should dominate for the a large quantum dot-mode detuning, while for a small detuning, the emission at the quantum dot wavelength, should be a dominant one. The ratio of the mode emission intensity to the total emission intensity (quantum dot + mode) determined in measurements that I performed remain in a qualitative agreement with the above prediction. Moreover, in the frame of the model of Naesby *et al.* the dynamics of the quantum dot and the mode emission should be the same, as it is observed in the measurement.

The work **[H4]** shows unequivocally that the Jaynes-Cumming's model working properly, e. g., in the domain of quantum optics, where the confined optical mode interacts in the vacuum with a single atom or a group of atoms,[38] is insufficient for a description of the semiconductor systems, where a quantum dot couples to the mode of the semiconductor microcavity. In the latter case both, the quantum dot and the microcavity are composed of a large density of atoms forming a crystal lattice subjected to the phonon excitations.

The presence of phonon excitations in the coupled quantum dot-microcavity mode systems affects the emission spectrum of the coupled system also in another unexpected way, different than the one described in the work **[H4]**. This issue is a subject of the work **[H5]**, where I study, together with coworkers, the effect of spectral *pulling* of the microcavity mode. *Pulling* of the optical mode of the resonant cavity in laser physics is a modification of the mode energy caused by a change of the dielectric susceptibility of the active medium in the presence of energy dependent gain.[39] The effects of such type have been observed so far only in laser physics, that is in systems, where many emitters couple to the mode of the cavity.[39] In the work **[H5]**, I report on a modification of the cavity mode energy resulting from an interaction with a single emitter (a quantum dot) in a presence of phonons, which I observed in the system of a GaAs/(Al,Ga)As quantum dot *weakly* coupled to a mode of the micropillar microcavity.

In the measurement I registered consecutive spectra as a function of the systematically increasing temperature, that is the quantum dot-mode detuning. I benefited here from the fact that the band gap a semiconductor is much more sensitive to a change of the temperature than its refractive index, which means that energy of an exciton confined in a quantum dot decreases much faster with the increasing temperature than the mode energy. I kept a temperature step between consecutive spectra at the order of a tenth of a Kelvin. It was much less than in previous studies [10,13,34] and allowed me to trace a variation of the mode and the exciton energies in a quasi-continuous way.
In order to gain qualitative information on the maxima related to the mode and to the quantum dot, I fitted a sum of two Lorentzian curves to the obtained spectra. A plot showing the energy position of the lines as a function of the detuning revealed a surprising effect of non-monotonic change of the mode energy in the vicinity of the resonance of the mode with the excitonic transition in the coupled quantum dot. This effect occurred when the mode approached the states of neutral exciton, the biexciton, as well as the charged exciton. The energy of excitonic transitions, however, varied with the detuning in a monotonic way, without any deviation from the principal direction of the shift, also in the vicinity of the resonance with the mode. As I have shown in the work **[H5]**, the observed behavior of the mode can be explained in a consistent way when assuming that a resultant emission spectrum is a product of a spectral density of the quantum dot state (broadened by the interaction with

acoustic phonons) and of the optical microcavity mode (taking a Lorentzian shape). Within such interpretation, when the mode approaches a resonance with the exciton (i) position of the zero-phonon line of the exciton remains practically not affected due to its small spectral width, (ii) a broad maximum of the mode filtered by the slope of the phonon broadened exciton line becomes shifted spectrally towards the zero-phonon exciton line. This results in the effect of the *pulling* as well as spectral narrowing of the mode. Moreover, when the mode is in the spectral vicinity between two excitonic transitions, it is *pulled* by each transition towards a different direction. This leads to a spectral broadening of the mode.

The most important consequence of the results described in the work **[H5]** for the domain of the semiconductor based cavity quantum electrodynamics is a contestation of a textbook picture [7] that the spectral width $\Delta\lambda$ and the wavelength of the optical mode λ always define unequivocally the quality factor of the cavity Q ($Q = \lambda/\Delta\lambda$). Since the phonon broadening of the optical transition of the exciton leads to either the narrowing or the broadening of the mode spectral width evidenced in the experiment, thus in the domain of the semiconductor based cavity quantum electrodynamics determination of the cavity quality factor can easily be erroneous. Hence, the work **[H5]** indicates further limitations of the Janes-Cumming model for the description of the light-matter interaction in the photonic semiconductor systems.

As compared to other works in the set, the work **[H6]** is oriented at a higher extent towards applications. In the work **[H6]** I utilize the cavity effects in order to obtain a highly bright semiconductor source of polarization entangled photon pairs. My research in this case started from an optical characterization of the fabricated photonic molecules, which parameters were varied in a systematic way. The photonic molecule is constituted by two coupled micropillars, each containing a microcavity.[40] The coupling of the modes of the microcavites results from evanescent leakage of the modes out of the volume of the micropillar. Adjustment of the diameter of the micropillars and their respective distance enables an efficient tuning of energy of the coupled modes.[40,41] Next, the molecules, which modes were coupled to optical transitions of a selected GaAs/(Al,Ga)As quantum dot were produced using a photolithography marking method [38]. Based on the performed characterization, the parameters of the molecules (the micropillars diameter and their respective distance) were tailored in such a way that both, the neutral exciton and biexciton were in resonance with the modes of the molecule. Thanks to the enhancement of the light-matter coupling through the cavity effect this enables us to increase the rate of spontaneous emission of excitons for about order of magnitude. Shortening of the neutral exciton lifetime led to the increase of its homogeneous linewidth above the FSS splitting value. (In the studied quantum dots, thanks to the applied growth method and a post-growth annealing of the sample the FSS splitting was relatively small, of the order of a few μeV). It enabled recovering of the indistinguishability of two decay paths of the radiative decay of the biexciton. The measurements of single photon correlations, which I with coworkers carried out proved a presence of polarization entanglement of photons emitted in the biexciton-exciton cascade from the quantum dot, which optical transitions are coupled to the modes of the molecule. **[H6]** The analysis of the density matrix of the entangled state revealed a record degree of entanglement with respect to the previously obtained in the emission from the quantum dot (fidelity on the level of 60 %, concurrence on the level of 35 %).

Thanks to the coupling, which transfers the emission of both, the exciton and the biexciton into the modes of the photonic molecule, the obtained source exhibits a very high efficiency (efficiency of emission collection around 35 % and on average 0.12 entangled photon pair per excitation pulse). It is more than an order of magnitude more than if one does not exploit the cavity effects. For example, in the case of a source based on a quantum dot in the bulk sample, due to a total internal reflection on the semiconductor/air interface, only around a few percent of the emitted light leaves the sample. It is also much more than in the case of the most widely used sources for a production of the entangled photons based on a parametric down conversion, which exhibits efficiency below 0.01 photon pair per excitation pulse.

Summary

As I have shown in the works **[H1-H6]** the effects related to the light interference influence the optical properties of the semiconductor structures independently of a dimensionality of these structures. In several cases a presence of the interferences makes difficult a proper interpretation of the optical spectra. Only taking them into account allows one to determine parameters of the semiconductor accurately.**[H1]** On the other hand, the intentional enhancement of the interference effects, e.g., by application of the optical microcavities, as well as the microstructuralization of such structures leads to an increase of the light-matter interaction constants. This enables enhancement of the magnetooptical effects in the semimagnetic semiconductors,**[H2-H3]** as well as the observation and studies of new and surprising effects, such as the emission at the wavelength of the cavity mode,**[H4]** or a modification of the mode energy resulting from the interaction with the single exciton in the *weak* light-matter coupling regime **[H5]**. Making use of cavity effects also enables one to obtain entangled photons in the emission of semiconductor quantum dot.**[H6]**

I asses that the most interesting directions in the domain of semiconductor photonics, which might be developed based on the results obtained in the works **[H1-H6]** are, among others: (i) Achievement of a highly efficient laser cooling [42] thanks to the application of the light-matter coupling in the presence of phonons in the optical microcavities. Effects of such type have been observed so far neglecting the use of the photonic effects. (ii) Achievement of an interaction between distant quantum emitters, which would be mediated by a delocalized mode of vertically coupled optical microcavities. Thanks to a photon contribution to a wavefunction of the exciton and the emergence of polaritons, the tunneling between the two microcavites would take place for a distance of the order of a micrometer, so that larger for more than an order of magnitude than observed so far [43] for excitons.

5. Description of other scientific achievements

In my Master thesis entitled **„Studies of exciton polarization in quantum wells coupled through a semimagnetic barrier"** effectuated under a supervision of prof. dr hab. M. Nawrocki and defended with distinction in 2002 at the Faculty of Physics I dealt with a problem of spin dependent exciton tunneling through a barrier potential. I performed magnetospectroscopy measurements on CdTe quantum wells separated by (Cd,Mn)Te barrier and I described the obtained results solving the Schrödinger equation for the confined carriers in the frame of the effective mass approximation. The results obtained during the work on Master thesis entered into **4** publications that I co-authored.

My PhD thesis **"Correlations between photons emitted from individual CdTe/ZnTe quantum dots"** effectuated under a supervision of prof. dr hab. M. Nawrocki and defended with distinction in 2007 at the Faculty of Physics was devoted to properties of a single photon emission from single CdTe/ZnTe quantum dots. In 2003, to get familiar with a technique of single photon correlation measurements I performed a three month training at the University of J. Fourier in Grenoble in a group of prof. J.-P. Poizat. To obtainthe results to my PhD thesis I designed and constructed a setup for the single photon correlation measurements, which was absent in Warsaw before. The setup provides a valuable enhancement of measurement capabilities at the Faculty of Physics. The conducted research brought important information on the dynamics and mechanisms of optical excitation of semiconductor quantum dot. The obtained results are a basis for **10** publications, including two in Physical Review B, where I am the first author.

During my postdoc training (2007-2009), which I effectuated in laboratory LPN/CNRS in Marcoussis in a group of prof. P. Senellart I get familiar with the physics of the light-matter coupling in the system of a quantum dot coupled to the optical mode of the microcavity. I participated in elaboration of the method of fabrication by photolithography marking of coupled III-V systems and next I comprehensively studied emission properties of them. Overall, the postdoc training and the resulting scientific collaboration brought **8** scientific papers, published in years 2008-2014.

During the next postdoc training (2009-2013), which I effectuated at the Faculty of Physics I worked within the frame of the ERC project **"Functionalization of diluted magnetic semiconductors"** headed by prof. dr hab. T. Dietl. Magnetospectroscopy measurements I carried out on GaN and ZnO based semimagnetic semiconductors allowed, e. g., for a determination or confirmation of exchange constants of magnetic ion-carrier or magnetic ion- magnetic ion interaction in these materials.

In parallel, in years 2010-2013 I headed NCBiR project LIDER entitled **"Wide band-gap semiconductors with metallic nanoclusters for optoelectronics"**. In the frame of the research I studied, e. g., a coupling between excitons in semiconductor and plasmonic excitations in hybrid semiconductor-metal structures. Obtained results allowed for determination of the impact of metallic precipitations in a semiconductor layer, as well as of metallic layer deposited on the semiconductor layer surface on the layer optical properties.

In year 2011, I realized MNiSW project Juventus Plus entitled **"Nitrides and selenides based quantum wells doped with magnetic ions for spin electronics"**. Conducted research showed, e. g., a possibility of tuning the concentration of free carriers in GaN/(Al,Ga)N quantum wells by an additional illumination of the structures below the GaN band-gap.

Projects ran over the years 2009-2013 resulted in **12** scientific publications, including 7, where I am the first of a corresponding author, as well as **2** invited talks. Final reports of the projects that I conducted gained a positive assessment of the funding agencies.

Between XI.2013 and XII.2016 I performed research in a frame of a project **„Fabrication and spectroscopy of single InAs/GaAs quantum dots with magnetic ions in**

photonic structures" headed by dr T. Słupiński. One of the results of the project is a demonstration of a new solotronic system, namely (In,Al,Ga)As quantum dot in (Al,Ga)As barrier doped with a single Mn ion (publication in preparation).

Experience gained in the domain of the photonic (micro)structures embedding III-V quantum dots in France helped me in receiving in 2014 the NCN Sonata-Bis project **"Light-matter coupling in a system of two coupled optical microcavities based on II-VI semiconductors"** (qualified on the first place of the ranking list in the ST3 panel). The project resulted so far in **8** scientific publications. To the most important yet unpublished results include observation of an interaction of excitons confined in (Cd,Zn)Te and (Cd,Zn,Mn)Te quantum wells in two adjacent microcavities as well observation of a lasing action at room temperature in samples with a microcavity embedding a single CdSe quantum well.

Independently of the works carried out in a frame of the PhD thesis or the projects listed above I participated in an active way in the research conducted by my colleagues. They were devoted primarily, but not solely, to magnetospectroscopy of quantum dots and nanowires, also magnetically doped. E. g., in the recent years in collaboration with dr P. Wojnar I studied magnetooptical properties of II-VI DMS nanowires (which resulted in two papers in Nano Letters). Together with dr. hab. H. Teisseyre I study magnetooptical properties of ZnO/(Zn,Mg)O quantum wells. The research of the properties of the iron dopant in ZnO polycrystalline layers resulted in a comprehensive article published in December 2016 in Physical Review B.[44]

Below I provide a brief summary of my scientific accomplishments (the full information is contained in Attachment 4 to the Application):

- I am a coauthor of **59** reviewed scientific works in international journal (including **42** published after PhD thesis). Among others, the works were published in: Nature (1 article), Nature Communications (1), Physical Review Letters (2), Physical Review B (14), Applied Physics Letters (5) and Nano Letters (2).
- Number of citations according to Web of Science database *(as for Jan. 19th 2017)*: **996**
  Number of citations without self-citations: **921**
  Hirsch index according to Web of Science database: **15**
- I performed **37** peer reviews for international scientific journals in years 2010-2016, including: Reports on Progress in Physics (1 review), Physical Review Letters (2),

Physical Review B (7), Plasmonics (5), Journal of Luminescence (3), Solid State Communications (3), Acta Physica Polonica A (6).

- Overall, I participated in **9** research projects (including 1 running). I headed three of them (LIDER /2010-2013/, Juventus Plus /2011/, Sonata-Bis /2014-present/).

I have delivered:

- **12** oral presentations at international conferences, including:
  - International Conference on the Physics of Semiconductors /ICPS/ (3 oral presentations),
  - International Conference on Semiconductor Quantum Dots (1),
  - International School and Conference on the Physics of Semiconductors /Jaszowiec/ (4)
- **2** invited talks:
  - Joint Polish-Japanese Workshop „Spintronics - from new materials to applications" (Warsaw, 2011)
  - European Materials Research Society (E-MRS) Fall Meeting (Warsaw, 2013)
- **9** invited seminars in Polish or foreign institutions, including:
  - Johannes Kepler Universität, Linz, Austria
  - Université de Versailles, Versailles, France
  - Laboratoire National des Champs Magnétiques Intenses, Grenoble, France
  - Mikołaj Kopernik University, Toruń

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