Załącznik 3.

AUTOREFERAT

1. *Name:* Jacek Szczytko

2. *Diplomas , degrees / arts - with the name , place and year of their acquisition and the title of the doctoral dissertation.*

- 2001 - Ph.D. in Physics (condensed matter physics) , Department of Physics, University of Warsaw, title of thesis: " Semimagnetic semiconductors of group III- V ", supervised by prof. Andrzej Twardowski.
- 1996 - M.Sc. , Department of Physics, University of Warsaw , „Magneto-optical study of the *s,p-d* exchange interaction in GaAs doped with Mn ", supervised by prof. Andrzej Twardowski.

3. *Information on previous employment*

- Since 2005 : adiunkt, Faculty of Physics, University of Warsaw
- 2001-2004 : post-doc at Ecole Polytechnique Fédérale de Lausanne, Switzerland
- Short term fellowships
  - August 2007 visiting professor at the National Chiao Tung University, Taiwan
  - June-August 2009 fellowship at the Universite de Montpellier II, France
  - December 2011, fellowship at the Center for Physical Sciences and Technology, Vilnius, Lithuania
  - June-August 2012 fellowship at the Universite de Montpellier II, France

4. *Scientifiv achievements under Article 16 paragraph 2 of the Act of 14 March 2003 on Academic Degrees and Title and Degrees and Title in Art (Dz. U. nr 65, poz. 595 ze zm.)*:

4.1) Series of publications: *Optical properties of plasma in semiconductor and metal nanostructures.*

4.2) *Papers:*

H1. **J. Szczytko**, L. Kappei, J. Berney, F. Morier-Genoud, M. T. Portella-Oberli, and B. Deveaud, *Determination of the exciton formation in quantum wells from time-resolved interband luminescence,* Physical Review Letters **93**, 137401 (2004)
IF = 7,218 (2004), cited = 43
(60% of contribution: planning and caring out the experiment, analysis of the results in the model of kinetic equations, fitting the model to the experimental results)

H2. **J. Szczytko**, L. Kappei, J. Berney, F. Morier-Genoud, M. T. Portella-Oberli, and B. Deveaud; *Origin of excitonic luminescence in quantum wells: Direct comparison of the exciton population and Coulomb correlated plasma models;* Physical Review B **71**, 195313 (2005)
IF = 3,185 (2005), cited = 12
(70% of contribution: planning and caring out the experiment, analysis of the results in the model of kinetic equations, fitting the model to the experimental results)

H3. L. Kappei, **J. Szczytko**, F. Morier-Genoud, and B. Deveaud; *Direct Observation of the Mott Transition in an Optically Excited Semiconductor Quantum Well*, Physical Review Letters **94**, 147403 (2005)
IF = 7,489 (2005), cited = 54
(45% of contribution: planning and conducting the experiment, analyzing of the results)

H4. M. T. Portella-Oberli, J. Berney, L. Kappei, F. Morier-Genoud, **J. Szczytko**, and B. Deveaud-Plédran; *Dynamics of Trion Formation in $In_xGa_{1-x}As$ Quantum Wells*, Physical Review Letters **102**, 096402 (2009)
IF = 7,104 (2009), cited = 9
(45% of contribution: planning and caring out the experiment, analysis of the results in the model of kinetic equations, fitting the model to the experimental results)

H5. **Szczytko, Jacek**; Vaupotic, Natasa; Madrak, Karolina; Sznajder, Paweł; Górecka, Ewa; *Magnetic moment of a single metal nanoparticle determined from the Faraday effect;* Physical Review E **87**, 033201 (2013)
IF = 2,307 (2012), cited = 1
(65% of contribution; planning and caring out the experiment, analysis of the results, fitting the model to the experimental results)

H6. **Szczytko, Jacek**; Vaupotic, Natasa; Osipov, Mikhail; Madrak, Karolina; Górecka, Ewa; *Effect of dimerization on the field-induced birefringence in ferrofluids;* Physical Review E **87**, 062322 (2013)
IF = 2,307 (2012), cited = 0
(55% of contribution; planning and caring out the experiment, analysis of the results, fitting the model to the experimental results)

4.3) *discussion of the scientific research and the results, together with a discussion of their possible use.*

Series of publications concerns the optical properties of plasma in semiconductor and metal nanostructures.

Abstract

In my scientific work I focused on the optical properties of plasma in nanostructures – quantum wells and metallic nanoparticles. I focused on three main questions:

- How do the free electron-hole pairs form quasiparticles such as excitons and trions [H1-H4]?
- Does the electron-hole luminescence appear only after the binding to quasiparticles [H1-H2]?
- How to measure the plasma frequency of metallic nanoparticles and how do surface plasmons modify the optical properties of the medium in which nanoparticles are placed [H5-H6]?

The research was conducted by various optical methods (reflection, absorption, luminescence, photoluminescence excitation, time-resolved experiment with streak-camera), suitable for the phenomena caused by the presence of a high concentration of free carriers (electrons or holes).

A wide range of plasma concentrations were examined – starting with such whose properties are described by elementary excitations i.e. quasiparticles (electrons, holes, excitons, trions), then increasing concentrations in which Mott transition was observed, and finally large concentrations where collective phenomena were important (plasma frequency, surface plasmons). The results of these studies were: the parameters of kinetic equation describing the formation of excitons and trions, magneto-optical method of determining plasma frequency of metallic and magnetic nanoparticles and estimation of magnetization of the nanoparticles. It was also possible to answer the question how magnetic nanoparticles form a chain and whether it is rigid or flexible.

In condensed matter physics the term *plasma* means a gas of free carriers (electrons or holes) located in the crystal lattice of charged ions. As the result of mutual screening, in a good approximation, plasma can be considered as free i.e. non-interacting carriers. Ironically, the lack of interaction of plasma components is driven by a strong Coulomb interaction - the possibility of free movement of carriers means that they can very effectively compensate the emergence of a charge of opposite sign. This leads to a Coulomb potential screening at distances of the so-called Debye length $\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{n\, e^2}}$ – shorter for larger carrier concentrations n (ε_0 the vacuum permittivity, k_B is the Boltzmann's constant and e is the electron charge). In the case of condensed matter, there are also interactions with the crystal lattice - band structure (e.g. the resulting effective mass of free carriers), lattice polarizability (permittivity ε_r, dielectric function $\varepsilon(\omega)$, etc.) and its mechanical properties (phonons, heat capacity, electron-phonon interaction, etc.). For example, in the formula for

the Debye length, in case of degenerate semiconductors and metals, instead of the thermal energy $k_B T$ the Fermi energy E_F and the permeability ε_r appear: $\lambda_D = \sqrt{\frac{\varepsilon_0 \varepsilon_r E_F}{n\, e^2}}$.

Thus, describing plasma and its excitation in semiconductors and metals, one should take into account properties of the medium in which this plasma is located. Thanks to this plasma-medium dependency it is possible to study phenomena difficult to observe in the gaseous plasma: it is possible to reduce the dimensionality and study the plasma in two- and one-dimension, changing the plasma density (concentration of electrons and/or holes), studying of plasma in helium and ambient temperatures, or investigating a spin-polarized plasma, etc. For instance, in the formul expressing the plasma frequency ω_p or cyclotron frequency ω_c , the electron mass is replaced by the effective mass of the carrier (electron or hole) m^* in a solid:

$$\omega_p^2 = \frac{ne^2}{\varepsilon_0 \varepsilon_\infty m^*}$$

(in three dimensions), where the high-frequency dielectric constant ε_∞ contains - through Lydd-Sachs-Teller relation - information on the longitudinal and transverse vibration modes of the crystal lattice (called LO and TO phonons)[1].

An example of plasma in condensed matter is the gas of free electrons in metal or heavily doped semiconductor, strongly degenerate gas in two-dimensional semiconductor heterostructures (the 2DEG – two dimensional electron gas), electron-hole plasma (e-h plasma) created by strong light excitation or as a result of injection of electrons and holes into the laser active region, etc. The diversity of phenomena associated with the presence of plasma in metals and semiconductors attracts the attention of many research groups over the world – both from the scientific and application point of view. For instance, the elementary excitation in plasma – so called *plasmons* – became the subject of intense research of a new field of knowledge – *plasmonics*, which emerged in the beginning of the twenty-first century. Plasmonics combines the development of nanotechnology in recent years, and all the knowledge accumulated from the times of the Drude-Sommerfeld model at the beginning of the 20th century[2]. In turn plasmonics can be applied nowadays for fast data transmission, photovoltaics (PV) and biological studies (detection sensors based on surface plasmon resonance (SPR) or surface enhanced Raman spectroscopy/scattering (SERS)) .

One of the most important achievements in solid state physics was to create systems of the so-called *reduced dimensionality* – in particular quantum wells (QW, two-dimensional systems, 2D). In such systems carriers are confined in the potential, in which the movement

[1] W. Cochran and R. A. Cowley, *Dielectric constants and lattice vibrations* J. Phys. Chem. Solids **23**, 447 (1962)
[2] Strictly speaking Drude model was proposed in 1900, in the last year of the nineteenth century.

of the carrier is limited (and thus quantized) in one direction leaving freedom in two dimensions.

My interest in plasma physics started with the problem of the mechanism of excitonic luminescence – how fast do electron and hole bind into excitons, and does the luminescence at the energy of the exciton come from bound carriers?

Work was done at the Ecole Polytechnique Federale de Lausanne (EPFL) in the group of prof. Benoit Deveaud in the laboratory of Marcia Portella-Oberli. The experiment was conducted under my supervision with two doctoral students (Lars Kappei and Jean Berney). Theoretical analysis, continued at the University of Warsaw, based on kinetic equation presented in [H1-H4] was also of my authorship.

[H1, H2, H3, H4] Time-resolved photoluminescence was measured. The quantum well was stimulated with a strong light pulse (about 40 fs short), which created electron-hole plasma (*e-h pairs*). Then carriers annihilated by emitting a photon which energy carried information about the physical processes prior to the recombination of electrons and holes. The quality of the sample should allow the observation and separation of optical transitions at certain energies. It means that the non-homogenous broadening (caused by the disorder present in the quantum well, such as fluctuations of its thickness) and the presence of non-radiative processes were negligible. The sample was grown by Franocis Morier-Genoud using molecular beam epitaxy (MBE) method at EPFL.

A brief survey of the literature till 2004 allows to find that experimentalists have reported exciton formation time ranging from less than 10 ps up to about 1 ns [H1. ref. 7–10] and theoretical values range from 100 ps to over 20 ns [H1. ref. 11-14]. On the theoretical side, binding of an electron-hole pair into an exciton requires, at low temperatures, the emission of an acoustic phonon, which brings long formation time due to the small coupling of acoustic phonons to excitons – while the experimental excitonic transitions occurred almost immediately [H1, ref. 7, 15]. Therefore, a group of theorists from Marburg in a series of papers denied the existence of excitons [H1, ref. 16] – according to the theory, developed by prof. Stephan Koch and prof. Mackillo Kira, *Coulomb correlations plasma* – and not bound states of the electron and hole – is responsible for optical transitions at energies of excitons (absorption and emission). Bound states ("real excitons”) can occur after a certain time after excitation (the time needed for bonding is of order of 100 ps). However, according to a group from Marburg, what we see for a very short time, the order of picoseconds after the creating plasma pulse, results from direct annihilation of electrons and holes due to the so-called "Coulomb correlations". This issue will be further discussed in [H2] .

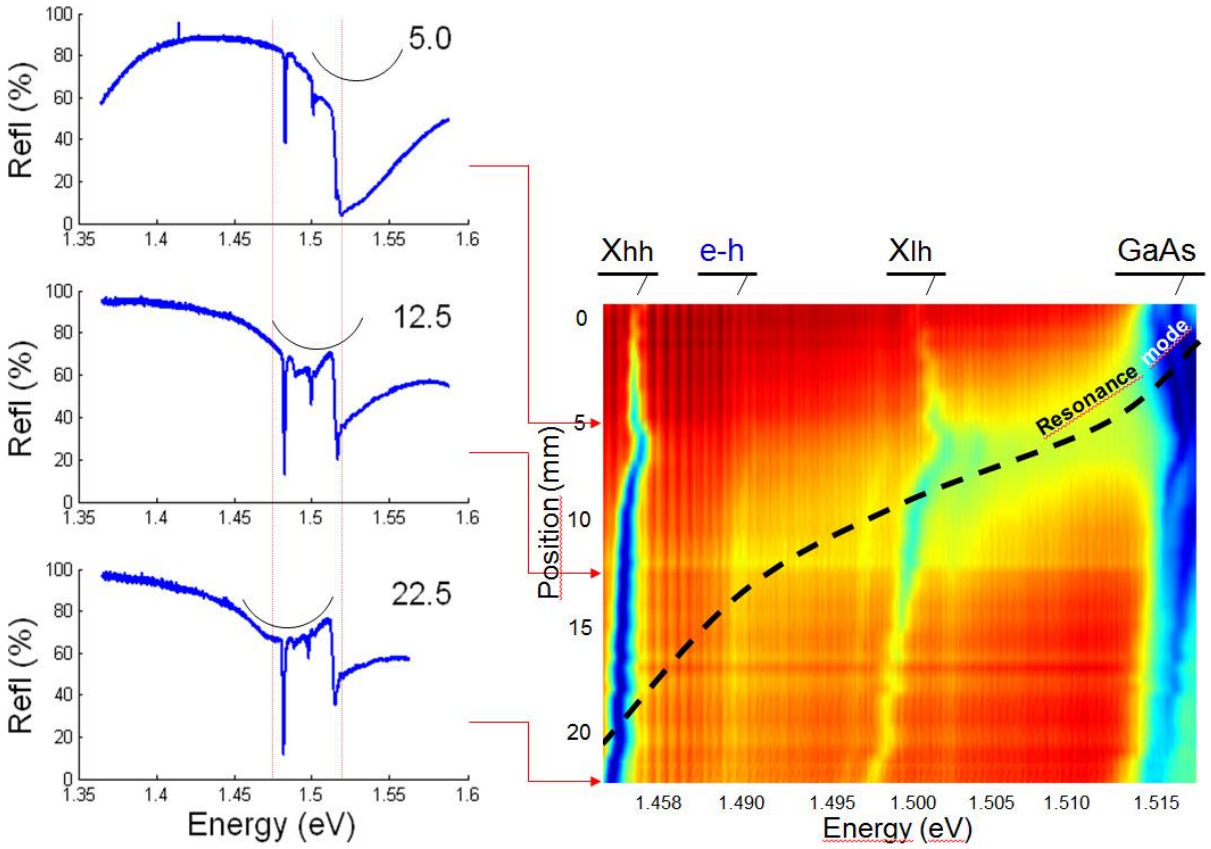

Fig. 1. The reflectivity spectra of the sample as a function of the position of the light spot on the sample. The transition of heavy-hole excitons (Xhh), ligtht-hole (Xlh), and e-h plasma and GaAs absorption edge is marked. The colors correspond to the intensity of the reflected light (red - high, blue – low intensity). On the left there are selected spectra with the particular cavity mode marked by a black bow. Vertical lines limit the range of energies shown on the colormap (unpublished).

In order to investigate e-h plasma and excitonic luminescence the special sample with a distributed Bragg reflector (DBR) has been grown. $In_xGa_{1-x}As$ ($x = 5\ \%$) quantum well was placed in the center of the GaAs cavity of a width corresponding approximately to the wavelength of excitonic resonance. This cavity was grown over 10 layers of DBR. Properly designed structure of the sample acted as a sort of amplifier – so formed a half-cavity[3] effectively enhanced the luminescence of the quantum well. Through a special growth process the GaAs cavity of varying thickness was obtained whose resonant mode could be tuned to the various optical transition energies. The width of the cavity mode in this case was about 40nm, so it was much wider than any other structures present in the sample spectrum (Fig. 1). As a result, in the time-resolved experiment (t - time) using streak camera e-h plasma luminescence (of intensity $I_{plasma}(t)$) was recorded for the first time along with the excitonic luminescence ($I_X(t)$), and charged excitons (so-called triones, $I_T(t)$, [H4]). The results of the luminescence and reflectivity measurements were compared (H1, Fig.1). It

[3] "Half" because it had a mirror at only the one side.

should be noted, that the measurement of reflectivity from the quantum well located above the Bragg mirrors meant in fact measurement of light transmission through the well, hence the observed reflection spectra resemble the structure of the transmission.

The thermalization process of e-h plasma was also investigated. The crystal was kept at 5.0K, but the initial light pulse, with a duration of 1.2 ps and an energy higher than the QW energy gap[4], built up the initial plasma population at a temperature above 100 K in a quantum well (H1, Figure 2 b). Analyzing the line shape, corresponding to the Maxwell-Boltzmann distribution of free-carrier gas, one can determine the temperature of plasma[5].

The decay of free carrier concentration n (plasma) versus time for a given plasma temperature T was determined assuming the relationship $n \propto \sqrt{I_{plasma}T}$. The experimental results enabled the analysis of the concentration of plasma n and excitons X time evolution using kinetic equations ([H1], eqn. 5). In the plasma of temperature T exciton ionization (a process opposite to the binding) is described by the two-dimensional Saha ionization equation, and the equilibrium exciton-plasma term $K(T)$[6]. The bimolecular exciton formation rate (from e-h plasma) was calculated by Piermarocchi et al. [H1, ref. 13] for GaAs. Knowing the concentration of plasma and excitons, the intensity of the luminescence was calculated and compared with the experimental results [H1, Figure 4]. Proposed model not only described the experimental data but also explained rapid formation of the excitonic emission spectrum.

The excitons formation process requires emission of optical and acoustic phonons from photoexcited plasma, and it was previously analyzed by Piermanocchi et al. [H1, ref. 13]. The corresponding kinetic term can be written as $Cnp \approx Cn^2$. For large e-h plasma concentrations formation time is very fast[7]. In addition, the initial plasma temperature is high which allows the emission of LO phonons. In other words, the excitonic luminescence in QW, in the case of strong excitation, appears "almost immediately" (several picoseconds) after the excitation because the binding process is very efficient. At the same time, a significant difference of plasma and exciton radiative times makes the intensity of the latter always dominate over the luminescence of plasma.

[4] The value of excitation energy has been carefully selected to avoid the resonant creation of excitons or triones (via LO phonons). For more details see [H2], and Figure Fig 2.

[5] The excitation pulse drove the physical system out from equilibrium. The light created e-h plasma at high temperature inside the crystal lattice of helium temperature (5.0K). It created the so-called *non-thermal plasma*, where the excess energy of electrons and holes has been dissipated by the slow (in the examined times) emission of phonons. The carrier-carrier interaction (between electrons and holes) in a dense plasma was so fast that one could introduce "plasma temperature" describing the thermal distribution of "free cooling" plasma.

[6] In terms of chemistry Saha equation is the *law of mass action*.

[7] Strictly speaking, the instantaneous formation time of excitons τ_f in a kinetic equation is inversely proportional to the concentration n, and hence the forming process is faster at higher concentration.

Kinetic equations explained how the e-h plasma formed bound states - excitons. The aforementioned spread of the experimental values of formation times might be related to the different experimental conditions. With strong stimulation, ie. a large initial concentration of created photocarriers, the process of excitonic formation is very short, less than 10 ps. However, for low-power excitation and thus low initial concentration, or after sufficiently long time, the probability of binding of electron and hole into pair decreases, and the process of exciton formation is extended (for example, in our experiment it was already of 1100 ps). In both cases there is no need for introducing the "Coulomb correlated plasma" model.

Model of "Coulomb correlated plasma" and model of the formation of the excitonic population were directly compared in [H2] using the data collected in [H1]. The transfer matrix calculations of the sample reflectivity (including cavity, QW, Bragg mirrors, the substrate) was performed [H2, Fig. 1]. I performed all the theoretical calculations presented in [H2], including fixed equations of exciton and plasma absorption from work of Atanasov et al. PRB **50**, 14381 (1994) (error in eqn. 33 and 34). I also determined the ratio of luminescence intensity corresponding to the energies of exciton 1s and 2s.

The results of calculations matched the shape of the observed reflections [H2, Fig. 1]. The luminescence due to *Coulomb correlated plasma* model was discussed. As mentioned before, this model had been proposed to explain the “immediate” emerging of excitonic luminescence after initial excitation. Theoretical models which do not take into account the bimolecular processes (i.e carrier concentration dependent) poorly describe the formation times of excitons from the e-h plasma. Group of physicists from Marburg (Kira, Koch et al.) And Tucson (Chattarjee, Gibbs et al.) proposed a model in which the plasma luminescence by itself, due to Coulomb correlations appear at the same energies as exciton luminescence, and can be observed even without any associated population of excitons [H2 ref. 18 and 19]. The plasma population distribution in *k*-space of electron f_k^e and holes f_k^h was governed by corresponding envelope of the density of excitons $|\phi_v^r(k)|^2$. At first glance, it seemed that such luminescence could not be distinguished from the luminescence of "ordinary" excitons. However, it turned out that the *Coulomb correlated plasma* model could be consequently applied to the states $\phi_v^r(k)$ described by the envelope of the exciton function 1s and 2s. This way one could determine the relationship between the luminescence of both these states I_{PL}^{1s}/I_{PL}^{2s} and compare it with experimental results. Such comparison could be performed for subsequent temperatures, determined from the intensity of the plasma transition given by the occupation of states f_k^e and f_k^h.

Coulomb correlated plasma model incorrectly predicted relative luminescence intensities associated with $2s$ and $1s$ luminescence. According to this model both transitions should be almost equally intense at low temperatures. A thorough analysis of the time-resolved experimental results made possible determination of the I_{PL}^{1s}/I_{PL}^{2s} ratio. The real temperature

dependence was opposite than in the case of Coulomb correlated plasma - at low temperature, instead of increasing, this ratio decreased. Simple theoretical estimates allowed to explain this behavior in the framework of the population of excitons - at a low temperatures the occupation of the states $2s$ was less likely than $1s$.

Data presented in [H1] and [H2] concerned the results of low power excitation experiments – the density of the carriers created by photons was at most of the order of 10^{10} cm^{-2}. With more excitation power Mott transition in QW was observed [H3] – the transition of insulating gas of excitons in quantum well to the conductive electron-hole plasma.

Above plasma density of $1{,}6 \times 10^{11}$ cm^{-2} the luminescence spectrum was dominated by the recombination of plasma of free carriers. The renormalization of the energy gap was observed. The energy gap decreased (*redshift*) due to many-body interactions in plasma, while filling the band with Fermi gas of electrons and holes was visible as a shift towards the blue part of the spectrum of luminescence (*blueshift*). The experiment was performed similarly as in [H1] and [H2], except that a spatial filter (pihole) was used for imaging the spectrum in a streak camera only at maximum excitation power - in order to collect the luminescence spectrum uniformly excited by light pulse.

The increase of e-h pairs concentration leads to a strong Coulomb screening at a distance of the order of Debye length λ_D – above a certain critical size bound electron-hole states are not possible. This distance – which depends on the concentration of carriers - is responsible for the appearance of the Mott transition. This leads to self-amplifying mechanism: the increase of the plasma concentration (by temperature or concentration change) leads to a reduction in the binding energy of excitons, which leads to ionization of the excitons, and therefore increase the plasma concentration, which further reduces the binding energy, etc.

Decay of the plasma concentration was determined [H2, Fig. 2] by fitting the luminescence spectrum – in particular widening of the spectrum through the mechanism of carrier-carrier scattering. Empirical formula introduced by Landsberg to describe Auger processes in spontaneous emission was used. It was proposed because it gave a very good theoretical approximation of the shape of the calculated spectrum [H3, Ref. 14-16]. Analyzing the shape of the luminescence spectrum at full with half maximum (FWHM) and comparing the results with fitting parameters obtained from theoretical modeling, one could notice redshift (i.e. decreasing energy gap through renormalization) and blueshift (the increase of the distance between the quasi-Fermi levels of electrons and holes), as expected [H3, Fig. 3].

The observation of the Mott transition was also proved in the analysis of luminescence decay [H3, Fig.4]. At low plasma concentrations (below 1×10^{10} cm^{-2}) the decay time is very long due to the long exciton formation time (of the order of hundreds of picoseconds). This behavior can be explained by model presented in [H1] and [H2] - the efficient creation of an

exciton requires high concentration of carriers because it is a bimolecular process. The luminescence decay time is then dominated by the long exciton formation. The increase of the plasma concentration decreases the excitons formation time. In certain range of the excitation power the luminescence decay time is dominated by the life time of exciton and is not dependent on the concentration of plasma (it corresponds to a density range of $1 \times 10^{10} - 1 \times 10^{11}$ cm^{-2}, for which the formation time of excitons is shorter than the decay time). For concentrations above the Mott transition, as long as the spectrum is dominated by plasma luminescence, an additional mechanism which shortens the luminescence is clearly observed – a fast radiative decay of degenerate e-h plasma. Only when the plasma concentration falls below the metal-insulator transition, radiative decay is again dominated by the lifetime of the exciton.

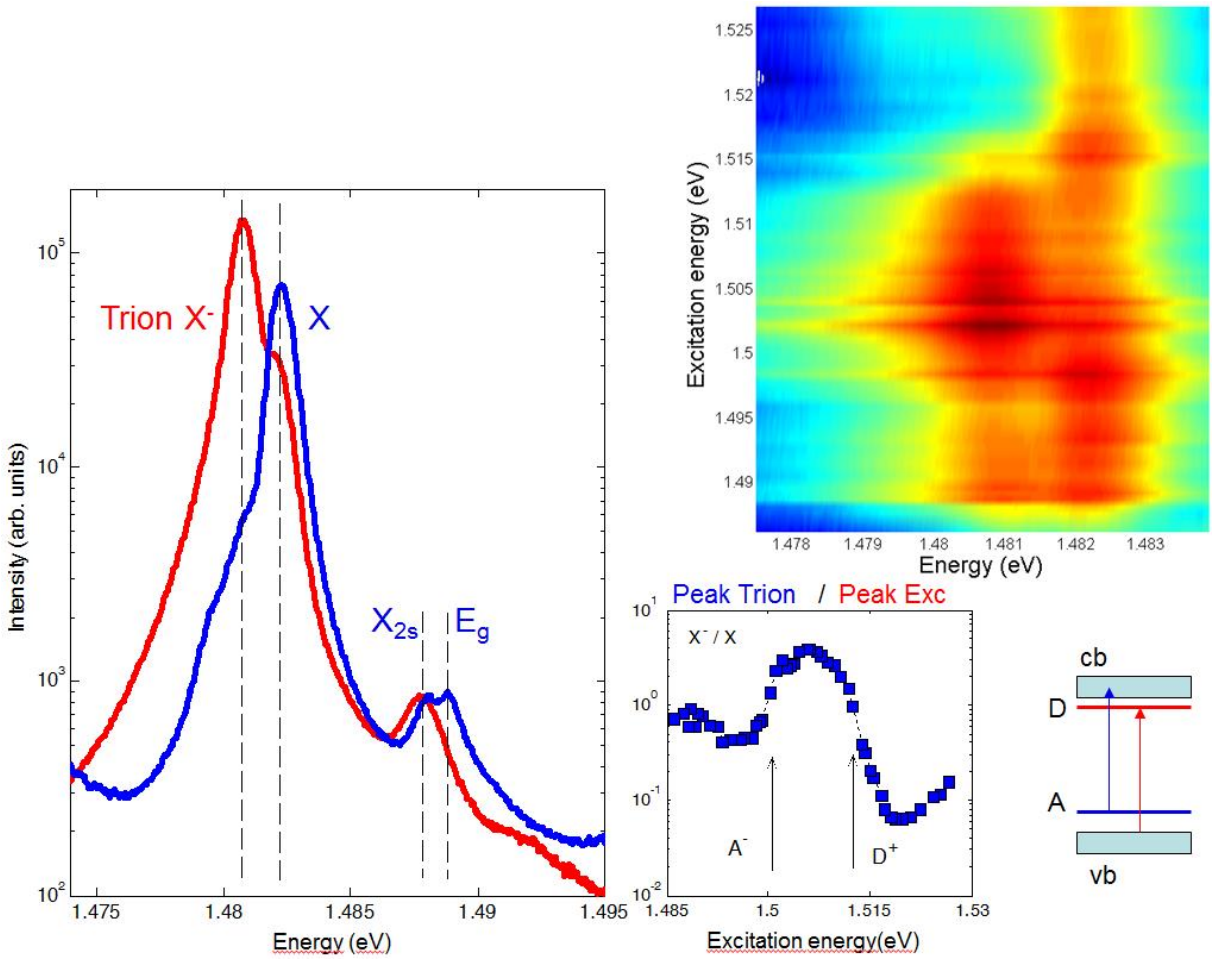

Fig. 2. Photoluminescence excitation (PLE) spectrum of the sample. Depending on the laser excitation energy the intensity of the luminescence attributed to exciton and trion transitions dominates the spectrum (color map represents the intensity of luminescence, an example spectrum excited by $\hbar\omega = 1{,}5072$ eV is marked in red, and $\hbar\omega = 1{,}5174$ eV in blue). The ratio of trion-exciton peak luminescence changes with excitation energy (blue squares). The letters A and D mark the absorption energies of unintentional acceptors and donors present in GaAs cavity. According to the diagram at the bottom of the figure they are the source of the carriers (unpublished).

Research [H1] - [H3] was related to the optical properties of neutral plasma - the densities of electrons and holes were approximately equal. Slightly different excitation conditions were used to create electrically charged quantum well (Fig. 2). Then the electron plasma was more dense than the hole plasma. It was possible to perform experiments on the so-called *trions* – charged excitons, composed of three carriers: two electrons and holes [H4].

In the kinetic equations additional bi- and tri-molecular processes were included: F_2 (neutral exciton-carrier) and F_3 (three carriers). The equilibrium constants K_2 and K_3 were determined from the law of mass action for the processes of the type $A + B \rightleftarrows C$ (eg A - exciton, B - electron, C - trion) and $A + B + C \rightleftarrows D$ (eg A, B - electrons, C - hole, D - trion) [H4]. The results of the work [H1] and [H2] were used. Jean Berney performed theoretical calculations for the parameters of bi- and tri- molecular formation (A_2 and A_3), presented in Figure 3 [H4, Fig. 3]. The experiment, fitting of parameters of the kinetic equation to the experimental results, the conclusions presented in Figure 4 [H4, Fig. 4] are of my authorship. One of the most important results of this work is the dependence of the luminescence intensity of plasma, excitons and trions in quantum wells, as a function of the (excess) concentration of electrons and holes. It turns out that in virtually all circumstances the luminescence spectrum contains all three components [H4, Fig. 4]. In particular, even for an electrically neutral QW (equal concentrations of holes and electrons $n = p$) bound states of charged excitons are created - either positive or negative triones. These states coexist in plasma, since the probability of the binding of exciton and an additional carrier (processes F_2) or bind the three carriers in trion (processes F_3) is never equal zero. Only when the difference of concentration between electrons and holes is very high, above 10^{10} cm^{-2}, the luminescence of trions dominates the spectrum. Due to the difference in mass of positive and negative trions, caused by the difference of the masses of the electron and hole, the experimentally observed coexistence of positive and negative trions (eg, [H4] Ref. 23, Glasberg et al.) does not necessary mean neutral quantum well - the well is charged negatively, and only then the intensity of different charged trions become comparable. With increasing carrier density the intensity of trion luminescence becomes saturated and is limited by the availability of carriers of opposite sign. For large carrier densities the kinetic equations [H4] show that in the absence of carriers of opposite sign neither trions nor excitons can be created. In addition, the electromagnetic wave does not penetrate the interior of the metal as a result of the negative dielectric function for the optical frequency range. Thus, the study of optical properties of plasma in metals requires different kinds of nanostructures.

In the case of metals it is difficult to speak about the low-dimensional objects (eg. wells or quantum dots) because the de Broglie wavelength of carrier at the Fermi surface of metal is typically of a fraction of nanometer. However, the change of metallic particle size leads to a significant change in the optical properties of metal – the coupling of electromagnetic wave

with collective oscillations of plasma, so-called *plasmons*. In particular, the effect of incident radiation coupling with a certain resonance energy of metallic nanoparticles was observed – it is called *surface plasmon*. In this case the reduction of the dimension is necessary to ensure that the transverse electromagnetic wave can excite longitudinal vibration of plasmon – and that requires an object whose shape, curvature, geometry, etc., varies within the distance comparable to the optical wavelength in the medium. The principle of momentum conservation cannot be met without the proper geometry of the system (hence the experimental methods such as the evanescent wave configurations of dielectric prism or a diffraction gratings experiments, or the use of nanostructure curvature (nanoparticles, nanostructured substrate) to excite plasma oscillations).

Continuing my studies of plasma in low-dimensional structures I became interested in the optical properties of plasma in ferromagnetic nanoparticles. Magneto-optical effects make possible determination of the dielectric tensor which contains all the information about the optical properties of the system – the speed of light in matter, dispersion, absorption, Faraday rotation, etc. In the case of nanometer-size structures additional use of static magnetic field makes possible developing new strategies for potential applications (see review article of Armellez et al[8])

Standard description of the optical properties of the electron plasma in metal uses Drude model. Metal dielectric tensor $\underline{\varepsilon}$,, derived from Maxwell's equations for free carriers in an external electric E_{ext} and magnetic B_{ext} fields, contains diagonal terms which are symmetric or independent of the field (typically denoted by ε) and anti-symmetric off-diagonal (denoted by A). They depend on the frequency of the incident radiation (ω), the frequency of the plasma metal ω_p and cyclotron frequency $\omega_c = eB/m^*$ (e - electron charge, m^* effective mass, in the case of metals it is often assumed that it is close to the free electron mass and B is the total magnetic field acting on carrier). Theoretical analysis contained in [H5] and [H6] was based on the Drude model.

In the case of ferromagnetic nanoparticles that are single domain, external magnetic field B_{ext} may be a small contribution to the internal field B_m inside the nanoparticle. Consideration of this field in the description of the dielectric tensor leads to the conclusion that the magnetic nanoparticles are inherently anisotropic – one should find the tensor $\underline{\varepsilon}$ in the eigenframe associated with the direction of magnetization. Macroscopic effect, derived for all of nanoparticles, is averaged over all orientations of the nanoparticles in the laboratory frame. Theoretical description was carried out in Maxwell-Garnett approximation which strictly treats the electric field inside the nanoparticles, but omits the interaction between them.

[8] Gaspar Armelles , Alfonso Cebollada , Antonio García-Martín , and María Ujué González *Magnetoplasmonics: Combining Magnetic and Plasmonic Functionalities*; Advanced Optical Materials **1**, 10 (2013)

Magneto-optical experiment in Faraday [H5] and Voigt [H6] configuration was performed on cobalt nanoparticles obtained from thermal decomposition of organometallic precursor: octacarbonyldicobalt (Fig. 3). The synthesis of nanoparticles and measurement under my supervision was conducted by Dr. Carolina Madrak (Faculty of Chemistry). These measurements were also subjects of the two master's theses under my supervision: Henryk Turski and Pawel Osewski. Synthesis was carried out at the Faculty of Chemistry, University of Warsaw in the group of prof. Ewa Górecka. Theoretical analysis presented in [H4], i.e. the idea to consider the dielectric tensor in the framework associated with the direction of magnetization, are of my authorship (it has been partially included in the Paweł Sznajder bachelor thesis). For rigorous theoretical calculations I asked for help Natasa Vaupotic from the University of Maribor (Slovenia) and Mikhail Osipov from the University of Strathclyde (United Kingdom) .

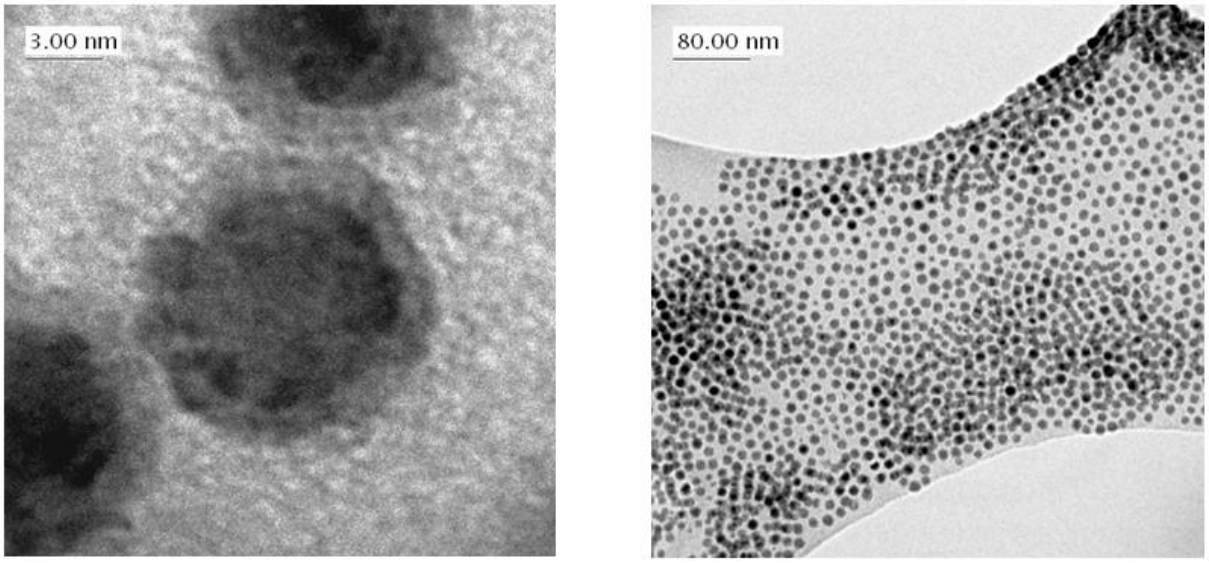

Fig. 3. Transmission electron microscope results of cobalt nanoparticles morphology. The nanoparticles are surrounded by oleic acid, visible on the left as brighter coating of thickness of about 2 nm (unpublished).

The nanoparticles form a stable dispersion in cyclohexane. The light passing through the cuvette of nanoparticle solution placed in the magnetic coil was investigated. It turned out that the rotation of the polarization plane, that is the Faraday effect [H5], and retardation, or Cotton-Mouton effect [H6], could be fit with Langevin function (with some modifications), corresponding to the magnetization of nanoparticles. Fitting of the magnetic moments in [H5, Fig. 1] enabled the determination of magnetization of “mean” nanoparticle (assumed monodispersity of nanoparticles studied). In this way a method to measure the mean magnetization μ of nanoparticles in ferrofluids by magneto-optics measurement was proposed. This method has been submitted in 2012 to the Polish Patent Office PL402159 "Method of determining the value of magnetization of magnetic nanoparticles and a device

for determining the value of magnetization of magnetic nanoparticles." This method can be used only for metallic nanoparticles, because the theoretical approach results from calculations based on plasma properties in Drude model.

Analysis of the results from Faraday configuration [H5 Figure 2] also made possible the determination of cobalt plasma frequency ω_p. In the literature known value of ω_p ranged within a factor of 2 from 162 to 318 nm; in the case of nanoparticles it was estimated with much greater precision on 198 ± 7 nm. In the formula for the Faraday rotation derived from the Maxwell-Garnet approximation surface plasmon frequency of spherical nanoparticles $\omega_p/\sqrt{1+2\varepsilon_h}$ appears in a natural way (plasmon between the metal and the dielectric medium of permittivity ε_h). The presence of these surface plasmons significantly modifies the optical properties of the medium – in spite of the low concentration of nanoparticles they dominate the optical properties of the entire ferrofluid: the *filling factor,* which is the ratio between the volume of solvent and volume of nanoparticles, was of the order of 10^{-5}.

Comparison between the size of nanoparticles measured by X-ray diffraction methods with the amount of determined magnetic moments N ("Bohr magnetons" μ_B) $\mu = \mu_B N$, suggested the presence of a thin layer of about 0.5-1 nm around the magnetic nanoparticles. Magnetic interactions within this layer are different from ferromagnetic inside. This observation is the subject of my further research (eg. thesis of mgr Magdalena Woińska published in Woinska, M; Szczytko, J, et al. *Magnetic interactions in an ensemble of cubic nanoparticles: A Monte Carlo study* Physical Review B **88**, 144421 (2013)).

An attempt to use the model [H5] as an explanation of the Cotton-Mouton [H6] effect ended in failure – observed birefringence was by more than four orders of magnitude greater than that expected from the model presented in the work for spherical nanoparticles [H5]. Thus, the source of the effect had to be different. It was known that the nanoparticles suspended in ferrofluid could form chains. For low concentrations, which were used in our study, the most probable were to find mono-mers or di-mers (in this case a “mer” was the single nanoparticle). Although in solution dimers were 10 000 times less than monomers, they dominated the Cotton-Mouton effect.

Consideration of the shape anisotropy, caused by the presence of dimers, makes possible the explanation of the shape of the retardation observed in the magnetic field [H6, Fig. 1], and its dependence on concentration [H6, Fig. 2]. This time the fit of magnetization gave information about the internal properties of dimers. It turns out that they do not form a rigid chain in solution (rigid, that is where the magnetic moment of the dimer is exactly two times larger than the monomer), but have the ability to change the mutual orientation.

The scientific work presented in this paper is the part of my research. It is worth to mention that above results were the basis for three doctorates (Lars Kappei (EPFL), Jean Berney (EPFL), Karolina Madrak (UW)), master's theses and a number of undergraduate work, which I supervised. Complete list of my students is located in the website:

http://www.fuw.edu.pl/~szczytko/index_students.html

5. *Other achievements of scientific research*

Optical studies of plasma are one of my scientific topics I started after my PhD. Today, I continue to study plasma in metals and semiconductors by optical methods [H1 - H4], especially in the THz domain [30, 36, 38][9] in collaboration with the group of Prof. Jerzy Łusakowski from the Physics Faculty, University of Warsaw. In December 2011 I went to the Center for Physical Sciences and Technology, Vilnius, Lithuania, where I was investigated THz transmission of plasma in thin layers of metallic gold and titanium. In March 2014 I performed experiment on free-electron laser (FEL) in the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Germany – I examined the impact of intense THz radiation on infrared light absorption of polaritons and e-h plasma in the micro-cavities.

My current research includes:

- Magnetization measurements using SQUID magnetometer in collaboration with prof. Andrzej Twardowski from the Physics Faculty, University of Warsaw. I study magnetic nanomaterials, especially carbon nanocapsules with magnetic nanoparticles and nanocapsules based on iron oxides (works [20, 22, 26 , 39 , 46, 48, and a chapter in the book *Combustion Synthesis : Novel Routes to Novel Materials*). I am a member of multidisciplinary teams consisting of chemists, physicists and biologists. Characterization of magnetic and magneto-optics [H5, H6] is an important element in materials research leading to new materials for medical diagnostics and therapy. The group has prepared polypyrrole microvessel structures modified with superparamagnetic nanoparticles for use as potential carriers of nucleotides [46] (I was responsible for the magnetic characterization of nanoparticles). I lead an ICM

[9] The bibliography references are listed in Zał. 5 „List of publications”

grant (Interdisciplinary Centre for Mathematical and Computational Modelling, University of Warsaw) for the Monte-Carlo calculation of the magnetic properties of cubic nanoparticles [39, 48] – dipole-dipole magnetic interaction in the system of nanoparticles with cubic anisotropy .

- I study chemical molecules containing magnetic ions and free radicals [25, 28, 31 - 35, 45, 51,52]. Thanks to the cooperation with prof. Ewa Górecka from the Department of Chemistry, University of Warsaw, and with prof. Piotr Kaszyński from the Department of Chemistry, Vanderbilt University, Nashville, USA, I began research on magnetic and photo-magnetic properties of molecules (mainly liquid crystals) containing magnetic ions and free radicals. This cooperation resulted in a OPUS grant "Magnetic, photomagnetic and structural studies of liquid crystal radicals" 2013/11/B/ST3/04193, of which I am the manager (July 2014 - June 2017). As part of the grant I will study the structure-magnetism correlation in liquid crystals based on verdazyl radicals and I will perform photo-magnetic research.
- I continue investigations undertaken within the framework of my PhD: the measurements of semimagnetic semiconductors and nanomaterials using magnetic (SQUID) and magneto-optical methods [11, 12, 21, 23, 24, 27, 37, 40 - 43, 49, 50].

My research goals are realized through cooperation with many research groups, both experimental and theoretical, with many academic centers, also from abroad. I'm trying to gain funding for modern research infrastructure - I was able to buy SQUID magnetometer and equip a magneto-optical laboratory at the Department of Physics at the University of Warsaw. In my research I incorporate students from Physics and Nanostructures Engineering at the Physics Faculty of the University of Warsaw - starting from 2006 up to 2013 I was the supervisor of 5 master and 15 bachelor theses.

5.1) scientific achievements - globally (Web of Science and Scopus, the data from May 24, 2014)

Number of publications – 52, including 48 from ISI Master Journal List
Sum of the Times Cited - 818
Sum of Times Cited without self-citations - 788
Average Citations per publication - 15,73
Hirsch index h – 13
Cumulative impact factor of scientific publications according to the list of Journal Citation Reports (JCR), according to year of publication – 124,548