

Piotr Wojnar
Institute of Physics,
Polish Academy of Sciences
Warsaw, 2016

Summary of Professional Achievements

Contents

1. Personal data.....	2
2. Education and degrees	2
3. Information on previous employment and long scientific visits	2
4. Scientific achievement being the basis for the habilitation procedure	2
4.1. Title of the publication series and the list of publications of which it consists	2
4.2. Bibliometric data.....	3
4.3. Introduction – scientific background.....	3
4.3.1. Vapor-liquid-solid growth mechanism of nanowires	5
4.3.2. Heterostructures in semiconductor nanowires	5
4.3.3. Magnetic ions inside nanowires	6
4.4. Optically active heterostructures in tellurium-anion based nanowires – description of the publication series H1-H6.....	7
5. Discussion of other scientific achievements not related to the publication series H1-H6...	15
5.1. Description of my scientific activity not related to semiconductor nanowires.....	15
5.3. Conferences, symposia and seminars.....	19
5.4. Organization of conferences and reviewer’s activity	21
5.5. Building of unique research equipments	21
5.6. Teaching and popular science activity	21

1. Personal data

Piotr Benedykt Wojnar

2. Education and degrees

October 2002, M. Sc. in Physics, University of Warsaw, Faculty of Physics, Institute of Experimental Physics. Thesis entitled: „*The influence of the magnetic polaron effect on the spin-flip Raman scattering in bulk CdMnTe*”

Advisor: dr hab. A. Golnik

October 2008, Ph.D. in Physics, Institute of Physics, Polish Academy of Sciences, dissertation entitled: „*Growth and optical spectroscopy of diluted magnetic quantum dots*”.

Advisor: prof. dr hab J. Kossut

3. Information on previous employment and long scientific visits

- 2003 – 2008 International Ph.D. studies at the Institute of Physics, Polish Academy of Sciences.
- 2004 – 1 month long scientific visit at University of Cincinnati, US,
- 2007 - 2008, 2 months long scientific visit at University of Dortmund, Germany
- 2008 – 2009 post doctoral position at Institute Neel CNRS (National Centre of Scientific Research) Grenoble, France
- Since October 2009 adjunct at the Institute of Physics, Polish Academy of Sciences in the Laboratory of Growth and Physics of Low Dimensional Crystals

4. Scientific achievement being the basis for the habilitation procedure in accordance with the art. 16 paragraph 2 of the Act of March 14th 2003

4.1. Title of the publication series and the list of publications which constitute this series.

The scientific achievement being the basis for the habilitation procedure consists of a series of six publications in international journals entitled: **”Optically active heterostructures in tellurium anion based nanowires”**.

The series constitute the following publications:

H1 **P. Wojnar**, M. Szymura, W. Zaleszczyk, Ł. Kłopotowski, E. Janik, M. Wiater, L. T. Baczewski, S. Kret, G. Karczewski, J. Kossut, and T. Wojtowicz, „*Activation of an intense near band edge emission from ZnTe/ZnMgTe core/shell nanowires grown on silicon*” *Nanotechnology* **24**, 365201 (2013). Impact factor 3.8

H2 **P. Wojnar**, E. Janik, L. T. Baczewski, S. Kret, G. Karczewski, T. Wojtowicz, M. Goryca, T. Kazimierzczuk, P. Kossacki, „*Growth and optical properties of CdTe quantum dots in ZnTe nanowires*”, *Appl. Phys. Lett.* **99**, 113109 (2011) Impact factor 3.3

H3 **P. Wojnar**, J. Płachta, W. Zaleszczyk, S. Kret, Ana M. Sanchez, R. Rudniewski, K. Raczkowska, M. Szymura, G. Karczewski, L. T. Baczewski, A. Pietruczik, T. Wojtowicz, J. Kossut, *Coexistence of optically active radial and axial CdTe insertions in single ZnTe Nanowire*, *Nanoscale* **8**, 5720 – 5727 (2016) Impact factor 7.3

H4 **P. Wojnar**, M. Zielinski, E. Janik, W. Zaleszczyk, T. Wojciechowski, R. Wojnar, M. Szymura, L. Kłopotowski, L. Baczewski, A. Pietruczik, M. Wiater, S. Kret, G. Karczewski, T. Wojtowicz, and J. Kossut, *Strain-induced energy gap variation in ZnTe/ZnMgTe core/shell nanowires* *Appl. Phys. Lett.* **104** 163111 (2014), Impact factor 3.3

H5 **P. Wojnar**, E. Janik, L.T. Baczewski, S. Kret, E. Dynowska, T. Wojciechowski, J. Suffczyński, J. Papierska, P. Kossacki, G. Karczewski, J. Kossut, T. Wojtowicz, „*Giant spin splitting in optically active ZnMnTe/ZnMgTe core/shell nanowires*” *NanoLetters* **12** 3404, (2012) Impact factor 13.6

H6 M. Szymura, **P. Wojnar**, Ł. Kłopotowski, J. Suffczyński, M. Goryca, T. Smoleński, P. Kossacki, W. Zaleszczyk, T. Wojciechowski, G. Karczewski, T. Wojtowicz, J. Kossut, „*Spin Splitting Anisotropy in Single Diluted Magnetic Nanowire Heterostructures*”, *NanoLetters* **15**, 1972-1978 (2015), Impact factor 13.6

The above mentioned series of publications consists of 6 papers published in years 2011-2016. It contains two publications in *NanoLetters*, one publication in *Nanoscale*, two publications in *Applied Physics Letters* and one publication in *Nanotechnology*. The total impact factor of the journals from this series amounts to 44.9.

4.2. Bibliometric data

My scientific activity resulted in **77 publications** in total, according to the *Journal of Citation Reports* basis, from which 57 publications appeared in journals with a non-zero impact factor. The other 20 publications are mostly conference proceedings. The total impact factor of all publications amounts to **174.9**, whereas the total number of citations is **737** and **506** without auto-citations. H-index of my publications amounts to **15**. The publications, in which I'm coauthor, appeared in many different journals, such as: *Physical Review B* – 18 publications, *Acta Physica Polonica* – 18 publications, *Applied Physics Letters* 4 publications, *Physical Review Letters* – 3 publications, *Journal of Applied Physics* - 3 publications, *NanoLetters* – 2 publications, *Nanotechnology* – 2 publications, *Solid State Communications* - 2 publications, and *Nanoscale*, *Journal of Crystal Growth*, *Crystal Growth and Design*, *European Physics Letters*, *Journal of Luminescence*, *Physica Status Solidi B* - one publication in each of these journals. The above data is in accordance with *Web of Science* (21st March 2016).

4.3. Introduction – scientific background

Semiconductor nanowires belong to the mostly studied structures with nanometer sizes. They consist of single crystals with typical diameters being in the range of a few or a few tens of nanometers and lengths of several micrometers. The interest in nanowires arises from their emerging applications in the field of electronics [1,2], photonics [3,4], photovoltaics [5], chemical and biological sensors [6,7].

Despite of the fact that the first reports on the growth of nanowires appeared more than 15 years ago [8], the interest of the scientific community on nanowires has been continuously

increasing, since then. The number of nanowire-related publications amounts to 20 000 in year 2015 only [9].

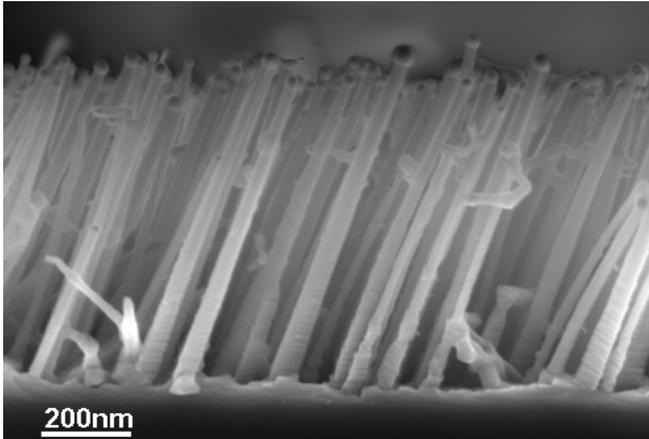


Figure 1 ZnTe nanowires, which I grew in the Institute of Physics Polish Academy of Sciences on (110)-GaAs substrate by employing vapor-liquid solid growth mechanism assisted with gold catalysts in a system for molecular beam epitaxy.

The above mentioned series of publications H1-H6 concerns the growth by molecular beam epitaxy and optical properties of heterostructures in nanowires built of tellurium anion-based semiconductors, such as ZnTe, (Zn,Mg)Te, (Zn,Mn)Te, CdTe, (Cd,Mn)Te. All these semiconductors are characterized by a direct energy gap at the Γ -point of the Brillouin zone, which energies correspond to the wavelength in the visible light spectral range. Therefore, they are potentially good emitters and detectors of visible light. This property is crucial from the point of view of possible applications in optoelectronic devices, such as light emitting diodes, photodetectors and solar cells, as well as from the point of view of basic research. The presence of the luminescence at energies corresponding to the energy gap, i.e., the near band edge emission, gives us, namely, the insight into the band structure close to the Γ -point of the Brillouin zone from which the emission originates. In particular, the band gap changes, the light and heavy hole bands splitting, as well as the spin splitting (Zeeman splitting) of band edges in the presence of an external magnetic field can be investigated.

The interest of tellurium anion based semiconductors is frequently related to the opportunity of dilution of magnetic Mn-ions inside of them. Even a small concentration of these ions results in a significant increase of spin-related properties inside of these materials due to *sp-d* exchange interaction of band carriers with magnetic ions [10]. This interaction is a typical feature of a class of semiconductors called semimagnetic semiconductors, or diluted magnetic semiconductors. One of the most pronounced effects related directly to the *sp-d* exchange interaction is the enhancement of the Zeeman splitting, even by a few orders of magnitude and the spin polarization of carriers present in these structures. The direct insight into these effects can be obtained by means of optical spectroscopy, e.g., by following of the spectral position and circular polarization of the near band edge emission in the presence of an external magnetic field [11].

The aim of my investigations is the fabrication of heterostructures in nanowires built of tellurium-based semiconductors which emit light in the near band edge emission range and employing, subsequently, this emission for the study of such effects as: strain induced energy gap variation, splitting of light and heavy hole bands and enhancement of the Zeeman splitting in nanowires containing magnetic ions due to *sp-d* exchange interaction.

In the introduction part, the vapor-liquid-solid growth mechanism used for the growth of Te-anion based nanowires is firstly introduced in section 4.3.1. It is followed by a short description of different types of heterostructures in semiconductor nanowires, section 4.3.2. The last part of the introduction, section 4.3.3, is devoted to the overview concerning nanowires containing magnetic dopants. It will be focused on the effects induced by the *sp-d* exchange interaction between the band carriers and magnetic ions in these structures. A detailed description of results published in all publications from the series H1-H6 will be given, subsequently, in section 4.4.

4.3.1. Vapor-liquid-solid growth mechanism of nanowires

One of the most frequently used methods for the nanowire growth relies on the vapor-liquid-solid mechanism, in which metallic nanodroplets, i.e., gold nanodroplets, serve as catalysts. The nanowires are fabricated at temperature in which the droplets are in the liquid phase. Frequently, they form an eutectic alloys with substrate atoms which additionally decreases their melting temperature. The reagents are provided in form of a vapor phase, for instance, as molecular beams in our particular case. Subsequently, an enhanced reagent adsorption takes place on catalyst surface, which leads to an oversaturation of reagents in the liquid catalysts. Finally, the recrystallization at the liquid-solid interface takes place. As effect, the nanowires grow *below* catalyst droplets. That is why there is a catalyst droplet on top of each nanowire, as clearly visible in Figure 1. The droplet diameter determines mostly the nanowire diameter, and the nanowire length is given by the growth time. The vapor-liquid-solid growth mechanism was used already in the 60's for the growth of structures with micrometer sizes [12]. The employment of this mechanism for the fabrication of silicon and germanium wires with nanometer sized diameters has given the raise for the development of the nanowires related research field, at the end of 90's [8]. All nanowires described in the publication series H1-H6 are grown by applying gold-catalysts assisted vapor-liquid-solid growth mechanism. One has, however, to note that nanowires can also be fabricated by using various methods not employing metallic catalysts, presently [13,14].

4.3.2. Heterostructures in semiconductor nanowires

Combining several semiconductors in a single nanowire may significantly increase the potential applications range of these structures. Depending on the growth direction one can obtain either axial or radial heterostructures. An important advantage of the nanowire geometry relies on the fact that semiconductors with a larger lattice mismatch as compared to planar structures can be merged in nanowires [15].

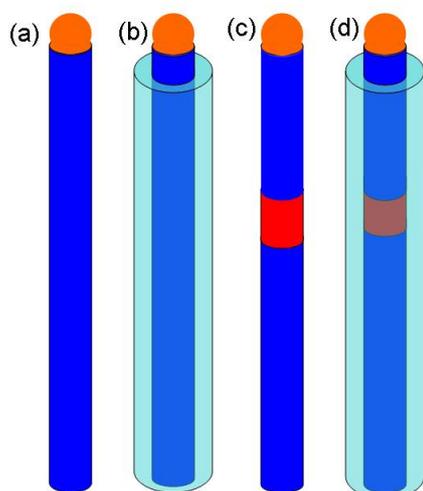


Figure 2 Schematic illustration of various types of heterostructures in nanowires: (a) nanowire grown using vapor-liquid-solid growth mechanism with a metallic droplet on the top (b) radial core/shell heterostructure (c) axial heterostructure (d) axial heterostructure with a radial shell

The presence of a radial shell in a nanowire, shown schematically in Figure 2b, may significantly affect the properties of carriers inside the nanowire core. In particular, a significant increase of carrier mobility is observed, which is due to the passivation of surface states [16,17]. The passivation of the surface is also the reason for the increase of the photoluminescence intensity in core/shell nanowires based on III-V semiconductors [18]. Moreover, radial core/shell nanowire heterostructures can be used as optically active building blocks of multicolor light emitting diodes [19,20], lasers [21] and photovoltaic devices [5,22,23]

The main motivation for the study of axial heterostructures in nanowires is the fabrication of zero-dimensional quantum dots inside of them [24], Figure 2c. These objects are characterized by a relatively short length of the axial insertions, comparable to the Bohr radius of exciton in this material [25-29]. Optical emission from such quantum dots raises the interest of the scientific community due to the particular character of the emitted photons. They are, namely, single photon sources [30], which may find their application in quantum cryptography, which goal is to encode information on single photons. The advantage of quantum dots placed inside nanowires relies on the opportunity of performing electrical contacts in a quite easy way. Moreover, an increase of photon collection efficiency is expected due to the waveguide effect caused by the dielectric environment of the nanowire [31]. Apart of fabrication of nanowire-based quantum dots, axial heterostructures in nanowires may also find their applications in efficient solar cells [32] and bar codes with nanometer sizes [33].

4.3.3. Magnetic ions inside nanowires

One of the main motivations for investigations of tellurium anion-based nanowires is the opportunity of introduction magnetic manganese ions into these nanometer-sized structures and carrying out studies of *sp-d* exchange interaction between the band carriers and magnetic ions inside of them.

The interest of the scientific community for nanowires containing magnetic ions is related either to the basic research of the impact of the size and dimensionality on the magnetic properties of nanometer-sized structures, or to possible applications in the field of spintronics, i.e., electronics which employs the carrier spin degree of freedom. Several effects not possible in bulk crystal may appear in nanowires due to their extreme shape anisotropy. For instance, spin rotations may be limited to only one axis - to the nanowire axis, in these structures. Moreover, the spin relaxation process in nanowires may be slowed down or even suppressed [34]. In case of nanowires with relatively large diameters, in which the radial quantum confinement does not take place, ferromagnetic spin ordering is possible due to strong *p-d* exchange interaction of magnetic ions with valence holes [35]. The effective magnetization can be directed either along [36] or perpendicular [37] to the nanowire axis depending on strain conditions. In relatively thin, one-dimensional nanowires, the ferromagnetic order is not expected to be the ground state. On the other hand, more exotic spin orderings such as, e.g., spin density waves, are possible to achieve.

Several publications are dedicated to the introduction of magnetic ions into nanowires including nanowires built of II-VI [38-40], III-V [36,37,41-43], and group IV [44,45] semiconductors. Only a few reports describe, however, effects related directly to *sp-d* exchange interaction between band carriers and magnetic ions in these structures. The insight into these properties is gained using either carrier magneto-transport measurements performed on individual nanowires [36,46,47], or X-ray magnetic circular dichroism measurements [48].

The direct insight into *sp-d* exchange interaction can be obtained directly by investigating the near band edge luminescence in an external magnetic field. This interaction is manifested by an enhancement of the Zeeman splitting of excitonic levels, as well established for bulk crystals [49]. Such measurements are, however, not always possible. In case of semiconductors doped with manganese, which energy gap is larger than 2.0 eV-2.2 eV, one has to take into account the presence of an internal manganese transition which induces a strong excitation transfer into Mn^{2+} ions. As effect, a significant decrease and, most frequently, the total suppression of the near band edge emission takes place [50]. This is the case for nanowires built of (Zn,Mn)S [51], (Cd,Mn)S [39] and (Ga,Mn)N [52]. In the case of nanowires containing (Ga,Mn)As, the near band edge emission is usually suppressed due to point defects which occur as result of the low temperature growth of (Ga,Mn)As. Semiconductors based on Te-anion, such as: (Cd,Mn)Te and (Zn,Mn)Te, are well suited for the measurements of the Zeeman splitting due to the appropriate value of the energy gap which is comparable to the energy of the internal manganese transition. Thanks to that, the insight into *sp-d* exchange interaction can be obtained in various structures built of these semiconductors.

4.4. Optically active heterostructures in tellurium-anion based nanowires – description of the publication series H1-H6

At the initial state of my research, any near band edge emission from tellurium anion-based nanowires had not been observed, yet. The luminescence was limited to the defect related emission, most likely due to zinc vacancies in case of ZnTe nanowires, and to the internal Mn^{2+} transition in case of (Zn,Mn)Te nanowires [54]. On the other hand, the growth procedure of ZnTe [53] and (Zn,Mn)Te [54] nanowires using gold assisted molecular beam epitaxy was already established. The absence of the near band edge emission from ZnTe nanowires grown by a similar growth procedure was confirmed also in the group of Prof. H. Mariette and Prof. J. Cibert from the French National Centre of Scientific Research (CNRS) in Grenoble. Therefore, it was feared that the observation of the near band edge emission would not be possible in these structures at all. Even a possible explanation for this state in terms of Au-precipitation from the eutectic alloy droplets into the nanowire body was speculated. The resulting deep level defects would suppress the near band edge emission. Despite of these speculations, my efforts were concentrated on the optical activation of the near band edge emission from tellurium-anion based nanowires, at the initial stage of my research. Fortunately, it turned out that surface states were mostly responsible for the initial absence of the near band edge emission from ZnTe nanowires and not Au-precipitation. Thanks to this finding, an intense emission is activated in several Te-anion based nanowire heterostructures.

The publications H1, H2, H3 describe the growth of several heterostructures in Te-anion based nanowires which exhibit an intense near band edge emission. The near band edge emission is activated in radial core/shell heterostructures, H1, axial nanowire quantum dots, H2, core/multishell structures H3, as well as in axial heterostructures with an additional radial shell, H3. Importantly, our investigations are not limited to the nanowire ensemble emission only. They are focused also on the emission from individual nanowires studied by means of cathodoluminescence and micro-photoluminescence in all these publications. In H4, the near band edge emission is used to study the impact of the strain in radial core/shell nanowires on the energy gap of the core semiconductor. The introduction of Mn-magnetic ions into tellurium anion-based nanowires is described in H5. Also in this case, the near band edge emission is studied. The most important result concerns the enhancement of the Zeeman

splitting of excitonic levels by 1-2 orders of magnitude due to *sp-d* exchange interaction in Mn-containing nanowires. In H6, it is demonstrated that the value of the Zeeman splitting depends strongly on the direction of the magnetic field with respect to the nanowire axis. In particular, the spin of the hole is ‘blocked’ along the nanowire axis and remains unchanged in a perpendicular magnetic field. Our interpretation of this result relies on the splitting of light and heavy hole bands. Moreover, the growth of semi-magnetic (Cd,Mn)Te axial insertions in non-magnetic ZnTe nanowires is further reported in H6. An enhancement of the Zeeman splitting due to the presence of magnetic ions by 1-2 orders of magnitude, as well as the nanowire shape related anisotropy of this splitting is observed also in these structures.

Activation of the near band edge emission in radial ZnTe/(Zn,Mg)Te core/shell nanowires, H1

In the first step, our goal is the activation of the near band edge emission from ZnTe nanowires. Several nanowire-containing samples are grown by molecular beam epitaxy at various growth conditions, such as: the substrate temperature and atomic flux ratio Zn/Te. In none of these samples, the near band edge emission is detected, even at liquid helium temperature. The subsequent annealing of ZnTe nanowires in Zn flux, has also no impact on the emission spectrum, despite of the fact that a similar procedure leads to an enhancement of the near band edge emission from ZnSe nanowires [55]. Finally, the near band edge emission is activated by coating ZnTe nanowires with a thin (Zn,Mg)Te radial shell, i.e., a semiconductor with a larger energy gap than ZnTe. Therefore, our conclusion is that surface states are mostly responsible for the initial absence of the near band edge emission from ZnTe nanowires and not the precipitation of gold atoms.

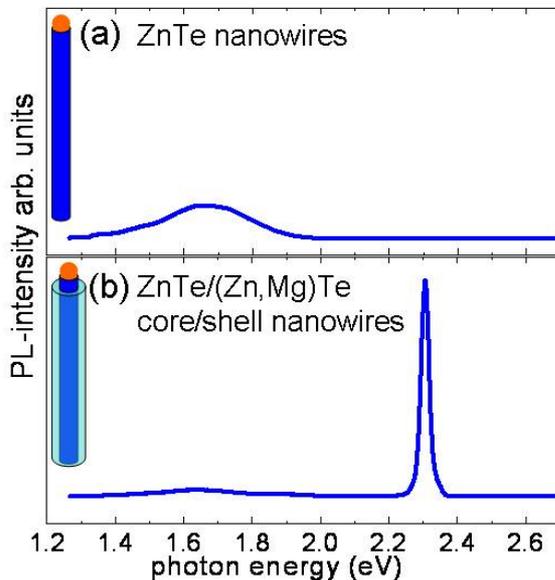


Figure. 3 Activation of the near band edge emission in ZnTe nanowires by coating them with (Zn,Mg)Te shells. (a) Photoluminescence (PL) of bare ZnTe nanowires without any shell, in which the defect related emission is observed at 1.65 eV only (b) ZnTe/(Zn,Mg)Te core/shell nanowires, characterized by an intense near band edge emission peak at 2.30 eV. Temperature 10 K, excitation with 405 nm laser.

The activation of the near band edge emission in ZnTe/(Zn,Mg)Te core/shell nanowires is described in H1. Our particular attention is paid to the role of the substrate used for the growth of these structures, as it turns out to be an important factor determining the emission intensity. The luminescence is about one order of magnitude more intense when Si-substrate is used than in the case of GaAs-substrate despite of similar crystalline properties of nanowires grown on both substrates. Moreover, a relatively strong defect-related emission appears in the case of nanowires grown on GaAs-substrate. Most likely, the precipitation of Ga atoms from Au/Ga catalyst droplets is responsible for the decrease of the near band edge

emission intensity from nanowires grown on GaAs substrate. This is the reason that in H3, H4 and H6, only Si-substrates are used.

Cathodoluminescence (CL) is used to evidence that the near band edge emission originates, indeed, from nanowires and not from any two-dimensional layer which is grown simultaneously between the nanowires. Monochromatic CL-mapping of the near band edge emission reveals that the emitting objects are well elongated and fit exactly into the location of individual nanowires. Moreover, it is demonstrated that this emission is sufficiently intense for the study of individual nanowires by means of micro-photoluminescence. As effect of this investigations, it is demonstrated that the emission from individual nanowires is linearly polarized in the direction along the nanowire axis. The latter effect is caused, most likely, by the large contrast of dielectric constants between the nanowire and surrounding air, as shown already for III-V nanowires [56].

Coating shells which passivate surface states of nanostructures and improve, therefore, their optical properties, have already been added to several types of nanostructures, in particular to nanowires built of III-V semiconductors [18]. This idea is successfully applied to II-VI semiconductor built nanowires in H1. This result opens the path for further investigations of optical properties of nanowires built of Te-anion based semiconductors.

Consistent with our results is the observation of the near band edge emission from ZnTe nanowires fabricated by means of wet chemistry methods after surface stabilization with oleic acid [57]. This result emphasizes also the role of the surface passivation for optical investigations of ZnTe-built nanowires. Moreover, the near band edge emission from bare ZnTe nanowires is observed in case of structures with large diameter, close to 500 nm [58,59]. In these nanowires, the surface effects are less important than in our case, when the diameters are in the range 15-40 nm.

CdTe quantum dots in ZnTe nanowires, H2

A structure consisting of a small axial insertion made of a semiconductor with a relatively small energy gap in a nanowire built of a semiconductor with a relatively large energy gap may constitute an effective light source with a specific character of emitted photons, as already mentioned in the introduction part. When the length of the insertion is comparable to the Bohr radius of excitons, one obtains a zero-dimensional structure – a quantum dot. Such object is a source of single photons which may find their applications in quantum cryptography.

The growth of CdTe quantum dots in ZnTe nanowires is described in H2. This is the first report on Te-anion based nanowire quantum dots, to the best of our knowledge. In the first step, the emission from CdTe quantum dots is identified by means of micro-photoluminescence, as shown in Figure 4. Subsequently, it is found that the emission from individual quantum dots is strongly linearly polarized which confirms that the dots are placed, indeed, inside nanowires. This effect is similar to that observed in core/shell nanowires, H1, and is, most likely, due to the dielectric surrounding of the nanowire. In the last step, the single photon character of the emission from an individual nanowire-based CdTe quantum dot is evidenced by means of photon correlation measurements in a standard Hanbury-Brown-Twiss setup. The latter result confirms the zero-dimensional character of the quantum confinement of these structures.

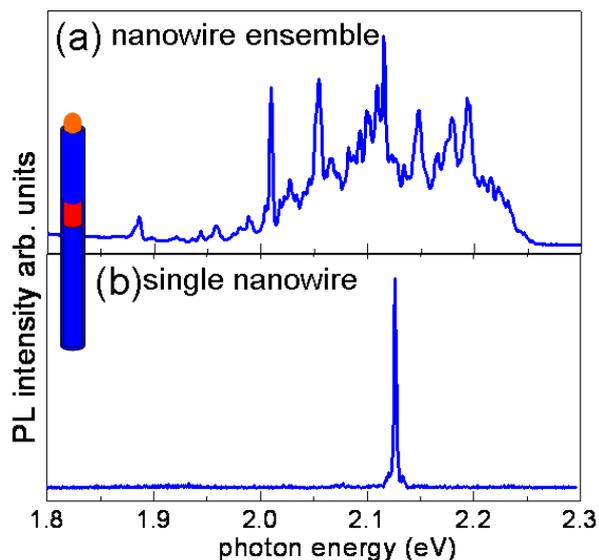


Figure. 4 Micro-photoluminescence from CdTe quantum dots in ZnTe nanowires (a) several quantum dots excited simultaneously, measured on ‘as grown’ sample (b) single quantum dot emission measured after dispersion of nanowires on a non-emitting substrate, Temperature 10 K, excitation with 473 nm laser line.

Let us note, that the nanowire surface is not passivated by any additional radial coating shell, in H2. In this particular case, however, the passivation of CdTe quantum dot surface takes place due to radial ZnTe overgrowth of CdTe quantum dots induced by a relatively low deposition temperature of the upper ZnTe nanowire part.

The intensity of CdTe insertion related emission can be further increased by adding an outer (Zn,Mg)Te passivation shell, i.e., by the growth of a structure presented in Figure 2d. Such heterostructures are one of the main topics investigated in H3.

Fabrication of optically active radial and axial heterostructures in single nanowire, H3

The summary of our results concerning the introduction of optically active CdTe insertions into ZnTe nanowires is presented in H3. All structures studied in this paper are coated with a radial (Zn,Mg)Te shell which ensures an intensive optical emission in the near band edge emission range due to the passivation of the surface. It is demonstrated that, depending on growth conditions, one obtains either axial or radial CdTe insertions. The latter structures consist, therefore, of several radial shells ZnTe/CdTe/ZnTe/(Zn,Mg)Te, whereas the CdTe shell only is optically active due to the smallest energy gap.

CdTe growth direction is controlled by means of its deposition temperature. At 350 °C CdTe grows only axially, whereas at 310 °C and 290 °C, there is also significant deposition on nanowire sidewalls resulting in radial core/shell heterostructures. The increase of the growth temperature above 360 °C induces a strong CdTe desorption which leads to the absence of any CdTe-related emission.

Our study involves consistent measurements performed by means of cathodoluminescence and energy dispersive X-ray spectroscopy – EDX on individual nanowires. It is demonstrated, in particular, that one can obtain structures in which axial and radial CdTe insertions coexists in the same nanowire. Moreover, cathodoluminescence mapping allows for the identification of the emission from both types of heterostructures, Figure 5 and microphotoluminescence

reveals a strong linear polarization of the emission from both types of heterostructures in the direction along the nanowire axis.

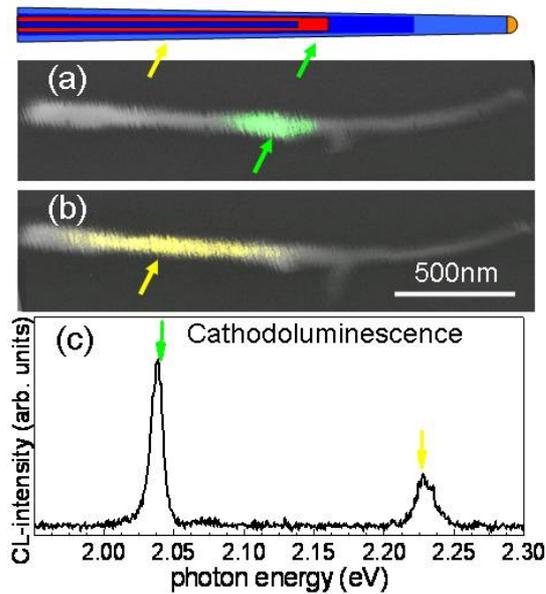


Figure. 5 Cathodoluminescence (CL) from an individual nanowire containing axial and radial CdTe insertions. (a) scanning electron microscope image of the nanowire superimposed with a cathodoluminescence map performed at 2.03 eV (green) which corresponds to the axial CdTe insertion (b) and at 2.23 eV (yellow) corresponding to the radial insertion. (c) CL-spectrum from the investigated nanowire. Temperature 8 K, excitation with a probe current of 500 pA, acceleration voltage 15 kV.

Strain in radial core/shell nanowires and its impact on the energy gap in the nanowire core, H4

An inherent property of core/shell nanowires is the strain originating from the lattice mismatch between the core and the shell semiconductor. The activation of the near band edge emission allows us for the study of the impact of the strain on the energy gap of the nanowire core semiconductor, H4. A relatively large lattice constant of (Zn,Mg)Te shell with respect to ZnTe core results in tensile strain acting on ZnTe-nanowire cores.

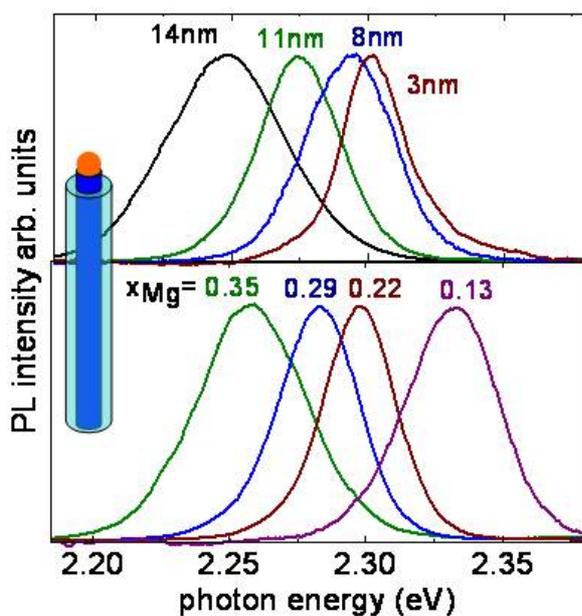


Figure 6 Variation of the near band edge emission from ZnTe nanowire cores depending on the strain present in ZnTe/(Zn,Mg)Te core/shell nanowires. The strain is governed by (a) shell thickness and (b) Mg-concentration in the shell, x_{Mg} . The increase of both parameters increases the tensile strain acting on nanowire cores and induces a significant redshift of the emission energy. All photoluminescence spectra are normalized. Temperature of the measurement is 10 K, excitation wavelength 405 nm.

The parameters which are used to control the strain conditions are: Mg-concentration in the shell and the shell thickness. In photoluminescence measurements, a significant variation of the energy gap is observed depending on these two parameters and amounts to max. 80 meV,

Figure 6. The larger Mg-concentration and the shell thickness the smaller energy gap is revealed in the optical emission spectrum. Theoretical calculations confirming that such large energy gap variation is induced, indeed, by the strain are performed.

The issue of the strain present in core/shell nanowires is described in many publications in the literature. The impact of this strain on the energy landscape, however, remains relatively unexplored. A few papers describe these properties for the particular case of III-V semiconductor based nanowires [18,60]. In H4, it is demonstrated that a large energy gap variation due to strain is present also in case of II-VI semiconductor-built nanowires. In our particular case, other contributions affecting the energy gap, such as Mg-diffusion across the interface and the quantum confinement, would shift the emission energy in the opposite direction than the strain. This is a great advantage of ZnTe/(Zn,Mg)Te system confirming that the main contribution to the energy shift is, indeed, due to the strain. Moreover, the results presented in H4 confirm the applicability of the theoretical model describing the impact of the strain inside core/shell nanowires on their band structure which is developed almost simultaneously to our work [61,62].

sp-d exchange interaction in (Zn,Mn)Te/(Zn,Mg)Te core/shell nanowires, H5

One of the most important scientific achievements described in the series of publications H1-H6 is the growth of nanowires containing magnetic ions and the evidence that these ions interact with band carriers via *sp-d* exchange interaction.

Optically active nanowires containing magnetic manganese ions are grown by a similar procedure to ZnTe/(Zn,Mg)Te core/shell nanowires, described already in H1. The difference relies on the addition of a small manganese flux during the growth of the nanowire core in the system for molecular beam epitaxy. A series of samples is grown in which Mn-concentration is varied in a systematic manner by changing the molecular fluxes. Mn-content does not exceed, however, 10% in any of these samples. The incorporation of Mn-ions in our structures is evidenced by the increase of the energy gap with increasing Mn-concentration, as well as by means of energy dispersive X-ray diffraction, where Mn-related X-ray emission lines are observed.

The most important result, however, is obtained by studying the core-related near band edge emission in an external magnetic field (applied in the Faraday configuration along the nanowire axis). A significant redshift of the emission lines accompanied by their partial circular polarization is observed. Both effects are at least one order of magnitude larger in comparison to non-magnetic nanowires. Moreover, it is shown that their magnitude scales directly with Mn-concentration. Our conclusion is, therefore, that these effects are due to *sp-d* exchange interaction between band carriers and Mn-ions, which results in the enhancement of the Zeeman splitting by at least one order of magnitude. The circular polarization of the emission reflects the spin-polarization of carriers.

The increase of the Zeeman splitting is particularly well visible in an experiment performed on an individual nanowire by means of micro-photoluminescence, Figure 7. Thanks to the micrometer size of the excitation spot, only a few nanowires are excited simultaneously. The emission from an individual nanowire can be spectrally isolated because different nanowires emit at slightly different energies. The relatively small spectral width of such individual emission lines makes the energy shift of about 40 meV particularly well visible.

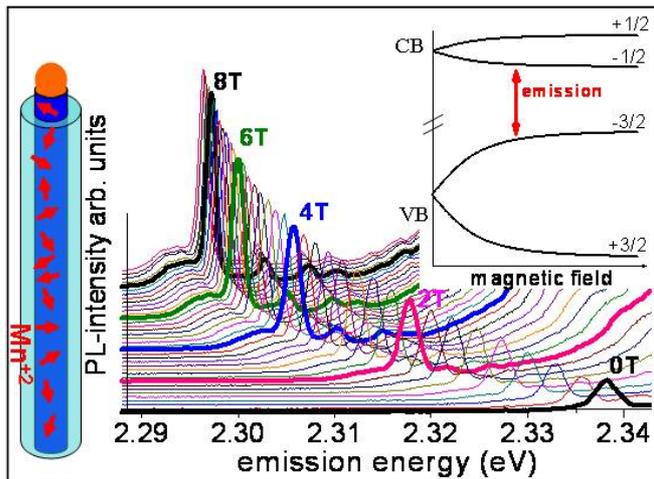


Figure 7 Giant Zeeman splitting in a single (Zn,Mn)Te/(Zn,Mg)Te core/shell nanowire. The emission line shifts by about 40 meV in a magnetic field of 8 T, whereas the shift in non-magnetic nanowires amounts to 3-5 meV. Temperature 2 K. In the inset, a schematic picture of the spin splitting of band edges in an external magnetic field is presented. The spin of carriers and the measured optical transition are marked. CB - bottom of the conduction band, VB – top of the valence band

For comparison, the energy shift amounts to 3-5 meV at 8 T only, in case of non-magnetic nanowires. Our investigations demonstrate that Mn-concentration in various nanowires grown in the same growth process does not vary significantly. For instance, Mn-concentration varies from 2.5% up to 4.5% depending on a particular nanowire in an ensemble with the average Mn-concentration of 3.5%. Most importantly, all nanowires contain magnetic ions.

Similar results to ours are obtained only for (Zn,Mn)Se nanowires [63], to the best of our knowledge. The authors of this paper state, however, that the optical emission from their structures contains also a significant contribution of ‘crooked’ nanowires which are grown simultaneously to the proper straight nanowires. Moreover, they investigate the emission of the nanowire ensemble and not the emission from individual nanowires. Therefore, our results constitute a significant contribution to the literature in the field of magnetic ion containing nanowires.

Spin splitting anisotropy in single nanowire heterostructures, H6

Diluted magnetic (Zn,Mn)Te/(Zn,Mg)Te core/shell nanowires are subject of a unique experiment, in which the influence of the magnetic field direction with respect to the nanowire axis on the value of the Zeeman splitting is investigated. H6. The Zeeman splitting is always a few times larger in a configuration when the magnetic field is applied along the nanowire axis than for the perpendicular magnetic field.

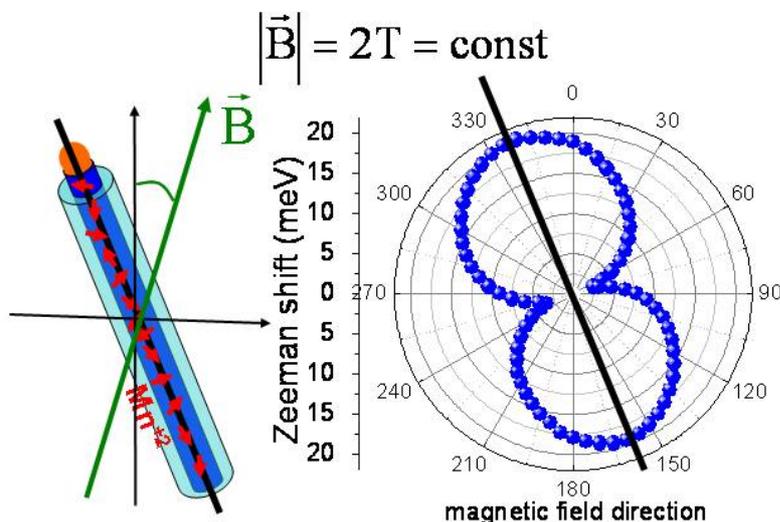


Figure 8 The influence of the magnetic field direction on the Zeeman shift in a single (Zn,Mn)Te/(Zn,Mg)Te core/shell nanowire. The largest shift is observed for the magnetic field parallel to the nanowire axis and the smallest for the perpendicular magnetic field. Magnetic field value is $B = 2$ T, temperature of the measurement - 2 K; excitation wavelength - 405 nm.

In order to confirm that this effect is due to the nanowire geometry, a further experiment is performed. The magnetic field direction is changed continuously while keeping its absolute value constant. The largest spin splitting is observed for the parallel magnetic field and the smallest for the perpendicular magnetic field, Figure 8.

The above mentioned effect has its origin in the band structure in the nanowire core, and in particular, in the splitting of light and heavy hole bands, which is most likely induced by the strain acting on (Zn,Mn)Te core due to the lattice mismatched (Zn,Mg)Te shell. As result, the spin of holes is 'blocked' along the nanowire axis, so that the application of a perpendicular magnetic field has no impact on its value. Theoretical calculations are performed confirming this interpretation and determining the value of the light hole - heavy hole band splitting. The application of the above mentioned experimental procedure gives us, therefore, the insight into the energy landscape of individual nanowires. In particular, we can determine which band represents the ground state in the valence band: the light hole band or the heavy hole band.

The fabrication of diluted magnetic (Cd,Mn)Te axial insertions in non-magnetic ZnTe nanowires is also an important achievement published in H6. The growth procedure of these structures is similar to that described in H2 with the difference relying on the addition of a small Mn-flux during the growth of the insertion only. The structure is coated with (Zn,Mg)Te shells in order to ensure strong optical transitions. The measurements of the near band edge emission in an external magnetic field reveal also a significant increase of the Zeeman splitting due to *sp-d* exchange interaction. Up to now, there has been no reports in the literature on the fabrication of nanowire quantum dots containing magnetic ions, to the best of our knowledge. The emission from an individual (Cd,Mn)Te quantum dot exhibits also a strong anisotropy of the Zeeman splitting depending on the orientation of the external magnetic field. The latter effect can be additionally increased due to quantum confinement effect which contributes to the splitting of the light and heavy hole bands.

In our further investigations, we will clarify whether there are significant differences between diluted magnetic quantum dots in nanowires and similar planar self-organized quantum dots. The difference may rely on the presence (or absence) of a spontaneous magnetic ordering inside of these structures – magnetic polarons.

Summary of achievements presented in H1-H6

In conclusions, the most important achievements presented in the publication series H1-H6 are the following:

- Activation of the near band edge emission from ZnTe nanowires grown in a molecular beam epitaxy setup by employing the vapor-liquid solid growth mechanism by adding a thin radial (Zn,Mg)Te shell, which passivates surface states, H1, H5.
- Growth of optically active CdTe quantum dots in ZnTe nanowires and the evidence of the single-photon character of their emission, H2.
- The control over the radial and axial deposition of CdTe insertions in ZnTe nanowires by means of the growth temperature which leads to the formation of optically active core/multishell structures, as well as to heterostructures, where radial and axial CdTe insertions coexist, H3.
- Identification of the optical emission from radial and axial heterostructures in individual nanowires by means of cathodoluminescence and micro-photoluminescence, H1-H3.

- Demonstration of the impact of the strain on the energy gap in ZnTe/(Zn,Mg)Te core/shell nanowires, H4.
- Introduction of magnetic manganese ions into (Zn,Mn)Te/(Zn,Mg)Te core/shell nanowires, H5, as well as into axial (Cd,Mn)Te insertions in non-magnetic ZnTe nanowires, H6.
- Demonstration of a significant increase of the Zeeman splitting reflecting directly *sp-d* exchange interaction between band carriers and magnetic ions in both kinds of magnetic ion containing structures, H5, H6.
- Demonstration of a strong anisotropy of the Zeeman splitting depending on the direction of the magnetic field with respect to the nanowire axis, which gives us the insight into the light hole/heavy hole band splitting in individual nanowires, H6.

Finally, I would like to emphasize my leading contribution to all publications from the series H1-H6. I have lead the projects including: the idea of the experiments, growth of the samples, characterization by means of photoluminescence and scanning electron microscopy, cathodoluminescence and micro-photoluminescence. In H6, the optical measurements are divided into two parts: concerning magneto-optical investigations of diluted magnetic core/shell nanowires and diluted magnetic quantum dots in nanowires. The latter part was performed by Małgorzata Szymura and her supervisor dr Łukasz Kłopotowski from the Institute of Physics, Polish Academy of Sciences. My contribution in this work is, however, significant and constitutes of the idea of the experiment, growth of the samples, participation and leading of the optical measurements of the core/shell nanowires, as well as theoretical calculations concerning the splitting of light and heavy hole bands in core/shell nanowires. In H4, dr hab. Michał Zieliński from the Nicolaus Copernicus University performed mostly the theoretical calculations.

5. Discussion of other scientific achievements not related to the publication series H1-H6

5.1. Description of my scientific activity not related to semiconductor nanowires

My scientific activity concerns in general the growth and optical spectroscopy of low-dimensional structures based on II-VI semiconductors. Beside the major topic of my research concerning optically active nanowires, which is the basis of the present habilitation procedure, my activity is related also to self-organized quantum dots and optical measurements of various structures emitting in the visible light spectral range. My bibliometric data has already been summarized in section 4.2.

The topic of my dissertation was related to the growth of self organized planar quantum dots in II-VI semiconductors. In the first step, I achieved the formation of CdTe quantum dots in ZnTe matrix in a system for molecular beam epitaxy by using the growth procedure described previously by Tinjod and coauthors [64]. After simplification of this method, I developed a relatively easy and reproducible procedure of Mn-ions introduction into these structures [N1,N2]. The main advantage of this procedure is the possibility of the control of Mn-concentration inside quantum dots. This is how quantum dots containing around 100 Mn⁺² ions per dot [N2], around 10 Mn⁺² ions per dot [N1], and also a single Mn⁺² ion [N3] per dot are fabricated. In the latter publication, a system consisting of a single Mn⁺² ion placed inside a single CdTe quantum dot is used by our collaborators from University of Warsaw for the manipulation of the single spin by means of optical spectroscopy methods. This is the most

cited paper where I'm coauthor, about 100 times. My contribution is mainly the growth of the structure.

Quite frequently, I performed photoluminescence measurements in frame of projects not related directly to the main topic of my research. For instance, I measured photoluminescence spectra of bulk (Cd,Mn)Te crystals grown in view of applications in X-ray and Gamma ray detectors [N4]. Moreover, I initialized, in cooperation with dr Ewa Przeździecka, photoluminescence measurements of bulk ZnO showing p-type conductivity in our laboratory [N5,N6].

During a one-year post-doc position at the Institute Neel belonging to French National Centre of Scientific Research (CNRS) in Grenoble, one of my main tasks was related to the electronic coupling of at least two quantum dots. Structures consisting of quantum dot multilayers were grown for this purpose [N7]. After my return to the Institute of Physics Polish Academy of Sciences, I continued the growth of similar structures, which resulted, finally, in the observation of the electronic coupling of two CdTe quantum dots [N8,N9]. The leading role in optical measurements of coupled quantum dots had dr Łukasz Kłopotowski. My contribution was the growth of the samples, indication of the research field and scientific discussions.

After finishing my post-doc study in France and the employment at the Institute of Physics, Polish Academy of Sciences, I continued the collaboration with researchers investigating properties of self-organized quantum dots, from the Institute of Experimental Physics, University of Warsaw, in particular. The high optical quality of nanostructures based on II-VI semiconductors encouraged an intensive study of optical properties of individual CdTe and (Cd,Mn)Te self organized quantum dots. In the frame of this collaboration, I grew many samples containing self organized quantum dots. Depending on the particular project, they were placed inside more sophisticated structures, such as, for instance, in p-n junctions. The growth and design of quantum dot containing samples, as well as scientific discussions resulted in more than 40 publications in international journals (after my dissertation). They constitute the main part of my research activity not related directly to the topic of the habilitation.

Among these publication, there are papers concerning the magnetic polaron formation in quantum dots containing manganese ions [N10,N11], manipulation of a single Mn^{2+} spin inside a quantum dot [N12-N16], transfer of excitons and spins between two quantum dots placed close to each other in the plane of the sample [N17-N19], control of the fine structure splitting of excitons by application of an external magnetic field [N20], spectroscopy of individual quantum dots in an electric field [N12,N13], dynamics of dark excitons in a single quantum dot [N15,N21] and the amplitude of the electron-electron and electron-hole exchange interactions inside individual CdTe quantum dots [N22-N24].

Moreover, I'm one of the authors of a review article entitled „Molecular beam epitaxy of semi-magnetic quantum dots” which is a chapter in the book “Molecular Beam Epitaxy: From research to mass production” edited by M. Henini [N25].

N1. **Wojnar P**, Suffczynski J, Kowalik K, Golnik A, Karczewski G, and Kossut J 2007 Phys. Rev. B **75** 155301

- N2. **Wojnar P**, Suffczynski J, Kowalik K, Aleszkiewicz M, Karczewski G, and Kossut J 2008 Nanotechnology **19** 235403
- N3. Goryca M, Kazimierzczuk T, Nawrocki M, Golnik A, Gaj J A, Kossacki P, **Wojnar P**, and Karczewski G 2009 Phys. Rev. Lett. **103** 087401
- N4. Mycielski A, Burger A, Sowinska M, Groza M, Szadkowski A, **Wojnar P**, Witkowska B, Kaliszek W, and Siffert P 2005 Physica Status Solidi C - Conferences and Critical Reviews, Vol 2, No 5 **2** 1578
- N5. Kaminska E, Piotrowska A, Kossut J, Barcz A, Butkute R, Dobrowolski W, Dynowska E, Jakiela R, Przedziecka E, Lukasiewicz R, Aleszkiewicz M, **Wojnar P**, and Kowalczyk E 2005 Solid State Commun. **135** 11
- N6. Kaminska E, Piotrowska A, Kossut J, Butkute R, Dobrowolski W, Lukasiewicz R, Barcz A, Jakiela R, Dynowska E, Przedziecka E, Aleszkiewicz M, **Wojnar P**, and Kowaczyk E 2005 E-Mrs 2004 Fall Meeting Symposia C and F **2** 1119
- N7. **Wojnar P**, Bougerol C, Bellet-Amalric E, Besombes L, Mariette H, and Boukari H 2011 J. Cryst. Growth **335** 28
- N8. Kłopotowski L, **Wojnar P**, Kret S, Parlinska-Wojtan M, Fronc K, Wojtowicz T, Karczewski G 2014 J. Appl. Phys. **117** 224306
- N9. Kłopotowski L, **Wojnar P**, Cywinski L, Jakubczyk T, Goryca M, Fronc K, Wojtowicz T, and Karczewski G 2015 Phys. Rev. B **92** 075303
- N10. Kłopotowski L, Cywinski L, Szymura M, Voliotis V, Grousson R, **Wojnar P**, Fronc K, Kazimierzczuk T, Golnik A, Karczewski G, and Wojtowicz T 2013 Phys. Rev. B **87** 245316
- N11. Kłopotowski L, Cywinski L, **Wojnar P**, Voliotis V, Fronc K, Kazimierzczuk T, Golnik A, Ravaro M, Grousson R, Karczewski G, and Wojtowicz T 2011 Phys. Rev. B **83** 081306
- N12. Kuklinski K, Kłopotowski L, Fronc K, Wiater M, **Wojnar P**, Rutkowski P, Voliotis V, Grousson R, Karczewski G, Kossut J, and Wojtowicz T 2011 Appl. Phys. Lett. **99** 141906
- N13. Kłopotowski L, Voliotis V, Kudelski A, Tartakovskii A, I, **Wojnar P**, Fronc K, Grousson R, Krebs O, Skolnick M, Karczewski G, and Wojtowicz T 2011 Phys. Rev. B **83** 155319
- N14. Goryca M, Kazimierzczuk T, Nawrocki M, Golnik A, Gaj J, Kossacki P, **Wojnar P**, and Karczewski G 2009 Phys. Rev. Lett. **103** 087401
- N15. Goryca M, Plochocka P, Kazimierzczuk T, **Wojnar P**, Karczewski G, Gaj J, Potemski M, and Kossacki P 2010 Phys. Rev. B **82** 165323
- N16. Goryca M, Koperski M, **Wojnar P**, Smolenski T, Kazimierzczuk T, Golnik A, and Kossacki P 2014 Phys. Rev. Lett. **113** 227202

- N17. Koperski M, Goryca M, Kazimierczuk T, Smolenski T, Golnik A, **Wojnar P**, and Kossacki P 2014 Phys. Rev. B **89** 075311
- N18. Kazimierczuk T, Suffczynski J, Golnik A, Gaj J, **Wojnar P**, and Kossacki P 2008 Journal of the Korean Physical Society **53** 154
- N19. Kazimierczuk T, Suffczynski J, Golnik A, Gaj J, Kossacki P, and **Wojnar P** 2009 Phys. Rev. B **79** 153301
- N20. Kowalik K, Krebs O, Golnik A, Suffczynski J, **Wojnar P**, Kossut J, Gaj J, and Voisin P 2007 Phys. Rev. B **75** 195340
- N21. Smolenski T, Kazimierczuk T, Goryca M, Jakubczyk T, Kłopotowski L, Cywinski L, **Wojnar P**, Golnik A, and Kossacki P 2012 Phys. Rev. B **86** 241305
- N22. Kazimierczuk T, Golnik A, Goryca M, **Wojnar P**, Gaj J, and Kossacki P 2009 Acta Phys. Pol. , A **116** 882
- N23. Kazimierczuk T, Smolenski T, Goryca M, Kłopotowski L, **Wojnar P**, Fronc K, Golnik A, Nawrocki M, Gaj J, and Kossacki P 2011 Phys. Rev. B **84** 165319
- N24. Kazimierczuk T, Smolenski T, Kobak J, Goryca M, Pacuski W, Golnik A, Fronc K, Kłopotowski L, **Wojnar P**, and Kossacki P 2013 Phys. Rev. B **87** 195302
- N25. **Wojnar P**, Kłopotowski Ł, Kossut J. „Molecular beam epitaxy of semi-magnetic quantum dots”. in: Henini M, editor. “Molecular Beam Epitaxy: From research to mass production”. Elsevier Inc., 2013. p. 529–545.

5.2. Scientific projects

Leading grants:

In years 2012-2014, I was Principal Investigator of the grant Iuventus Plus no. IP2011 061171, entitled „*Fabrication and spectroscopy of diluted magnetic nanowires*” awarded by the Polish Ministry of Science and Higher Education. The implementation of the grant was evaluated and obtained positive notes.

Since 2011, I’m Principal Investigator of the grant awarded by the National Centre of Sciences (Poland) no. 2011/01/D/ST5/05039 entitled “*Growth of optically active radial and axial heterostructures in nanowires built of Te-anion based semiconductors*” awarded for young scientists for the period of 5 years. After 3 years, the implementation of the grant was positively evaluated. It will be continued till December 2016.

Participation in grants:

- Since 2014, I’m investigator of Maestro Grant no. 2013/08/A/ST3/00297 awarded by the National Centre of Science and entitled “*Magnetic semiconductor quantum dots with copper*” lead by Prof. dr hab. Jacek Kossut. My task consists in the fabrication of CdTe and CdSe quantum dots containing copper ions by molecular beam epitaxy and determining their charge state.

- In years 2011-2014, I participated in Opus Grant no 2011/01/B/ST3/02287 awarded by the National Centre of Science and entitled “*Magnetic molecules built of CdMnTe quantum dots*” lead by dr Łukasz Kłopotowski, in frame of which I grew multilayers of CdTe quantum dots.
- During my Ph.D. studies, I was investigator of the grant no. N202 050 32/1187 awarded by the Committee of Scientific Research (Poland) entitled “*Growth and optical spectroscopy of diluted magnetic quantum dots*” lead by my advisor Prof. dr hab. Jacek Kossut.
- In years 2009-2013, I was partially employed in the Institute of Physics, Polish Academy of Sciences in the frame of NanoBiom Project POIG.01.01.02-00-008/08 entitled “*Semiconductor Nanostructures for Applications in Biology and Medicine – Development and Commercialization of new Generation Devices for Molecular Diagnostics on the Basis of New Polish Semiconductor Devices*” realized in the framework of the Operational Program Innovative Economy.
- I participated also in the European Project SANDiE – „*Self-Assembled semiconductor Nanostructures for new Devices in photonics and Electronics*”, in the frame of which I investigated my samples at the University of Dortmund in years 2007-2008. The total length of these scientific visits was 2 months.

5.3. Conferences, symposia and seminars

I have given 4 invited talks concerning the main topic of the habilitation procedure:

- I1. „*Giant spin splitting in ZnMnTe/ZnTgTe core/shell nanowires*“ 16th International Conference on II-VI Compounds and Related Materials, 9th – 13th September, 2013, Nagahama, Japan.
- I2. „*Spin splitting enhancement in ZnMnTe diluted magnetic nanowires*”, Workshop – Optical properties of individual nanowires and quantum dots in high magnetic field, 24th-26th September 2014, Toulouse, France
- I3. „*Growth of optically active diluted magnetic ZnMnTe/ZnMgTe core/shell nanowires*”, Polish-Japanese Workshop, Spintronics - from new materials to applications, Warsaw, 15th-18th November 2011.
- I4. „*Optically active nanowires built of II-VI materials*” III Konferencja Kwantowe Nanostruktury Półprzewodnikowe do Zastosowań w Biologii i Medycynie, Warsaw, 20th – 21st April 2011,

I have also given 7 presentations on seminars and symposia, from which 5 concern the topic of the habilitation, and 2 of them are related to the topic of my dissertation:

- S1. „*Nanowires ZnTe i ZnMnTe – Activation of the near band edge emission*”, Solid State Seminar, University of Warsaw, 22nd February 2013, Warsaw
- S2. „*Nanowires built of tellurium-based semiconductors – growth and optical properties*”, Seminar at the Physics Department of the Nicolaus Copernicus University, 15th April 2013, Toruń
- S3. „*Strain and magneto-optical anisotropy in (Zn,Mn)Te/(Zn,Mg)Te core/shell nanowires*” Solid State Seminar, University of Warsaw, 30th May 2014, Warsaw
- S4. „*Growth of tellurium anion based nanowires and their optical properties*”, Seminar of Continuum Mechanics Theory, Institute of Fundamental Technological Research, Polish Academy of Sciences, 28th March 2014, Warsaw

- S5. „*Core/shell nanowires: giant spin splitting in (Zn,Mn)Te nanowires*” Symposium of the National Laboratory of Quantum Technologies, Wrocław University of Technology, 20th October 2014, Wrocław
- S6. „*Fabrication and properties of CdTe /ZnTe quantum dots*“, Seminar of Continuum Mechanics Theory, Institute of Fundamental Technological Research, Polish Academy of Sciences, 23rd April 2010, Warsaw
- S7. „*Multilayers of CdTe/ZnTe quantum dots*“, Solid State Seminar, University of Warsaw, 19th March 2010, Warsaw

I have given 10 oral presentations on international and national conferences:

- R1. "*Strain induced energy gap variation and valence band mixing in (Zn,Mn)Te/(Zn,Mg)Te core/shell nanowires*", **P. Wojnar**, M. Szymura, Ł. Kłopotowski, M. Wiater, W. Zaleszczyk, J. Suffczyński, T. Smoleński, P. Kossacki, E. Janik, M. Zieliński, S. Kret, T. Wojciechowski, L.T. Baczewski, G. Karczewski, T. Wojtowicz, J. Kossut, 17th International Conference on II-VI Compounds, 13th – 18th September, 2015, Paris, France
- R2. "*Energy gap variation and valence band mixing in strained (Zn,Mn)Te/(Zn,Mg)Te core/shell nanowires*", **P. Wojnar**, M. Szymura, Ł. Kłopotowski, M. Wiater, W. Zaleszczyk, J. Suffczyński, T. Smoleński, P. Kossacki, E. Janik, M. Zieliński, S. Kret, T. Wojciechowski, L.T. Baczewski, G. Karczewski, T. Wojtowicz, J. Kossut, 44th "Jaszowiec" International School and Conference on the Physics of Semiconductors, 20th-25th June, 2015, Wisła, Poland
- R3. "*Magneto-optical anisotropy of ZnMnTe/ZnMgTe core/shell nanowires*" **Wojnar P.**, Suffczyński J., Smoleński T., Janik E., Zaleszczyk W., Kret S., Wojciechowski T., Kossacki P., Karczewski G., Wojtowicz T., Kossut J., 43rd "Jaszowiec" International School Conference on the Physics of Semiconductors, 7th June 2014, Wisła, Poland
- R4. „*Giant spin splitting in ZnMnTe/ ZnMgTe core/shell nanowires*" **P. Wojnar**, E. Janik, J. Suffczyński, J. Papierska, P. Kossacki, M. Szymura, W. Zaleszczyk, Ł. Kłopotowski, S. Kret, T. Wojciechowski, L.T. Baczewski, G. Karczewski, T. Wojtowicz, J. Kossut, 5th International Conference on One dimensional Nanomaterials, ICON 2013, 23rd-26th September, 2013, Annecy, France.
- R5. „*Giant spin splitting in optically active ZnMnTe/ ZnMgTe core/shell nanowires*“ **P. Wojnar**, E. Janik, J. Suffczyński, J. Papierska, M. Szymura, S. Kret, Ł. Kłopotowski, T. Wojciechowski, L.T. Baczewski, G. Karczewski, T. Wojtowicz, and J. Kossut, 17th European Molecular Beam Epitaxy Workshop, 10th-13th March 2013 Levi, Finland.
- R6. „*Activation of fan intensive near band edge emission from ZnTe/ZnMgTe core/shell nanowires grown on silicon substrate*“, **P. Wojnar**, V Konferencja Kwantowe Nanostruktury Półprzewodnikowe do Zastosowań w Biologii i Medycynie (5th Conference on Quantum Structures for Applications in Biology and Medicine), 17th – 18th April 2013, Warsaw
- R7. „*Near band edge emission of Te-based nanowire heterostructures*" **P. Wojnar**, E. Janik, S. Kret, E. Dynowska, L. T. Baczewski, G. Karczewski, T. Wojtowicz, 15th International Conference on II-VI Compounds, 21st-26th September 2011, Mayan Riviera, Mexico.
- R8. „*Growth of optically active CdTe quantum nanowires*“ **P. Wojnar**, E. Janik, S. Kret, A. Petrouchik, M. Goryca, T. Kazimierzczuk, P. Kossacki, G. Karczewski, and T. Wojtowicz, 40th „Jaszowiec“ International School and Conference on the Physics of Semiconductors. 25th June – 1st July 2011, Krynica, Poland

- R9. „Growth and characterization of optically active radial and axial heterostructures in Te-anion based semiconductor nanowires” **P. Wojnar**, E. Janik, L. Baczewski, S. Kret, E. Dynowska, T. Wojtowicz, M. Goryca, T. Kazimierczuk, P. Kossacki, Konferencja „Technologie Kwantowe 2011”(Conference „Quantum Technologies”), March 2011, Warsaw
- R10. „Growth and micro-luminescence from diluted magnetic quantum dots“, **P. Wojnar**, G. Karczewski, J. Suffczyński, M. Goryca, A. Golnik, K. Kowalik, and J. Kossut, E-MRS Fall Meeting 13th-17th September 2010, Warsaw.

The total number of all conference presentations including posters in which I’m coauthor (including those which are not listed in *Journal of Citation Reports*) amounts to **98**, whereas **32** presentations are directly related to the topic of the habilitation procedure.

5.4. Organization of conferences and reviewer’s activity

I took part in the Organizing Committee of “41st School and Conference on the Physics of Semiconductors, Jaszowiec 2012” in Krynica Zdrój as the secretary of the conference (8th-15th June 2012). Next, I was guest editor of the conference proceedings in Acta Physica Polonica A, vol 122 no 6.

I was reviewer of about 20 publications in various scientific journals: Journal of Alloy and Compounds – 3 reviews, Thin Solid Films – 2 reviews, Nanoresearch - 1 review, Journal of Applied Physics - 4 reviews, Physica E – 1 review, Acta Physica Polonica – 10 reviews.

5.5. Building of unique research equipment

I took part in the purchase and the installation of two unique experimental setups in the Institute of Physics, Polish Academy of Sciences: for low-temperature cathodoluminescence and optical micro-spectroscopy in an external magnetic field.

5.6. Teaching and popular science activity

I gave classes for students from the Physics Department of the Warsaw University of Technology in the frame of Laboratory of Nanostructures in years 2014-2015. The supervisor of the whole Laboratory of Nanostructures was dr hab. Tomasz Pietrzyk from Warsaw University of Technology.

I gave classes for second year students of Nanostructure Engineering from University of Warsaw in cooperation with Łukasz Kłopotowski and Wojciech Zaleszczyk in the frame of laboratory: “Technology and Design of New Materials”. The supervisor of the whole laboratory is Prof. dr hab. Maria Kamińska from University of Warsaw.

I supervised 3 students during their practice in the Institute of Physics, PAS:
Rafał Rudniewski – student of the Physics Department of the University of Warsaw
Emma Grodzicka – student of the Physics Department of the University of Warsaw
Jakub Płachta – student of the Physics Department of Warsaw University of Technology

Presently, I supervise the license thesis of Emma Grodzicka from University of Warsaw. I co-supervise also PhD studies of M Sc. Jakub Płachta since October 2015.

Popular science activity:

I've given several popular science lessons for students from secondary and high schools in the laboratory for molecular beam epitaxy, in years 2012-2016. The lessons are part of the popular science offer for schools of the Institute of Physics, PAS.

I gave (in cooperation with Prof. dr hab. Jacek Kossut) popular science lessons for students from Eindhoven University of Technology who visited Poland in frame of "van der Waals Stiftung" in 2015.

Three times, I took part in the annual workshop organized by the Polish Children Fund, in the Institute of Physics PAS, in years 2012-2014. I supervised one of the exercises entitled: "Light Emitting Nanostructures". The Coordinator of the whole workshop was dr hab Grzegorz Grabecki.

I co-organized also the annual Day of Nanotechnology in the Institute of Physics PAS in years 2011-2014, which is dedicated to students of the 3-4 year from the Mechatronics Faculty of the Warsaw University of Technology. My contribution relied whether on oral presentations entitled "Fabrication of low dimensional structures – nanotechnology" in years 2011 and 2013, or on special lessons in the laboratory for molecular beam epitaxy in years 2012 and 2014.

5.7 Awards

I got the Scientific Prize of the Director of the Institute of Physics, Polish Academy of Sciences for the best publication in year 2015. This awarded publication is H6 from the above discussed series of publications.



Piotr Wojnar

References

- [1] Lu W and Lieber C M 2007 Nat. Mater. **6** 841
- [2] Yan H, Choe H S, Nam S W, Hu Y J, Das S, Klemic J F, Ellenbogen J C, and Lieber C M 2011 Nature **470** 240
- [3] Hayden O, Agarwal R, and Lu W 2010 Nano Today **3** 12

- [4] Pauzauskie P J and Yang P 2006 *Materials Today* **9** 36
- [5] Tian B, Zheng X, Kempa T J, Fang Y, Yu N, Yu G, Huang J, and Lieber C M 2007 *Nature* **449** 885
- [6] Cui Y, Wei Q, Park H, and Lieber C M 2001 *Science* **293** 1289
- [7] Patolsky F and Lieber C M 2005 *Materials Today* **8** 20
- [8] Morales A M and Lieber C M 1998 *Science* **279** 208
- [9] The data is based on *ISI Web of Knowledge*. The search items are 'nanowire' AND 'nanowires' for year 2015
- [10] Kossut J and Dobrowolski W 1997 "*Properties of diluted magnetic semiconductors*" in "*Narrow gap II VI compounds for optoelectronic and electromagnetic applications*" edited by P. Capper, Chapman & Hall, 1997, London, UK
- [11] J.A.Gaj and J.Kossut, 2010, "*Introduction into Physics of Diluted Magnetic Semiconductors*", Springer Series in Material Science 144
- [12] Wagner R S and Ellis W C 1964 *Appl. Phys. Lett.* **4** 89
- [13] Calleja E, Sanchez-Garcia M A, Sanchez F J, Calle F, Naranjo F B, Munoz E, Jahn U, and Ploog K 2000 *Phys. Rev. B* **62** 16826
- [14] Morral A F I, Spirkoska D, Arbiol J, Heigoldt M, Morante J R, and Abstreiter G 2008 *Small* **4** 899
- [15] Glas F 2006 *Phys. Rev. B* **74** 121302
- [16] Jiang X, Xiong Q, Nam S, Qian F, Li Y, and Lieber C M 2007 *Nano Lett.* **7** 3214
- [17] Xiang J, Lu W, Hu Y, Wu Y, Yan H, and Lieber C M 2006 *Nature* **441** 489
- [18] Sköld N, Karlsson L S, Larsson M W, Pistol M E, Selfert W, Tragardh J, and Samuelson L 2005 *Nano Lett.* **5** 1943
- [19] Qian F, Li Y, Gradecak S, Wang D L, Barrelet C J, and Lieber C M 2004 *Nano Lett.* **4** 1975
- [20] Qian F, Gradecak S, Li Y, Wen C Y, and Lieber C M 2005 *Nano Lett.* **5** 2287
- [21] Qian F, Li Y, Gradecak S, Park H G, Dong Y J, Ding Y, Wang Z L, and Lieber C M 2008 *Nat. Mater.* **7** 701
- [22] Fan Z Y, Razavi H, Do J W, Moriwaki A, Ergen O, Chueh Y L, Leu P W, Ho J C, Takahashi T, Reichertz L A, Neale S, Yu K, Wu M, Ager J W, and Javey A 2009 *Nat. Mater.* **8** 648
- [23] Williams B, Taylor A, Mendis B, Phillips L, Bowen L, Major J, and Durose K 2014 *Appl. Phys. Lett.* **104** 053867

- [24] Björk M T, Ohlsson B J, Sass T, Persson A I, Thelander C, Magnusson M H, Deppert K, Wallenberg L R, and Samuelson L 2002 *Nano Lett.* **2** 87
- [25] Aichele T, Tribu A, Sallen G, Bocquel J, Bellet-Amalric E, Bougerol C, Poizat J P, Kheng K, Andre R, Tatarenko S, and Mariette H 2009 *J. Cryst. Growth* **311** 2123
- [26] Borgstrom M T, Zwiller V, Muller E, and Imamoglu A 2005 *Nano Lett.* **5** 1439
- [27] Bounouar S, Elouneq-Jamroz M, Den Hertog M, Morchutt C, Bellet-Amalric E, Andre R, Bougerol C, Genuist Y, Poizat J, Tatarenko S, and Kheng K 2012 *Nano Lett.* **12** 2977
- [28] Tchernycheva M, Cirlin G E, Patriarche G, Travers L, Zwiller V, Perinetti U, and Harmand J C 2007 *Nano Lett.* **7** 1500
- [29] van Weert M H M, Akopian N, Kelkensberg F, Perinetti U, van Kouwen M P, Rivas J G, Borgstrom M T, Algra R E, Verheijen M A, Bakkers E P A M, Kouwenhoven L P, and Zwiller V 2009 *Small* **5** 2134
- [30] Michler P, Kiraz A, Becher C, Schoenfeld W V, Petroff P M, Zhang L D, Hu E, and Imamoglu A 2000 *Science* **290** 2282
- [31] Reimer M E, Bulgarini G, Akopian N, Hocevar M, Bavinck M B, Verheijen M A, Bakkers E P, Kouwenhoven L P, and Zwiller V 2012 *Nature Communications* **3** 737
- [32] Wallentin J, Anttu N, Asoli D, Huffman M, Aberg I, Magnusson M H, Siefer G, Fuss-Kailuweit P, Dimroth F, Witzigmann B, Xu H, Samuelson L, Deppert K, and Borgstrom M T 2013 *Science* **339** 1057
- [33] Qin L, Banholzer M J, Millstone J E, and Mirkin C A 2007 *Nano Lett.* **7** 3849
- [34] Holleitner A, Sih V, Myers R, Gossard A, and Awschalom D 2006 *Phys. Rev. Lett.* **97** 052108
- [35] Dietl T, Ohno H, Matsukura F, Cibert J, and Ferrand D 2000 *Science* **287** 1019
- [36] Butschkow C, Reiger E, Rudolph A, Geissler S, Neumaier D, Soda M, Schuh D, Woltersdorf G, Wegscheider W, and Weiss D 2013 *Phys. Rev. B* **87** 245303
- [37] Siusys A, Sadowski J, Sawicki M, Kret S, Wojciechowski T, Gas K, Szuszkiewicz W, Kaminska A, and Story T 2014 *Nano Lett.* **14** 4263
- [38] Chen L, Klar P J, Heimbrodt W, Brieler F J, Froba M, von Nidda H A, Kurz T, and Loidl A 2003 *J. Appl. Phys.* **93** 1326
- [39] Na C W, Han D S, Kim D S, Kang Y J, Lee J Y, Park J, Oh D K, Kim K S, and Kim D 2006 *J. Phys. Chem. B* **110** 6699
- [40] Oh E, Choi J H, Oh D K, and Park J 2008 *Appl. Phys. Lett.* **93** 041911
- [41] Borschel C, Messing M E, Borgstrom M T, Paschoal W, Jr., Wallentin J, Kumar S, Mergenthaler K, Deppert K, Canali C M, Pettersson H, Samuelson L, and Ronning C 2011 *Nano Lett.* **11** 3935

- [42] Bouravleuv A, Cirilin G, Sapega V, Werner P, Savin A, and Lipsanen H 2013 J. Appl. Phys. **113** 144303
- [43] Sadowski J, Dluzewski P, Kret S, Janik E, Lusakowska E, Kanski J, Presz A, Terki F, Charar S, and Tang D 2007 Nano Lett. **7** 2724
- [44] Kazakova O, Kulkarni J S, Holmes J D, and Demokritov S O 2005 Phys. Rev. B **72** 094415
- [45] Seong H K, Kim U, Jeon E K, Park T E, Oh H, Lee T H, Kim J J, Choi H J, and Kim J Y 2009 Journal of Physical Chemistry C **113** 10847
- [46] Liang W, Yuhas B D, and Yang P 2009 Nano Lett. **9** 892
- [47] Kumar S, Paschoal W, Jr., Johannes A, Jacobsson D, Borschel C, Pertsova A, Wang C H, Wu M K, Canali C M, Ronning C, Samuelson L, and Pettersson H 2013 Nano Lett. **13** 5079
- [48] Hegde M, Farvid S S, Hosein I D, and Radovanovic P V 2011 Acs Nano **5** 6365
- [49] J.A.Gaj and J.Kossut, 2010, "*Introduction into Physics of Diluted Magnetic Semiconductors*", Springer Series in Material Science 144
- [50] Nawrocki M, Rubo Y, Lascaray J P, and Coquillat D 1995 Phys. Rev. B **52** R2241
- [51] Chen L, Kirilenko D, Stesmans A, Nguyen X S, Binnemans K, Goderis B, Vanacken J, Lebedev O, Van Tendeloo G, and Moshchalkov V V 2010 Appl. Phys. Lett. **97** 041918
- [52] Radovanovic P V, Barrelet C J, Gradecak S, Qian F, and Lieber C M 2005 Nano Lett. **5** 1407
- [53] Janik E, Sadowski J, Dluzewski P, Kret S, Baczewski L T, Petrouchik A, Lusakowska E, Wrobel J, Zaleszczyk W, Karczewski G, Wojtowicz T, and Presz A 2006 Appl. Phys. Lett. **89** 133114
- [54] Zaleszczyk W, Janik E, Presz A, Dluzewski P, Kret S, Szuszkiewicz W, Morhange J F, Dynowska E, Kirmse H, Neumann W, Petrouchik A, Baczewski L T, Karczewski G, and Wojtowicz T 2008 Nano Lett. **8** 4061
- [55] Philipose U, Xu T, Yang S, Sun P, Ruda H E, Wang Y, and Kavanagh K 2006 J. Appl. Phys. **100** 084316
- [56] Wang J, Gudixsen M S, Duan X, Cui Y, and Lieber C M 2001 Science **293** 1455
- [57] Hou L, Zhang Q, Ling L, Li C X, Chen L, and Chen S 2013 J. Am. Chem. Soc. **135** 10618
- [58] Song M S and Kim Y 2014 Nanotechnology **25** 505605
- [59] Moon S R, Kim J H, and Kim Y 2012 Journal of Physical Chemistry C **116** 10368
- [60] Rigutti L, Jacopin G, Largeau L, Galopin E, Bugallo A, Julien F, Harmand J, Glas F, and Tchernycheva M 2011 Phys. Rev. B **83** 155320

- [61] Artioli A, Rueda-Fonseca P, Stepanov P, Bellet-Amalric E, Den Hertog M, Bougerol C, Genuist Y, Donatini F, Andre R, Nogues G, Kheng K, Tatarenko S, Ferrand D, and Cibert J 2013 Appl. Phys. Lett. **103** 222106
- [62] Ferrand D and Cibert J 2014 European Physical Journal-Applied Physics **67** 30403
- [63] Cooley B J, Clark T E, Liu B Z, Eichfeld C M, Dickey E C, Mohny S E, Crooker S A, and Samarth N 2009 Nano Lett. **9** 3142
- [64] Tinjod F, Gilles B, Moehl S, Kheng K, and Mariette H 2003 Appl. Phys. Lett. **82** 4340