Bartłomiej Sławomir Witkowski
Institute of Physics of the Polish Academy of Sciences
Warsaw, 2019

Summary of Professional Achievements

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1. Personal data

Bartłomiej Sławomir Witkowski

2. Education and degrees

2009-2014 Ph.D. degree in physics, Institute of Physics of the Polish Academy of Sciences, 2014
Dissertation title: ***„Hydrothermal technology of growth of the ZnO nanorods"***
Supervisor: Prof. dr hab. Marek Godlewski

2007-2009 M.Sc. degree in physics, Faculty of Mathematics and Natural Sciences. School of Exact Sciences, Cardinal Stefan Wyszyński University in Warsaw, 2009
Thesis title: ***„Structural studies using electron microscopy of zinc oxide layers doped with manganese and cobalt"***
Supervisor: Prof. dr hab. Marek Godlewski

2004-2007 B.Sc. degree in mathematics, physics and chemistry with specialization of applied informatics, Faculty of Mathematics and Natural Sciences. School of Exact Sciences, Cardinal Stefan Wyszyński University in Warsaw, 2007
Thesis title: ***„ Stretching of the proteins - an interactive database BSDB"***
Supervisor: dr. Joanna Idea Sułkowska

3. Employment in scientific institutions

2015 - present Institute of Physics of the Polish Academy of Sciences
Position: Adjunct

2016 - 2017 Research and Development Center of Technology for Industry
Position: Researcher
(realization of the research projects)

2009 - 2015 Institute of Physics of the Polish Academy of Sciences
Position: Physicist

4. The scientific achievement, in accordance with art.16 paragraph 2 of the Act of March 14th, 2003, concerning the scientific degrees and titles (Dz. U. item no. 882, 2016, with amendments in Dz. U. item no. 1311, 2016), being the basis of the habilitation procedure.

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 is the cycle of nine articles published in international journals entitled:

“**Development of the growth technology, analysis of optical properties of ZnO nano/microrods and examples of their applications in photoresitor and photovoltaic cells”.**

The first eight papers of the series are articles containing new results and constituting the main scientific value of the habilitation cycle. In the first four articles of the cycle I am the first author, and in the four subsequent papers the first authors are PhD students, whom I have been or still am an auxiliary supervisor. The last paper of the cycle is a one-author article, which, although does not contain my new results, is a large review on the applications of ZnO nanords, in which my and my colleagues' works were presented on background of other research groups.

List of publications constituting the scientific achievement:

H1. B.S. Witkowski, R. Pietruszka, S. Gieraltowska, L. Wachnicki, H. Przybylinska, M. Godlewski
Photoresistor based on ZnO nanorods grown on p-type silicon substrate,
Opto-Electronics Review 25 (1), 15-18 (2017)

H2. B.S. Witkowski, L. Wachnicki, S. Gieraltowska, A. Reszka, B.J. Kowalski, M. Godlewski
Low-Temperature Cathodoluminescence Investigations of High-Quality Zinc Oxide Nanorods,
Microscopy and Microanalysis 21 (3), 564-569 (2015)

H3. B.S. Witkowski, V.Y. Ivanov, Ł. Wachnicki, S. Gierałtowska, M. Godlewski
Optical Characterization of ZnO Nanorods Grown by the Ultra-Fast and Low Temperature Hydrothermal Process,
Acta Physica Polonica A 130 (5), 1199-1201 (2016)

H4. B.S. Witkowski, P. Dluzewski, J. Kaszewski, L. Wachnicki, S. Gieraltowska, B. Kurowska, M. Godlewski
Ultra-fast epitaxial growth of ZnO nano/microrods on a GaN substrate, using the microwave-assisted hydrothermal method
Materials Chemistry and Physics 205, 16-22 (2018)

H5. A. Pieniążek, B.S. Witkowski, A. Reszka, M. Godlewski, B.J. Kowalski
Optical properties of ZnO microrods grown by a hydrothermal method
– a cathodoluminescence study
Optical Materials Express 6 (12), 3741-3750 (2016)

H6. R. Pietruszka, B.S. Witkowski, G. Luka, L. Wachnicki, S. Gieraltowska, K. Kopalko, E. Zielony, P. Bieganski, E. Placzek-Popko and M. Godlewski
Photovoltaic properties of ZnO nanorods/p-type Si heterojunction structures
Beilstein Journal Nanotechnology 5, 173–179 (2014)

H7. R. Pietruszka, B.S. Witkowski, S. Gieraltowska, P. Caban, L. Wachnicki, E. Zielony, K. Gwozdz, P. Bieganski, E. Placzek-Popko, M. Godlewski
New efficient solar cell structures based on zinc oxide nanorods
Solar Energy Materials & Solar Cells 143, 99–104 (2015)

H8. R. Pietruszka, B.S. Witkowski, E. Zielony, K. Gwozdz, E. Placzek-Popko, M. Godlewski
ZnO/Si heterojunction solar cell fabricated by atomic layer deposition and hydrothermal methods
Solar Energy 155, 1282-1288 (2017)

H9. B.S. Witkowski
Applications of ZnO nanorods and nanowires - a review
Acta Physica Polonica A 134 (6), 1226-1246 (2018)

4.2 Bibliometric summary

My scientific achievements consist of **118** publications indexed in the Journal of Citation Reports (JCR) database, of which **100** publications were published in magazines with “impact factor” (IF). The total IF of scientific publications according to this list is **202,236**, and the total number of citations - **1012**, without self-citations - **792**. Hirsch index of my publications is **17**. Scientific achievements consist of papers from various scientific journals, including: Nucleic Acids Research (IF 2017: 11,561), ACS Appl. Mater. Interfaces (IF 2017: 8,097), Nanoscale (IF 2017: 7,233), Nanomedicine: Nanotechnology, Biology and Medicine (IF 2017: 6,5), Acta Materialia (IF 2017: 6,036), Electrochimica Acta (IF 2017: 5,116), Solar Energy Materials & Solar Cells (IF 2017: 5,018), Materials & Design (IF 2017: 4,525), Solar Energy (IF 2017: 4,374), Scientific Reports (IF 2017: 4,122), Physical Review B (IF 2017: 3,813), Journal of Alloys and Compounds (IF 2017: 3,779), Applied Physics Letters (IF 2017: 3,495), CrystEngComm (IF 2017: 3,304).

The full list of articles can be found in attachment no. 4. The above data has been compiled on the basis of the Web of Science (9 January 2019).

4.3 Introduction - research background

Zinc oxide (ZnO) is a semiconductor of II-VI group with a wide energy gap (near-ultraviolet spectral range), crystallographic structure of wurtzite (cubic structure is unstable) and natural n-type conductivity [1]. Due to its properties, it is an extremely wide and intensely studied material in the last twenty years, especially in the context of potential applications in electronics, optoelectronics, piezoelectric devices, or in sensors and detectors. These applications are discussed in review H9. For many of these applications, the transition to the nanometer scale can open completely new possibilities. Zinc oxide can occur in a huge number of forms of nanostructures, e.g. as rods [2], tubes [3], fibers [2], stripes [2,4,5], rings [2], spirals [6], arches [2], needles [2], which can additionally be produced by various methods from high temperature processes in a vacuum to low temperature processes in the water environment [7,8]. Despite many very promising results in various fields [H9], ZnO nanostructures have not been still applied industrially. It can be related with used technologies and sophisticated procedures which, while providing very promising results in a laboratory scale, are not suitable for industrial implementation due to costs, scaling difficulties or complexity of procedures. This conclusion is based on a review of the papers listed in article H9.

In my work I focused on ZnO nanorods (NRs) grown from water solution by the method developed and presented in my PhD thesis (2013) [9], in which were presented the possibilities of the method, the basic characterization of the obtained NRs, and an example of their applications in ultraviolet detector [10].

Often in physics, nanostructures are understood as objects with dimensions for which quantum phenomena appear, while in chemistry or biology as a nanostructures we mean all objects that have one dimension smaller than 1μm. Due to the lack of a clear definition of nanorods, or generally nanostructures, I would like to specify the concept I use. Under the name of the nanords that I use in this text, I mean structures for which at least two dimensions are less than 1 μm. The text also contains the concept of microrods, which refers to ZnO structures grown on the GaN substrate. In this case, I mean structures for which all dimensions are of the order of a single micrometer.

After obtaining the PhD degree, I focused on new aspects of research related to ZnO NRs. The first goal was further development of the method, including a deeper understanding of the growth mechanism, scaling of the method to larger sizes of substrates and investigation on epitaxial growth. The second goal was deep understanding of the properties of the obtained NRs. In particular, the subject of intense research were their optical properties, which understanding is crucial for optoelectronic applications. Another goal was to demonstrate the possibility of using NRs in photovoltaic cells, using their properties and crystallographic quality. In the realization of the above objectives, I worked together with my two young colleagues - Agnieszka Pieniążek (I am still her auxiliary supervisor) and Rafał Pietruszka (I was his auxiliary supervisor, he already obtained the PhD degree in 2016 [11]).

The growth method of ZnO NRs from aqueous solution was developed in the early 90's. First work was presented by Andres Verges [12] (longitudinal nanostructures grown from the solution, but not attached to any substrate), and in the following years, Lionel Vayssieres presented in his work [7, 13] the method of growth of ZnO NRs on the substrate and he is considered as a pioneer in this field. This method was based on the slow precipitation of ZnO from the supersaturated zinc hydroxide solution.

The method presented in my Ph.D. thesis was a new approach based on a dynamic chemical reaction, which significantly reduced the time of growth and decreased the temperature of growth. Thus, achieved an additional advantage - the obtained NRs are single crystals without oxygen vacancies and this is the basic value of the method (next to low costs, simplicity, scalability and ecological aspects). This result is a great opportunity for many applications for which the crystallographic quality is a key feature, and which previously could not be realized due to the complexity or costs of the technology.

One of the most interesting results obtained during the Ph.D. studies was the observation that samples containing ZnO NRs on high-resistive silicon substrates (the standard substrate) drastically change the resistance under the influence of visible light. This result became the base of the scientific project of which I was the head (project Preludium financed by National Science Center), entitled "Explanation of the mechanisms of changes of the electrical properties of ZnO nanorods grown by the hydrothermal method under the influence of light from the visible and UV range". During the realization of the project it quickly turned out that the observed behavior is related to the junction between ZnO NRs and used silicon substrate, and for the transparent substrate (e.g. quartz, glass) the structure reacted only to light from the UV range (which became the basis of the UV detector presented in the dissertation). In the case of silicon substrate, the situation was much more complicated and these works were continued after obtaining the Ph.D. degree. Eventually, the mechanism of resistance changes was explained and published in the first work included in the habilitation cycle [H1], closing the scientific project I headed.

In the following years (after receiving the Ph.D. degree) I continued development of the method focusing mainly on the aspect of the possibility of using different types of nucleation of the growth and scalability (the first processes were performed for the substrate sizes of 1x1cm2, and at the moment the method allows the growth of NRs on 15.6x15,6cm^2 - the size of the basic photovoltaic cell), as well as further characterization of the NRs, in particular their optical properties (works H2 and H3).

The next research direction only indicated in the Ph.D. thesis, and developed after obtaining the Ph.D. degree is the growth of epitaxial and oriented NRs on substrates crystallography matched (i.e GaN). In this area, two papers have been included in the habilitation cycle. The first one (H4) presents a description of the growth method, its possibilities and a deeper understanding of the mechanism of growth. The H5 paper presents an analysis of the optical properties of such NRs, in particular their use as an optical resonator.

The next articles in the cycle (H6, H7, H8) concern the application of ZnO NRs in photovoltaic silicon cells and this is part of the work with the greatest potential of industrial application. The research material published in these works is the result of Rafał Pietruszka's Ph.D. dissertation, of which I was an auxiliary supervisor. Due to the huge financial investments performed worldwide into the silicon photovoltaic (PV) cell industry, further development of this field is expected, which however requires reducing the cost of cell production by modifying the technology of existing production lines. That is why our work focused on modifying the architecture of silicon cells, where the junction Si (p) / Si (n) has been replaced with the junction of Si (p) / ZnO (n). Such solution can reduce the production costs of cells, as well as eliminate the energy-consuming and toxic processes associated with the formation of the Si (n) layer and nanostructurization of the cell surface.

The last article in the habilitation cycle (H9) is a review describing the various potential applications of ZnO NRs in devices such as light emitters and detectors, field emitters, transistors, chemical sensors, PV cells and electric nanogenerators, in which my and my colleagues' achievements were presented compared to other research groups.

All the articles included in the habilitation cycle (with the exception of part of work H2, which is specified later in the text) constitute a new scientific achievement, which was not included in my Ph.D. dissertation.

4.4 Photoresistor based on ZnO nanorods on p-type silicon substrate (H1)

The first paper from the habilitation cycle was published as a part of the project funded by the National Science Center, entitled „Explanation of the mechanisms of changes of the electrical properties of ZnO nanorods grown by the hydrothermal method under the influence of light from the visible and UV range". The mechanism of reaction to ultraviolet light was analyzed and presented in my Ph.D. thesis, while study on the reaction to visible light was found to be a much more complex problem, which was analyzed after obtaining the Ph.D. degree, and the results of this analysis were presented in the paper H1.

In particular, this work describes the analysis of the resistance changes of ZnO NRs / Si structure. Under the influence of visible light, this structure unusually fast reduces the resistivity and rapidly returns to its original value after light exposure (Fig. 1).

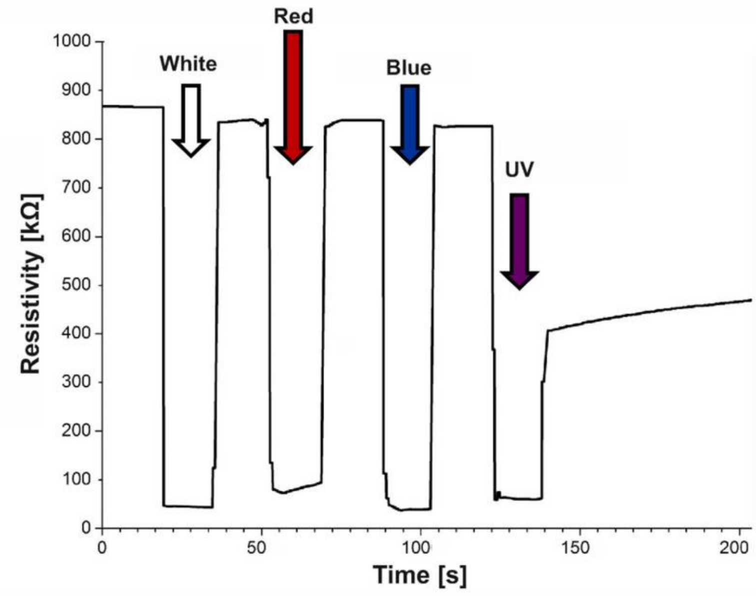


Fig. 1. Resistivity of ZnO/Si structure under illumination at different wavelengths. This figure comes from publication H1.

This measurements were repeated for different environments (air, oxygen, nitrogen, vacuum), which did not affect the mechanism of change in resistance, as well as for different intensities and wavelengths of the applied light. It turned out that this effect only slightly depends on the intensity or wavelength of light (in the visible range) and relatively quickly saturates even for small power of incident light (which allows its use as an optical switch) (Fig. 2).

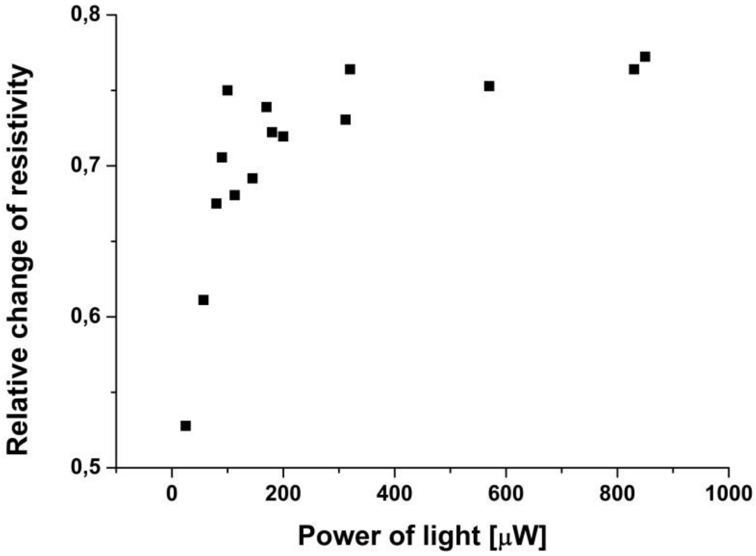


Fig. 2. Relative changes of the resistance as a function of light power. The experiment was performed for light of different wavelengths in a spectral region from 400 to 1100 nm.

Measurements of the electrical properties of the structure were made. Based on results the band diagram (fig. 3) was determined according to the Anderson model [14].

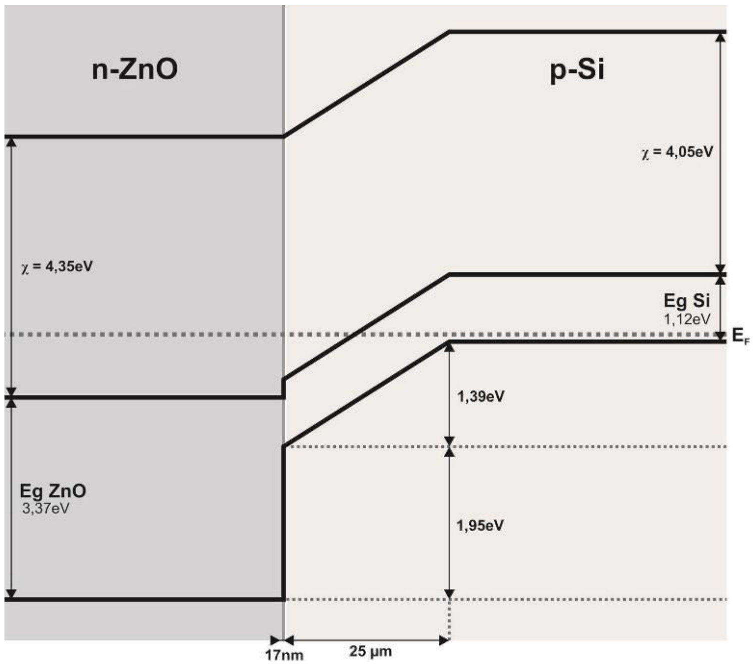


Fig. 3. Band diagram of the ZnO/Si heterojunction. This figure comes from publication H1.

According to calculations, almost the entire depletion layer of width of 25 μm is on the silicon side (only 17 nm on the ZnO side). These calcualtions allowed to propose a mechanism of resistance changes. Visible light absorbed in the junction area (on the silicon side) generates electron-hole pairs that are effectively separated in the junction area. Electrons, which due to the band bending travel to NRs, do not take a part in the measured conductivity. Holes, however, accumulate in the surface layer of silicon, creating an effective conduction channel (causing a macroscopic change in resistance). Due to relatively huge width of the junction area, the separation of generated carriers is very efficient. For higher light intensities, the number of carriers increases, and thus the junctions area decreasis and seperation is less effective. Therefore, for a very low light intensities (~ µW) the sensitivity of the detector is very high, while for higher light intensity we obserbe saturation of resistance changes and decreases of sensitivity.

4.5 Analysis of optical properties of ZnO nanorods (H2, H3)

The high crystallographic quality of the ZnO NRs allows for applications in many different areas, including optoelectronic devices, e.g. in "random lasers". The first literature reports on this type of application of ZnO NRs appeared after 2000 [15,16]. Having in mind this type of application, it is extremely important to recognize the material's properties and luminescence processes. Therefore, another work in the habilitation cycle concerns the optical characterization of ZnO NRs. H2 work contains a group of results taken at low-temperature cathodoluminescence (CL) (at 5K) and temperature dependence (from 5K to room temperature). The first part of the results presented in this paper was included in my Ph.D. thesis - studies of the effects of carriers localization using CL (temperature dependence of the spectral position of CL emission, CL maps), analysis of homogeneity of NRs (analysis of the position of the maximum intensity along the nanorod) and a comparison of these properties with the properties of high quality layers obtained by the ALD method. The obtained results confirmed the extremely high quality of NRs and their homogeneity. The observed luminescence (one emission band) was of excitonic nature, other emission bands associated with crystallographic defects were not observed. However, the most important results included in this article arose after obtaining the Ph.D. degree and because of these results the work was included in the habilitation cycle. In the this experiment, single NRs were excited with an electron beam. In the first case, the NR was detached from the substrate and suspended on a carbonaceous membrane. In the second case, the NR was surrounded by other NRs in the matrix (obtaining such results was possible due to the combination of the CL system with the scanning electron microscope – SEM). It turned out that the luminescence in these two cases was significantly different.

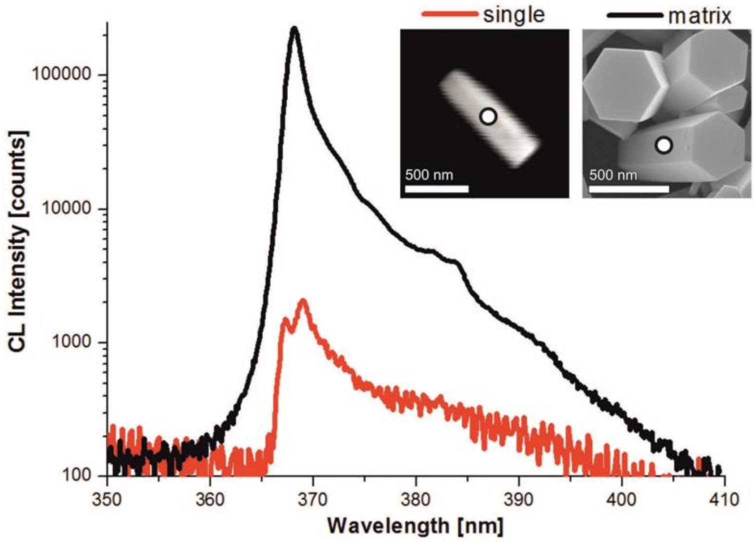
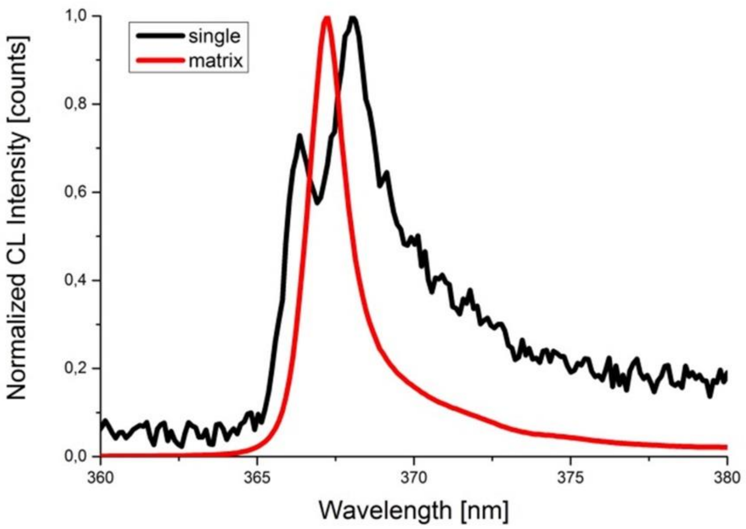


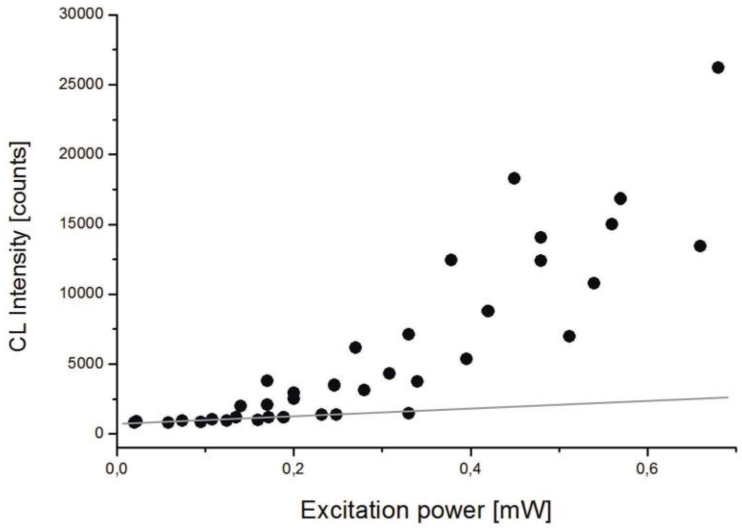
Fig. 4. CL spectrum for a nanorod in a matrix (black curve) and for an isolated nanorod (red curve) collected at a temperature of 5 K and SEM images with defined points of excitation. This figure comes from publications H2.

The first difference concerns the luminescence intensity. The luminescence (basically catholuminescence) of the separated NR was approximately 100 times less intense than for the NR in the matrix (Fig. 4), while in both cases we excitated the single NR and we used the same excitation power. Of course, the difference in intensity can be explained by the fact that in the matrix part of the electrons from the beam through scattering and diffusion also reache and excitate other NRs nearby, but the difference should not be so huge. The second difference is related to the character of luminescence. Two emission bands are visible for the separated NR. Based on the available photoluminescence (PL) results, we found that the first (higher energy band) is associated with the free exciton, while the second with the exciton bound at the neutral donor [17] (Fig. 5).



Rys. 5. Normalized (to the identical intensity) CL spectrum for a nanorod in a matrix and for an isolated nanorod collected at a temperature of 5 K.

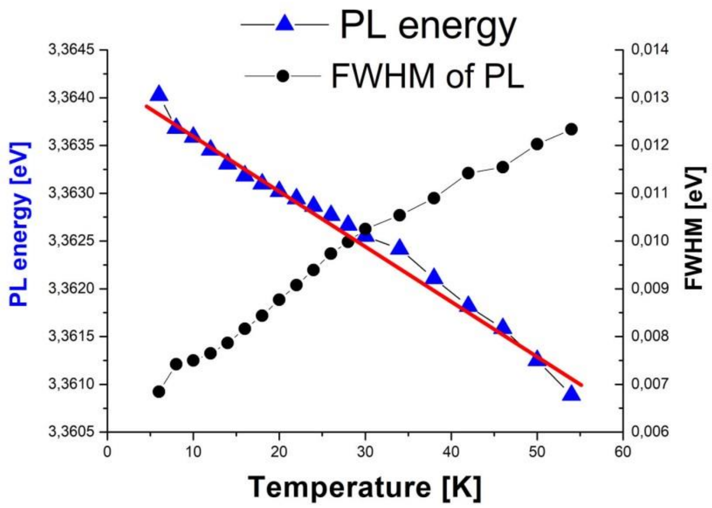
In the case of the NR in the matrix, only one band is visible with a smaller half-width than in the case of a separated NR. Observed differences suggest an additional mechanism of enhancement the luminescence of the NRs in the matrix. As a potential explanation for this effect, the phenomenon of superradiation was proposed [18]. In the case of stimulation of the NR in the matrix, probably many nearby NRs are in an "excited state" (as a result of energy transfer) which can lead to the coupling of their luminescence. The appearance of this phenomenon should affect the dynamics of luminescence, but this measurement was not possible in the used system. However, another experiment was carried out – measurement of the integrated intensity of CL from NRs matrix as a function of excitation power starting from very small powers, for which stimulation of several nearby NRs was unlikely (Fig. 6). For small powers the dependence of the luminescence intensity in the function of excitation power should be linear.



Rys. 6. Integrated counts from CL spectra for ZnO NRs matrix in a function of excitation power. This figure comes from article H2.

For relatively small excitation powers, the CL intensity slowly and linearly increases with increasing excitation power. The classic phenomenon of independent recombination of electron-hole pairs is observed. With the further increase in power, this relation changes. The number of excited NRs is increasing and we observe coherent emission of a much higher intensity. This dependence in the case of the separated NR was of a completely different nature. With the increase of excitation power, the initially observed linear relationship becomes saturated and the intensity of luminescence increases more slowly with the excitation power, which was presented in the work H2. The observed dependence on the NRs in the matrix strongly suggests the appearance of a superradation effect, but final confirmation of this thesis will require additional measurements, in particular the analysis of the dynamics of luminescence. However, the explanation of the observed phenomenon by the superradation effect seems to be correct. The effects of this type have already been observed for low-dimensional systems, e.g. for the quantum dots system [19].

Another article in the habilitation cycle concerns the optical characterization of ZnO NRs using PL measurements. In particular, measurements of the temperature dependence of the PL spectra were used, which, as in the case of CL measurements, was dominated by an excitonic emission. The analysis of the PL spectra, whose shape indicated a multi-band character, was made by approximating the individual components of the emission bands with the Gaussian function. (a standard approximation for the PL bands). Thanks to this, it was possible to identify individual emission bands and estimate their half widths. The dominant band was identified as the luminescence of a donor bound exciton (DBE) [17]. The energy position and the half width of individual bands were analyzed along with the temperature increase (starting from the temperature of 6K). This type of analysis is used to estimate the role of potential fluctuation and the localization of carriers. In the case of a large role of these effects, the characteristic behavior of the energy band position in a function of the temperature is observed, which is called "S-shape" [20] (e.g. observed for ZnO layers [21]). In the case of NRs this relationship did not occur. The half width of the DBE band linearly increases with temperature, which is characteristic for exciton-phonon scattering characteristic for high quality material (Fig. 7).



Rys. 7. Energy position of the DBE PL peak and its half width in function of temperature. This figure comes from article H3.

In addition, the strength of exciton-phonon coupling was determined, which was much stronger than in systems with large potential fluctuations. The PL measurements presented in the H3 work are a complement to the CL measurements. Both papers confirm the high quality of the ZnO NRs, which is crucial for optoelectronic applications.

The huge application potential in optoelectronic devices also has zinc oxide and gallium nitride heterostructures. Both materials have a similar energy gap, the same crystallographic structure and similar lattice parameters. There are many publications in the literature showing the potential of such heterostructures, in particular in applications in LED diodes [22, 23]. However, such applications require additional optimization of technology. Due to this, our research has been focused on the epitaxial growth of ZnO NRs on gallium nitride substrates.

4.6 Growth and properties of ZnO NRs epitaxially grown on gallium nitride substrates (H4, H5)

The next two articles of the cycle concern ZnO nano/microrods grown epitaxially on a crystallographically matched gallium nitride substrate by method developed by me. The possibility of growth such structures has only been demonstrated in my Ph.D. thesis, and the H4 article is a further development of this topic presenting the possibilities of growth and control, as well as the characterization of the oriented NRs. In particular, the H4 article shows that, similarly to the growth of NRs on unmatched crystallographic substrates, also in the case of a matched substrate, growth control is not based on the duration of the process, but only through chemical parameters such as pH value of the solution or zinc concentration in the growth solution (Fig. 8 and 9).

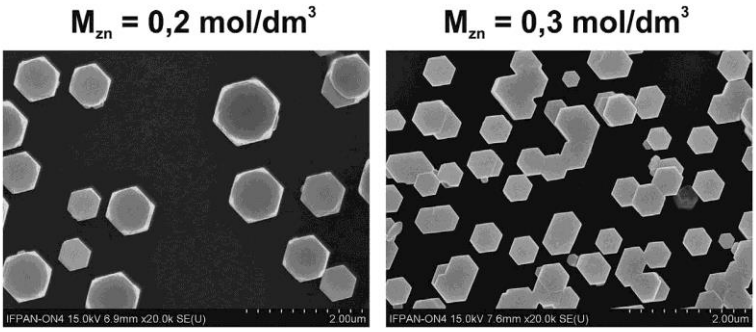
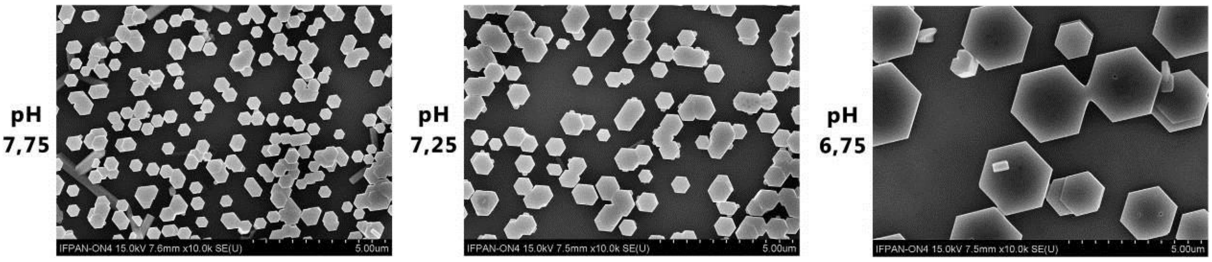


Fig. 8. SEM images of ZnO nano/microrods grown from solutions with the same pH value of 7,75 but for different values of Zn concentration. This figure comes from article H4.

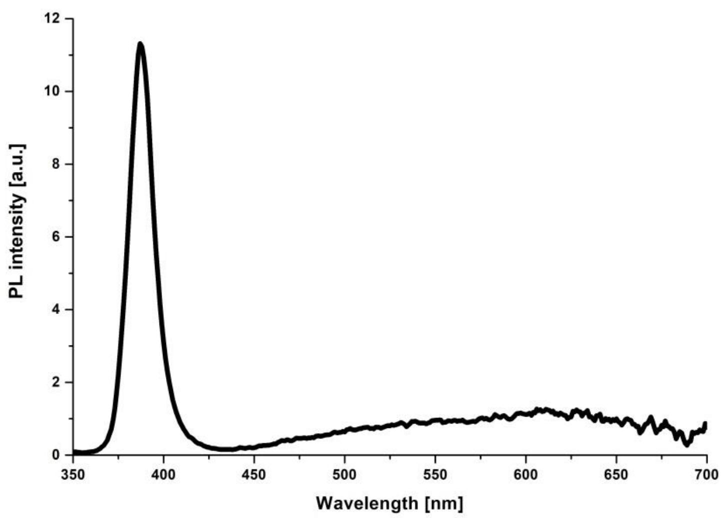


Rys. 9. SEM images of ZnO nano/microrods grown from solutions with the same Zn concentration of 0.3 mol/dm^3 but for different pH values. This figure comes from article H4.

The growth mechanism of ZnO NRs was initially proposed in my Ph.D. dissertation. This topic was the subject to further analysis after obtaining the Ph.D. degree. As a result of this work, a growth model was developed, which is the closest to the model proposed by W. Li [24], but in our case it has been slightly modified. It was presented in the article H4. Proposed model explains the quite complex dependence of the pH value of the solution on the sizes of the NRs. In brief - for lower pH values the dominant form of zinc is $Zn(CH_3COO)_2$, and its reaction with surface OH groups is the driving force of growth. The increase of the pH value causes dissociation of zinc acetate and, indirectly, the appearance of sodium acetate, which blocks the growth of NRs on nonpolar planes (side walls). Therefore, for higher pH values, the NRs have a high aspect ratio.

The influence of zinc concentration on the density of NRs is relatively easy to explain. For a higher concentration of zinc, the probability of zinc-surface binding increases, leading to higher number of nanostructures.

In addition, the article H4 contains the characterization of the obtained NRs. The orientation of NRs visible in SEM images and its relation to the orientation of the gallium nitride substrate were confirmed by X-ray diffraction and transmission electron microscopy. Ideal hexagonal shape of the NRs characteristic for wurtzite structure suggests high quality of the material. However, PL measurements alongside of the strong excitonic band also revealed a small and wide emission band associated with defects (Figure 10). These defects are most likely related to stacking faults, which were presented in the transmission electron microscopy images. Slightly lower crystallographic quality of the epitaxial NRs is probably related to the small lattice mismatch ZnO with the GaN substrate (about 1.9%), which causes stress, and these in turn generate errors in the crystal arrangement. It was quite a surprising result, as in the case of NRs grown on strongly crystallographic unmatched substrates (without epitaxial relation) the presence of this type of defect was not observed, and the crystallographic quality of nanostructures was very high.



Rys. 10. PL spectra of oriented ZnO NRs on GaN substrate. Figure comes from article H4.

The H5 article is an original continuation of research on optical properties of oriented nano/microrods on gallium nitride substrates. The possibility of use of ZnO microrods (MRs) as optical resonators is discussed, using the previously demonstrated high crystallographic quality and the nature of their luminescence. In particular, the H5 work focuses on the analysis of the CL investigations of individual MRs, demonstrating the correlation of optical properties with the sizes and shape of structures. ZnO MRs can be used as natural optical resonators due to their geometry. Six side walls of the NR can serve as mirrors “closing” the light inside, enhancing the resonance modes of the circulating light. Of course, the light will not propagate inside forever, but it is gradually radiated around the corners and side walls. By excitation with the electron beam the center of the microrod, the generated light has a low probability of entering the resonance mod due to the high angle of incidence on the side walls. However, when excitating near the side walls or vertices, the probability of the resonant mode increases significantly, which explains the CL maps shown in Fig. 11. The H5 article, presenting a detailed analysis of this effect, will be part of Agnieszka Pieniazek's Ph.D. thesis, of which I am an auxiliary supervisor. Research of this fascinating phenomenon is being continued. It should be noted here that resonant modes have been observed so far for structures with the highest crystallographic quality made by expensive technological methods [25,26,27].

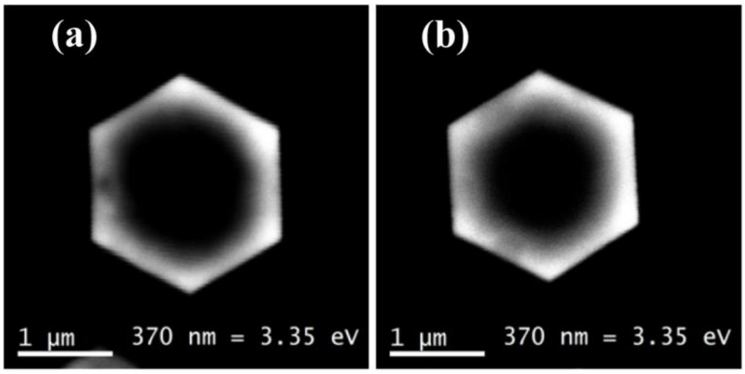
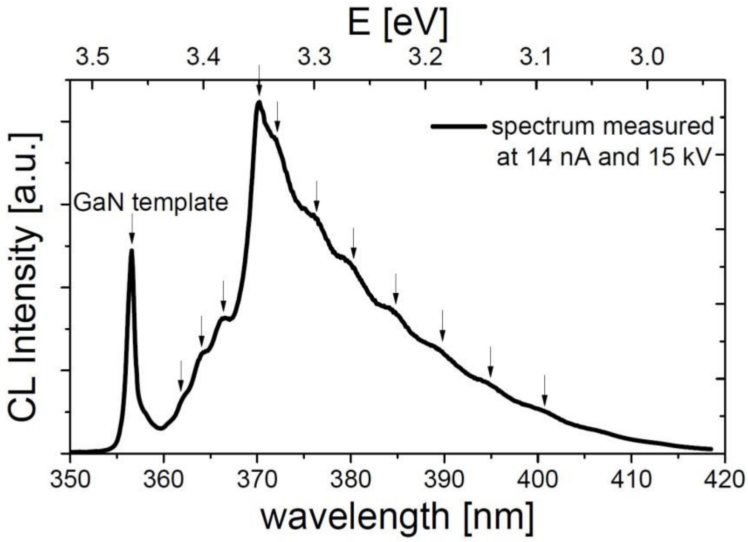


Fig. 11. Monochromatic CL maps of two individual ZnO microrods. This figure comes from article H5.

The CL maps were taken for light at about 370 nm of wavelength, because the examined NRs were only characterized by an excitonic luminescence.

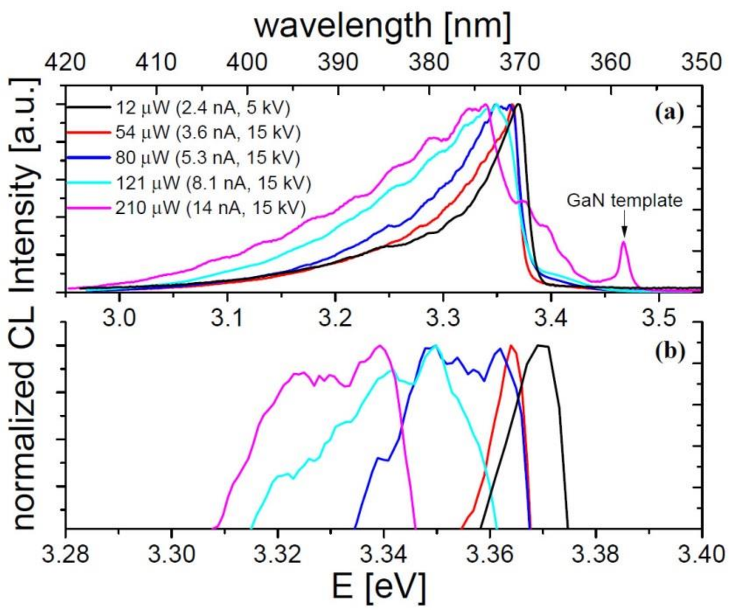
The exact CL spectrum collected for a relatively large microrod (with a width of 2.24µm) shown its multiband character (Figure 12).



Rys. 12. CL spectra taken for individual ZnO microrod at temperature of 5K. This figure comes from article H5.

Analysis of energy distances between the individual bands excluded phonon replicas as their source. The explanation of the character of the spectrum was based on a simple wave model assuming the coexistence of electric and magnetic resonant modes. The presented analysis together with experimental results for various sizes of nano/microrods (2.24µm, 1.49µm and 532 nm) shown the influence of the cavity dimensions on resonance modes. Along with the increase in the width of the cavity, resonant modes become more visible, which is associated with smaller optical losses. The effect of the size of the cavity can be explained by the plane wave model. Resonance amplification occurs when the size of the cavity and wavelength meet the condition of constructive interference. For the smallest cavity, the model stops working, because the cavity has sizes comparable to the wavelength, in this case resonant modes are not observed.

In addition, the article presents an analysis of the luminescence of the microrods as a function of excitation power. Due to the possibility of use local high density excitation power in CL and the emergence of resonance modes enhancing luminescence, the possibility of switching from excitonic luminescence to luminescence of the electron-hole plasma was presented, which is extremely important in the context of possible laser applications. With increasing excitation power, luminescence expands spectacularly, new emission bands appear on the side of longer wavelengths, and the dominant band shifts towards lower energies, which is a typical phenomenon for an electron-hole plasma emission (Fig. 13).



Rys. 13. CL spectras of ZnO microrod of 2,24µm width taken for different CL excitation powers. This figure comes from article H5.

The presented CL analysis prove that despite the very simple, cheap and fast growth technology, the obtained structures are characterized by very high crystallographic quality and it is possible to observe in them such luminescent effects as resonance modes or luminescence of the electron-hole plasma.

During development of the growth possibilities of nanostructures, we became interested in the idea of implementing NRs into the construction of PV cells, for which interesting results were demonstrated, e.g. work from Lund University [28], in which the application of InP NRs was presented. Over time, the topic of the PV cells has become one of the main areas of research in our group.

4.7 Application of ZnO NRs in PV cells (H6, H7, H8)

The next three articles in the cycle discuss the application of NRs in silicon-based PV cells. These works were the subject of Rafał Pietruszka's Ph.D. thesis, of which I was the auxiliary supervisor. Our group proposed a new architecture of PV cells [29], based on silicon, but as an alternative to classic silicon cells. This architecture is based on a p-type silicon substrate, and the p-n junction is created with the ZnO n-type layer deposited by the ALD method. This approach was aimed at eliminating the technological processes involved in the formation of the n-type conductivity layer on the silicon surface, which are energy-consuming and expensive. It is required to implant the surface of silicon with phosphor, and next the annealing. Although zinc oxide has a wide energy gap in the ultraviolet spectral region and is unable to absorb light from the visible range, it can form a very efficient junction with silicon, in which light absorption takes place.

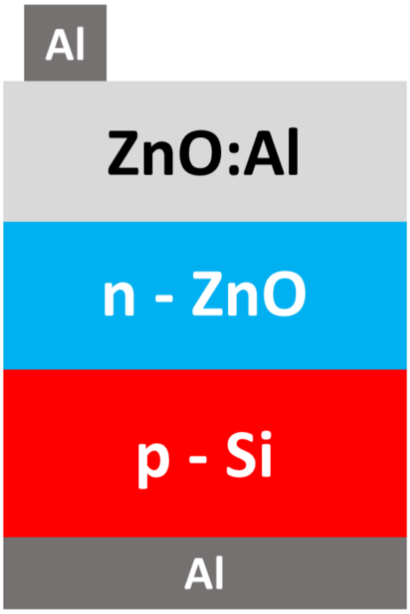


Fig. 14. PV cell architecture based on the Si/ZnO junction.

In addition, a layer of ZnO doped with aluminum (AZO) was deposited on the ZnO n-type layer, which is characterized by high transparency and conductivity creating an efficient transparent electrode (fig. 14). Structures of this type after optimization of the layer thickness shown PV efficiency of approx. 6% [29].

Article H6 presents the first attempt to apply ZnO NRs to this structure (shown in fig 14), but the layer of n-ZnO obtained by the method of ALD has been replaced with ZnO NRs. The scheme of a such structure is presented in the fig. 15.

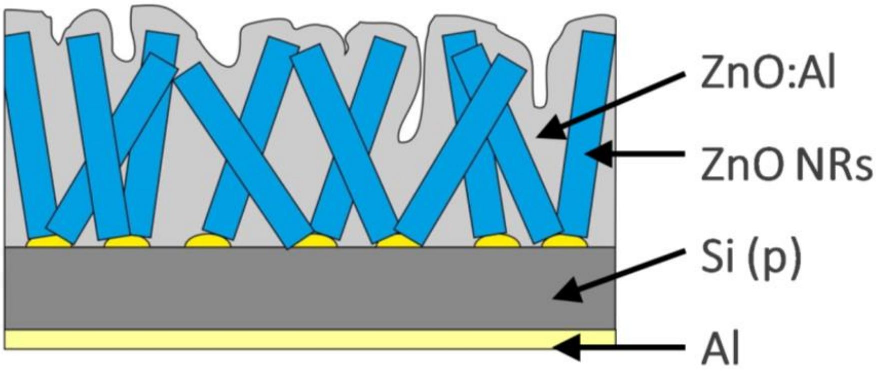


Fig. 15. Scheme of PV cell architecture – Si / ZnO NRs / AZO.

The idea of using ZnO NRs in such cell architecture was based on several assumptions. Firstly, in this type of structures, apart from the generation of electron-hole pairs, an extremely important aspect is carriers separation. In the case of a ZnO layer of a polycrystalline nature, recombination of the generated carriers, e.g. at the grain boundaries, can often lead to the lost of part of the generated current. ZnO nanostructures, due to their high crystallographic quality and geometry, can create the type of channels that efficiently pull out the electrons from the junction area, thus limiting the loss of carriers. The second reason, also related to high quality, is the low concentration of carriers (lower than in the case of ZnO-ALD layers), which results in the widening of the effective junction area, in particular also on the ZnO side. For this reason, the PV cells of this architecture have improved absorption of the light for shorter wavelengths. A third reason for the use of NRs is to improve the collection of light (naturally rough surface). In addition, the method of growth of ZnO NRs even in comparison with the low-cost ALD method is a much cheaper alternative to the structuring used in the production of silicon cells. In this case, the silicon is digested using aggressive chemicals harmful to the environment.

Various variants of NRs were tested (for different pH values of the solution - 7, 7.5 and 8, which determine the sizes and density of the NRs). The best results were obtained for the pH value of 8, for which the NRs were the smallest and the most dense (figures 16 and 17).

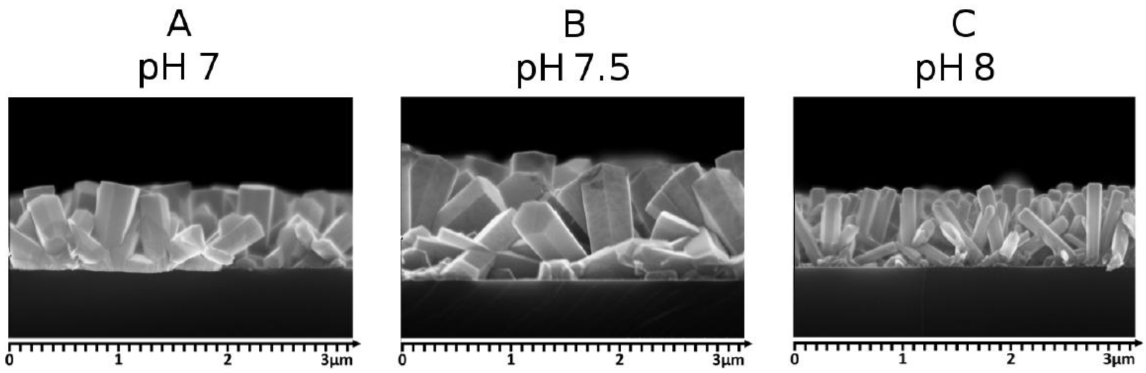


Fig. 16. SEM images of NRs for different values of pH of used growth solution. This figure comes from article H6.

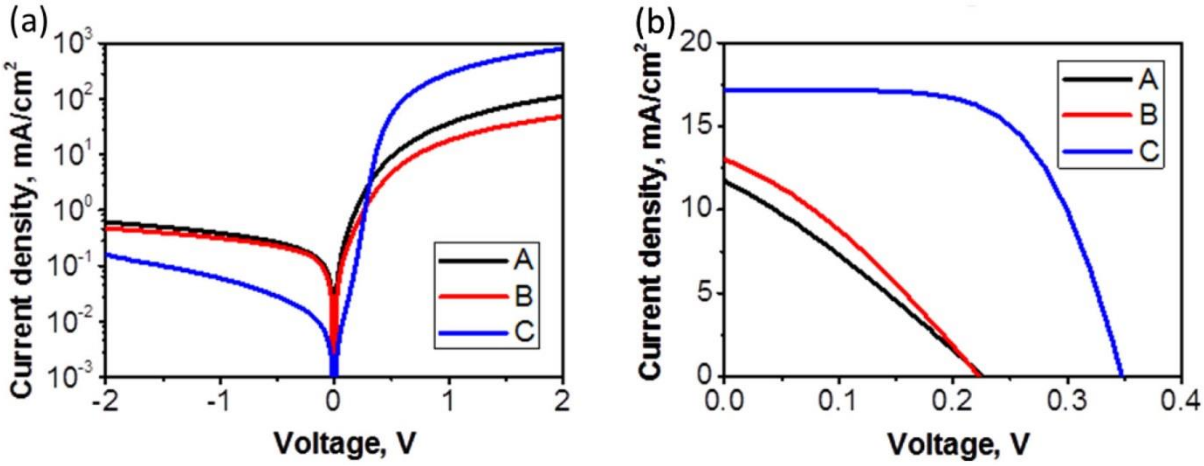


Fig. 17. I-V characteristic measured for samples cotaining ZnO NRs growth for different pH value of growth solution under light exposure (A: pH = 7, B: pH = 7,5, C: pH = 8). This figure comes from article H6.

The obtained cell efficiency was only 3.6% which in comparison to the planar structure was not a breaking result. This situation could be related to the surface of the effective junction - the NRs do not uniformly cover the entire silicon surface (there are free spaces between the NRs), which consequently leads to a reduction of the effective junction surface in which the electron-hole pairs are separated. As a result of the analysis of this problem, the structure of the cell has been modified, and the obtained results have been described in the next paper from the cycle - H7. Using the main advantage of the ALD method - the homogeneity of covering even the most complicated structures, the spaces between the NRs (including silicon surface areas that previously did not form an effective junction) were filled with an additional layer of ZnO. As a result, the entire silicon surface began to form an effective junctiont (fig 18).

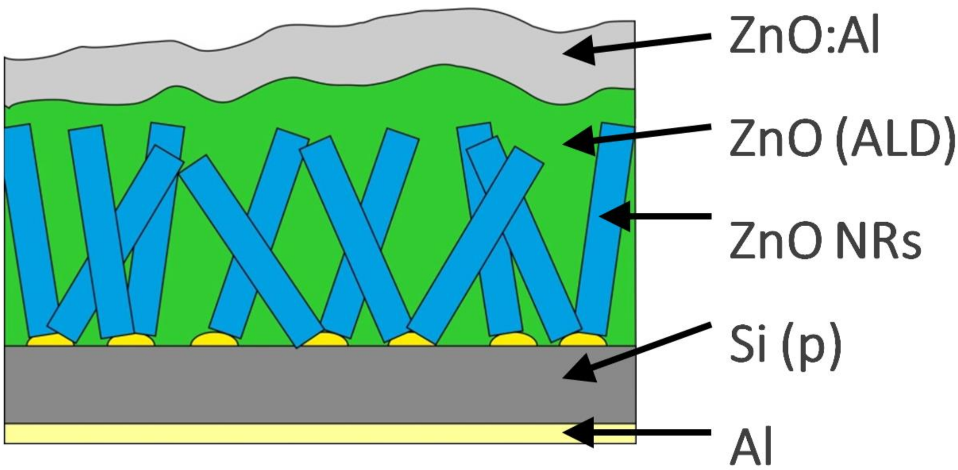


Fig. 18. Scheme of PV cell architecture – Si / ZnO NRs /ZnO-ALD / AZO.

In this case, the use of ZnO NRs has an additional advantage - ZnO layer grown by the ALD method on the NRs is characterized by a much higher quality, than in case of the growth directly on silicon. ZnO-ALD layer continues columnar growth, extending and widening the NRs (Fig. 19).

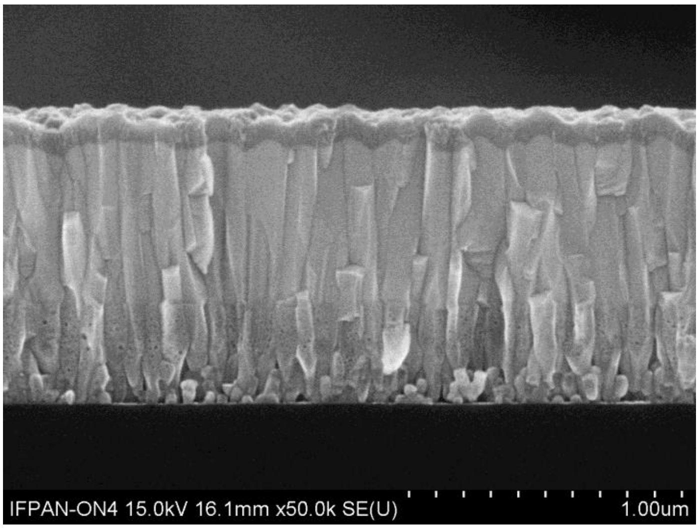


Fig. 19. SEM image of structure - Si / ZnO NRs /ZnO-ALD / AZO. This figure comes from article H7.

In the H7 paper a comparison of samples for different thicknesses of the additional ZnO layer filling the spaces between the NRs was presented. In every case the application of such solution significantly improved the obtained results (Fig. 20).

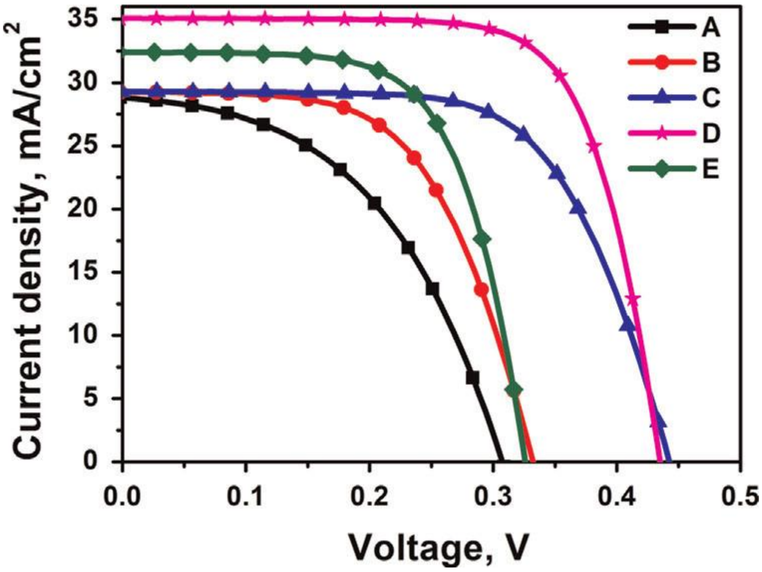


Fig. 20. I-V characteristics under illumination of PV cells with different thickness of additional ZnO layer (A – 50nm, B – 100nm, C – 300nm, D – 500 nm, E – 800nm). This figure comes from H7 article.

The manufactured cell with a ZnO layer with a thickness of approx. 500 nm showed a efficieny of almost 11% (measurements made with the use of a sun simulator), which was a huge improvement compared to the first attempt with ZnO NRs.

The continuation of the group's work in this topic concerned engineering of the silicon-ZnO band interface matching. In order to improve the quality of the junction (stronger lowering the concentration of carriers on the ZnO side), the ZnO layer doped with magnesium was used instead of the ZnO layer [30], which earlier resulted in the increase of the efficiency in the case of the planar cell. This solution was also used in cells with ZnO NRs. The next work in the cycle (H8) presents a comparison of a planar cell (using the architecture Si / ZnO:Mg / AZO) with cells containing ZnO NRs

(Si / ZnO NRs / ZnO:Mg / AZO). The effect of the density of NRs on cell performance was also checked (fig. 21). The applied solution led to another significant increase in the efficiency of the cell, which for the best sample reached 14% (figure 22). The best performance was obtained for the NRs with denser packing, but in both cases the efficiency was higher than for the planar structure (10.5%). These results were obtained among others for the point top contact and without optimizing the thickness of the silicon, so there are still many further ways for further optimization.

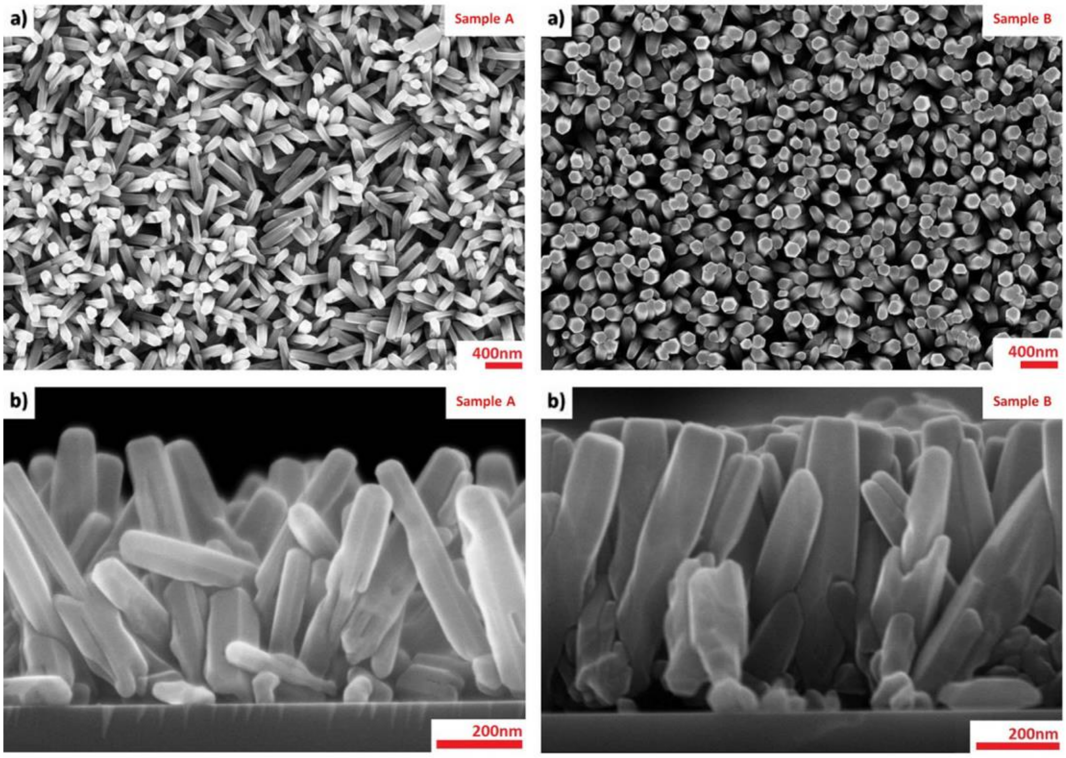


Fig. 21. SEM images of ZnO NRs, which were used for PV cell construction, A (NRs of a small density), B (NRs of a high density). This figure comes from H8 article.

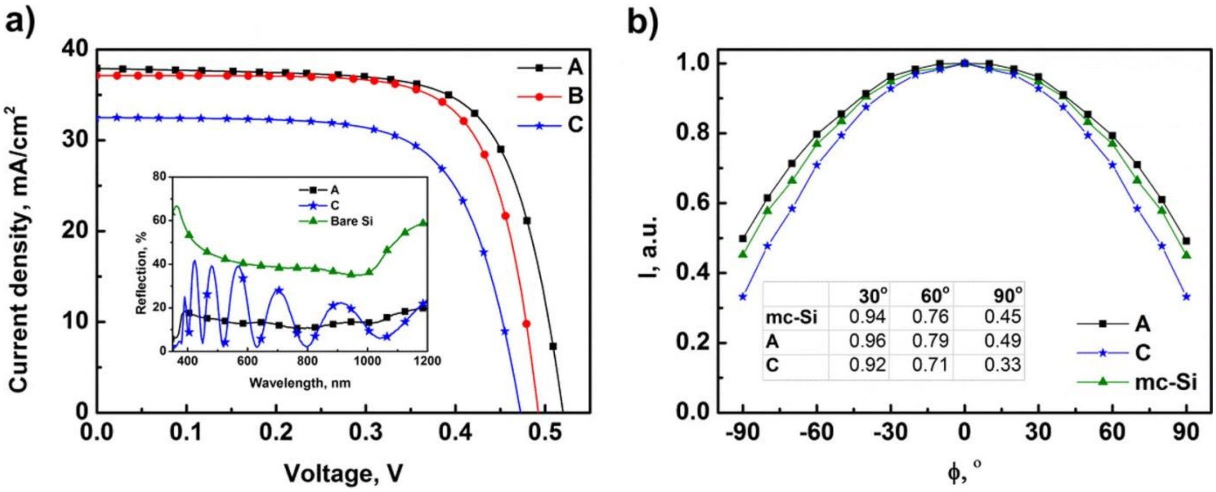


Fig. 22. a) Current-voltage relationships for samples with various NRs A and B (NRs shown in fig. 21) and for a reference planar cell - C. The contribution to the graph shows the reflection of light from samples and pure silicon. b) Comparison of angular dependence of relative performance for a cell with NRs, a reference planar cell and a commercial silicon cell with surface nanostructurisation. This figure comes from H8 article.

In addition, it has been shown that the use of NRs also affects the reduction of the reflection of incident light, especially for large angles and even in comparison with a commercial cell with a structured surface (fig. 22 b).

The results presented in the papers H6, H7 and H8 are the next stages of optimization of the construction of PV cells, which started with the analysis of physical processes taking place in the cells (as well as technological aspects of their production). These analysis leed to higher measured efficiency. Initial assumptions, being the starting point for technological works, turned out to be correct, and the efficiency of cells using ZnO nanostructures showed an increase by several percentage points (in relation to planar architecture). The presented works are of great practical importance. Currently, they are continued as part of the program received in the TechMatStrateg competition (financed by NCBiR) with the participation of an industrial partner.

4.8 An overview of the potential applications of ZnO NRs [H9]

Paper H9 in the habilitation cycle is an additional article, which although does not contain my new research results, but provides the review describing the potential applications of ZnO NRs. In particular, this review presents applications in light emitters (light emitting diodes and lasers) and detectors (on single nanorod or nanorods matrices), photovoltaic cells (dye-sensitized, perovskite-based, thin film, organic and silicon solar cells), photocatalytic applications, field emitters, field effect transistors, chemical and biological sensors, and electric nanogenerators. In particular in the chapters on light detectors and photovoltaic cells, my and my colleagues' achievements have been placed on the background of other research groups.

The work appeared in the habilitation cycle, because the analysis of the technological state included in it is a kind of justification for undertaking research works related to the technology of the growth of ZnO NRs. Namely, ZnO NRs are presented in many fields of physics as very promising nanostructures for many applications. For twenty years, prototype devices with ZnO NRs have been demonstrated in a laboratory scale. Unfortunately, until now, ZnO NRs have not found real commercial application. The analysis of this issue contained in the article H9 suggests that the source of this problem is related to the used growth methods and technological solutions (often complex procedures) that provide extremely interesting results in the laboratory scale, but unfortunately do not meet the requirements of industrial application. The development of a simple, fast, non-toxic and scalable growth method of ZnO NRs, allowing the production of high quality structures should allow for industrial applications. I believe that the method that was presented in my dissertation and developed in the following years meets these requirements. The presented characterization of the obtained structures and examples of applications, in particular in the context of PV cell applications, are a confirmation of this thesis.

4.9 Summary - the most important achievements

- Proposing a mechanism of resistance changes of ZnO / silicon structure under the influence of visible light - article H1
- Characterization of the optical properties of ZnO NRs using CL and PL. In particular, demonstration of the difference in luminescence for the separated NR and NR in the matrix with the same excitation power, and demonstrating the possibility for occurrence of collective luminescence phenomena for the matrix of ZnO NRs- articles H2 and H3
- Demonstration the possibility of growth of epitaxial NRs on GaN substrates and proposing the mechanism of growth during hydrothermal process - article H4
- Demonstration the high quality of ZnO MRs by observations of luminescence effects such as resonance modes or luminescence of electron-hole plasma - article H5
- Demonstration of photovoltaic cell efficiency increase after introduction of ZnO NRs in their architecture - articles H6, H7 and H8

5. Discussion of other scientific and research achievements

5.1 Description of scientific achievements unrelated to the topic of habilitation

A significant part of my scientific activity not related with the topic of habilitation cycle concerns the characterization of materials and structures by SEM, along with accompanying techniques - EDS (Energy Dispersive Spectroscopy) and CL (73 publications from the JCR list). The scope of these works and the cross-section of materials that I characterized is very large, however, it is possible to identify several topics in this group, which constitute a permanent scientific cooperation. One of these topic groups are nanopowders from oxide materials doped with rare earth ions, optimized for applications in the diagnosis and therapy of cancer. I have been cooperating on this subject for many years with dr. Jarosław Kaszewski (IFPAN) and dr. hab. Michał Godlewski (SGGW), comprehensively characterizing the produced nanomaterials, which resulted in numerous publications in this field, including:

- J. Kaszewski, **B.S. Witkowski**, L. Wachnicki, H. Przybylinska, B. Kozankiewicz, E. Mijowska, M. Godlewski, Luminescence enhancement in nanocrystalline Eu_2O_3 nanorods - Microwave hydrothermal crystallization and thermal degradation of cubic phase,
  Optical Materials 59, 76-82 (2016)

- J. Kaszewski, M.M. Godlewski, **B.S. Witkowski**, A. Słońska, E. Wolska-Kornio, Ł. Wachnicki, H. Przybylińska, B. Kozankiewicz, A. Szal, M.A. Domino, E. Mijowska, M. Godlewski,
  Y_2O_3:Eu nanocrystals as biomarkers prepared by a microwave hydrothermal method,
  Optical Materials 59, 157-164 (2016)

- J. Kaszewski, **B.S. Witkowski**, Ł. Wachnicki, H. Przybylińska, B. Kozankiewicz, E. Mijowska, M. Godlewski,
  Reduction of Tb^{4+} ions in luminescent Y_2O_3:Tb nanorods prepared by microwave hydrothermal method,
  Journal of Rare Earths 34(8), 774-781 (2016)

- J. Kaszewski, E. Borgstrom, **B.S.Witkowski**, Ł. Wachnicki, P. Kiełbik, A. Slonska, M.A.Dominoc, U. Narkiewicz, Z. Gajewski, J.-F. Hochepied, M.M. Godlewski, M. Godlewski,
  Terbium content affects the luminescence properties of ZrO_2:Tb nanoparticles for mammary cancer imaging in mice
  Optical Materials 74, 16-26 (2017)

- P. Kielbik, J. Kaszewski, J. Rosowska, E. Wolska, **B.S.Witkowski**, M. A.Gralak, Z. Gajewski, M. Godlewski, M.M.Godlewski, Biodegradation of the ZnO:Eu nanoparticles in the tissues of adult mouse after alimentary application
  Nanomedicine: Nanotechnology, Biology and Medicine 13 (3), 843-852 (2017)

- J. Olszewski, P. Kielbik, J. Kaszewski, **B.S. Witkowski**, Z. Gajewski, M. Godlewski, M.M. Godlewski
  Multimodal non-gadolinium oxide nanoparticles for MRI and fluorescence labelling
  Biophotonics: Photonic Solutions for Better Health Care VI 10685, 106852M (2018)

- P. Kielbik, J. Kaszewski, **B. S. Witkowski**, Z. Gajewski, M. A. Gralak, M. Godlewski, M. M. Godlewski, Microscopy Science Book Series titled "Microscopy and imaging science: practical approaches to applied research and education", chapter "Cytometric analysis of Zn-based nanoparticles for biomedical applications", FORMATEX publishing

Another group in which I conduct stable cooperation is the characterization of layers of metal oxides grown by the ALD method. This is an extremely wide area, because the ALD method is the main technology developed in our research group. I participated in the optimization of a whole range of oxide layers, like: ZnO, ZnO:Al, ZnMgO, ZnO:Cu, ZnO:Co, ZnMgO:Al, Al_2O_3, ZrO_2, TiO_2, HfO_2. The most important artciles in this group are:

- Ł. Wachnicki, T. Krajewski, G. Łuka, **B. Witkowski**, B. Kowalski, K. Kopalko, J.Z. Domagała, M. Guziewicz, M. Godlewski, E. Guziewicz, Monocrystalline Zinc Oxide Films Grown by Atomic Layer Deposition, Thin Solid Films 518 (16), 4556-4559 (2010)

- M. Łukasiewicz, **B. Witkowski**, M. Godlewski, E. Guziewicz, M. Sawicki, W. Paszkowicz, R. Jakieła, T. Krajewski, G. Łuka, Effects related to deposition temperature in ZnCoO films grown by Atomic Layer Deposition – uniformity of Co distribution, structural, electric and magnetic properties, Phys. Status Solidi (b) 247, 1666 (2010)

- G. Luka, L. Wachnicki, **B.S. Witkowski**, T.A. Krajewski, R. Jakiela, E. Guziewicz, M. Godlewski, The uniformity of Al distribution in aluminum-doped zinc oxide films grown by atomic layer deposition, Mat. Sci. Eng. (b) 176 (3), 237-241 (2011)

- M.I. Łukasiewicz, **B.S. Witkowski**, Ł. Wachnicki, K. Kopalko, S. Gierałtowska, A. Wittlin, M. Jaworski, E. Guziewicz, M. Godlewski , (Zn,Cu)O Films by Atomic Layer Deposition - Structural, Optical and Electric Properties, Acta Phys. Pol. A 120 (6A), A34-A36 (2011)

- S. Gieraltowska, L. Wachnicki, **B.S. Witkowski**, T.A. Krajewski, M. Godlewski, E. Guziewicz, Atomic layer deposition grown composite dielectric oxides and ZnO for transparent electronic applications, Thin Solid Films 520 (14), 4694-4697 (2012)

- S. Gierałtowska, Ł. Wachmicki, **B.S. Witkowski**, E. Guziewicz, M. Godlewski, Thin Films of High-k Oxides and ZnO for Transparent Electronic Devices, Chem. Vap. Deposition 19, 213–220 (2013)

- G. Luka, **B.S. Witkowski**, L. Wachnicki, M. Andrzejczuk, M. Lewandowska, M. Godlewski Kinetics of anatase phase formation in TiO_2 films during atomic layer deposition and post-deposition annealing, CrystEngComm 15, 9949 (2013)

- G. Luka, **B.S. Witkowski**, L. Wachnicki, K. Goscinski, R. Jakiela, E. Guziewicz, M. Godlewski, E. Zielony, P. Bieganski, E. Placzek-Popko, W. Lisowski, J.W. Sobczak, A. Jablonski Atomic layer deposition of $Zn_{1-x}Mg_xO$:Al transparent conducting films, Journal of Materials Science 49 (4), 1512-1518 (2014)

- S. Gieraltowska, L. Wachnicki, **B.S. Witkowski**, R. Mroczynski, P. Dluzewski, M. Godlewski Characterization of dielectric layers grown at low temperature by atomic layer deposition, Thin Solid Films 577, 97-102 (2015)

In this group, the CL analysis of layers deserve special attention, which have become my second specialty. These studies led to the publication of many articles, including:

- **B.S. Witkowski**, M. Łukasiewicz, K. Kopalko, B.J. Kowalski, E. Guziewicz, M. Godlewski Cathodoluminescence Profiling for Checking Uniformity of ZnO and ZnCoO Thin Films Acta Phys. Pol. A 119, 675 (2011)

- **B.S. Witkowski**, Ł. Wachnicki, R. Jakiela, E. Guziewicz, M. Godlewski, Cathodoluminescence Measurements at Liquid Helium Temperature of Poly- and Monocrystalline ZnO Films, Acta Phys. Pol. A 120 (6A), A28-A30 (2011)

- K. Sobczak, P. Dluzewski, **B.S. Witkowski**, J. Dabrowski, M. Kozlowski, E. Kowalska, E. Czerwosz, TEM and CL investigations of Pd nanograins included in carbonaceous film Solid State Phenomena 186, 177-181 (2012) (Electron Microscopy XIV)

- M. Godlewski, M.I. Lukasiewicz, E. Guziewicz, V.Y. Ivanov, L. Owczarczyk, **B.S. Witkowski**, Optical and magnetic properties of ZnCoO layers, Opt. Mat. 34 (12), 2045-2049 (2012)

- **B.S. Witkowski**, Ł. Wachnicki, P. Nowakowski, A. Suchocki, M. Godlewski, Temperature-dependence of cathodoluminescence of zinc oxide monolayers obtained by Atomic Layer Deposition, Optica Applicata 43 (1), 187 (2013)

- V.Y. Ivanov, A.J. Zakrzewski, **B.S. Witkowski**, M. Godlewski, Optical properties of ZnO doped with Cobalt ions, Optical Materials 59, 15-19 (2016)

- E. Guziewicz, E. Przezdziecka, D. Snigurenko, D. Jarosz, **B. S. Witkowski**, P. Dluzewski, and W. Paszkowicz , Abundant Acceptor Emission from Nitrogen-Doped ZnO Films Prepared by Atomic Layer Deposition under Oxygen-Rich Conditions, ACS Appl. Mater. Interfaces 9 (31), 26143-26150 (2017)
- E. Przezdziecka, E. Guziewicz, **B.S. Witkowski**, Photoluminescence investigation of the carrier recombination processes in N-doped and undoped ZnO ALD films grown at low temperature Journal of Luminescence 198, 68-76 (2018)

Beyond the microscopic characterization of materials, part of my scientific activity concerns scientific cooperation based on the growth technology of ZnO NRs. There are works related to the use of NRs in PV cells (other works than included in the habilitation cycle) and detectors, including:

- E. Placzek-Popko, K. Gwozdz, Z. Gumienny, E. Zielony, R. Pietruszka, **B. S. Witkowski**, Ł. Wachnicki, S. Gieraltowska, M. Godlewski, W. Jacak and Liann-Be Chang, Si/ZnO nanorods/Ag/AZO structures as promising photovoltaic plasmonic cells, Journal of Applied Physics 117, 193101 (2015)
- W. Jacak, E. Popko, A. Henrykowski, E. Zielony, K. Gwozdz, G. Luka, R. Pietruszka, **B. Witkowski**, Ł. Wachnicki, L.-B. Chang, M.-J. Jeng, On the size dependence and spatial range for the plasmon effect in photovoltaic efficiency enhancement, Solar Energy Materials and Solar Cells 147, 1-16 (2016)
- P. Materska, **B.S. Witkowski**, M. Godlewski, Influence of Annealing on Optical Properties of ZnO Nanorods Obtained by the Microwave-Assisted Hydrothermal Process, Acta Physica Polonica A 130 (5), 1202-1204 (2016)
- K. Gwozdz, E. Placzek-Popko, E. Zielony, K.M. Paradowska, R. Pietruszka, **B.S. Witkowski**, K. Kopalko, M.Godlewski, Liann-be Chang, Deep traps in the ZnO nanorods/Si solar cells Journal of Alloys and Compounds 708, 247-254 (2017)
- S. Kimiagar, V. Najafi, **B. Witkowski**, R. Pietruszka, M. Godlewski , High performance and low temperature coal mine gas sensor activated by UV-irradiation, Scientific Reports 8 (1), 16298 (2018)
- S. Kimiagar, F. Abrinaei, **B. Witkowski**, R. Pietruszka, M. Godlewski, Nonlinear optical response of ZnO/HfO_2 core/shell nanorod arrays under continuous wave laser irradiation, Journal of Materials Science: Materials in Electronics 30 (1), 797-805 (2019)

In addition, I took part in many other scientific projects. One of the most interesting was cooperation with the biological physics group led by prof. Marek Cieplak at the Institute of Physics of the Polish Academy of Sciences on the database containing the results of protein stretching simulation. This cooperation was a continuation of my B.Sc. thesis and led to the publication: *M. Sikora, J.I. Sułkowska, B.S. Witkowski, M. Cieplak, BSDB: the biomolecule streching database, Nucl. Acid Res. 39,* *D443-D450 (2011)*, while the database itself is available on the website of the Institute of Physics of the Polish Academy of Sciences (http://jowisz.ifpan.edu.pl/BSDB/).

A full list of scientific publications can be found in attachment no. 3.

Apart from scientific activity, I also focused intensively on the aspects of the promotion of science and the building of scientific cooperation with the industry. Being one of the employees of the Technology Transfer Center of the Institute of Physics of the Polish Academy of Sciences (this was also related to the function in the Eagle project - details are in attachment no. 3) I focused on activities related to participation in innovation fairs and organization of workshops aimed at activating scientific cooperation between science and industry.

5.2 Lectures presented at conferences

I gave 10 invited lectures:

1. ***B.S. Witkowski**, Ł. Wachnicki, S. Gierałtowska, M. Godlewski*
   ZnO nanorods grown by the hydrothermal method
   VI Doctoral Symposium of IP PAS, Mądralin, 16-17 May 2014
2. ***B.S. Witkowski**, Ł. Wachnicki, S. Gierałtowska, R. Pietruszka, G. Łuka, P. Sybilski, M. Godlewski*
   Nanosłupki ZnO o wysokiej jakości - technologia i zastosowania
   XIII Krajowa Konferencja Elektroniki, Darłówko Wschodnie, 9-13 June 2014
3. ***B.S. Witkowski**, Ł. Wachnicki, S. Gierałtowska, R. Pietruszka, M. Godlewski*
   High Quality ZnO Nanorods – From A New Technology To Applications
   22'nd International Conference on Composites/Nanoengineering (ICCE-23)
   Malta, St. Julian, 13-19 July 2014
4. ***B.S. Witkowski**, Ł. Wachnicki, S. Gierałtowska, R. Pietruszka, G. Łuka, P. Sybilski, E. Zielony, P. Bieganski, E. Popko, M. Godlewski*
   High quality ZnO nanorods grown by an ultra fast hydrothermal process - technology and applications
   EMRS Fall Meeting 2014, Warsaw, 15-20 September 2014
5. ***B.S. Witkowski**, Ł. Wachnicki, S. Gierałtowska, A. Pieniążek, A. Reszka, B.J. Kowalski, M. Godlewski*
   Charakteryzacja nanosłupków ZnO wzrastanych z roztworu wodnego metodami skaningowej mikroskopii elektronowej
   X Konferencja Techniki Próżni, Cedzyna k. Kielc, 22-25 September 2014
6. ***B.S. Witkowski**, L. Wachnicki, S. Gieraltowska, R. Pietruszka, P. Sybilski, M. Godlewski*
   Zinc oxide nanorods: growth technology, characterization and applications
   8th Symposium on Vacuum based Science and Technology, Kaiserlautern, Germany,
   30 September - 2 October 2014

7. ***B.S. Witkowski**, S. Gierałtowska, Ł. Wachnicki, R. Pietruszka, P. Sybilski, M. Godlewski*
   Charakteryzacja i zastosowania nanosłupków ZnO otrzymywanych metodą hydrotermalną
   Krajowa Konferencja Elektroniki, Darłówko Wschodnie, 8-12 June 2015

8. ***B.S. Witkowski**, Rafał Pietruszka, Marek Godlewski*
   Technologia wzrostu nanosłupków ZnO i ich zastosowanie w ogniwach fotowoltaicznych,
   Krajowa Konferencja Elektroniki 2016, 6-10 June 2016, Darłówko Wschodnie

9. ***B.S. Witkowski**, N. Cichocka, M. Ożga, R. Pietruszka, Ł. Owczarczyk, V.Yu. Ivanov, M. Godlewski*
   Badania luminescencji nanosłupków ZnO otrzymywanych metodą hydrotermalną wspomaganą mikrofalowo
   XI Konferencja Techniki Próżni, Cedzyna k. Kielc, 25-28 September 2017

10. ***B.S. Witkowski**, M. Godlewski,*
    Will our civilization survive?
    Conference "Nauka przed wyzwaniami cywilizacyjnymi" organized as an event accompanying the fair INTARG 2018, 20 June 2018, Katowice

In addition, I presented seven oral contributions and 23 poster presentations at scientific conferences. The total number of conference presentations: over 140 (including co-authored poster and oral presentations).

Detailed information can be found in attachment no. 3.

Moreover, I gave a number of internal seminars at the Institute of Physics of the Polish Academy of Sciences, as well as presentations on panels and summaries of projects implemented under OP IE.

5.3 Organizational, editorial and reviewer activities

I have co-organised 8 international scientific conferences:

1. International Symposium on Growth of III-Nitrides ISGN-7, 5-10 August 2018, Warsaw - I was responsible for coordinating the abstract submission process

2. 47th International School and Conference on the Physics of Semiconductors "Jaszowiec 2018", Szczyrk , 16-22 June 2018 – Scientific Secretary, member of the Program Committee and the Organizing Committee
   I was also a guest editor of the conference edition of the volume of Acta Physica Polonica A 134 (4).

3. Conference „High-k oxides by ALD", Wrocław, 7-10 March 2018 – Head of the Organizing Committee

4. 46th International School and Conference on the Physics of Semiconductors "Jaszowiec 2017", Szczyrk , 17-23 czerwca 2017r. – Scientific Secretary, member of the Program Committee and the Organizing Committee
   I was also a guest editor of the conference edition of the volume of Acta Physica Polonica A 132 (2).

5. 45th International School and Conference on the Physics of Semiconductors "Jaszowiec 2016", Szczyrk , 18-24 czerwca 2016r. – Scientific Secretary, member of the Program Committee and the Organizing Committee
   I was also a guest editor of the conference edition of the volume of Acta Physica Polonica A 130 (5).

6. 44th International School and Conference on the Physics of Semiconductors "Jaszowiec 2015", Wisła , 20-25 June 2015 – member of the the Organizing Committee

7. 43rd International School and Conference on the Physics of Semiconductors "Jaszowiec 2014", Wisła , 7-12 June 2014 – member of the the Organizing Committee

8. 42nd International School and Conference on the Physics of Semiconductors "Jaszowiec 2013", Wisła , 22-27 June 2013 – member of the the Organizing Committee

In addition, I was a reviewer of diploma theses at the Faculty of Mathematics and Natural Sciences of the Cardinal Stefan Wyszyński University and a reviewer of articles for scientific journals. Detailed data can be found in attachment no. 3.

5.4 Didactic and popularizing activities

Since 2017, I am a member of the Board of the Polish Vacuum Society.

I am / I was an auxiliary supervisor in the following doctoral dissertation:

- Rafał Pietruszka, Institute of Physics of the Polish Academy of Sciences (the defense of the Ph.D. thesis took place on 2 June 2016)
- Agnieszka Pieniążek, Institute of Physics of the Polish Academy of Sciences

Since 2014 I have been teaching regularly at the Faculty of Mathematics and Natural Sciences of the Cardinal Stefan Wyszyński University in Warsaw. In addition, I took care of the diploma theses performed at this Faculty (4 bachelor's theses and 3 master's theses).

In years 2012-2018 I participated in various innovation fairs and exhibitions of inventions (13 participations) promoting the achievements of the Institute of Physics of the Polish Academy of Sciences (including Brussels Innova). Detailed data can be found in attachment no. 3.

5.5 Participation in scientific projects

I was a leader of the following scientific project:

- Explanation of the mechanisms of changes of the electrical properties of ZnO nanorods grown by the hydrothermal method under the influence of light from the visible and UV range,
  Project no.: UMO-2012/07/N/ST3/03144,
  Source of financing: National Science Center
  Duration: 2013-2015
  (the project has been finished and positively evaluated by the National Science Center)

I was also a vice leader of the work package 5 in the following project:

- European Action towards Leading Centre for Innovative Materials – EAgLE
  Project no.: FP7-REGPOT-2012-2013-1
  Source of financing: European Union funds
  Duration: 2014-2016

I was (or still am) a contractor in 20 scientific-research projects. Detailed information can be found in attachment no. 3.

5.6 Received rewards, scholarships and distinctions

1. Scientific Award of the Director of the Institute of Physics of the Polish Academy of Sciences in 2014 for outstanding Ph.D. dissertation „***Hydrothermal technology of growth of the ZnO nanorods***”.
2. Minister's scholarship for an outstanding young scientist for the years 2015-2018
3. Scholarship received as part of the system project of the Mazovia Self-Government "Scientific potential support for the Mazovia economy - scholarships for PhD students" in the academic year 2011/2012.
4. Bronze Innovation Laurel for the application titled "Photovoltaic cells based on nanorods and ZnO layers", of which I am a co-author.
5. Distinction of the doctoral dissertation in the 6th edition of the "Innovator of Mazovia" competition.
6. Award for the best work presented by a young scientist, “XIII Seminarium Powierzchnia i Struktury Cienkowarstwowe - SemPiSC 2015”, 16-18 September 2015, Szklarska Poręba

7. Award for the best presentation in the technology section," XII Seminarium Powierzchnia i Struktury Cienkowarstwowe – SemPiSC 2012", 9-12 May 2012, Szklarska Poręba

8. Award for the best presentation given by a young scientist, EMRS Fall Meeting 2014 conference, Symposium L, Warsaw, 15-19 September 2014

9. Award for the best presentation given by a young scientist, Krajowa Konferencja Elektroniki „KKE 2014", Special session about transparent oxide semiconductors, Darłówko Wschodnie, 9-13 June 2014

10. Award for the best poster during the "IX Konferencja Techniki Próżni", Cedzyna near Kielce, 6-8 June 2011

11. Diploma of appreciation of the Rector of Warsaw University of Life Sciences in Warsaw prof. dr. hab. Wiesław Bielawski for scientific achievements, 1 October 2018 (for common scientific publications)

In addition, I was a co-author of solutions and inventions, for which the Institute of Physics of the Polish Academy of Sciences received 34 awards and medals at the Innovation Fairs and Invent Exhibitions. Detailed data can be found in attachment no. 3.

5.7 Construction of unique research equipment

In 2014, in cooperation with Ertec (producer of microwave-assisted hydrothermal reactors), I participated in the development of a new type of reactor with a modified chamber, which allowed the growth of ZnO nanorods on 5x5cm^2 substrates (previously the limit of the substrate size was 1.5x1.5 cm^2). This was the only one prototype of this type of reactor.

In 2012, I participated in the construction of a sensor-optical chamber, which allows monitoring of electrical properties in various gas environments and different tempreatures (up to 300 ° C) with the possibility of delivery of the source of light through a quartz window. The results obtained with the help of the chamber were used in publications and trade fair applications concerning the UV detector and gas sensors.

5.8 Patents and patent applications

I am co-author of 12 patents and 8 patent applications (including 4 applications at the European Patent Office and 2 applications at the patent office in the USA).

5.9 References

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