Warsaw August 20th ,2012 .

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SELF REPORT

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1. Personal Data

Henryk Grzegorz Teisseyre
Born: December 10 1966 in Warsaw
Parents names: Juliusz, Maria
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PESEL: [redacted]

2. Eductation and Degrees

Ph.D. in Physics	2001 – Institute of Physics, Polish Academy of Sciences, Warsaw, specialization: Solid State Physics thesis topic: **Optical studies of the impurities and defects in GaN under hydrostatic pressure** Ph.D. Advisor: prof. dr hab. Tadeusz Suski
M.Sc. in Physics 1988	1990 – Faculty of Physics, Warsaw University specialization: Solid State Physics thesis topic: **Light induce recovery of the EL_2 ground state from its metastable state in GaAs** supervisor: prof. dr hab. Jacek Baranowski
Secondary Education	1985 – XXVII High School im. T.Czackiego in Warsaw, mathematics and physics profile

3. Information on Previous Employment

2008 - :	**Research Associate**, ON-4, Institute of Physics, Polish Academy of Sciences, Warsaw
2008 – 2003:	**Research Associate**, Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw
1990 – 2003:	Research Assistant and Ph. D. student, Institute of High Pressure Physics, Polish Academy of Sciences, Warsaw

4. Information on Published Scientific Papers and Creative Professional Works

4.1. Total number of Publications = **85**, including **47** after obtaining a Ph.D. degree in Physics. The papers were published in peer-reviewed journals having high international reputation, such as:

Physical Rewiev Letter and Physical Rewiev B – 6 articles, including 3 published after obtaining a Ph.D. degree in Physics

- **Applied Physics Letters**– 13 articles, including 11 published after obtaining a Ph.D. degree in Physics,
- **Journal of Applied Physics**– 7 articles, including 4 published after obtaining a Ph.D. degree in Physics

Applied Physics Express– 1 article, published after obtaining a Ph.D. degree in Physics.

In the Web of Science base (WoS) **85** publications are included.

4.2. Total Impact Factor of publications after the Journal Citation Reports (JCR), according to year of publication = **118,936**.

4.3. Total citation number of publications after the WoS base, of. 20.VII.2012 = **1603**.

Hirsch Index of publications after the WoS base, of 20.VII.2012 = **19**.

5. List of Published the Series of Articles Constituting the Scientific Achievement, in accordance with the Art. 16 Paragraph 2 of the Act of March 14th, 2003 (Dz. U. No. 65, item 595, as amended)

Subject of publications:

Studies of the internal electric fields in low dimensions nitride structures for the different crystallographic orientation.

A1. **H. Teisseyre**, T. Suski, S. P. Łepkowski, S. Anceau, P. Perlin, P. Lefebvre, L. Kończewicz, H. Hirayama and Y. Aoyagi, "**Determination of built-in** electric fields in quaternary InAlGaN heterostructures" APPLIED PHYSICS LETTERS **82**, 1541 **(2003).**

A2. **H. Teisseyre**, T. Suski, S. P. Łepkowski, P. Perlin, G. Jurczak, P. Dłużewski, B. Daudin, N. Grandjean, "Strong electric field and nonuniformity effects in GaN/AlN quantum dots revealed by high pressure studies" APPLIED PHYSICS LETTERS **89,** 051902 **(2006).**

A3. **H. Teisseyre,** A. Kamińska, G. Franssen, A. Dussaigne, N. Grandjean, I. Grzegory, B. Łucznik, and T. Suski, "Different pressure behavior of GaN/AlGaN quantum structures grown along polar and nonpolar crystallographic directions" JOURNAL OF APPLIED PHYSICS **105,** 063104 **(2009).**

A4. **H. Teisseyre,** C. Skierbiszewski, B. Łucznik, G. Kamler, A. Feduniewicz, M. Siekacz, T. Suski, P. Perlin, I. Grzegory, and S. Porowski, "Free and bound excitons in GaN/AlGaN homoepitaxial quantum wells **grown on bulk GaN substrate along the nonpolar (11-20)** direction" APPLIED PHYSICS LETTERS **86,** 162112 **(2005).**

A5. **H. Teisseyre,** C. Skierbiszewski, A. Khachapuridze, A. Feduniewicz-Żmuda, M. Siekacz, B. Łucznik, G. Kamler, M. Kryśko, T. Suski, P. Perlin, I. Grzegory, and S. Porowski, "Optically pumped GaN/AlGaN **separate-confinement heterostructure laser grown along the (11-20)** nonpolar direction" APPLIED PHYSICS LETTERS **90,** 081104 **(2007).**

A6. **H. Teisseyre,** M. Szymański, A. Khachapuridze, T. Świetlik, C. Skierbiszewski, A. Feduniewicz-Żmuda, M. Siekacz, B. Łucznik, G. Kamler, M. Kryśko, T. Suski, P. Perlin, I. Grzegory and S. Porowski, "Optically pumped lasing of GaN/AlGaN structures grown along a non-**polar crystallographic** direction" Phys. Stat. Sol. (c) 5, 2173 **(2008).**

A7. **H. Teisseyre,** J. Z. Domagała, B. Łucznik, A. Reszka, B. J. Kowalski, M. Boćkowski, G. Kamler, and I. Grzegory, 'Characterization of the Nonpolar GaN Substrate Obtained by Multistep Regrowth by Hydride Vapor Phase Epitaxy" Applied Physics Express 5 011001 **(2012).**

A8. I. Grzegory, **H. Teisseyre,** B Łucznik, B. Pastuszka, M. Boćkowski and S.Porowski "Nonpolar GaN **Quasi**-Wafers Sliced from bulk GaN crystals grown by High Pressure Solution and HVPE methods" **in Nitride with Nonpolar Surfaces, ed. Paskova (Wiley-VCH, Weinheim, 2007) p. 53.**

A9. G. Rossbach, J. Levrat, A. Dussaigne, G. Cosendey, M. Glauser, M. Cobet, R. Butte, and N. Grandjean, **H. Teisseyre,** M. Boćkowski, I. Grzegory, and T. Suski "Tailoring the light-**matter coupling in anisotropic microcavities: Redistribution of oscillator strength in strained *m*-plane GaN/AlGaN** quantum wells" **PHYSICAL REVIEW B 84,** 115315 **(2011).**

A10. P. Corfdir, A. Dussaigne, **H. Teisseyre,** T. Suski, I. Grzegory, P. Lefebvre, E. Giraud, J.-D. Ganiere, N. Grandjean, and B. Deveaud-Pledran "Thermal carrier emission and nonradiative recombinations in **nonpolar (Al,Ga)N/GaN** quantum wells grown on bulk GaN" JOURNAL OF APPLIED PHYSICS **111, 033517 (2012).**

The statements of the co-authors, specifying their individual contribution to the publications, are attached in alphabetical order in the annex No. 8 entitled: „The co-authors statements". The statement of mgr inż. Bogdan Pastuszko is not attached due to his death in 2011.

Scientific Achievement Being the Subject of Habilitation - the Series of Publications Entitled:

Studies of the internal electric fields in low dimensions nitride structures for the different crystallographic orientation.

There has been a significant increase in interest in the third group nitrides in the last twenty years. The huge potential makes nitrides the second semiconductor family after silicon in terms of market share. It should be emphasized that such increases of nitrides based electronics and optoelectronics managed to take place in spite of the lack of good quality GaN substrate. The development of nitrides electronics and optoelectronics were based on structures grown on sapphire, silicon carbide and more recently, silicon. Lack of good quality large substrates of gallium nitride is related to the fact that the growth of GaN crystals is a complex and complicated issue. Traditional bulk growth techniques, such as Czochralski, Bridgman or Verneuil are not applicable to GaN. Due to its extreme melting conditions GaN melts congruently at high nitrogen pressure (6 GPa) and high temperature (2497 K)[1] and decomposition occurs even below this temperature.

In my academic career, I was working as a researcher in the Institute of High Pressure Physics (IHPP PAS), in the group that for years almost had a monopoly of GaN bulk crystals grown under high nitrogen pressure (up to 20 kbars). In 2001 the first Polish blue laser diode, based on such GaN crystals was demonstrated (I contributed to these results and I'm also co-author of the publication).[2,3]

Most of the available nitride structures, both to commercial and research applications, have been grow along the c-axis, (0001) crystallographic direction. In this direction, a strong built-in electric field is present due to spontaneous and piezoelectric polarization. Spontaneous polarization exists as a result of the lack of inversion symmetry in the wurtzite structure, when piezoelectric polarization is rather related to strain generated between semiconductor layers. The important consequences of the built-in electric field in nitride quantum wells is the shift of the electrons and holes to opposite sides of the quantum well, this effect decreased the overlap integral and reduced the recombination efficiency of the system.

In photoluminescence (PL) experiments these are visible as a shift of the emission spectra towards lower energies and a strong reduction in the emission intensity. This effect also leads to a significant increase in the recombination lifetime and it is commonly known in literature as the Quantum Confined Stark Effect (QCSE).[4]

To avoid the problem of very large internal electric fields the growth along nonpolar crystallographic axis (1-100) and (11-20) or along semi-polar direction has been proposed (Fig.1).[5,6] The existence of built-in electric field might be regarded as an unwanted effect in nitride light emitting diodes but also probably have negative influences on the properties of nitride lasers. From the optical pumping experiments done on nonpolar GaN/AlGaN laser structures, it is clear that during stimulated and spontaneous emission the built-in electric fields are not fully screened. In nitrides, built-in electric fields due to spontaneous and piezoelectric polarization are very strong reaching the value of a few MV/cm for GaN/AlN structures (for GaN/AlGaN the values of the built-in electric fields are higher than for InGaN/GaN structures).

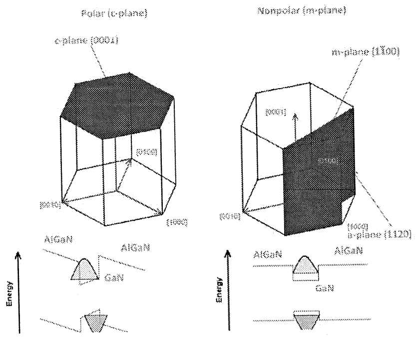

Fig. 1. Conventional polar C-plane GaN orientation is on top of the crystal face, while nonpolar (m-plane) GaN orientation is on the side of the crystal. The energy-band diagrams illustrate the separation of the electron and hole wavefunctions for GaN quantum wells with AlGaN barriers.

Publications included in the dissertation below can be divided into two parts:

- first, articles related to defining and evaluating the value of the built-in electric fields mainly by the methods of optical spectroscopy under hydrostatic pressure
- second, articles related to optical properties of nonpolar quantum structures, studies of the excitons in nonpolar quantum wells, the spontaneous and stimulated emission of nonpolar laser structures and recently also nonpolar micro-cavities structures and Bose-Einstein condensate of cavity polaritons.

The first group of experiments were mainly performed on samples from foreign laboratories, the second group of publications was largely based on experiments done on samples grown by MBE (molecular beam epitaxy) by prof Czeslaw Skierbiszewski on high-quality substrates made by HVPE (hydride vapor phase epitaxy) growth technique.

As I mentioned previously, one of my first scientific issues that I worked on after receiving my PhD degree, was the direct comparison of the pressure coefficients of the hexagonal (with built-in electric fields) and cubic quantum wells (without built-in electric fields).[7] For this I used the optical spectroscopy method and the diamond anvil cell technique. These results, which are not included in this dissertation, became the first of a series of similar experiments. The pressure coefficients determined from spectroscopic experiments was later compared with theoretical models to establish the value of the built-in electric fields and its changes with pressure. General trends observed in these experiments are as follows: for a large value of the coefficient of pressure (40-30 meV / GPa) little or no valueof the built-in electric fields was observed, for low pressure coefficient (less than 30 meV / GPa, up to even negative values) - a larger value of the built-in electric fields and their increasing as a function of the hydrostatic pressure was observed. I also applied the high-pressure spectroscopy method to determine values of the embedded electric fields in quaternary nitrides compounds (AlInGaN). At the time of these experiments (2002), quaternary nitrides compounds were new materials, and the question of estimation of their parameters (built-in electric fields) was important and significant. There are advantages of InAlGaN based quantum wells over the GaN/AlGaN QW systems which result in better optical properties of the former ones. Firstly, segregation of In in InAlGaN layers leads to formation of potential fluctuations. In the case of hexagonal InGaN/GaN or GaN/AlGaN QWs the large internal electric fields due to spontaneous and piezoelectric polarizations. On the contrary, for the case of InAlGaN based QWs we may consider cases where the QWs are strained with compressive or tensile strain or unstrained. In particular, one may expect that for properly chosen compositions of barriers and QWs the internal electric field is negligible since a term coming from the spontaneous polarization cancels a term from the piezoelectric effect. In such a case no reduction of the optical transition probability due to QCSE occurs. In high pressure experiments we used the structures of quantum wells of the different width, containing quaternary compounds in both regions, the barrier and the quantum wells. Measurements of hydrostatic pressure coefficients gave value (34-36 meV / GPa) close to the value of the pressure-induced changes GaN band gap. This behaviour is characteristic for the structures with a low value of the built-in electric field. Which was confirmed through time resolved experiments, performed at the University of Montpellier.

In these experiments the measured values of PL decay times for the studied samples are located between 1 and 2 ns and show no dependence of the QW width. For comparison, the measurements of the decay times obtained for a series of wurtzite $In_{0.2}Ga_{0.8}N$/GaN (built-in electric field 2.4 MV/cm) quantum wells grown along c axis shows increase by about four orders of magnitude with the thickness of the well varying from 2 to 5.5 nm. It should also be emphasized that these measurements were one of the first experimental determination of the embedded electric fields in quaternary nitrides compounds (AlInGaN), and these results were published in Applied Physics Letters. [A1]

During this period I was also involved in studies of the GaN/AlN quantum dots. Such quantum dots are interesting systems due to the fact that this is a quantum system with higher built-in electric fields from the other side there are no indium fluctuation like in InGaN/GaN systems. GaN/AlN quantum dots are also very promising as a material for UV emitting diode or lasers. The quantum dots lasers hold tremendous promise for reducing the threshold current density due to of reduction in the density of states. It is also expected that such systems grown even on the strain substrates might offer higher quantum efficiency. In many articles, it was proposed that quantum dots can act as nano-scale indium composition fluctuations in InGaN which should increase recombination rate and also lead to higher quantum efficiency.

The AlN/GaN quantum dots, like other quantum structures grown along the **c**-axis, exhibits a huge internal electric field as a consequence of the spontaneous and piezoelectric polarization. Furthermore, the large confinement energy and the large hole effective mass lead to strong localization effects. Some questions related to the value of the electric fields inside such quantum dots or strain inside quantum dots are still subject to debate. The GaN/AlN quantum dots having the shape of truncated hexagonal pyramids placed on thick wetting layer. Due to internal electric fields electrons are located on the top of such pyramids where holes are located close to the wetting layer. In these experiments two samples have been studied:

- one from CNRS laboratory in Valbonne grown by Nicola Grandjeana by using plasma assisted MBE.
- second from CNRS laboratory in Grenoble grown by Bruno Daudin by using ammonia based MBE.

Despite the fact that both samples were grown on different substrates with various dimensions and layer sequence, their pressure behaviour was similar. In both cases experimentally determined pressure coefficients were negative and range from −8 up to −15 meV/GPa. This is unusual, especially when compared with the positive value of the pressure-induced increase of the GaN and AlN band gap 41.4 meV/GPa and 49.1 meV/GPa respectively. The increasing of pressure leads to a significant decrease of light emission intensity and to an asymmetric broadening of the PL bands. The negative pressure coefficient was related to increase of piezoelectric fields and to nonlinearity piezoelectric coefficients (which was theoretically predicted by Schimada).[8,9] We showed that the pressure induced asymmetry of the

PL peak can be associated with the distribution in height and lateral dimensions of GaN dots embedded in AlN matrix. We compared our experimental results with the results of theoretical calculations of the pressure coefficients of the light emission from GaN/AlN QDs using the model based on second-order elastic theory and the k•p method (with 8x8 Hamiltonian). In these calculations we used strain-dependent piezoelectric coefficients of GaN and AlN. The agreement between theory and experiment demonstrates the validity of the proposed theoretical model. The average vertical component of the built-in electric field changed with a pressure with coefficient 0.12 and 0.14 MV/ (cm GPa) for dots from the first and the second sets, respectively. The results of these measurements were published in Applied Physics Letters. [A2]

In the next publication, I also performed direct comparisons of pressure properties for wurzite quantum wells grown along polar (with built-in electric fields) and nonpolar directions (without built-in electric fields) [A3]. This was possible due to the close collaboration between Polish groups and École Polytechnique Fédérale de Lausanne and all the samples used in these measurements were prepared during my stay in Switzerland. In hydrostatic pressure experiments for both polar and nonpolar QWs, we observed qualitatively different results. For the polar samples an evident reduction in the pressure coefficient with QW width was observed. The decrease in the pressure coefficients was more pronounced for wider wells and leads to a much smaller pressure coefficient value than the observed value for the band gap pressure coefficient in GaN. On the contrary, in the nonpolar sample pressure coefficients followed the pressure behaviour of the GaN band gap and the quantum confinement remains practically independent of the applied hydrostatic pressure.

In theoretical calculations, firstly the pressure dependencies of the strain tensor components for all materials was taken in to account. Secondly, the piezoelectric polarizations component was calculated from the strain dependencies of nonlinear piezoelectric constants.[8,9] A direct comparison between the experimental data for the polar and nonpolar samples used in our experiment and the calculated value of the built-in electric field give good agreement. I should also mention that this was the first experimental comparison of pressure properties of the polar and nonpolar nitride samples.

The second group of issues that I would like to include on the following dissertation are related to properties of structure and devices grown along nonpolar nitrides. With the help of new growth techniques (HVPE) nonpolar substrates with good crystal quality were obtained. This method based on multistep regrowth by HVPE when crystals thicker than 4–5mm were deposited in a few subsequent growth runs. After the growth, such crystals were sliced along a nonpolar plane or semipolar crystallographic direction. The influence of the multistep regrowth on the physical properties of these crystals were examined recently and will be discussed later in this dissertation. Much faster than the detailed characterization of these samples were done, they had been used as substrates for epitaxy. These substrates were used to grow GaN/AlGaN multi-quantum wells by using plasma assisted MBE technique. From PL experiments (Fig.2 and Fig.3) we observed a pronounced shift of the emission peak due to the quantum confined Stark effect (QCSE) for polar samples. [A4] On the contrary, for nonpolar samples this effect was not observed and emission energy of lines related to nonpolar quantum wells were located over GaN band gap (Fig.3b). The simple rectangular QW model (simple envelope function method, including the excitonic binding energy) was used to describe the measured peak positions for nonpolar samples. We also observed a much higher intensity of PL spectra for the nonpolar samples than those observed for the identical polar ones. Both of these facts support previous findings about the absence of electric field and the increasing of quantum efficiency for sample grown along the nonpolar directions. Low temperature PL spectra of the nonpolar samples show well pronounced excitonic lines. Detailed interpretation of the PL data required analyses of the valance band structure in GaN/AlGaN quantum wells. In the case of a bulk wurtzite GaN crystal, the A, B, and C free excitons correspond to Γ_{7c}-Γ_{9v} , Γ_{7c}-Γ_{7v} and Γ_{7c}-Γ_{7v} transitions from conduction band to the split valence band. But the situation is more complicated for GaN/AlGaN quantum wells. The calculations were performed in a self-consistent way by solving Schrodinger equations for 6×6 Hamiltonian for holes. From these calculations (Fig.4) we found that the spacing between the upper two sub-bands did not change with the quantum wells width (between 2 and 4 nm). At the same time, we observed a changed in shape of the lowest sub-bands and shift of the Γ point towards lowers energy. On the basic of these results, we are able to make the conclusion that for thinner QWs only two excitons related to higher bands may be visible.

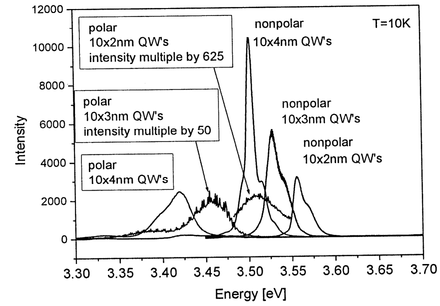

Fig. 2. Photoluminescence spectra of GaN/AlGaN multiquantum wells of different thicknesses grown on nonpolar a-plane and polar c-plane direction of bulk GaN crystal.

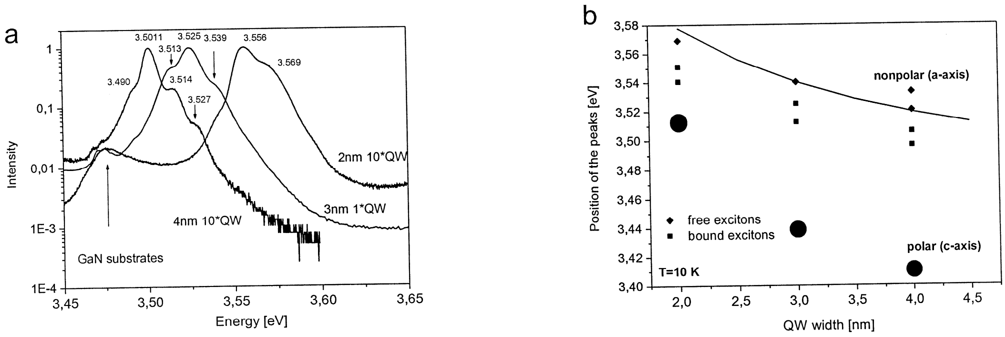

Fig. 3a. Low temperature PL spectra of 10 period 4 and 2 nm GaN/Al11Ga89N QWs and 3 nm GaN/$Al_{11}Ga_{89}N$ single QW grown on the nonpolar (11-20) direction of bulk GaN substrate. Fig. 3b. Comparison between the energetic positions of the photoluminescence bands observed in polar and nonpolar GaN/AlGaN QW samples. The lowering of energy in peak positions for polar samples is related to the quantum confine Stark effect.

Furthermore light polarization studies have been performed for these samples but also for homoepitaxial layers. For the nonpolar GaN homoepitaxial layers, the two bound excitons related to A exciton followed group theory very closely. These means that the corresponding exciton lines were visible in one configuration (E perpendicular to the c axis) but disappeared in the second configuration (E parallel to the c-axis). This result followed the results of calculations.[10] The lines related to the B and C excitons were visible in both configurations with approximately equal intensities. Generally speaking the situation is more complicated for quantum wells where breaking of the selection rules occurs. In this case, we were not able to see A,B, and C excitons directly but rather as transitions that originate from the split valence band, sometimes described as E1,E2 and E3. We found that the degree of light polarization in our samples depended on the thickness of the quantum wells . For the 4-nm quantum wells, we observed four lines with two of them almost following the selection rules of the A excition (E1). The other two, probably originated from E2 and E3 are highly polarized along the second crystallographic direction. In contrast to the 4 nm wells, only three lines were observed for both the 3 and 2 nm wells. Two lower energy lines follow the results for the 4 nm sample and a high energy line is polarized in a second crystallographic direction. The polarization experiments were published as a chapter in the book "**Nitride with Nonpolar Surfaces**" [A8] and polarization dependent reflection measurements were published in Applied Physics Letters.[11]

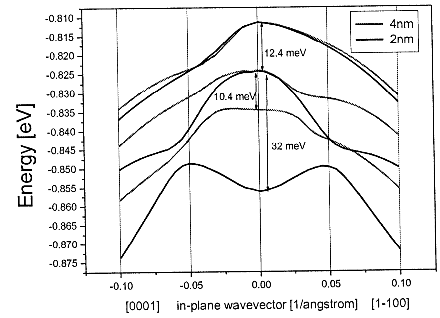

Fig. 4. Valence band structure for the 4 and 2 nm GaN/$Al_{11}Ga_{89}N$ *quantum wells structure grown along □□□□□□crystallographic direction.*

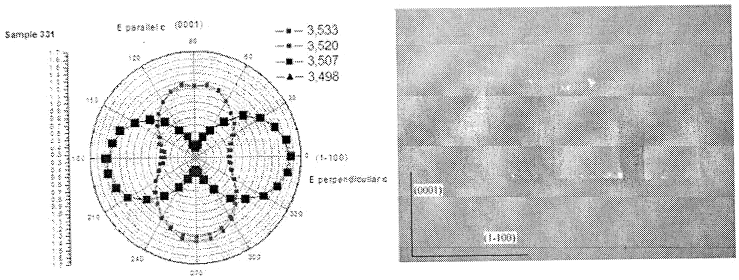

Fig. 5. Polarization of the light emitted from GaN/AlGaN grown on nonpolar GaN substrates. On the enclose photograph laser stripes cleaved from nonpolar substrate.

The polarizations measurements were importuned not only from the scientific point of view but also opened a way for the construction of nonpolar laser structures, - which was done in 2006. GaN-based laser diodes since their first demonstration in 1996 have achieved remarkable progress, and efforts of many research groups were concentrated on reduction dislocation densities and improvement of epitaxial layers quality.[12] However, it was believed that laser structures grown along nonpolar directions give a possibility of lowering threshold current and the laser emission can be extended towards longer wavelengths (green emission region). In 2006 the nonpolar laser structures along (11-20) were grown by PA-MBE system in IHPP in Warsaw. These structures were designed for optical pumping experiments by using 263nm line of YAG:Nd laser.

The results of these experiments were published in 2007, just a few months before two other reports - both of them about nonpolar laser diodes. [A5] The first one was published by a group from UCSB (University of California Santa Barbara), the second by a group from ROHM (Japan) independently reported the fabrication of the first nonpolar GaN based laser diodes. The devices from UCSB worked in a pulsed mode with the threshold current density of 7.5 kA/cm^2 where ROHM announced continuous–wave operation with the output power 10 mW and threshold current density at level 4.0 kA/cm^2.[13,14] Both research teams used nonpolar substrates from Mitsubishi Chemical with (1-100) crystallographic orientation. In fact our results were published before but we didn't reported electrically injected laser diodes but optically pumped laser structure. In the optical pumping experiments our laser structures exhibits threshold character. On fig. 5. both upper curves represented stimulated emission (over threshold) whereas the two bottom ones are related to spontaneous emission (below threshold).

The evidence of the laser emission from our samples were following:

- multimode structures from the laser emission.
- laser line was fully TE polarized.
- threshold for the stimulated emission by optical pumping.
- the drastic narrowing of the spontaneous emission spectrum.
- changes of the energetic position of the laser line with cavity length -similar effect was reported in CdTe/CdMnTe laser structures.[15]

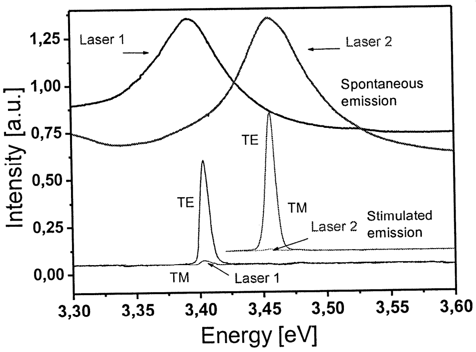

Fig. 6. Spectra of the stimulated emission at room temperature for transverse electric (TE) and transverse magnetic (TM) polarization , for two types of lasers with different quantum well thickness. The two upper spectra represent the spontaneous emission from both laser structures

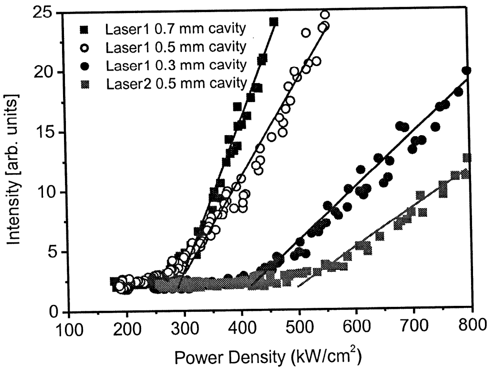

Fig. 7. Excitation power density dependence at room temperature for laser 1 and laser 2. laser 1 was cleaved with 300, 500, and 700 nm laser cavities; laser 2 possessed a 500 nm laser cavity.

The other significant achievement was optical gain measurements performed by variable length stripe method. These measurements confirmed theoretical predictions of S. Park[16] about the higher value of optical gain for nonpolar structures than for polar one. The other very interesting phenomenon, occurring during the optical pumping experiments, was the absence of screening effects of the intrinsic electric fields during high power optical pumping of nonpolar structures (Fig. 8). The explanation of this effect requires further study, but probably it is related to the fact that carrier density requirement for the full screening of intrinsic electric fields is higher than the threshold carrier density. In such a case, laser action occurs before screening of electric fields. We also found that optical losses are on the value of 20 cm^{-1}. These results were published in physica status solid. [A7]

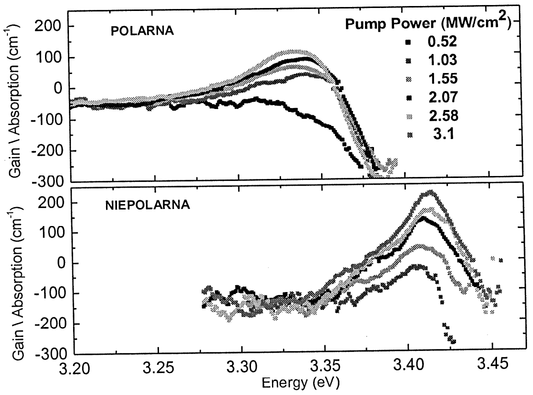

Fig. 8. Gain spectra for polar and nonpolar laser structures for laser structure with 5 nm QWs in active region measured by variable stripe length method. The gain is higher for nonpolar structure different position of the maxima are related to lack of the screening effects.

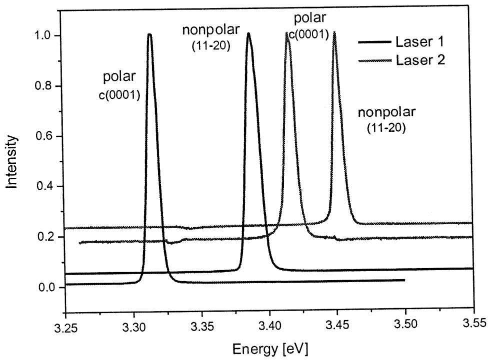

Fig.9. Laser emission for two sets of polar and nonpolar structures which possess different thickens of QWs in active region . Different position of the emission line is due to lack of the screening effects

In 2008, continuing professional development, I changed my position from the Institute of High Pressure Physics to the Institute of Physics Polish Academy of Sciences. Where I was employed in the new group which started experiments with nitride and oxide ZnO/ZnMgO MBE systems. This gave me the opportunity to learn a new technique (MBE) and a new semiconductor system (ZnO/ZnMgO). To reach this goal I also established closer cooperation with two people, who are high-class specialists with extensive practical knowledge in nitride structures and MBE growth method. The first was dr. Amélie Dussaigne, the second was dr. Benjaminem Damilano.

The first collaboration proved to be extremely fruitful. During my periodic visit to École polytechnique fédérale de Lausanne. I was involved in growing a number of samples by MBE technique (with ammonia as source of nitrogen). The growth was performed on nonpolar bulk GaN substrates from IHPP PAS. With the development of cooperation between IHHP and the group in Lausanne, there was a need for a more careful characterization of structural and physical properties of nonpolar GaN. The article published this year in Applied Physics Express is a result of the activities carried out in this direction. In this publication we mostly concentrated on the structural characterization of nonpolar substrates grown by multistep regrowth by Multistep Regrowth by HVPE. The HVPE is a method in which both large-area bulk wafers and relatively high growth rate can be achieved (in our case, 70–130 μm/h). [A7,A8] The system used to obtain GaN boules was a horizontal custom-built quartz reactor and the growth was performed at a temperature of 1050 °C. Due to parasitic nucleation of GaN microcrystals at the outlet of GaCl gas flow, the horizontal reactor allowed only processes up to approximately 10 h. Crystals thicker than 4–5 mm were, hence, deposited in a few subsequent growth runs. The multistep growth process was performed in the following way. First, the metal organic chemical vapor deposition (MOCVD) templates were grown, patterned using a titanium mask and in the next step, overgrown by hydride vapor phase epitaxy to a thickness of around 1 mm. After self-separation from sapphire, we obtained good-quality GaN free-standing substrates. In the next few steps, such crystals were overgrown by IIVPE to a thickness of about 4–5 mm. Finally, we cut such crystals along a nonpolar plane, perpendicular to the c-plane and polished them mechanochemically (example of such substrate is presented on Fig 9).

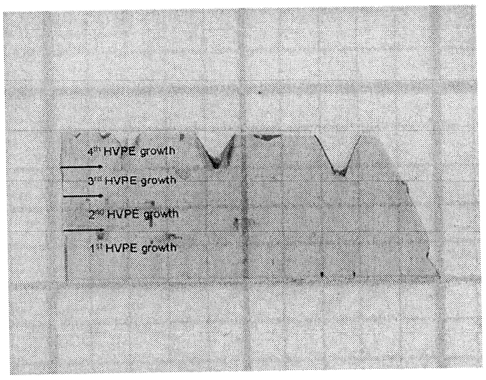

Fig. 10. Nonpolar substrate (11-20) *slice of thick GaN crystal grown in four HVPE runs. The inverted pyramid pit visible on the photograph starts from the bottom and recovers in every subsequent growth run. The distance between grid lines is 1 mm.*

High-resolution X-ray characterization of these substrates have been performed by dr. J.Z. Domagala. The most important results are as follows:

☐ Very low value of full width at half maximum (FWHM) of the rocking curve. Plane wave simulations for the 11-20 reflection from a perfect GaN crystal gave FWHM values of rocking curve equal to 11 arcsec. They increase to 27 arcsec when the influences of the monochromator and chosen reflection are included. The observed crystal bending with a radius of about 22 m.

- We have shown that at the beginning of the growth process, nonpolar substrates possess superior structural quality with rocking curve FWHM on the level of 27 arcsec but at the end of the regrowth step, this quality slightly degrades due to the instability of the growth front.
- The influence of regrowth is even more visible in low temperature (4.2 K) cathodoluminescent experiments. In the cathodoluminescent image, the interface between the two regrowth steps is clearly visible. We also used spectrally resolved cathodoluminescence to distinguish between the different recombination processes. Generally, we observe an increased intensity of the free excition lines after regrowth. In contrast, both the emission related to bound excition, to donor acceptor pairs, and the ''yellow'' luminescence are more intense in front of the regrowth step. This is probably caused by different concentrations of the residual dopants before and after the regrowth step.

These published results (at Applied Physics Express [A7]) are one of only a few reports concerning properties of the nonpolar substrates grown in multistep regrowth method by HVPE. These substrates are also used in the next two publications which I would like to describe, both of them were the effect of close collaboration with the group of prof. Nicola Grandjean. Nonpolar substrates have been used as a substrate in ammonia MBE system during my periodic visits in Lausanne.

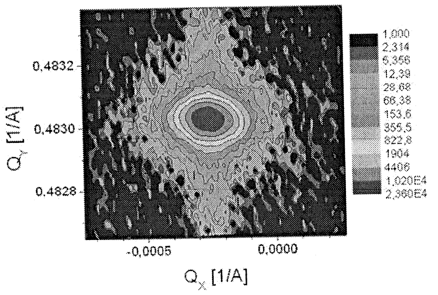

Fig. 11. X-ray reciprocal space map for (11-20) reflection taken for the sample region where FWHM of 1120 rocking curve (collected with 0.05mm slit) achieved about 27 arcsec.

The first of these publications was related to polariton condensation in nonpolar GaN/AlGaN system. The main motivation for this research was from one side lack of built-in electric fields in structures grown along nonpolar directions, on the other hand the two reports were about room temperature polariton lasing in a GaN/AlGaN multiple quantum well grown along polar direction.[17,18] Studies of a Bose–Einstein condensate of polaritons are important both for understanding of the basic physics as well as for potential applications in the optoelectronic. A Bose–Einstein condensate was observed in diluted atomic gases at very low temperature (Nobel prize 2002) and condensate of polaritons giving a possibility to observed similar effects even at room temperature. We might also expect significantly lower threshold current in polariton lasers which is related to the fact that polaritons possess a mass four or five orders of magnitude less than electrons. The two studies cited above were based on samples grown along polar directions in which internal electric fields lead to a marked reduction in electron-hole overlap and reduce optical matrix elements. These factors potentially undermine the effectiveness of strong light-matter coupling regime which is necessary to obtain polaritons condensation. The growth was performed by ammonia based MBE system . At the beginning , a 50-pair $Al_{0.15}Ga_{0.85}N/Al_{0.35}Ga_{0.65}N$ distributed Bragg reflector (DBR) were grown. This was overgrown by five QW sets each formed by four 5-nm-thick GaN QWs with 5-nm-thick $Al_{0.13}Ga_{0.87}N$ barriers. SiO_2/ZrO_2 DBR was deposited on the top.

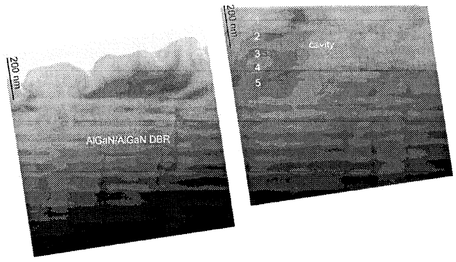

Fig. 12: HRTEM image of a DBR structure containing an AlGaN/AlGaN superlattice.

At the first stage, characterization of this structure (without top SiO_2/ZrO_2 DBR) the PL and angle-resolved reflectivity measurements were performed. This interpretation is in perfect agreement with reflectivity measurements . From these measurements (Fig. 11) it is clearly visible that stopband of the DBR is centred at different energies along the two polarization directions and covered one of the exitonic lines from active region. At the next stage, the full cavity (with top SiO_2/ZrO_2 DBR) was analysed. It has been pointed out that the sample shows a polarization-dependent coupling regime, i.e., weak- and strong-coupling regimes coexist along orthogonal polarization planes. In one crystallographic direction (**E** along **c** direction) both lower and upper polariton branches were observed. PL studies were carried out by using (YAG) laser ($\lambda = 266$ nm), as an excitation source. Laser power used in these experiments changed from 0.46 up to 1.42 of the threshold power required to obtain polariton lasing in one crystallographic direction, in the second crystallographic direction strong coupling conditions hasn't been obtain and only excitonic lasing was observed. Reflectivity and PL studies are in excellent agreement with $k \cdot p$ calculations and indicate the possibility to tune the nature of the light-matter coupling in anisotropic microcavities by managing the strain state of the QWs.

These studies have been published in Physical Review B [A9] (I'm co-author of this publication) and perhaps the most valuable results are following:

☐ High quality GaN/AlGaN active region (in which BEC was observed) was grown on top of an AlGaN-based DBR using nonpolar bulk GaN as the substrate.

☐ The active region has been subjected to compressive stress resulting in breaking of the polarization selection rules (different than that for bulk GaN) . The results of PL and optical reflection measurements were consistent with the $k \cdot p$ calculation under assumption that the active region was grown on the top of the AlGaN layer with an average composition of 28% aluminium. Similar calculations for strained structures of GaN / AlGaN have been published in Acta Physica Polonica.[19]

☐ For the first time Bose-Einstein condensate of polaritons in nonpolar nitride system have been observed. Such system coexistence of strong and weak coupling regime can take place. This system is even more interesting experimentally due to the fact that the transition from weak to strong coupling can be made by changing the light polarization.

The exact nature of physical process and coexisting of weak- and strong-coupling regime in these structures are still under study by group of prof. Nicola Grandjean.

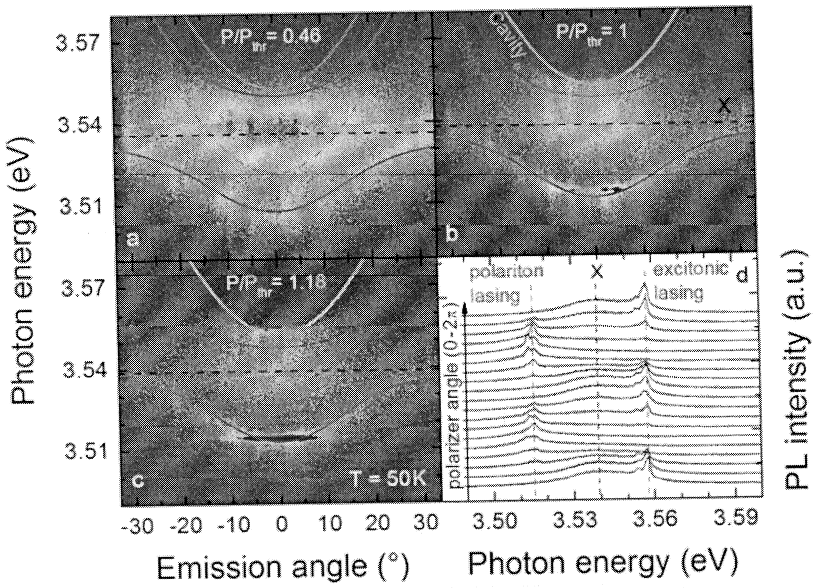

Fig. 13. Photoluminescence (PL) measurements at 50 K: (a-c) Far field spectra as a function of excitation power Pthr corresponds to the threshold of polariton lasing emission) taken without polarization selection. Modes were fitted with a 2-level system for both directions: red denotes features being polarized parallel to the optical axis (e-extraordinary) and green perpendicular (o-ordinary). The exciton (black dashed line) radiates in both directions. (d) Polarization-resolved PL collected around k = 0 (P/Pthr = 1.43, spectra were vertically shifted for clarity): Observed lasing modes from the lower polariton branch (LPB) are counter-polarized with respect to the exciton and the lasing emission from the exciton through the cavity mode.

Finally, the last subject I wanted to briefly touch upon is related to recombination mechanism in nonpolar structure grown along **a**(11-20) direction [A10]. In fact, there are two publications which are specifically related to this subject and done on the same samples; one in Journal of Applied Physics [A10], the second in Physical Review B.[20] From the room temperature CL mapping dislocations density on the order of 2×10^5 cm^{-2} were established.[20,21] This value is four orders of magnitude lower than what is observed in heterostructure grown on foreign substrates.[22,23] Also black lines along c and m crystallographic directions were not observed in our samples due to lack of basal and prismatic stacking faults.[24] Also the analysis of the CL intensity in the vicinity of a dislocation yields an exciton diffusion length Ldiff = 100 nm.[25] Therefore, in a PL experiment, only a small fraction of photogenerated excitons is affected by dislocations at room temperature. The high quality of the samples and the drastic reduction of nonradiative recombination process result in the uncommon optical effects – centre-of-mass quantized exciton-polaritons. This scarce effect can be observed in thick semiconductor layers and manifests itself as a resonance structure in optical spectra (PL). These effects was reported in the following semiconductors CdS, CdSe, CdTe and GaAs.[26,27,28] In GaN this effect was visible only once for the structures grown on polar bulk samples produce in IHHP.[29] Such a difference between the optical properties of nitrides and other classes of semiconductors originates from high density of dislocations normally existing in nitride samples which are grown on mismatched substrates such as sapphire, silicon carbide or silicon. High dislocation density limit exciton coherence length., the distance covered by an exciton between two dephasing events, and prevents the formation of polariton standing waves along the growth axis. In our samples, low dislocation density increased the polariton coherence length opening a way for centre-of-mass quantized exciton-polaritons observation.

In the next step we analyse the time-resolved measurements for single QW samples. The samples were grown on **a** plane with different QW thickness 2, 4 i 7nm and $Al_{0.06}Ga_{0.94}N$ barrier, one sample possesses QW thickness of 2 nm and high aluminium concentration in the barrier region $Al_{0.12}Ga_{0.88}N$. Emission from quantum wells possess full width at half maximum range from 8 up to 15 meV. With increase of the temperature quantum wells emission possess characteristic " S shape " behaviour. Such behaviour is characteristic to the delocalization of excitons toward the continuum of two-dimensional states of the QW.[30,31] From these measurements we deduce a QW exciton localization energy from 3 up to 14 meV for QWs thickness from 7 to 2 nm. The lower value of the localization energy agrees well with the 3.5 meV localization energy that we calculate by envelope function calculations for an exciton bound to a single monolayer well-width fluctuation.[32] In higher temperature range emission from quantum wells followed the temperature behaviour of the GaN band gap.[33] Low quantum wells localization energy confirm very good quality of these samples. The temperature dependence of the decay time for QW emission is presented on fig 15.

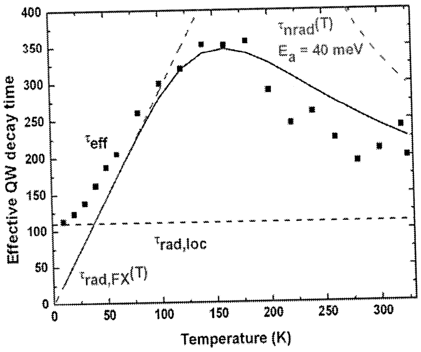

Fig. 14. Effective PL lifetimes as a function of T for nonpolar quantum wells. The increase of QW PL lifetime with T is due to the combined delocalization of exciton in real and reciprocal spaces and it evidences the negligible role played by non-radiative centers in the overall recombination mechanisms. After a slight increase in lifetime between 10 K and 30 K due to deeper localization in the disordered alloy, the capture of (Al,Ga)N excitons by the QW results in a drastic reduction of PL lifetime. At higher T, QW and barriers excitons get thermalized, resulting in an increase of PL effective lifetime in the barriers

With increasing T, the effective PL decay time τ_{eff} also increased up to 150 K. Although the direct observation of longer radiative lifetime through the increase in effective lifetime is now common in III-arsenides or II-VI, in nitrides was reported once (in the range up to 60 K). Our experiments clearly demonstrate that in the 10–150 K temperature range, even when excitons are delocalized in the whole QW plane, radiative mechanisms dominate the recombination processes. At higher temperature, we observe the thermal escape of excitons from the QW toward the (Al,Ga)N barriers and we attribute the drop in QW PL lifetime to nonradiative recombination in the barriers.

At the end of this dissertation I would like to emphasize the most important achievements:

- Sequence of works related to determination of the built-in electric fields in different type of materials and structure based on group of III nitrides. [A1,A2,A3]
- Observation of the excitonic lines related to the individual subbands valence band in nonpolar quantum well structure, and confirmation of its origin by $k \cdot p$ calculation and polarization measurements. [A4,A5]
- Research related to nonpolar lasers and its characteristic by optical pumping method. [A5,A6]
- Participation in the research related to Bose Einstein condensation on nonpolar nitride structures. [A9]

My several years of involvement in research have led to many interesting scientific results, which have been published in 85 publications. I also hope for the continuing development of research topics, as well as getting further interesting and precious scientific results as well as on nonpolar oxide materials (ZnO/ZnMgO).

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