Warsaw 01.03.2013

Michał Boćkowski

Institute of High Pressure Physics PAS

Sokołowska 29/37, 01-142 Warsaw

Summary of professional accomplishments

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1. <u>Personal information</u>

Name and Surname: Michał Stanisław Boćkowski

Date and place of birth: 1964.05.03, Milanówek, Poland

Nationality: polish

Maritial status: married

Address:

Home: Klaudyny 32 m 313, 01-684, Warsaw, Poland

Work: Institute of High Pressure Physisc PAS, Sokołowska 29/37 01-142, Warsaw, Poland

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2. Education and scientific degrees

Degrees: M.Sc. Eng. (Solid State Physics), Warsaw University of Technology, Faculty of Applied Physics and Mathematics, 1989, Warsaw, Poland

PhD, Academie de Montpellier, Université Montpellier II, **Formation Doctorale: Matériaux de l'Electronique et de l'Ionique du Solide**, Ecole Doctorale: Matière Condensée, Specialite: Chemie des Materiaux France, 1995

Subject of the PhD thesis: "Synthése du nitrure d'aluminium par combustion auto-propagée sous haute pression hydrostatique de gaz"

(High pressure combustion synthesis of aluminum nitride)

3. Employment

1989-1991 – Research Worker, IHPP PAS

1992-1995 - PhD student, Academie do Montpellier, Universite Montpellier II, France, Formation Doctorale: Matériaux de l'Electronique et de l'Ionique du Solide, Ecole Doctorale: Matière Condensée, Specialite: Chemie des Materiaux

1996 to this day – Research Associate, IHPP PAS

work on crystallization of GaN by HNPS and HVPE methods; preparation of GaN crystals to the epi-ready state GaN substrates.

2004-2008 – Technologist, TopGaN Ltd.

crystallization of GaN by HNPS and HVPE methods; preparation of GaN crystals to the epi-ready state GaN substrates.

September 2008-to this day – Vice president TopGaN Ltd.

responsible for the ongoing work of the TopGaN's Management Board, responsible for the implementation of scientific and technological projects carried out by the Company, responsible for work related to the crystallization of gallium nitride crystals, substrates preparation and their surface preparation to the epi-ready state.

4. Information on published scientific papers and professional creative work

4.1 Total number of scientific papers

154 papers to 01.03.2013 (according to ISI Web of Knowledge; http://pcs.isiknowledge.com)
(**to the end of 1995 (PhD thesis)- 16 paper**)

including, inter alia:

23 papers in Journal of Crystal Growth
9 papers in Applied Physics Letters
8 papers in Physica Review B
7 papers in Journal of Applied Physics

4.2 Total Impact Factor of scientific papers by the Journal Citation Report (according to year of publication)

216,515

4.3 Total number of citations and Hirsh factor by the Web of Science database of 01.03.2013

2068 citations

(to the end of 1995 (PhD thesis)-380 citations)

Hirsh factor: 26

(to the end of 1995 (PhD thesis) -7)

4.4 Other creative professional work

Participation in 45 scientific conferences

19 invited lectures

Co-editor of "Technology of Gallium Nitride Crystal Growth" (Springer Series in Materials Science 133) Springer; 1st Edition. (Feb 12 2010) ISBN-10: 3642048285; ISBN-13: 978-3642048289

Guest Editor - Journal of Crystal Growth Vol 312 Issue 18 1 Sept. 2010 ISSN 0022-0248

Chairman of 6th International Workshop on Bulk Nitride Semiconductors (IWBNS-VI), 23rd-28th August 2009, Galindia Mazurski Eden, Poland

Co-Chairman of 7th International Workshop on Bulk Nitride Semiconductors (IWBNS-VII), 15th-20th March, 2011, Koyasan, Wakayama, Japan

Co-Chairman of 2013 Japanese Society of Applied Physics (JSAP) Autumn Meeting Symposium J: Nitride Simiconductors-Bulk and Related Growth and Characterization, 16-20 Sept. 2013, Kyoto, Japan

Chairman and Co-Chairman of a number of sessions devoted to the growth of nitride semiconductors during the main nitrides semiconductors conferences such as the International Workshop of Nitrides (IWN), the International Conference on Nitride Semiconductors (ICNS) and the International Workshop of Bulk Nitride Semiconductors (IWBNS)

Expert in the National Foresight Programme “Polska 2020” 2007-2008

Key expert of Foresight Mazovia 2007

Member of Committee on Electronics and Telecommunication PAS, Division of Electronic Materials Technology, 2003 - 2006

Member of Polish Society for Crystal Growth, from 2001 do this day

Member of Scientific Board of Institute of High Pressure Physics, PAS, from 1995 to 2010

5. Leadership and participation in national and international research projects

In the IHPP PAS:

1. From 2012 to 2014 **project manager in NCBiR grant PBS No 177589** „Examination of HVPE GaN crystallization on ammonothermally grown GaN substrates”
2. From 2013 to 2015 **project manager in NCN grant 2012/05/B/ST3/02516** „Determination of nonlinear elastic constants of bulk GaN”
3. From 2012 to 2015 **participation in NCN grant 2011/03/B/ST3/02647** „Beryllium-doped gallium nitride towards a new generation of optical converters”
4. From 2012 to 2015 **participation in Mazovia grant „**Celestynów Unipress Innovation Park” (responsible for the construction and development of the Laboratory of Crystallization)
5. From 2008 to 2013 **participation in grant No POIG.01.01.02-00-008/08** „Quantum semiconductors nanostructures for application in biology and medicine-Development and commercialization of new generation devices based on new polish semiconductors devices”
6. From 2007 to 2008 **project manager in grant WKP_1/1.4.3/2/2005/13/132/322/2007/U „**Laboratory of Semiconductors Nanostructures”
7. From 2006 to 2008 **participation in grant R003601** „Technology of low dislocation density (less than 10^5 cm^{-2}) 2 inch GaN substrates by high pressure solution and HVPE growth methods”
8. From 2005 to 2007 **participation in grant 3T08A03329** „Nonpolar GaN substrates: crystal growth by HVPE method and physical properties”
9. From 2000 to 2004 **participation in grant 2700/C.T11-8/2000** „Blue Optoelectronics”
10. From 2000 to 2002 **project manager in grant 1291/T08/2000/18** “Crystal growth of aluminum nitride under high nitrogen pressure”
11. From 1996 to 1998 **participation in grant 1270/C T08-7/95** „Implementation of GaN single crystals growth under high nitrogen pressure into the production of substrates for blue lasers”

In the TopGaN Ltd.:

1. From 01.12.2009 to 01.12.2013 **supervisor in grant** „Surface engineered InGaN heterostructures on N-polar and nonpolar GaN-substrates for green light emitters" **(SINOPLE) PIAP-GA-2009-230765**;
2. From 01.05.2011 to 30.04.2013 **supervisor in grant** „Microsystem Based on Wide Band Gap Materials for Future Space Transmitting Ultra Wideband Receiving Systems" **(SATURNE) 242458**
3. From 01.05.2011 to 30.04.2013 **supervisor in grant** „Nanostructured materials and RF-MEMS RFIC/MMIC technologies for highly adaptive and reliable RF systems" **(NANOTEC**) **288531**;
4. From 01.03.2010 to 28.02.2013 **supervisor in grant** „Micro and Nano Technologies Based on Wide Band Materials for Future Transmitting Receiving and Sensing Systems" **(MERCURE) NCBiR/ENIAC-2009-1/3/2010**;
5. From 02.01.2011 to 31.12.2013 **supervisor in grant** „Reconfigurable Microsystem Based on Wide Band Gap Materials, Miniaturized and Nanostructured RF-MEMS" **(NANOCOM) ENIAC-2010-1/3/2010**;
6. From 01.01.2011 to 31.10.2012 **supervisor in grant** „Next Generation Intelligent Microsystems Based on Wide Band Gap Materials" (MEGA) **E!Eur-07-304/27/NCBiR/11**;
7. From 01.09.2008 to 01.08. 2011 **supervisor in grant** „UV lasers diodes arrays" **UDA-POIG.01.04.00-14-052/09 UDA-POIG.04.01.00-14-052/09;**
8. From 01.03.2012 to 28.02.2014 **supervisor in grant** „New generation of patterned and plasmonic GaN substrates" **POIG .01.04.00-14-153/11;**
9. From 01.10.2012 to 30.09.2014 **supervisor in grant "**Optimization of GaN and SiC substrate off-orientation for manufacturing of electronic and optoelectronic devices" **POIG.01.04.00-14-007/12**
10. From 01.10.2011 to 30.09.2013 **supervisor in grant** „UV laser diodes and their arrays based on AlGaInN" **uv LASE (EUROSTARS);**
11. From 01.01.2012 to 01.12.2014 **supervisor in grant „**UV laser diodes for spectroscopic applications**" (**UFOLA**), NCBIR ID: 157751;**.
12. From 01.05.2012 to 30.04.2015 **supervisor in grant** „Green and blue laser diodes made by MBE on GaN substrtates" **(ZNANO) INNOTECH-K1/IN1/68/157829/NCBR/12;**
13. From 01.10.2012 to 31.03.2015 **supervisor in grant „**Laser diodes structures on semipolar GaN substrates" **(POLARPOL) PBS1/B5/8/2012;**
14. From 03.2012 to 06.2013 **supervisor in grant** „Improving the competitiveness of TopGaN Sp. of o.o. through participation in international fairs and exhibitions and trade mission"
15. From 01.11.2012 to 30.10.2014 **supervisor in grant** „Laser module to the color panels" (**MILLE) (EUROSTARS);**.
16. From 01.05.2012 to 30.04.2016 **supervisor in grant** „Sustainable Hydrothermal Manufacturing of Nanomaterials" **(SHYMAN); 280983;**
17. From 01.05.2012 to 30.04.2016 **supervisor in grant** „Nanostructured Efficient White LEDs based on short-period superlattices and quantum dots" (**NEWLED) 318388;**.

6. List of invited papers presented at international and national scientific conferences

1. "Recent results in the crystal growth of GaN at high N_2 pressure" EGW 1 (European GaN Workshop), 12-14th June, 1996, Rigi, Switzerland
2. "High pressure direct synthesis of III-V nitrides" XXXVI EHPRG (European High Pressure Research Group), 6-12th September 1998, Catania, Italy
3. "Growth and doping of single crystals of GaN and AlN under high nitrogen pressure" PCCG VI (Polish Conference on Crystal Growth), 20-23rd Mai 2001, Poznan, Poland
4. "Directional crystallization of GaN on high-pressure solution grown substrates by growth from solution and HVPE" 2nd International Workshop of Bulk Nitride Semiconductors II, 18-23 May, 2002, Amazonas, Brazil (workshop by invitation only)
5. "Device advantage of the dislocation free pressure grown GaN substrates" ISPN-2003 (1st International Symposium on Point Defect and Nonstoichiometry), 20-22 March 2003, Sendai, Japan
6. "Growth of GaN on patterned GaN/sapphire substrates by high pressure solution method" 3rd International Workshop of Bulk Nitride Semiconductors III, 4-9 September, 2004 Zakopane, Poland (workshop by invitation only)
7. "Growth of GaN on patterned GaN/sapphire substrates with various metallic masks by high pressure solution method" Photonics West Optoelectronics 2006 Gallium Nitride Materials and Devices, 22-26 January, 2006, San Jose, USA"Platelets and needles: Two habits of pressure-grown GaN crystals" 4th International Workshop of Bulk Nitride Semiconductors, 17-22 October, 2006 Makino, Shiga-pref., Japan (workshop by invitation only)
9. "Bulk growth of gallium nitride. Challenges and difficulties" The Fifth International Conference on Solid State Crystals & Eight Polish Conference on Crystal Growth (ICSSC-5 & PCCG-8 Conference), 20-24 May, 2007, Zakopane
10. "GaN crystallization by the high-pressure solution growth method on HVPE bulk seed" 5th International Workshop on Bulk Nitride Semiconductors, 24-28 September, 2007, Itaparica, Salvador, Bahia, Brazil (workshop by invitation only)- scene setter;
11. „Polski wkład w rodzący się rynek niebieskiej optoelektroniki" Ogólnopolska konferencja naukowo-techniczna „Warunki rozwoju innowacji w Polsce" Akademia Inżynierska w Polsce, Autorski Park Technologiczny W. Nawrota, 24 Października 2007
12. „Rola azotku galu we współczesnej fizyce i technologii" Otwarte spotkanie „Monitorowanie i prognozowanie (Foresight) priorytetowych, innowacyjnych technologii dla zrównoważonego rozwoju województwa mazowieckiego" w obszarach: Energia, Zasoby Naturalne i Nowe Materiały, Przemysłowy Instytut Automatyk i Pomiarów PIAP, 11 Grudnia 2007
13. "Ca_3N_2 as a flux for crystallization of GaN" 6th International Workshop on Bulk Nitride Semiconductors, 23-28 August, 2009, Galindia Mazurski Eden, Poland (workshop by invitation only)
14. "Multi feed seed (MFS) high pressure crystallization of 1-2 in GaN" 7th International Workshop on Bulk Nitride Semiconductors, 15-20 March, 2011, Koyasan, Wakayama, Japan (workshop by invitation only)- scene setter;
15. "High nitrogen pressure solution growth of GaN in multi-feed-seed configuration" 2011 International Symposium on Crystal Growth, 13th – 15th October 2011, Seoul, Korea

16. “Growth of GaN from Ga Solution” German-Polish Workshop on Nitride-Semiconductors-WideBase, 19th March 2012 Berlin, Germany
17. “Growth of GaN from solution” 2012 International Symposium on Strategy of III-Nitride Epitaxial Substrates and Epi-wafer Development 22nd-23rd Sept. 2012 Dongguan, Guangdong, China
18. “High Nitrogen Pressure Solution (HNPS) growth of GaN in Multi Feed Seed (MFS) configuration. Highly conductive and semi-insulating crystals. Role of impurities: oxygen, magnesium and beryllium.” International Workshop on Nitride Semiconductors IWN 2012 14-19 Oct. 2012 Sapporo, Japan
19. “Growth of bulk GaN” Intensive Discussion on Growth of Nitride Semiconductors 22-23 Oct. 2012, Sendai, Japan

7. List of scientific papers that are scientific achievement in accordance with Art. 16, & 2 of the Act of 14 March 2003 (Journal of Laws No. 65 item. 595)

Subject:

Directional crystallization of GaN on seeds by High Nitrogen Pressure Solution growth method

H1 **M. Bockowski**, I. Grzegory, S. Krukowski, B. Lucznik, Z. Romanowski, M. Wroblewski, J. Borysiuk, J. Weyher, P. Hageman, S. Porowski,. Directional crystallization of GaN on high-pressure solution grown substrates by growth from solution and HVPE. *Journal of Crystal Growth*, *246 (2002) 194-206.*

My contribution to this paper consisted of planning, preparation and analysis of all high-pressure crystallization processes and comparing the results with the results of the crystallization by the HVPE method. My role was to prepare the manuscript. I can estimate my contribution to this paper at 60%.

H2 **M. Boćkowski**, I. Grzegory, S. Krukowski, B. Łucznik, M. Wróblewski, G. Kamler, J. Borysiuk, P. Kwiatkowski, K. Jasik and S. Porowski, Deposition of bulk GaN from solution in gallium under high N_2 pressure on silicon carbide and sapphire substrates. *Journal of Crystal Growth* 270 (2004) *409-419*

My contribution to this paper consisted of planning, preparation and analysis of all high-pressure crystallization processes and preparation of the manuscript. I can estimate my contribution to this paper at 60%.

H3 **M. Boćkowski**; I. Grzegory; S. Krukowski; B. Lucznik, M. Wróblewski; G. Kamler. J. Borysiuk, P. Kwiatkowski, K. Jasik and S. Porowski, Gallium nitride growth on sapphire/GaN templates at high pressure and high temperatures. *Journal of Crystal Growth* 274 (2005) *55-64*

My contribution to this paper consisted of planning, preparation and analysis of all high-pressure crystallization processes and preparation of the manuscript. I can estimate my contribution to this paper at 60%.

H4. **M. Boćkowski**; I. Grzegory; S. Krukowski; B. Lucznik, M. Wróblewski; G. Kamler. J. Borysiuk, P. Kwiatkowski, K. Jasik and S. Porowski, Growth of GaN on patterned GaN/sapphire substrates by high pressure solution method *Journal of. Crystal Growth*, 281 (2005) 11-16

My contribution to this paper consisted of planning, preparation and analysis of all high-pressure crystallization processes and preparation of the manuscript. I can estimate my contribution to this paper at 60%.

H5 **M. Bockowski**, P. Strak, P. Kempisty, I. Grzegory, S. Krukowski, B. Lucznik, S. Porowski, High pressure-high temperature seeded growth of GaN on 1 in sapphire/GaN templates: analysis of convective transport, *Journal-of-Crystal-Growth.307 (2007) 259-267*

My contribution to this paper consisted of planning, preparation and analysis of all high-pressure crystallization processes, analysis of the calculation results and preparation of the manuscript. I can estimate my contribution to this paper at 60%.

H6 **M. Bockowski**, P. Strak, I. Grzegory, B. Lucznik, S. Porowski, GaN crystallization by the high-pressure solution growth method on HVPE bulk seed, *Journal-of-Crystal-Growth. 310 (2008) 3924-3933*

My contribution to this paper consisted of planning, preparation and analysis of all high-pressure crystallization processes, analysis of the calculation results and preparation of the manuscript. I can estimate my contribution to this paper at 60%.

H7 **M. Bockowski**, I. Grzegory, B. Lucznik, T. Sochacki, G. Nowak B. Sadovyi, P. Strak, G. Kamler, E. Litwin-Staszewska and S. Porowski, Multi feed seed (MFS) high pressure crystallization of 1-2 in GaN, *Journal-of-Crystal-Growth. 350, (2012) 5-10*

My contribution to this paper consisted of planning, preparation and analysis of all high-pressure crystallization processes, analysis of the calculation results and preparation of the manuscript. I can estimate my contribution to this paper at 60%.

Declarations by my co-authors of determining the individual contribution of each of them in the creation of the publications cited above are included in alphabetical order in Annex 9 "Statements by co-authors."

8. Personal experience

8.1Scientific achievements before PhD thesis

In 1989, I graduated from the Faculty of Applied Physics and Mathematics of Warsaw University of Technology, receiving the title of Master of Science in Solid State Physics. The same year I started working in the Crystal Growth Laboratory of the Institute of High Pressure Physics PAS (IHPP PAS). I had worked on thermodynamics and crystal growth of III-V and II-VI semiconductors. In 1992 I began my PhD studies at the University of Montpellier II, France. In 1995, I defended a PhD thesis, with the highest distinction ("Trés honorable avec félicitations"), presenting an essay about the preparation of aluminum nitride by self-propagating high temperature synthesis under high gas hydrostatic pressure ("Synthése du nitrure d'aluminium par combustion auto-propagée sous haute pression hydrostatique de gaz"). Until the doctoral degree I was an author or co-author of 16 papers cited 380 times, with Hirsh factor 7. To the end of my PhD study I took part in the six conferences and one summer school of physics "Conception of Materials Under High Pressure" in Bordeaux (France) in 1990.

8.2Scientific achievements after PhD thesis

In 1996 I started working again in IHPP PAS in Crystal Growth Laboratory. I had worked on crystallization of gallium nitride and aluminum nitride under high nitrogen pressure. In 1998, I was awarded by European High Pressure Research Group (EHPRG) for the work on semiconductors, in particular from the group of nitrides. In 2010, I was a co-editor of a book "Gallium Nitride Technology of Crystal Growth" published by Springer. In 2011, the book was translated into Russian and published in Russia by Technosphere. The book has been also available on the web-pages of the publisher (Springer online platforms). By June 2012, the chapters of the book were downloaded from the website 2552 times. By the end of 2012, my academic achievements included two international patents, more than 150 publications cited more than 2000 times, and the Hirsh index was 26. I participated in 45 conferences giving 19 invited lectures. I was a co-author of several chapters of books published by such publishers as: Wiley, Oxford University Press, and Springer. I have been a project manager and supervisor in many Polish and European research projects. In 2004-2008, I worked as a technologist in TopGaN Ltd. Since 2008 I have been a vice presidents of this company.

8.2.1 Subject of habilitation-series of scientific papers „**Directional crystallization of GaN on seeds by High Nitrogen Pressure Solution growth method**"-discussion of scientific and technological goals and results

The aim of this work was to determine and examine an optimal experimental configuration setup for seeded growth of gallium nitride by high-pressure crystallization from a solution of atomic nitrogen in the liquid gallium (High Nitrogen Pressure Solution (HNPS) growth method). All papers have been published in the same journal; the Journal of Crystal Growth, and represented not only the study of the crystallization process, but also the description of the way for obtaining the GaN substrates suitable for the construction of optoelectronic devices (laser diodes).

In the 90-ies of the last century and early 21st century, the spontaneously grown by HNPS method GaN platelets and needles were very popular and modern [1]. However, due to their small sizes (1 cm^2) and poor reproducibility of the crystallization processes, the seeded growth had to be started. At the same time, the most popular and developed technology in GaN crystallization was a crystal growth from a vapor phase called Hydride Vapor Phase Epitaxy (HVPE). In the first decade of the 21st century it resulted in 2 inch gallium nitride crystals [2,3]. In 2007, first ammonothermally grown GaN crystals were reported [4]. At the beginning of the second decade of the 21st century one could see an intensification of study and work on the crystallization of GaN. Excellent results have been obtained by the HVPE technology [5,6,7,8]. On the other hand, the best quality crystals have been obtained by ammonothermal method [9]. A sodium flux growth method also allowed to crystallize high quality 2 and 3 in. GaN crystals [10]. A multi-feed-seed (MFS) configuration was implemented to the HNPS growth method. It has allowed to obtain 1 in. and 1.5 in. GaN crystals suitable for further practical applications (preparation of substrates for construction of some optoelectronic devices) [11]. A road to develop the MFS configuration is described in this habilitation.

In the first paper [H1], the crystallization in the c directions on the Ga-and N-polar surfaces of HNPS grown GaN substrates by growth from liquid solution (HNPS method) and HVPE was examined. For both methods, the growth on the Ga-polar surface seemed more promising. The typical growth rates obtained in a configuration presented in Fig. 1a varied from 2 to 10 mm/h and depended on the temperature gradient in the liquid gallium. For a small axial temperature gradient (20 K/cm), the crystallization front was flat and the growth was very slow (2 μm/h). A bigger temperature gradient (50 K/cm) led to an increase in growth rate (up to 10 μm/h). However, due to the large radial temperature gradients, the formation of macrosteps and step bunching was observed. This perturbed and slowed down the crystallization process. The maximum growth rate obtained by the HVPE method was 50 μm/h and the GaN layers had fewer than 10^2 cm^{-2} dislocations. The main drawback of this method was the surface preparation of the Ga-terminated GaN substrates. Each of the presented methods was interesting and showed promise for obtaining GaN substrates with low dislocation density.

It should be mentioned that the HVPE crystallization processes were carried out in the Netherlands, at the University of Nijmegen. IHPP PAS did not have any HVPE reactor in this time. Interestingly, after 10 years, the author of this work is a manager of a project PBS (No. 177589) devoted to the HVPE crystallization of GaN on amonotermally grown GaN seeds.

In the next paper [H2], the results of directional growth of GaN (in the same experimental configuration to this one presented in [H1]), from solution in gallium at high N2 pressure, on: silicon carbide, sapphire substrates and GaN/sapphire templates, were described. There was a few reasons why these foreign substrates were used as seeds. First of all, they were the most common substrates for epitaxial growth of GaN and GaN based structures by low-temperature methods like metal-organic chemical vapor deposition (MOCVD) and hydride vapor-phase epitaxy (HVPE). However, in a normal CVD system for GaN growth, the epitaxy temperature does not exceed 1400 K. The use of N2 pressure (up to 1 GPa) allowed to increase the growth temperature to 1800 K. From what I know, this was the first time that GaN were crystallized directly on SiC and sapphire at such high temperature. The next reason for the GaN crystallization under pressure on foreign substrates and GaN templates was that we wanted to use the directional crystallization method for our large volume high-pressure systems, where the use on 2 in. substrates was possible. Such big GaN substrates were not commercially available in contrast to SiC, sapphire or GaN thin epi-layer on them. However, before growing at large volume we should have known in details the process of the GaN deposition on SiC and Al_2O_3 at smaller volumes. In particular, to determine and examine the growth parameters (N2 pressure, growth temperature, supercooling and supersaturation), growth mechanisms and growth rate. Therefore, in this paper the results of directional growth of GaN on 1 cm^2 silicon carbide and sapphire substrates and also on Al_2O_3/GaN MOCVD templates were presented. The role of nitrogen pressure and supersaturation for the growth process and determine the condition for the stable growth on the chosen substrates were discussed. The growth experiments were done at some N_2 overpressure compared to the equilibrium one, to prevent decomposition of GaN containing structural defects. For stable (in thermodynamic sense) growth of GaN on SiC or sapphire the nitrogen pressure had to be higher than N2 pressure necessary for the growth on a GaN seed. This overpressure was approximately equal to 100 MPa. The typical growth rate varied from 1 to 5 mm/h and depended on the temperature gradient in the liquid gallium. For small axial temperature gradients the growth rate was slow (1–2 μm/h). The bigger temperature gradient led to an increase in growth rate, but also introduced the formation of the instabilities, like macrosteps, step bunching and cellular growth. The change of temperature gradient configuration from positive one to the negative one (see Figs. 1a and 1b respectively) allowed to increase in the growth rate by a factor of 2 but also accelerated the appearance of the instabilities. The GaN growth on pure sapphire was polycrystalline. The growth on GaN/sapphire templates looked more perspective. It was very similar to the crystallization on gallium nitride crystals (despite dislocation density). A different growth mode was observed during crystallization on pure SiC. The main mechanism was the formation of many small hillocks and their coalescence. The average dislocation density in GaN crystallized on foreign substrates reached $5x10^7$ cm^{-2}, and it was a very promising and perspective result.

In the next paper [H3] the results of directional high-pressure growth of GaN on sapphire/GaN MOCVD templates were described. The use of a baffle plate was presented, in order to obtain the flat crystallization front at the substrate. Consequently, it allowed to maintain a flat GaN surface during a long time of crystallization run. Thus, the limiting thickness of stable growth (100 μm) disappeared. The GaN growth rate as a function of the applied temperature gradient and time was analyzed in details. Based on these two dependences, it was shown that there were two factors responsible for GaN growth in the c-direction. For a short time the growth rate was governed mainly by nitrogen transport to the crystallization zone. In a longer time, even at big temperature gradients, the surface kinetics factor was more important. The formation of macrosteps and terraces slowed down and finally stopped the GaN growth in the c-direction. This phenomenon was not only related to the growth on sapphire/GaN templates but also on the GaN crystals. The defect selective etching method and transmission electron microscopy were used to determine the dislocation density in the deposited GaN material. All results were compared to those obtained for directional growth of GaN on pressure grown GaN crystals (platelets).

In the paper [H4] the growth of GaN on patterned GaN/sapphire substrates by high-pressure solution method was examined. The patterns were GaN stripes arranged along <10-10> and <11-20> directions. The surface between stripes was bare sapphire or remaining gallium nitride. From two initial stripe orientations, the <11-20> direction was better for lateral overgrowth. The stripes increased their width due to lateral growth by 3 to 10 times. This depended on the distance between stripes, the material between stripes and the crystal growth conditions, especially the temperature gradient on the growing crystal surface. The dislocation densities in the laterally overgrown areas were in the range of $5x10^5$–10^6 cm^{-2}. This was 2 orders of magnitude lower than in the initial GaN stripes. However, in order to get such values of dislocation densities in the overgrown material, some conditions defined in this paper, should be assured. First of all, the crystallization process has to be performed on a patterned substrate with a mask such as Si_xN_y. Then, the laterally overgrown stripes will not be coupled to the template or substrate and the crystallization will not be perturbed by random and spontaneous growth of GaN between stripes. The growth of GaN on patterned GaN/sapphire substrates with various masks was continued and the results were presented in [12, 13]. However, those papers have not been included to this habilitation.

In this paper, [H5], the seeded growth on 1 in sapphire/GaN templates by HNPS method was described. Five crystallization runs different in geometry but at the same growth conditions i.e. growth temperature, time, temperature gradient (thus at the same supercooling and supersaturation), were analyzed in details. The 1 in. substrates enforced the use of a bigger high-pressure reactor and a crucible. In turn, it allowed precise determination of the mass of crystallized material in whole process. Thus it allowed comparing the GaN mass crystallized on the seed with the GaN mass crystallized on the crucible walls or on the baffle (the crystals obtained by spontaneous way-parasitic crystals). This comparison indicated that the growth rate on the seed was governed mainly by surface kinetics. All nitrogen atoms from the solution reached the seed's surface could not be adsorbed there. The same growth conditions during each experiment simplified the use of the finite element calculation for modeling the convective transport in the solution especially the effects of the crucible wall, seed and baffle. These effects were analyzed and discussed in details. The stream lines, convectional flow velocity vectors and isotherm lines in liquid metal were determined based on experimentally measured temperatures in the crucible wall. The influence of the seed and the baffle for convection in liquid metal was analyzed in details. The modeling of the convective transport in the solution allowed us to show that the measurements of the temperature distribution in the wall and bottom of the crucible did not reflect the real temperature distribution in liquid gallium. It was also shown that the flat seed (substrate) in the crucible set in order the convectional flow in the solution. The baffle plate allowed reducing the convectional flow close to the seed and thus obtaining macroscopically flat growth of GaN from the liquid phase. Modeling of the convective transport in the solution was continued using GaN and SiC substrates. The results were published in [14]. This paper has not been included to the habilitation.

Bulk GaN crystallization may take place when a properly prepared GaN seed is wholly immersed in the liquid solution Ga:N. Then, the growth can proceed in any of the available crystallographic directions. Therefore, in the next paper [H6], the new experimental configuration for seeded growth on HVPE free-standing GaN crystals was proposed (see Fig. 1c). At constant temperature conditions, the Ostwald–Miers zone (supersaturated metastable zone in which crystallization is possible, but spontaneous nucleation does not take place) in the solution was found. Using the finite element calculation, the convective transport in liquid gallium was determined. The convectional flow velocity vectors in liquid gallium were determined from experimentally measured temperatures and by solving the set of Navier–Stokes equations. Time dependent solutions for convectional flow velocity were presented. The crystallization with convective flow of gallium under control allowed us to obtain the stable growth of GaN on the Ga polar surface of the HVPE seeds. The nitrogen side grew in an unstable way. The growth rate on both sides was similar and varied from 1 to 3 μm/h. The growth in the non-polar direction was not observed. The growth of a relatively thick GaN layer on the HVPE seed and the possibility of cutting off the new grown material from the seed in order to obtain a high-quality free-standing pressure grown crystal was the goal of the future work and finally was achieved.

In the last paper [H7] the growth and physical properties of GaN crystallized in a multi feed-seed (MFS) configuration (see Fig. 1 d) by High Nitrogen Pressure Solution (HNPS) growth method were presented in detail. The idea of this configuration was given by I. Grzegory. The conversion of free standing HVPE-GaN crystals to free standing HNPS-GaN was the basis of the MFS configuration. The influence of the experimental conditions (i.e. growth temperature, temperature gradient etc.), the c-plane bowing of the initial substrate, the electrical properties of HNPS-GaN, and the rate and mode of growth from solution were analyzed. A finite element calculation was used for modeling the convective transport in liquid gallium. The influence of the c-plane bowing in the initial substrate on structural quality of HNPS-GaN was also analyzed. It was shown that the HNPS-GaN crystals had better structural quality than their HVPE-GaN seeds. The defect density decreased with increasing growth temperature, reaching $5x10^{5}$ cm^{-2} for crystals grown at $1420^{o}C$ or higher. In contrast, the free carrier concentration in HNPS-GaN increased with increasing growth temperature, reaching $7x10^{19}$ cm^{-3} for samples crystallized at $1440^{o}C$. Thus the possibility to obtain good quality plasmonic GaN substrates for laser diodes could be realized.

It should be noted that the MFS configuration has allowed to obtain not only highly conductive GaN crystals but also semi-insulating material (doped with Mg) [15]. Today, this configuration is the basis for the preparation of substrates for some electronic and optoelectronic devices made in the IHPP PAS and TopGaN Ltd.. The MFS configuration has been described in the journal Compound Semiconductor [11] and some other scientific papers [16,17,18]. It was a subject of an invited lecture during IWN 2012 (Sapporo, Japan). Using the MFS configuration the project “New generation of patterned and plasmonic GaN substrates” (POIG .01.04.00-14-153/11) is being realized in TopGaN Ltd.

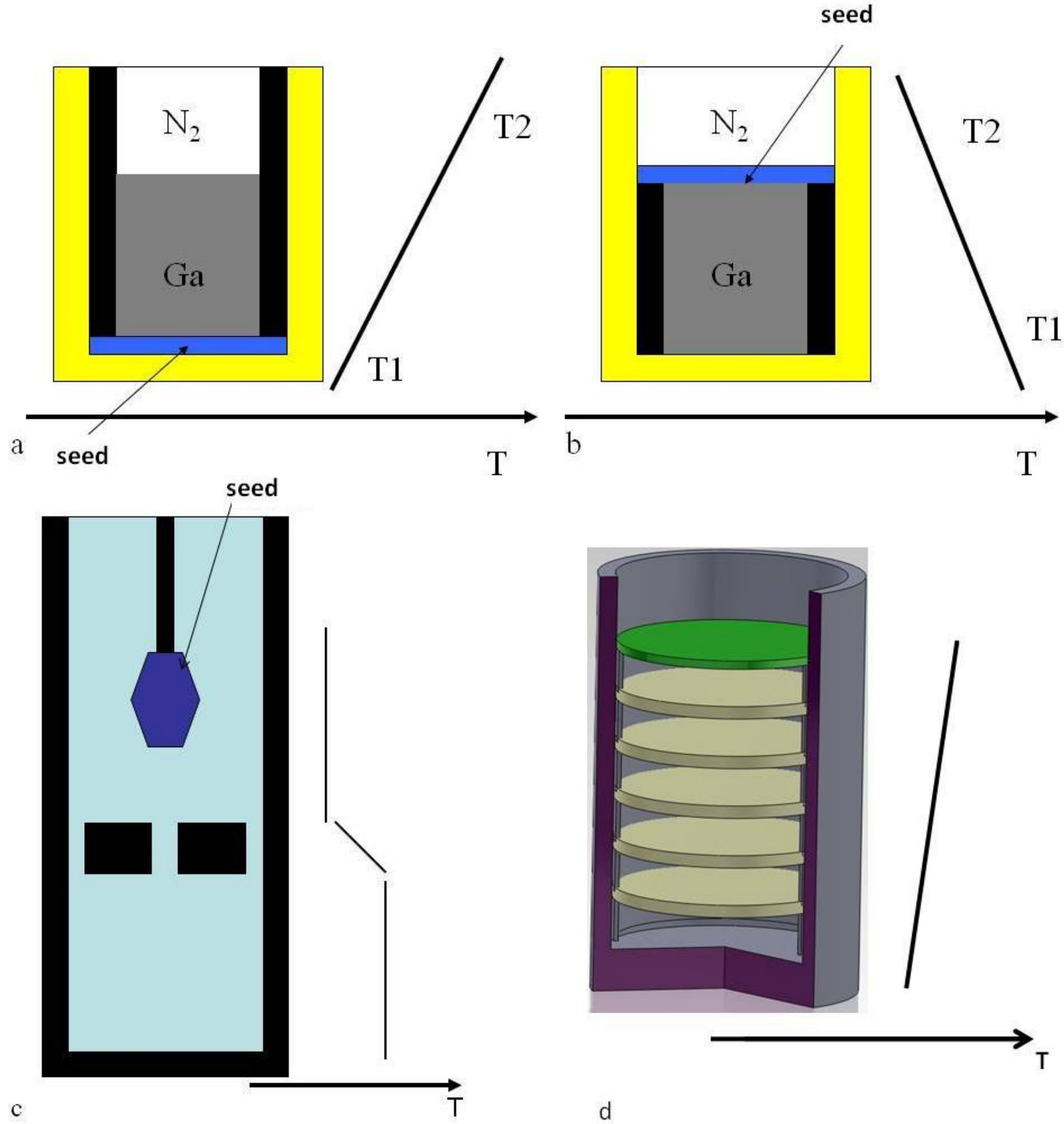

Figure 1 Experimental configurations for seeded growth by HNPS method: a) natural configuration; the substrate is placed at the bottom of the crucible; b) reverse configuration; the substrate is place at the top of the crucible; the direction of the temperature gradient is opposite to that in natural configuration; c) the seed is immersed in liquid gallium and it can be grown in any directions; using platelets as seeds, the growth proceeds in polar <0001> and <000-1> directions; d) MFS configuration; the seeds are placed one over another one; liquid gallium is between them; the temperature gradient is applied along the axis of the crucible.

8.2.2 Activities in other research areas

My work has been focused on the crystallization of nitrides, in particular gallium nitride (works on the crystallization of the aluminum nitride were stopped in 2002). My activities in other areas than that presented in the section. 8.2.1 can be divided into following topics:

i/ work on the crystallization of gallium nitride in order to obtain suitable substrates for epitaxial quantum electronic and optoelectronic semiconductor nanostructures. The work performed mainly in collaboration with the Laboratory NL-2 of IHPP PAS, headed by prof. T. Suski, and with TopGaN company and its R&D groups, led respectively by Professors M. Leszczynski, P. Perlin, C. Skierbiszewski.

ii / work on the crystallization of GaN doped with magnesium and beryllium in order to fabricate semi-insulating GaN single crystals. The work carried out mostly in collaboration with the Laboratory NL-2 of IHPP PAS, headed by prof. T. Suski, and more recently, in collaboration with the Institute of Physics, Polish Academy of Sciences (Grant NCN entitled "Gallium nitride doped with beryllium in the direction of a new generation of optical converters" 2011/03/B/ST3/02647 NCN)

iii / work on the crystallization of gallium nitride doped with spintronics and rare earth elements. This work has been carried out in collaboration with the Department of Physics, University of Warsaw, Institute of Physics PAS and the Institute of Physics of Warsaw University of Technology.

iv / work related to annealing at high pressures and temperatures the GaN crystals and MOCVD-GaN/sapphire and MOCVD-AlN/sapphire templates doped with rare earths and other elements. The work carried out mostly with groups from Portugal (Universidade Técnica de Lisboa), Scotland (Strathclyde Univ.), Sweden (Linkoping Univ.) and Finland (Aalto Univ.).

v / work on the crystallization of the HVPE-GaN at NL-3 Laboratory of IHPP PAS. I am a project manager of NCBiR grant PBS (No. 177589), on crystallization of the HVPE-GaN on ammonothermally grown GaN seeds.

vi / research work related to the physical properties of GaN single crystals carried out in collaboration with the University of Warsaw, Institute of Physics PAS, Institute of Low Temperature PAS and others (joint papers with such famous professors as B. Monemar, and M. Cardona) .

8.2.3 Other activities and achievements

In 2010 I was a co-editor of a book “Gallium Nitride Technology of Crystal Growth "(Springer Series in Materials Science 133) Springer, 1st Edition. (Feb 12 2010) ISBN-10: 3642048285, ISBN-13: 978-3642048289. In 2011, the book was translated into Russian and published in Russia by Technosphere. The book has been also available on the web-page publisher (Springer online platforms). By June 2012, the chapters from the book were downloaded 2,552 times.

In 2010, I was a co-editor of the special edition of Journal of Crystal Growth (Vol 312 Issue 18 1 Sept. 2010 ISSN 0022-0248). Then, I had a great pleasure to be a chairman of the 6th International Workshop on Bulk Nitride Semiconductors (IWBNS-VI). Two years later I was a co-chairman of the 7th International Workshop on Bulk Nitride Semiconductors (IWBNS-VII). I am a member of the International Advisory Committee of the IWBNS.

I have been a chair and co-chair of many sessions devoted to the growth of nitride semiconductors during International Workshop of Nitrides (IWN), the International Conference on Nitride Semiconductors (ICNS). Recently I have been invited to be a co-chairman of the conference organized by the Japanese Society of Applied Physics (JSAP) Autumn Meeting Symposium J: Simiconductors-Bulk Nitride and Related Growth and Characterization, 16-20 September 2013, in Kyoto, Japan.

In 2007-2008, I was an expert at the National Foresight Programme "Poland 2020". In 2007, I was a key expert in the Foresight Mazovia project.

From 2003 to 2006 I was a member of the Committee on Electronics and Telecommunication PAS, Division of Electronic Materials Technology and from 2001 to today, I have been a member of the Polish Society for Crystal Growth. From 1995 to 2010 I was a member of Scientific Board of Institute of High Pressure Physics, PAS.

In 1998 I was awarded by the European High Pressure Research Group (EHPRG) for the work on semiconductors, in particular from the group of nitride. In 2011 I was awarded by Korean Association of Crystal Growth (Plaque of Appreciation).

From 2004 to 2008 I worked as a technologist in TopGaN Ltd.. Since September 2008, I have been a vice president of this company.

8.3 Summary

24 years of my work in the Crystal Growth Laboratory of the IHPP PAS and 24 years of cooperation with such eminent and prominent physicists as professors I. Grzegory, S. Porowski, S. Krukowski, B. Lucznik, M. Leszczynski, P. Perlin, C. Skierbiszewski and T. Suski resulted in many papers and conference presentations. Studies of nitrides in the IHPP PAS and TopGaN Ltd. are being continued and developed. A lot of new and interesting projects about nitrides are being realized. Many new and young researchers have been appeared in the nitrides area. New ideas and concepts about nitrides growth are still being created. An advanced research on the crystallization of HVPE-GaN on high quality ammonotherally grown GaN seeds are being realized. The new obtained HVPE-GaN crystals will be used as seeds for ammonothermal and HNPS growth methods and also in HVPE. In this last method (technology) the crystallization of GaN doped by germanium and silicon (n-type) and magnesium and iron (semi-insulating) has to be started.

In the HNPS method, faster growth rate is needed thus some changes of Ga solution properties should be carried out. It is believed that this can be increased by increasing nitrogen solubility in gallium through the addition of calcium, sodium or lithium impurities into the high pressure solution. First attempts (crystallization using the calcium nitride) did not yield positive results [19].

New GaN crystals can give new possibilities for new measurements and determination of unknown properties of GaN As an example we can consider a project NCN 2012/05/B/ST3/02516 "Determination of nonlinear elastic constants of bulk GaN " recently implemented in the IHPP PAS. The author of this habilitation is its project manager.

8.3References

[1] M. Bockowski, I. Grzegory, G. Kamler, B. Lucznik, S. Krukowski, M. Wroblewski, P. Kwiatkowski, K. Jasik, S. Porowski, Journal-of-Crystal-Growth; 305(2): 414-20 (2007)
[2] Y. Oshima, T. Eri, M. Shibata, H. Sunakawa, K. Kobayashi, T. Ichihashi, A. Usui, Japanese Journal of Applied Physics Part 2-Letters Vol: 42, Issue: 1A-B, Pages: L1-L3 (2003)
[3] K. Motoki, T. Okahisa, R. Hirota, S. Nakahata, K. Uematsu, N. Matsumoto J. Cryst Growth 305 (2007) 377
[4] R. Dwilinski, R. Doradzinski, J. Garczynski, L.P. Sierzputowski, A. Puchalski, Y. Kanbara, K. Yagi, H. Minakuchi, H. Hayashi, *Excellent crystallinity of truly bulk ammonothermal GaN*, Journal of Crystal Growth **310** (2008), pp. 3911
[5] K. Motoki, SEI Technical Review, Number 70, April 2010; 28
[6] Y. Oshima, T. Yoshida, T. Eri, K. Watanabe, M. Shibata, T. Mishima in Technology of Gallium Nitride Crystal Growth, edited by D.Ehrentraut, E. Meissner, and M. Boćkowski, (Springer-Verlag, Heidelberg, ISBN 978-3-642-04828-9), 79-95 (2010)
[7] H. Geng, H. Sunakawa, N. Sumi, K. Yamamoto, A.A. Yamaguchi, A. Usui, Journal of Crystal Growth, 350 (1), 44-49, (2012)
[8] B. Lucznik, B. Pastuszka, G. Kamler, I. Grzegory, S. Porowski in Technology of Gallium Nitride Crystal Growth, edited by D.Ehrentraut, E. Meissner, and M. Boćkowski, (Springer-Verlag, Heidelberg, ISBN 978-3-642-04828-9), 61-78 (2010)
[9] R. Doradziński, R. Dwilinski, J. Garczynski, L.P. Sierzputowski, Y. Kanbara, in Technology of Gallium Nitride Crystal Growth, edited by D.Ehrentraut, E. Meissner, and M. Boćkowski, (Springer-Verlag, Heidelberg, ISBN 978-3-642-04828-9), 137-158, (2010)
[10] Y. Mori, M. Imade. K. Murakami, H. Takazawa, H. Imabayashi, Y. Todoroki, K. Kikamoto, M. Maruyama, M. Yoshimura, Y. Kitaoka, T. Sasaki, Journal of Crystal Growth, 350 (1), 72-74, (2012)
[11] Compound Semiconductor, Jan/Feb 2012, p 42
[12] M. Bockowski, I. Grzegory, G. Nowak, B. Lucznik, B. Pastuszka, G. Kamler, M. Wroblewski, P. Kwiatkowski, K. Jasik, W. Wawer, S. Krukowski, S. Porowski, Physica Status Solidi C, 6 1487 (2006)
[13] M. Boćkowski, I. Grzegory, G. Nowak, G. Kamler, B. Łucznik, M. Wróblewski, P. Kwiatkowski, K. Jasik, S. Krukowski, S. Porowski, Proc. of SPIE Vol. 6121, 612103 (2006)
[14] M. Bockowski, P. Strak, P. Kempisty, I. Grzegory, B. Lucznik, S. Krukowski, S. Porowski, Physica-Status-Solidi-C.; 5(6): 1539-42 (2008)
[15] I. Grzegory, M. Bockowski, B. Lucznik, J. L. Weyher, E. Litwin-Staszewska, L. Konczewicz, B. Sadovyi, P. Nowakowski, S. Porowski. Journal of Crystal Growth 350 (1), 50–55 (2012)
[16] M. Bockowski, I. Grzegory, B. Łucznik, T. Sochacki, M. Krysko, G. Kamler, S. Porowski, Sci China Tech Sci, 54 (1), 42-46, (2011)
[17] M. Bockowski, I. Grzegory, B. Łucznik, T. Sochacki, M. Kryśko, P. Strak, I. Dzięcielewski, E. Litwin-Staszewska and S. Porowski, Phys. Status Solidi A, 208 (7) 1507-1510, (2011)
[18] M. Bockowski, B. Łucznik, T. Sochacki, B. Sadovyi, G. Nowak, E. Litwin-Staszewska, I. Grzegory, Phys. Status Solidi C 9 (3–4), 453–456 (2012)
[19] M. Bockowski, I. Grzegory, A. Kchahapuridze, S. Gierlotka, S. Porowski, Journal of Crystal Growth Vol: 312, Issue: 18, 2574-2578 (2010)

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8.3References

[1] M. Bockowski, I. Grzegory, G. Kamler, B. Lucznik, S. Krukowski, M. Wroblewski, P. Kwiatkowski, K. Jasik, S. Porowski, Journal-of-Crystal-Growth; 305(2): 414-20 (2007)

[2]_Y. Oshima, T. Eri, M. Shibata, H. Sunakawa, K. Kobayashi, T. Ichihashi, A. Usui, Japanese Journal of Applied Physics Part 2-Letters Vol: 42, Issue: 1A-B, Pages: L1-L3 (2003)

[3] K. Motoki, T. Okahisa, R. Hirota, S. Nakahata, K. Uematsu, N. Matsumoto J. Cryst Growth 305 (2007) 377

[4] R. Dwilinski, R. Doradzinski, J. Garczynski, L.P. Sierzputowski, A. Puchalski, Y. Kanbara, K. Yagi, H. Minakuchi, H. Hayashi, *Excellent crystallinity of truly bulk ammonothermal GaN*, Journal of Crystal Growth **310** (2008), pp. 3911

[5] K. Motoki, SEI Technical Review, Number 70, April 2010; 28

[6] Y. Oshima, T. Yoshida, T. Eri, K. Watanabe, M. Shibata, T. Mishima in Technology of Gallium Nitride Crystal Growth, edited by D.Ehrentraut, E. Meissner, and M. Boćkowski, (Springer-Verlag, Heidelberg, ISBN 978-3-642-04828-9), 79-95 (2010)

[7] H. Geng, H. Sunakawa, N. Sumi, K. Yamamoto, A.A. Yamaguchi, A. Usui, Journal of Crystal Growth, 350 (1), 44-49, (2012)

[8] B. Lucznik, B. Pastuszka, G. Kamler, I. Grzegory, S. Porowski in Technology of Gallium Nitride Crystal Growth, edited by D.Ehrentraut, E. Meissner, and M. Boćkowski, (Springer-Verlag, Heidelberg, ISBN 978-3-642-04828-9), 61-78 (2010)

[9] R. Doradziński, R. Dwilinski, J. Garczynski, L.P. Sierzputowski, Y. Kanbara, in Technology of Gallium Nitride Crystal Growth, edited by D.Ehrentraut, E. Meissner, and M. Boćkowski, (Springer-Verlag, Heidelberg, ISBN 978-3-642-04828-9), 137-158, (2010)

[10] Y. Mori, M. Imade. K. Murakami, H. Takazawa, H. Imabayashi, Y. Todoroki, K. Kikamoto, M. Maruyama, M. Yoshimura, Y. Kitaoka, T. Sasaki, Journal of Crystal Growth, 350 (1), 72-74, (2012)

[11] Compound Semiconductor, Jan/Feb 2012, p 42

[12] M. Bockowski, I. Grzegory, G. Nowak, B. Lucznik, B. Pastuszka, G. Kamler, M. Wroblewski, P. Kwiatkowski, K. Jasik, W. Wawer, S. Krukowski, S. Porowski, Physica Status Solidi C, 6 1487 (2006)

[13] M. Boćkowski, I. Grzegory, G. Nowak, G. Kamler, B. Łucznik, M. Wróblewski, P. Kwiatkowski, K. Jasik, S. Krukowski, S. Porowski, Proc. of SPIE Vol. 6121, 612103 (2006)

[14] M. Bockowski, P. Strak, P. Kempisty, I. Grzegory, B. Lucznik, S. Krukowski, S. Porowski, Physica-Status-Solidi-C.; 5(6): 1539-42 (2008)

[15] I. Grzegory, M. Bockowski, B. Lucznik, J. L. Weyher, E. Litwin-Staszewska, L. Konczewicz, B. Sadovyi, P. Nowakowski, S. Porowski. Journal of Crystal Growth 350 (1), 50–55 (2012)

[16] M. Bockowski, I. Grzegory, B. Łucznik, T. Sochacki, M. Krysko, G. Kamler, S. Porowski, Sci China Tech Sci, 54 (1), 42-46, (2011)

[17] M. Bockowski, I. Grzegory, B. Łucznik, T. Sochacki, M. Kryśko, P. Strak, I. Dzięcielewski, E. Litwin-Staszewska and S. Porowski, Phys. Status Solidi A, 208 (7) 1507-1510, (2011)

[18] M. Bockowski, B. Łucznik, T. Sochacki, B. Sadovyi, G. Nowak, E. Litwin-Staszewska, I. Grzegory, Phys. Status Solidi C 9 (3–4), 453–456 (2012)

[19] M. Bockowski, I. Grzegory, A. Kchahapuridze, S. Gierlotka, S. Porowski, Journal of Crystal Growth Vol: 312, Issue: 18, 2574-2578 (2010)

Warszawa 2013.03.01