

# Challenges and Opportunities in GaN and ZnO Devices and Materials

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This special issue spawned from mainly the motivation used by the scientific community in regard to potential applications of ZnO to electronic and optoelectronic devices which seemingly are centering about device applications already addressed by GaN to a large extent. The late Dr. Cole W. Litton (Fig. 1) successfully made the case that a small group of experts in both the GaN and ZnO communities be brought together for a probing discussion which would then lead to a report which manifested itself as this special issue. Because of his uncanny vision and relentless effort in convincing Dr. D. J. Silversmith of the Air Force Office of Scientific Research to fund such a meeting and convincing already overly committed H. Morkoç to host the meeting in Richmond, VA, October 18–20, 2007, this special issue is dedicated to the memory of Dr. Litton.

**This special issue addresses to a large extent the challenges and opportunities in GaN and ZnO devices and materials deemed critical to both the GaN- and ZnO-based technologies.**

Facilitated by scene setting presentations, the topics discussed included bulk GaN and ZnO, defects, *p*-type doping paradox, particularly for ZnO, promising heterostructures and devices based on ZnO, ferromagnetism in GaN and ZnO, doping of high mole fraction AlGaIn and InGaIn, particularly *p*-type, light extraction and efficiency in GaN-based light-emitting diodes (LEDs), degradation mechanisms in GaN-based lasers and heterojunction field-effect transistors (HFETs) and potential measures to enhance lifetime and performance, negative differential resistance in GaN-based heterostructures, and intersubband transitions. This special issue addresses to a large extent the aforementioned subjects deemed critical to both the GaN- and ZnO-based technologies.



**Fig. 1. Dr. Cole W. Litton, 1930–2010.**

The special issue begins with an invited manuscript by Matulionis *et al.* “Ultrafast removal of LO-mode heat from a GaN-based two-dimensional channel,” discussing the new physics involved in dissipating the heat from hot electrons in GaN. Unlike other high-performance FET materials, the electron–phonon coupling in GaN is very strong, and therefore, the heat is removed via the path of scattering of hot electrons with longitudinal optical (LO) phonons, followed by LO phonon decay to longitudinal acoustic (LA) phonons, which is where all the new physics came to being, and removal of heat by LA phonons to the thermal bath. The discovery is that the long and detrimental hot LO phonon lifetime can be reduced by tuning the 2-D electron gas density (2DEG), mainly by doping and of course device bias, so that the plasma frequency resonates with the LO phonon frequency. This also happens to be the point where the carrier velocity is the highest and degradation lowest, which then paves the way for the best performance.

This fundamental treatment is then followed by a manuscript by Leach *et al.*, “Status of reliability of GaN-based heterojunction field effect transistors,” which reviews the performance and reliability of GaN-based HFETs incorporating the fundamental hot LO phonon physics into the picture which is not necessarily con-

sidered in reliability narrative among the practitioners. The GaN material provides additional challenges, mixed with very high-performance and high-voltage in that it is a piezoelectric and pyroelectric material with a dose of defects already present, the density of which has been steadily coming down to mind the reader. Presence of high fields near the drain side of the gate electrode together with the aforementioned inherent properties of the material sets the stage for additional defect generation during operation, which must be considered. Furthermore, the gate also tends to inject electrons to the surface and/or the barrier or both which manifests itself as an extension of the metallurgical gate, a slow one at best. Therefore, the ability of the channel to respond to the gate modulation at high frequencies is hampered by this slow charge in addition to causing stability problems, some of which are reversible. To reiterate, Leach *et al.* consider the problem of stability and reliability with physics unique to GaN taken into consideration.

The GaN FETs would have to be turned into functional elements such as amplifiers for which the equivalent circuit for the FET must be available. Because of device issues specific to GaN, the equivalent circuit models along with the extraction routines used mainly for GaAs-based FETs would have to be revisited. The manuscript by Fan *et al.*, “Small signal equivalent circuit modeling for AlGaIn/GaN HFET: Hybrid extraction method for determining circuit elements of AlGaIn/GaN HFET,” addresses the unique problems and advances in the available methodologies used to extract device parameters in the form of a descriptive and representative circuit model for GaN-based HFETs. A combination of “cold” and “biased or hot” conditions along with extraction routines are used to determine an equivalent circuit which best describes the device operation for a range of frequencies as well as tackling some of the issues related to nonlinearities which come about in high-power applications.

The GaN material has long been touted as a potential material for high-power switching applications as well. This particular field is gaining additional notoriety with the advent of all electric vehicles and hybrid electric vehicles in addition to transmission and management of electrical power generated at small and distributed stations such as solar cell and wind power banks. Consequently, a good deal of effort is currently devoted to developing FET as well as two terminal devices with very high hold voltages and low on resistances. Owing to its large bandgap and also relatively high mobility, for its bandgap, GaN is proving to be a formidable material for switching applications as well. Addressing to just the FET aspect of this wide field, Ikeda *et al.*, “GaN power transistors on Si substrates for switching applications,” report on the effort at Furukawa Electric wherein GaN FET technology with high hold voltages and low on resistances is being developed on readily available Si with reasonably good thermal conductivity. This effort was spearheaded and managed by late Dr. Seikoh Yoshida (Fig. 2) whom we lost suddenly in 2008. It is, therefore, very fitting to dedicate this particular paper to him in recognition of his many decades of stellar contributions to the field.

GaN is also in the center of one of the largest commercial and scientific developments owing to its being a



**Fig. 2. Dr. Seikoh Yoshida, 1956–2008.**

platform for high-performance LEDs. LEDs have seen a blazing transformation from being just indicator lamps to display devices and recently to illuminators. If it has not already happened it is about to happen in full force. The LEDs are taking over the entire automotive industry when it comes to lighting and signaling. With over 50% power conversion efficiencies, unparalleled longevity, Hg free, and nearly temperate independent operation, they are now poised to penetrate in a large way into the general illumination market. In the paper by Tsao *et al.*, "Solid-state lighting: An integrated human factors, technology, and economic perspective," the exciting journey, including what is to be expected and what is needed for indoor illumination, is laid out. Following the manuscript by Tsao *et al.*, two manuscripts, one dealing with the loss of efficiency retention at high injection current levels and the other dealing with its technology, adorn the pages of this special issue. The loss of efficiency at high injection levels beyond that expected from the heat generated at the junction has been attributed to processes that are deemed inherent to the GaN material system, inherent to the device structure, and inherent to the fabrication and packaging schemes. Özgür *et al.*, "GaN-based light-emitting diodes: Efficiency at high injection levels," take up the processes dealing with the inherent properties of the semiconductor material and device structure while that by Chu *et al.*, "High brightness GaN vertical light-emitting diodes on metal alloy for general lighting application," discuss a high-performance device mounting and packaging technology, which is imperative, along with a discussion of the performance of GaN-based LEDs.

The aforementioned manuscripts on LEDs segue into the discussion of InGaN/GaN lasers from two perspectives. That by Tomiya *et al.*, "Structural defects and degradation phenomena in high-power pure-blue InGaN-based laser diodes," focuses on the role the structural defect-induced point defects, particularly at the heterointerfaces,

play on the generation of additional defects. Tomiya *et al.* also address the facet damage issue by devising a topology wherein a certain length of the laser cavity next to the facets forming the mirrors is left unpumped dubbed the noninjected facet (NIF), meaning no intentional injection current. This discussion is followed by a treatise of manifestation of laser degradation in terms of the role of point defects, heating, characteristic temperature, degradation of high reflectivity coatings, etc., by Perlin *et al.*, "Degradation mechanisms of InGaN laser diodes."

With edge-emitting GaN-based lasers in many commercial systems and consumer electronics such as Sony's Playstation 3, and the BluRay high-definition video players, attention at the research level at least is shifting to surface emitters. These encompass microcavity (MC)-based vertical cavity surface-emitting lasers (VCSELs) which have been developed successfully in more conventional III-V semiconductors, and polariton lasers. The impetus centers on applications such as high-speed/high-resolution laser printing/scanning technology, lighting, and new types of coherent but nearly thresholdless optical sources. Room-temperature operations of GaN-based VCSELs by electrical injection have been recently reported, and the research on GaN-based VCSELs is paving the way for new opportunities such as polariton-based lasers, details of which are treated by Shimada and Morkoç in a review paper "Wide bandgap semiconductor-based surface-emitting lasers: Recent progress in GaN-based vertical cavity surface-emitting lasers and GaN/ZnO-based polariton lasers." Moving from interband transitions to structures taking advantage of intraband or intersubband transitions, Hofstetter *et al.*, "Intersubband transition-based processes and devices in AlN/GaN-based heterostructures," discuss the physics, epitaxial growth, fabrication, and characterization of optoelectronic devices based on intersubband transitions in the AlN/GaN material system. Following the pertinent fundamentals,

the authors focus on the fabrication and characterization of modulators, switches, photodetectors, and also light emitters, all capped with an outlook for this technology.

Vertical unipolar devices such as resonant tunneling diodes and hot electron transistors fabricated in conventional III-V semiconductors have received considerable attention in the research community. As a natural extension, resonant tunneling structures based on GaN received some attention as the materials quality improved over the years despite the polarization-induced field along the *c*-direction. There is, however, some level of controversy regarding the basis of the experimentally observed characteristics which tantalizingly act as if there is tunneling-induced negative differential resistance. Motivated in part to provide some clarity, the article by Litvinov, "Resonant tunneling in III-nitrides," reviews what has transpired in the field and possible source(s) of the observed negative differential resistance.

Switching gears to ZnO, the manuscript by Özgür *et al.*, "ZnO devices and applications: A review of current status and future prospects," critically reviews device efforts based on ZnO. The motivation is first provided to answer the question why "ZnO," which is mainly based on the large (60 meV) exciton binding energy, followed by a discussion of the need to achieve decidedly *p*-type ZnO if this material system has any chance of producing devices such as light emitters. On the electronic side, unipolar devices can be considered without *p*-doping. One must, however, keep in mind that the electron mobility is relatively low in ZnO. Coupled with low thermal conductivity and even stronger electron phonon coupling, as compared to that in GaN, and some fabrication issues, it is very unlikely that this material would be able to compete with GaN. However, ZnO has many advantages in terms of aiding light extraction in LEDs and photon absorption in photovoltaic solar cells. Furthermore, doped ZnO

is an excellent material for transparent conducting oxides as discussed in the Özgür *et al.* paper.

As alluded to above, the doping asymmetry in ZnO, namely the ease of which to obtain *n*-type and impossibility or near impossibility of obtaining *p*-type, is discussed by Avrutin *et al.*, “Doping asymmetry problem in ZnO: Current status and outlook.” The paper critically reviews the literature and any progress made, points out the difficulties and complexities involved as well as the possible misinterpretation of the data in reports of *p*-type doping achievement in ZnO. Given that *p*-type doping is at best elusive and nonexistent at worst, hybrid structures can be formed where *n*-type ZnO is juxtaposed to another *p*-type material, which is compatible with ZnO such as *p*-type GaN, to construct *p-n* junctions. The manuscript by Bakin *et al.*, “ZnO-GaN hybrid heterostructures as potential cost efficient LED technology,” addresses this very critical issue as well as hybrid GaN-ZnO LEDs.

Both GaN and ZnO received considerable attention owing to the predictions that both of these materials can be made ferromagnetic at room temperature when doped with a suitable magnetic ion. The front runner GaAs doped with Mn has a critical temperature of about 170 K at best above which the thermal fluctuations destroy the magnetic ordering. The possibility of a dilute magnetic

semiconductor at or above room temperature has caused quite a stir with potential applications wherein spin of an electron as opposed to its charge alone can be used for a plethora of devices. However, as in the case of reports of *p*-type ZnO, there are many unanswered questions as well as controversial data in both GaN and ZnO doped with magnetic ions. The paper by Avrutin *et al.*, “Ferromagnetism in ZnO- and GaN-based diluted magnetic semiconductors: Achievements and challenges,” addresses this very controversial issue from a fundamental point of view and discusses critically the advantages and limitations of different measurement techniques employed to interrogate any magnetic ordering in diluted magnetic semiconductors (DMS).

Any technology, to be successful, needs a native substrate on which to deposit the device structures. GaN appears to have relaxed this issue, with early resistance of course, in that reasonably high-quality devices could be produced on sapphire. However, as the demand for better performance set in, the search initially focused on what we would consider interim approaches followed by effort looking into the bulk GaN substrate material. In fact, because the bulk ZnO was available for this purpose before the bulk GaN, this fact was hoisted as a notable advantage over GaN. In a series of papers in this special issue, various approaches for

producing bulk GaN and ZnO are discussed. The paper by Avrutin *et al.*, “Growth of bulk GaN and AlN: Progress and challenges,” gives an overall view of various approaches used to produce bulk GaN. Another paper by Ehrentraut and Fukuda, “The ammonothermal crystal growth of gallium nitride—A technique on the up rise,” discusses a specific method, ammonothermal growth mechanism. This is followed by a paper by Paskova *et al.*, “GaN substrates for III-nitride devices,” which discusses what could be construed as an interim solution in that thick GaN layers are grown with hydride vapor phase epitaxy which boasts large growth rates (20–100  $\mu\text{m/h}$ ) on typically sapphire substrates; GaN is then liberated from the sapphire substrate, cut and polished, and used for device structures. By cutting along various crystallographic directions, *c*-, *m*-, and *a*-plane GaN substrate material can be obtained. The special issue is wrapped up by a paper discussing the growth methodologies involved in producing bulk ZnO by Avrutin *et al.*, “Bulk ZnO: Current status, challenges, and prospects.” The paper discusses three competing approaches, namely, the hydrothermal method, melt growth, and seeded vapor transport growth, and makes the case that all have now reached or are approaching commercial viability, pending successful device applications to be developed. ■

## ABOUT THE GUEST EDITORS

**Hadis Morkoç** received the B.S.E.E. and M.S.E.E. degrees from Istanbul Technical University, Istanbul, Turkey, in 1968 and 1969, respectively, and the Ph.D. degree in electrical engineering from Cornell University, Ithaca, NY, in 1975.

He had employments and leaves of absences at Varian Associates, Palo Alto, CA, University of Illinois at Urbana-Champaign, AT&T Bell Laboratories, and the California Institute of Technology and Jet Propulsion Laboratory. He is currently the Founders Professor at the newly established School of Engineering, Virginia Commonwealth University, Richmond. His interests are on synthesis, electrical, magnetic and optical aspects of wide bandgap group III-nitrides and devices, multifunctional oxides, and compact microwave passive components. He has authored, coauthored or edited, a two-volume book on MODFETs, a book titled *Wide Bandgap Nitrides and Devices*, a three-volume book titled *Advanced Semiconductor and Organic Nano-Techniques* (New York: Academic, 2003), a three-volume handbook titled *Nitride Semiconductors and Devices* (New York: Springer-Verlag, 1999), a book titled *Zinc Oxide: Fundamentals, Materials and Device Technology* (New York: Wiley, 2009), 45 book chapters, 62 tutorial-review-popular articles, electronic and optoelectronic devices, and over 1500 technical journal articles and conference papers, all dealing with heterostructures.

Dr. Morkoç is a Fellow of the American Association for the Advancement of Science, a Life Fellow of the American Physical Society, and is an inactive Fellow of IEEE.

**Jen-Inn Chyi** (Senior Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from National Tsing-Hua University, Hsin-Chu, Taiwan, in 1982 and 1984, respectively, and the Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign, Urbana, in 1990.

In 1991, he joined the Department of Electrical Engineering, National Central University, Jhongli, Taiwan. He was the Director of Optical Sciences Center of the University from 2000 to 2007. He is currently Dean of the College of Electrical Engineering and Computer Science, Chair Professor of Electrical Engineering, and Chair Professor of the University System of Taiwan. His research interests are in the areas of III-V semiconductor heterostructures for high-speed electronic and optoelectronic devices. His current research projects include MBE growth of InP-based heterojunction bipolar transistors, Sb-based transistors on Si, quantum dot photonic devices, and MOVPE growth of GaN-based ultraviolet, blue, green light emitters, and high-temperature, high-power devices. He has authored or coauthored over 260 journal papers and been granted 22 patents.

Dr. Chyi received the 2002 Distinguished Research Award of the National Science Council, the Distinguished Professor of the Chinese Institute of Electrical Engineering in 2004, and the Industrial Technology Advancement Award of the Ministry of Economic Affairs in 2008. He also served as a Distinguished Lecturer of IEEE EDS from 2004 to 2009. He is an Associate Editor of the IEEE PHOTONICS TECHNOLOGY LETTERS and the *Japanese Journal of Applied Physics*. He is a member of Phi Tau Phi.



**Alois Krost** received the diploma and doctoral degrees in physics from RWTH Aachen, Germany.

He then joined Technical University Berlin, Berlin, Germany, as a Head of the Materials Department. Since 1998, he has been a Full Professor at Otto-von-Guericke-University, Magdeburg, Germany. In the past 30 years, he has been involved in growth and characterization of semiconductors including  $V_2VI_3$ -, semimagnetic II-VI-, IV-VI-, and conventional III-V compounds for electronic and optoelectronic applications including self-organized InGaAs quantum dot lasers. Currently, his main focus is on metalorganic vapour phase epitaxy growth and characterization of wide bandgap group-III nitrides, and ZnO. Especially, his group has pioneered metal organic vapour phase epitaxy of GaN-on-silicon as a cheap alternative to growth on conventional sapphire and SiC substrates. These activities led to a startup company, AZZURRO Semiconductors, Magdeburg, Germany. His special interest is on advanced X-ray characterization methods. He authored or coauthored around 300 papers and filed 30 patent applications and patents.

Dr. Krost is a member of the German Physical Society, The International Society for Optical Engineers (SPIE), and TMS.



**Yasushi Nanishi**, photograph and biography not available at the time of publication.

**Donald J. Silversmith** (Life Senior Member, IEEE) received the Ph.D. degree in materials science from the Massachusetts Institute of Technology (MIT), Cambridge.

As AFOSR Program Manager for Semiconductor and Electromagnetic Materials, he managed a program of fundamental research activities in heterostructure and wide bandgap semiconductor materials for prospective advanced electronic and photonic applications for Air Force systems. This program included quantum well, wire and dot structures at the Air Force Research Laboratory (AFRL) and at academic institutions in the United States and throughout the world. In prior roles, he was the first IEEE Senior Diplomacy Fellow at the U.S. Department of State, Associate Dean of Engineering at Wayne State University, Detroit, MI, Program Director for Solid State and Microstructures at the National Science Foundation (NSF), and a research staff member at the Lincoln Laboratory, MIT, at North American Philips, and at Bell Labs. After a 40-year career, he is currently pursuing active retirement.

