Guest Editorial - Special Issue on GaN Electronic Devices

Foreword

With the continuous demanding of performance in the wireless communication market and the need of more efficient power conversion systems, microwave and power transistors are playing critical roles in many aspects of human activities. In mobile communication applications, next- generation cellphones and basestations require wider bandwidth and improved efficiency. In parallel, the power electronics market is looking at new devices with enhanced performances to further reduce power conversion losses for a more efficient energy usage at silicon cost levels.

Over the last decade, GaN-based High Electron Mobility Transistors (HEMTs) have emerged as excellent devices for a number of applications. Devices with f_T in excess of 300 GHz at Lg=30 nm, a power-added efficiency (PAE) of 73% at 4 GHz frequency and 45 V drain bias, and output power density in excess of 40 W/mm have been demonstrated, thus clearing the way for the adoption of HEMTs in high power/frequency systems. In addition, GaN Technology now offers transistor, diode and even IC 's compatible with Power Electronic expectations, at least in the 0-600 V range.

Most of the commercial applications of III-N electronics today are in the field of solid-state radar and mobile communication base stations. The intrinsic advantage to form compact and simple broadband power amplifiers has introduced this technology much faster than anybody anticipated. Further, there are strong hopes in the power business to use the simplicity of compact converters to save energy in the field of power conversion. Last but not least, III-N devices offer the chance to close the solid-state millimeter-wave power gap to achieve Watt-level operation per chip in the frequency range of 100 GHz and beyond.

However, GaN electronic devices still face great challenges related to the development of new device architectures, techniques for normally-off operation with large threshold voltage, gate scaling, substrate costs, thermal management, packaging, degradation modes and mechanisms not yet fully understood, that today are limiting the market penetration of GaN based devices.

Due to the rapid advances taking place in the development and application of GaN electronics, there is an immediate need to take cognizance of the recent technological improvements and bring the potential and opportunities that exist in the area to a wider device community. The primary goal of this special issue is, therefore, to put together works in different aspects, including modeling, design, technology, characterization and applications so that this special issue will not only be of great archival value but also attract new researchers into this area for further accelerating the application of III-Nitride devices in building reliable, cheaper, and high-performance electronic systems.

The papers collected in this special issue have been grouped in six topics:

1. Fabrication and characterization of GaN Based devices
2. High power GaN HEMTs for power switching applications
3. High speed GaN HEMTs for RF applications
4. Reliability and parasitic issues in GaN HEMTs
5. Simulation-based development of GaN HEMTs devices
6. GaN-based low noise amplifiers and Gate drive circuits

1) Fabrication and characterization of GaN based devices

The first invited paper in this section "Scaling of GaN HEMTs and Schottky Diodes For Sub-Millimeter-Wave MMIC Applications" by Shinohara *et al*. from HRL Laboratories, reports the state-of-the-art high frequency performance of GaN-based high electron mobility transistors (HEMTs) and Schottky diodes. Ultrahigh $f_{T,}$ exceeding 450 GHz and f_{max} close to 600 GHz were obtained in deeply-scaled GaN HEMTs while maintaining superior Johnson figure of merit (*JFoM*). Excellent low-power noise performance and DCFL ring oscillator circuits are demonstrated.

In the second invited paper "Current Stability in Multi-Mesa-Channel AlGaN/GaN HEMTs" by Ohi *et al*. from Hokkaido University, Sapporo, and CREST (Japan Science and Technology Agency) multi-mesa-channel (MMC) AlGaN/GaN high-electron-mobility transistors (HEMTs) are fabricated and characterized. The advantageous properties with respect to device scaling are discussed.

The third paper "p-Channel enhancement and depletion mode GaN-based HFETs with quaternary backbarriers" by Hahn *et al*. from RWTH Aachen, Germany provides a comprehensive study of enhancement and depletion mode p-channel GaN/AlInGaN heterostructure field effect transistors.

Two research groups from South Korea (Kyungpook National University and Samsung Electronics Co., Ltd) and France (University of Montpellier II and IMEP-MINATEC) present in the paper "High-Performance GaN-based Nanochannel FinFETs With/Without AlGaN/GaN Heterostructure" by Im *et al*. two types of fin-shaped field-effect transistors (FinFETs), one with AlGaN/GaN heterojunction and the other with heavily doped heterojunction-free GaN layer operating in junctionless mode, and provides a performance comparison.

The group from the Hong Kong University of Science and Technology reports, in "DC and RF Performance of Gate-last AlN/GaN MOSHEMTs on Si with Regrown Source/Drain" by Huang *et al*., on the fabrication and characteristics of self-aligned gate-last AlN/GaN metal-oxide-semiconductor high electron mobility transistors (MOSHEMTs). They feature regrown source/drain for low on-state resistance (R_{on}).

The sixth paper "Sidewall dominated characteristics on fin-gate AlGaN/GaN MOS-channel-HEMTs" by Takashima *et al*. from Fuji Electric and Rensselaer Polytechnic Institute concerns fin-gate structures. They were fabricated onto AlGaN/GaN MOS channel-high electron mobility transistors (MOSC-HEMTs), and the fin sidewall contribution to the MOS channel characteristics was investigated. The results demonstrate sidewall-dominated characteristics of these FIN-MOSC-HEMTs.

In the next paper "AlGaN/GaN based-Lateral Type Schottky Barrier Diode with Very Low Reverse Recovery Charge at High Temperature" by Lee *et al*. from Samsung Electronics and Kyungpook National University (South Korea), lateral multi-finger type Schottky barrier diode (SBD) are discussed with bonding pad over active (BPOA) structure fabricated on the AlGaN/GaN heterostructure prepared on sapphire substrate. They exhibited excellent device characteristics such as forward current and reverse recovery in comparison to silicon devices.

The paper "Fabrication and Characterization of Enhancement-Mode High-κ $LaLuO_3$-AlGaN/GaN MIS-HEMTs" by Yang *et al*. from the Hong Kong University of Science and Technology, the Chinese Academy of Sciences and Peter Grünberg Institute (Germany), proposes enhancement-mode (E-mode) $LaLuO_3$-

AlGaN/GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs) fabricated using fluorine (F) plasma ion implantation.

Finally, the paper entitled "AlGaN/GaN Three Terminal Junction Devices for Rectification and Transistor Applications on 3C-SiC/Si Pseudosubstrates" by Hiller *et al.* from Technische Universität Ilmenau, Germany, describes three terminal junction devices featuring an in-plane side gate that is capable of modulating current flow at a nanoscale junction fabricated on AlGaN/GaN heterojunctions. The process techniques and mechanisms for rectification and transistor operations are discussed.

2) High power GaN HEMTs for power switching applications

This section starts with two invited papers describing advanced technology for next-generation GaN power switching applications.

The first paper "GaN on Si technologies for power switching devices" by Ishida *et al.,* from Panasonic, Japan, the device technology for fabricating normally-off GaN-based Gate Injection Transistors (GIT's) on 200mm Si substrates is described is described. GaN-based GIT's are further implemented in a three-phase inverter for motor drive applications, delivering a high efficiency of 99.3% at a high output power of 1500 W.

The second paper entitled "Lateral and Vertical transistors using the AlGaN/GaN heterostructure" by Chowdhury *et al.* from Arizona State University and Transphorm, USA, provides a comprehensive overview on the latest development in lateral and vertical power switching devices featuring AlGaN/GaN heterostructures. The application-specific benefits and challenges of the lateral and vertical device structures and technology are discussed.

Utilizing pseudo-bulk GaN substrates, the third paper entitled "High Voltage Vertical GaN PN Diodes with Avalanche Capability by Kizilyalli *et al.* from Avogy Inc., San Jose, USA reports on vertical GaN PN diodes with breakdown voltages of 2600 V and a differential specific on-resistance of 2mΩ-cm^2. A positive temperature coefficient of the breakdown voltage is observed, indicating that the breakdown is due to impact ionization and avalanche.

The next two papers in this section focus on the technology of metal-insulator-semiconductor high electron mobility transistors (MIS-HEMTs) that possess desirable features for power switching applications, but also face challenging issues regarding to the gate dielectric.

The paper entitled "Fabrication and Performance of Au-free AlGaN/GaN-on-Silicon Power Devices with Al_2O_3 and Si_3N_4/Al_2O_3 Gate Dielectrics" by Van Hove *et al.* from IMEC, Belgium, presents GaN-based MIS-HEMTs fabricated on 150-mm Si substrates using an Au-free process. Both single-layer Al_2O_3 and bilayer (with *in situ* Si_3N_4 and *ex situ* Al_2O_3) gate dielectrics are investigated with the latter showing robust performance and a breakdown voltage over 600 V.

The paper entitled "High Drain Current Density E-mode Al2O3/AlGaN/GaN MOS-HEMT on Si with Enhanced Power Device Figure-of-Merit (4 x 10^8 V^2 $W^{-1}cm^{-2}$) by Freedsman *et al.* from Nagoya Institute of Technology reports on the enhancement-mode (E-mode) Al_2O_3/AlGaN/GaN MIS-HEMTs. The E-mode operation is obtained by utilizing the negative charges in the Al_2O_3 gate dielectric deposited by atomic layer deposition.

The last paper entitled "Improved Vertical Isolation for Normally-off High Voltage GaN-HFETs on n-SiC Substrates" by Hilt *et al.* from Ferdinand-Braun-Institut, Berlin, Germany, presents an Argon implantation technique for improving the vertical isolation in lateral normally-off high voltage AlGaN/GaN heterojunction FET's on n-SiC substrates. Vertical leakage reduction and breakdown voltage improvement are achieved.

3) High speed GaN HEMTs for RF applications

Each one of the four papers in this section pushes the state-of-the-art in GaN-based transistors for RF applications.

The first invited paper "AlInN-Based HEMTs for Large-Signal Operation at 40 GHz", by Tirelli *et al*. from ETH-Zürich, Switzerland, studies the impact of GaN and AlN capping layers on the performance of AlInN/GaN high electron mobility transistors (HEMTs). It is found that while AlN-capped epilayers have higher current levels and reduced dispersion, the GaN-cap improves channel control. A maximum power density of 5.8 W/mm is achieved on GaN-capped InAlN/GaN transistors.

In a second invited paper "InAlN barrier scaled devices for very high Ft and for Low-Voltage RF applications" by Saunier *et al*. from TriQuint Semiconductor, the microwave and mm-wave performance is studied of InAlN/AlN/GaN HEMTs with gate lengths in the 30 to 50 nm range. Both enhancement-mode and depletion-mode devices are reported with frequency performance well in excess of 200 GHz. Excellent large signal performance at 30 GHz and a noise figure of 0.25 dB at 10 GHz are demonstrated.

In the third paper, "Optimization of $Al_{0.29}Ga_{0.71}N$/GaN High Electron Mobility Heterostructures for High Power/Frequency Performances," by Rennesson *et al*. from CNRS-CRHEA and IEMN (Lille), France, study the optimization of AlGaN/GaN transistor structures grown on a Silicon substrate to maximize their high power and frequency performance. A power density of 1.5 W/mm at 40 GHz is obtained after finding the best trade-off between barrier layer thickness and electrostatic channel control.

The RF Devices section concludes with the paper "High-gain Millimeter-Wave AlGaN/GaN Transistors" by Schwantuschke *et al*. from Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany, on high-gain mm-wave AlGaN/GaN transistors. The paper demonstrates dual-gate devices for substantial improvement in bandwidth and gain per stage at the circuit level.

4) Reliability and parasitic issues in GaN HEMTs

This section start with an invited paper "AlGaN/GaN-Based HEMTs Failure Physics and Reliability: Mechanisms Affecting Gate Edge and Schottky Junction" by Zanoni *et al.* from the University of Padova, Italy, reporting a comprehensive review of AlGaN/GaN HEMT reliability related failure modes and mechanisms focusing on the well-known gate-drain edge degradation issue. Physical effects at the origin of device degradation (inverse piezoelectric effect, time dependent trap formation and percolative conductive paths formation, and electrochemical AlGaN and GaN degradation) are discussed.

In the second paper "Reliability analysis of permanent degradations on AlGaN/GaN HEMTs" from Marcon *et al.* from IMEC, Belgium, and the University of Padova, Italy, a detailed report on the understandings on the two most common failure modes of GaN-based HEMTs is presented, namely, permanent gate leakage current increase and output current drop.

The following three papers of this section, presents electro-mechanical numerical simulations addressing both reliability issues and device performances.

In “AlGaN/GaN HEMT degradation by Dislocation formation: an electro-thermo-mechanical simulation” by Auf der Maur *et al.* from the University of Rome Tor Vergata, Italy, presents fully self-consistent degradation simulation results based on an electro-thermo-mechanical model of a typical AlGaN/GaN HEMT structure. The mechanical stress state is analyzed under different DC operating conditions identifying possible dislocation formation and movement.

In the paper “Impact of intrinsic stress in diamond capping layers on the electrical behavior of AlGaN/GaN HEMTs” by Wang *et al.* from Universidad Politécnica de Madrid, Spain, the Naval Research Laboratory, Washington, and the University of Bristol, Bristol, UK, the impact of intrinsic stress in diamond capping layers is reported on the electrical behavior of AlGaN/GaN HEMTs.

Then, the paper “Gate Leakage Mechanisms in AlGaN/GaN and AlInN/GaN HEMTs: Comparison and Modeling” from Turuvekere *et al.* from IIT Madras and Tata Institute of Fundamental Research, Mumbai, India, reports on the gate leakage mechanisms in AlInN/GaN and AlGaN/GaN High Electron Mobility Transistors (HEMTs); the reverse bias gate current has been decomposed it into three components: Thermionic Emission (TE), Poole-Frenkel (PF) emission and Fowler-Nordheim (FN) tunneling.

The second part of this reliability section deals with the very critical problem of charge trapping and traps identification in GaN based HEMTs.

The sixth paper “Deep Levels Characterization in GaN HEMTs-Part I: Advantages and Limitations of Drain Current Transient Measurements” by Bisi *et al.* from the Universities of Padova and Modena & Reggio Emilia, Italy, and Fraunhofer Institute, Freiburg, Germany, investigates the advantages and limitations of the current-transient methods adopted for the study of the deep levels in GaN-based high electron mobility transistors (HEMTs); they also present a database of defects described in more than 60 papers on GaN technology which can be used to extract information on the nature and origin of the trap levels responsible for current collapse in AlGaN/GaN HEMTs.

The effects of device self-heating on the extraction of traps activation energy are investigated by means of experimental measurements and numerical simulations in the seventh paper, “Deep Levels Characterization in GaN HEMTs-Part II: Experimental and Numerical Evaluation of Self-Heating Effects on the Extraction of Traps Activation Energy” by Chini *et al.* from Universities of Padova and Modena & Reggio Emilia, Italy .

Then, the paper “Evaluation of Electron Trapping Speed of AlGaN/GaN HEMT with Real-Time Electro Luminescence and Pulsed I-V Measurements” by Wakejima *et al.* from Nagoya Institute of Technology, Japan, reports an experimental technique for the evaluation of electron trapping in AlGaN/GaN HEMT by means of a real-time electro luminescence and pulsed measurements.

In the ninth paper “Methodology for the Study of Dynamic ON-Resistance in GaN High-Voltage Field-Effect Transistors” by Jin *et al.* from MIT, a new methodology is developed for the investigation of the dynamic ON-resistance (RON) capable of spanning across 10 decades under a variety of bias conditions allowing a detailed characterization of charge trapping in power GaN HEMTs.

Finally, the charge trapping characteristics in dielectric-gated AlGaN/GaN high electron mobility transistors (HEMTs) with atomic layer deposited HfO_2 is reported in the paper "Threshold Voltage Shift due to Charge Trapping in Dielectric-Gated AlGaN/GaN High Electron Mobility Transistors Examined in Au-Free Technology" by Johnson *et al.* from Texas A&M University, Texas State University and SEMATECH, Albany, USA. The paper also demonstrates and discusses the stability of the enhancement mode operation of HEMTs.

5) Simulation-based development of GaN HEMTs devices

The first (invited) paper in this section "Theory of Carriers Transport in III-Nitride Materials: State of the Art and Future Outlook" from Bellotti *et al*. from Boston University and Politecnico di Torino, Italy, describes the state of the art in the numerical simulation of the carrier transport properties of GaN and its ternary alloys, with a view to the application to a state of the art full-band Monte Carlo model including carrier-phonon interaction and a full quantum mechanical model for multi-band transport, that is critical to modeling high-field transport.

The second paper "A Robust Surface-Potential-Based Compact Model for GaN HEMT IC Design" by Khandelwal *et al*. from the Norwegian University of Science and Technology, the Indian Institute of Technology, Kanpur, IMS Bordeaux and IEMN, Lille, France, presents an accurate surface-potential-based compact model for the simulation of GaN HEMT based circuits; the presented model is robust according to bench-mark tests like the DC and AC symmetry tests, reciprocity test and harmonic balance simulations test.

The third paper "Electric Field Distribution around Drain Side Gate Edge in AlGaN/GaN HEMTs: an Analytical Approach" by Si *et al*. from the University of Electronic Science and Technology of China, proposes a conformal-mapping based analytical model for the surface electric field around the drain side gate edge in the AlGaN/GaN HEMT, to which the gate leakage, current collapse, etc. are highly related, and compare the model to numerical simulations.

The last paper "Design and Simulation of 5-20 kV GaN Enhancement-Mode Vertical Superjunction HEMT" Li *et al*. from Rensselaer Polytechnic, describes a systematic design process using numerical simulations of the novel GaN E-mode vertical superjunction HEMT with breakdown voltage in the range of 5-20 kV. The simulated on-state breakdown voltage of the GaN vertical superjunction HEMT shows 4.5% drop from the off-state breakdown voltage, and is only slightly higher than the 1.7% drop of the conventional GaN vertical HEMT.

6) GaN-based low noise amplifiers and Gate drive circuits

Finally, two papers are devoted to low-noise and driver applications of GaN HEMTs. Although GaN devices are mainly intended as power (switching or RF) devices, they have a remarkable potential in other fields, paving the way e.g. to robust multifunctional integrated circuits including RX and TX stages.

A first paper in this section "GaN-Based Robust Low-Noise Amplifiers" by Colangeli *et al*. from University of Rome Tor Vergata, Italy, reports an overview of GaN-based LNAs, highlighting their noise performance together with high linearity and robustness (over 40 dBm input power level without gain penalty).

The last paper "A Capacitor-less Gate Drive Circuit Capable of High-Efficiency Operation for GaN FETs" by Hattori *et al*. from Shimane University, Matsue, Japan, proposes a capacitor-less gate drive circuit for power applications of GaN-based devices able to increase their efficiency. Drive loss analysis of an inverted gate drive circuit showing the lowest losses among capacitor-type gate drive circuits and a capacitor-less gate drive circuit was made to examine the differences between them; the results show that higher efficiency operation is obtained by applying a capacitor-less gate drive circuit to simple test circuits.

The six guest editors would like to sincerely thank the reviewers who carefully and meticulously reviewed each manuscript and the revised versions in a very timely manner. We would also like to thank the authors for their cooperation in submitting revised manuscripts in a shorter-than-normal time frame and in documenting important research results on GaN-based technology and devices, so that they are available to the wider research and user communities. We would also like to thank and greatly appreciate the supporting work by Jo Ann Marsh of the EDS publications office. Last but not least, a warm thank goes to the EIC John Cressler for his support to this Special Issue. We have greatly enjoyed putting together this Special Issue, and we hope that the readers will enjoy it as well.

Giovanni Ghione, Guest Editor in Chief
Politecnico di Torino, Italy
giovanni.ghione@polito.it

Kevin J. Chen, Guest Editor
Hong Kong University Of Science and Technology, Hong Kong
eekjchen@ust.hk

Takashi Egawa, Guest Editor
Nagoya Institute of Technology, Nagoya, Japan
egawa.takashi@nitech.ac.jp

Gaudenzio Meneghesso, Guest Editor
University of Padova, Italy
gaudenzio.meneghesso@unipd.it

Tomas Palacios, Guest Editor
MIT Boston, USA
tpalacios@MIT.EDU

Ruediger Quay, Guest Editor
Fraunhofer, IAF, Germany
Ruediger.Quay@iaf.fraunhofer.de

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