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Introduction

Power semiconductor devices have been at the heart of power electronics industry. Application of power semiconductor devices has led to reduction in energy losses resulting in an increased system efficiency and also enables compact designing of power electronic systems. Silicon has been the semiconductor of choice for power device applications due to wide availability and mature technology. However, with increased focus towards renewable energy sources, electric vehicles and high-speed communications there is an increase in demand for highly efficient and compact systems with support for higher bandwidths. In addition to this, according to international energy agency, the demand for global energy consumption is increasing continuously and is estimated to see an increase of ~40% by 2040 [(IEA) 2016] of which a large fraction is of electrical energy (~60 %). The major performance limitation of these power electronic systems comes from the fact that a large portion of the generated electrical energy is lost during transformations carried out by the power semiconductor devices in the power electronic systems, like, DC-DC, AC-DC, DC-AC converters, industrial motor drives, switching mode power supplies, inverters for renewable energy, etc. In order to increase energy conversion efficiencies of these systems, it is essential to increase efficiency of power semiconductor devices by minimizing losses. In addition to this, as power semiconductor devices are expected to sustain high applied voltages, it is imperative for these devices to have high voltage blocking capabilities. However, increasing breakdown voltage of the device involves a trade-off with ON-resistance of the device, resulting in higher power losses. Although Si has been able to fulfill these demands for past few decades, it is challenging for Si based power devices to meet the requirements of modern power electronic systems. With device structure optimization reaching its limit and with more reliable production process, the performance of Si-based power devices is more and more limited by material properties. Material properties of Si imposes serious restrictions on its voltage blocking capability, operating temperature and switching frequency. Certain device design techniques have shown the capability to surpass these material limitations, like super junction based devices [AG 2008], but involve a substantial design and development cost.

In order to overcome material limitations, it is desirable to search for alternatives to Silicon. For power devices, semiconductor materials having a wider band-gap are desirable as the fundamental property of these semiconductors (wider band gap) leads to a higher critical electric field which enables reduction in conduction and switching losses while maintaining higher breakdown voltage. In addition to this, having a wider band gap results in devices having high temperature capability, high breakdown voltage and high thermal conductivity.

1.1 WIDE BAND-GAP SEMICONDUCTORS: ALTERNATIVE TO SILICON IN POWER APPLICATIONS

The term wide band-gap refers to a wide range of semiconductor materials, like diamond (C), group IV-IV compound semiconductor SiC, and group III-V semiconductors like GaN, AlN. A wider band gap carries several advantages important for applications in power domain, like, a higher thermal stability due to reduced intrinsic concentration, a higher critical electric field enabling a higher breakdown voltage with reduced ON-resistance. In addition to this, according to [Hudgins *et al.* 2003], wide band gap materials offer an additional advantage over their Silicon

counterpart in terms of coefficient of thermal expansion (CTE), which is better suited for ceramics used in packaging technology. With respect to CTE, it is expected that semiconductor materials having a closer CTE match to the thermally conducting ceramics can be easily adapted for higher power applications and can be operated up-to much wider temperature ranges. Keeping this restriction in mind, the possible material choices to replace Si in power semiconductor domain narrows down to C, GaN and SiC [Hudgins *et al.* 2003]. Several other material properties of these wide band gap semiconductors making them advantageous over Si for power applications are listed in Table 1.1.

Table 1.1: Material properties of wide band gap semiconductors compared to Silicon.

Parameter	*Unit*	*Silicon*	*4H-SiC*	*GaN*	*Diamond*
Band gap	eV	1.1	3.26	3.39	5.47
Intrinsic concentration	cm^{-3}	1.4×10^{10}	8.2×10^{-9}	1.9×10^{-10}	1×10^{-22}
Critical electric field E_C	MV/cm	0.23	2.2	3.3	5.6
Electron mobility μ_n	cm^2/V.sec	1400	950	~1500-2000	1800
Permittivity ϵ_r		11.8	9.7	9.0	5.7
Thermal conductivity	W/cm. K	1.5	3.8	1.3	20
BFoM: $\epsilon_r . \mu_n E_C^{-3}$	Normalized to Si	1	500	2400	9000

From these properties it is straight forward to infer the voltage handling capacity, as it is directly proportional to the band gap energy. However, in order to determine the dependence of ON-resistance on material properties Balliga's Figure of Merit (BFOM) = $\epsilon_r \mu_n E_c^3$, is a widely accepted performance metric [Baliga 2010] and is also listed in Table 1.1 for different semi-conductor materials. While diamond shows the most desirable properties for application in power domain with highest value for BFOM, however, the material and device fabrication facility for diamond (C) is much less mature as compared to SiC and GaN and moreover, the CTE of diamond is very low. This makes SiC and GaN as the most favorable candidates to replace Silicon [Hudgins *et al.* 2003, Abdelrahman *et al.* 2018, Bindra 2018b, Bindra 2018a]. GaN shows an incredibly high BFOM value when compared to Si or SiC, thereby suggesting a higher performance theoretically possible. Considering the BFOM, the theoretical material limits for specific ON-resistance compared with breakdown voltage of the device is as shown in Fig. 1.1.

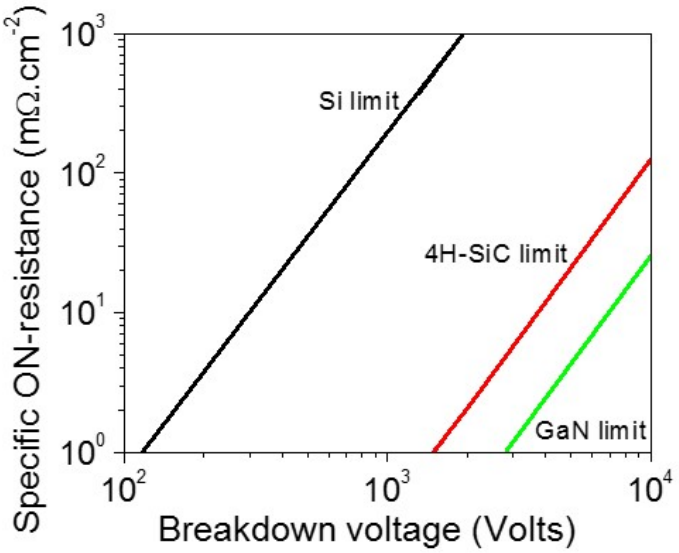

Figure 1.1: Theoretical material limit on ON-resistance v/s breakdown voltage trade off compared for three prominent semi-conductors in power electronics marker, Si, 4H-SiC and GaN [Baliga 2010].

Fig. 1.1 clearly indicates that GaN offers the minimum possible ON-resistance for high breakdown voltage that can be theoretically achieved. Thus, the physical properties of GaN, such as high critical electric field and high saturation velocity [Quay 2008] enable fabrication of power devices with higher breakdown voltage having a low specific ON-resistance and possibility to achieve higher operating switching frequency [Meneghini *et al.* 2017]. In addition to this, GaN offers a possibility of band gap engineering by employing GaN related alloys and hetero-structures, resulting in AlGaN/GaN High Electron Mobility Transistors (HEMTs). These hetero-structures show formation of a 2-Dimensional electron gas (2DEG) with sheet carrier density in range of ~10^{13} cm^{-2} and with higher electron mobility achieved in the range of 1500-2000 $cm^2/V.s$. The high electron density achieved in these devices results from presence of high spontaneous and piezoelectric polarization in these compound semiconductors combined with donor type surface traps present on AlGaN surface [Ambacher *et al.* 1999a, Ambacher *et al.* 2000, Ibbetson *et al.* 2000]. This in turn eliminates any need for doping in the AlGaN/GaN HEMT structures. In addition to this, it has been pointed out in [Chen *et al.* 2017] that lateral GaN HEMTs have a zero reverse recovery charge. This is enabled by absence of junctions in these devices and an effectively confined current flow in the polarization induced channel. This property results in GaN HEMTs to be the first choice in applications involving continuous switching on a reverse biased device such as in half-bridge or full-bridge configurations [Chen *et al.* 2017]. In addition to this, the GaN HEMT output capacitance shows a very linear characteristics resulting from expansion of space charge layer within an un-doped substrate. As a result, the capacitive charging time is reduced, leading to GaN HEMTs being faster than state-of-the-art Super Junction device by a factor of ~3.3 [Infineon].

1.2 POSSIBILITY OF GAN TO REPLACE SILICON IN POWER/RF SEGMENT

According to [Chen *et al.* 2017], for any technology to have a disruptive impact on the semiconductor market following four criteria must be satisfied:

1) It should enable significant new application areas,
2) should be easy to use,
3) should be cost effective,
4) should be robust.

1.2.1 GaN: Enabling new application areas

Superior material properties like high channel carrier density and higher electron mobility combined with high saturation velocity enables transistors and ICs based on GaN to be significantly faster and smaller than their Silicon counterparts. The operational speed achieved by GaN on Si has resulted in emergence of several new application areas like LiDAR for autonomous vehicles [Ohnsman], augmented reality systems, robotics [Gruber 2014], medical imaging and diagnostics [Murphy 2015, Twieg *et al.* 2015, Gudino *et al.* 2016], wireless power transfer [Lidow *et al.* 2014b, Morita *et al.* 2014, Ueda *et al.* 2014], and wideband data transmission such as that used in 4G/LTE base stations [Taranovich , Zhang *et al.* 2016] and several other application areas as described in [Ray 2016, Abdelrahman *et al.* 2018]. Increased physical understanding and technological progress gained in GaN based devices has resulted in commercial GaN transistors and ICs that are 5 to 50 times faster than their Si counterpart [Chen *et al.* 2017]. AlGaN/GaN HEMTs have been making steady progress in high-frequency and high-power performances [Shinohara *et al.* 2013, Roccaforte *et al.* 2014, Kuzuhara *et al.* 2015, Hashizume *et al.* 2017]. For breakdown voltages up to 600 V, highly efficient and high-frequency switching systems with compact size have been successfully demonstrated using GaN [Roccaforte *et al.* 2014, Kuzuhara *et al.* 2015, Jones *et al.* 2016]. In addition to this, GaN HEMTs are particularly well-suited for high power radio frequency (RF) applications owing to material properties like electron saturation velocity of 2x 10^7 cm/s and high sheet carrier density of 1 x 10^{13} cm^{-2}. These characteristics are highly desirable in the emerging 5G wireless system [Hashizume *et al.* 2017]. Even with such promising results, performance of GaN transistors is several magnitude lower

than what can be theoretically achieved [Lidow *et al.* 2014a]. Improvement in device performance is further expected with improved understanding of the material and device properties and technological advancement in growth of better quality GaN buffers. Enabled by these improvements several new application areas are expected to emerge.

1.2.2 Ease of use:

While GaN devices show promise of much improved speed of operation with minimized losses, it however poses serious challenges for device engineers as they need to pay special attention to parasitic elements in the circuit in order to harvest the true potential of GaN devices [Reusch *et al.* 2015]. In addition to this, while smaller size of GaN devices offers several advantages, this in turn requires tighter assembly tolerances which are similar to those used in computer and telecom equipment but are less familiar to power engineers [Chen *et al.* 2017]. However, according to [Chen *et al.* 2017], with technology engineers gaining experience with these smaller and faster GaN devices these problems can be effectively addressed for GaN technology which has already demonstrated capacity to seamlessly fit into the infrastructure built for silicon MOSFETs.

1.2.3 Cost effective technology:

With smaller device size, theoretically it is possible to accommodate a greater number of devices per manufacturing run, thereby reducing the per unit device cost. E. J. Lum has pointed out the advantages of HEMTs [Lum 1997] which exhibit three times higher power densities than MESFETs and as a result reduces the chip area. In addition to this, the lower device ON-resistance relaxes the need of costly packaging as compared to their Si alternatives especially in the lower voltage (< 500 V) regime [Lidow *et al.* 2015]. According to [Chen *et al.* 2017], this factor alone can reduce the cost by a factor of 2. Above factors combined with improved yield results in cheaper GaN transistors as compared to Si power MOSFETs which are much inferior in performance compared to GaN power devices [Lidow *et al.* 2014a]. However, the GaN transistors are still performing much below the theoretical limit and it is expected that with their performance reaching theoretical limits, it is possible to design GaN transistors that are more than 1000 times smaller than the Si power MOSFETs with same ON-resistance and voltage [Lidow *et al.* 2014a]. With technological advancement this gap between practical and theoretical performance of GaN device can be reduced and it is expected that the prices will further decline in future giving the GaN based systems an edge over the Si MOSFET based systems.

1.2.4 Reliability:

GaN devices have a significant advantage of being built on a wide band gap semiconductor. This increases the reliability of device at higher temperatures. In addition to this, several GaN transistor manufacturers have reported excellent results from the in-house electrical stress testing of GaN transistors [Bahl , Jacubiec]. With increased interest in GaN based devices, several studies have emerged explaining the physics behind failure mechanisms and performance degrading factors in AlGaN/GaN HEMTs. This improved understanding of device physics enables device design to have improved failure rates under actual operating conditions [Lidow].

The above discussion establishes that GaN has already achieved the four pre-requisites required to displace Silicon in the power market, especially in the voltage range of 15-650 V [Chen *et al.* 2017]. Higher switching speed, smaller size, competitive cost and improved reliability have resulted in a positive trajectory to displace silicon MOSFET in power conversion applications [Chen *et al.* 2017]. However, an improved knowledge of the device functionality and performance limiting factors is required to further improve device performance and reliability.

1.3 APPLICATIONS OF GAN:

While several advantages of wide band gap semiconductors, specifically GaN, have been discussed above with relevant application areas, this section discusses applications of GaN in power semiconductor devices in detail.

- In power generation and distribution, Micro-Grids with distributed generation are expected to reduce the emissions and greenhouse effect. Micro-grids require power converters with higher energy and minimized losses. However, power converters designed using Si are bulky and less efficient resulting in power losses. GaN based devices offer advantages in terms of reduced size and more efficient operation. The higher possible switching frequency and reduced voltage drop in GaN based devices will contribute to smaller and more efficient converters.

- Size and cost of the systems employing renewable energy power sources (Solar Power, Wind Power, etc.) can be reduced by improvement in conversion efficiency, higher frequency and high temperature operation enabled by GaN based devices.

- Automobile market is heading towards electric and hybrid vehicles. These systems will gain due to the high-temperature capability, high power density, and high efficiency offered by GaN devices [Abdelrahman *et al.* 2018]. In addition to this, size and weight of the GaN based systems will be considerably lower than that of Si based systems which will directly affect the whole power train system design and cost in these vehicles.

- Wider band gap increases the robustness of the device against temperature and radiations enabling use of GaN based devices in space applications.

- The lower ON-resistance and lower gate capacitance achieved in GaN devices will enable high efficiencies and high switching frequencies due to their low on-state resistance and low gate capacitance, respectively. In [Gamand *et al.* 2012] a dc/dc boost converter with a switching frequency of 10 MHz and an efficiency above 90% is presented. Moreover, techniques such as dead time optimization are also feasible using GaN switches [Joo *et al.* 2016].

- For wireless power transfer, an inverter using GaN power switches is demonstrated in [Choi *et al.* 2015]. Device characteristics such as fast switching capability, lower gate capacitance along with lower on resistance combined with the low inductive package make GaN device an ideal component for this application.

- Compact and highly efficient power inverters are desired for application in solar power generation and several other power-hungry appliances. Power inverters based on GaN switches have already demonstrated efficiencies above 99% with power output of 2kW operating at frequency of 120 kHz [Lei *et al.* 2016]. Several non-typical topologies are enabled by GaN power switches which could bring additional benefits not present yet [Colmenares 2016].

- Improved system efficiency provided by GaN based systems can benefit several other applications areas such as Envelope tracking, Light Distancing and Ranging (LiDAR), and Class D audio amplifiers. Improved efficiency in these systems could result in production of less heat, would save space and cost, and extend the battery life in portable systems.

1.4 GAN BASED HIGH ELECTRON MOBILITY TRANSISTORS:

With the above listed properties of GaN as a wide band gap semiconductor and with a wide range of application areas, devices based on GaN as a channel material hold the potential

to replace Silicon in the power semiconductor market. In order for the device to be adopted in power and RF domain, higher voltage handling capability and speed of the operation are most desirable properties for a semiconductor device.

With respect to higher speed of operation and reduced ON-resistance, device structures with enhanced mobility are desirable. On the other hand, a proper device design combined with material property of high critical electric field will eventually result in high breakdown voltages. With these requirements and possibility of GaN to form ternary compound with AlN, AlGaN/GaN HEMT devices are one of the most suitable candidates with desirable properties for power and RF applications. Taking advantage of the higher critical electric field of GaN, these devices offer a higher voltage blocking capability, and polarization field combined with improved channel mobility results in a higher channel carrier density as well as mobility. The AlGaN/GaN HEMT architecture and details relating to device design and associated reliability challenges will be discussed in chapter 2.

1.5 OUTLINE OF THE THESIS

With the promising properties offered by GaN combined with exciting features offered by HEMT structure, there has been an impetus on development of AlGaN/GaN HEMT devices with increased output power density and frequency of operation. In order to enhance device performance, it is of paramount importance to understand the device behavior and failure mechanisms. Computational analysis of the device behavior is an effective tool to understand device behavior, failure mechanisms and can also enable proposals to improve device performance. The primary objective of this work is to establish a well-defined computational approach to accurately estimate DC performance of the device. The computational framework is then employed to estimate avalanche breakdown in AlGaN/GaN HEMT devices in presence of carbon doping in GaN buffer.

While the aim of chapter 1 was to establish the introduction for this work explaining the focus on AlGaN/GaN HEMT devices, the device architecture, optimization parameters, reliability challenges, and associated physics are discussed in detail in chapter 2. The chapter will also establish the fundamental requirements to be fulfilled by a computational module to successfully replicate device characteristics. The relevance of computations in understanding the device physics and failure mechanisms along with its impact on technology development of GaN based devices is also discussed.

A detailed computational modelling framework for estimating DC performance of the device is discussed in chapter 3. Modeling of physical parameters important to estimate device performance in AlGaN/GaN HEMTs is discussed. Impact of buffer traps and lattice heating on the negative differential resistance (NDR) in AlGaN/GaN HEMTs is discussed with an objective to establish the source of NDR. Impact of polarization charge on energy bands and formation of parasitic channels in the device is discussed in combination donor type traps on device surface to model the 2-DEG channel at AlGaN/GaN interface. In addition to this, quantum effects along with carrier heating and Schottky gate leakage in combination with MESA induced leakage are taken into account to accurately estimate the output as well as transfer characteristics of the device along with the gate leakage.

In chapter 4, the computational framework is utilized for discussing device design with respect to one of the most important parameters for breakdown voltage improvement in these devices, i.e., GaN buffer. Specifically, behavior of C-Doping in GaN buffer leading to an improvement in breakdown performance of the device is discussed in detail. The physical origin for experimentally observed improvement in breakdown voltage on C-doping of GaN buffer is identified and reported for the very first time. The chapter also discusses the GaN buffer design

with respect to impact of C-Doping of GaN buffer on breakdown and DC performance of the device.

Based on the understanding developed in chapter 4 over the behavior of C-Doping in GaN buffer, a novel technique to improve device reliability and DC performance while maintaining high breakdown voltage is presented in chapter 5. The proposals rely on independently engineering acceptor and donor trap concentrations in GaN buffer to optimize the C-Doping requirement achieving ultra-high breakdown voltages with minimum possible acceptor traps in GaN buffer.

Summary and conclusion of the work carried out for this thesis is presented in chapter 6 along with the possible future research directions.

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