Studies of GaN-on-GaN vertical Schottky diodes for radiation sensing applications

Sandupatla, Abhinay

2019

Sandupatla, A. (2019). Studies of GaN-on-GaN vertical Schottky diodes for radiation sensing applications. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/137398>

<https://doi.org/10.32657/10356/137398>

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STUDIES OF GAN-ON-GAN VERTICAL SCHOTTKY DIODES FOR RADIATION SENSING APPLICATIONS

**ABHINAY SANDUPATLA
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**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

Studies of GaN-on-GaN Vertical Schottky Diodes for Radiation Sensing Applications

ABHINAY SANDUPATLA

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University in partial
fulfillment of the requirements for the degree of Doctor of Philosophy

2019

To

My wife

K. Gayathree

My Parents

S. Mahesh Kumar

S. Jyothsna

My Sister

S. Amani

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarized materials, and has not been submitted for a higher degree to any other University or Institution.

14th Aug-2019

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Date

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Abhinay Sandupatla

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

15 Aug 2019

Date

Prof. Ng Geok Ing

Authorship Attribution Statement

This thesis contains material from 8 paper(s) published in the following peer-reviewed journals and from papers accepted at conferences in which I am listed as an author.

Chapter 3 includes 4 publications

- A. Sandupatla, S. Arulkumaran, G. I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda and a. H. Amano, "GaN Drift layer thickness effects in vertical Schottky barrier diodes on free-standing HVPE GaN substrates," *AIP Advances*, **9**, 045007 (2019); DOI: 10.1063/1.5087491;
- A. Sandupatla, S. Arulkumaran, G. I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda and a. H. Amano, "Effect of GaN Drift Layer Thicknesses in vertical Schottky Barrier Diodes on Free-standing GaN substrate", SSDM – 2018, Tokyo, Japan.
- A. Sandupatla, S. Arulkumaran, G. I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda and a. H. Amano, "Enhanced breakdown voltage in vertical Schottky diodes on compensated GaN drift layer grown on free-standing GaN", ICNS-2019, Bellvue, Washington-USA
- A. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda, H. Amano, "Improved breakdown voltage in vertical GaN Schottky Barrier Diodes on free-standing GaN with

Mg-compensated Drift Layer” , JJAP-RC, vol. 59, no. 1, p. 010906, 2020.

The contributions of the co-authors are as follows:

- I co-designed this project with Dr. Arul and Prof. Ng Geok Ing, performed all laboratory work including simulation, fabrication, measurements and preparation of manuscript drafts.
- Prof. G.I. Ng provided valuable guidance, assisted in interpretation of results and edited the manuscript drafts.
- Dr S. Arulkumaran provided initial project direction, assisted with the analysis and edited manuscript drafts.
- K. Ranjan helped in the initial fabrication of devices, simulation of devices, establishing a measurement setup and edited the manuscript drafts
- Prof. Deki, Prof. Nitta, Prof. Honda and Prof. Amano were our collaborators from Nagoya University, who provided us GaN wafers and valuable guidance regarding the growth process along with help in editing the manuscript drafts.

Chapter 4 includes 2 publications

- Sandupatla, S. Arulkumaran, G. I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda and a. H. Amano “Effects of Drift Layer Thicknesses in Reverse Conduction Mechanism on Vertical GaN-on-GaN SBDs grown by MOCVD” in EDTM – 2019, Singapore
- A. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda, H. Amano, “*Change of high-voltage conduction*

mechanism in vertical GaN-on-GaN Schottky diodes at elevated temperatures", Applied Physics Express

The contributions of the co-authors are as follows:

- I co-designed this project with Dr. Arul and Prof. Ng Geok Ing, performed all laboratory work including measurements, analysis and preparation of manuscript drafts.
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- Prof. Deki, Prof. Nitta, Prof. Honda and Prof. Amano were our collaborators from Nagoya University, who provided us GaN wafers and valuable guidance regarding the growth process along with help in editing the manuscript drafts.

Chapter 5 includes 2 publications

- A. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, P. Murmu, J. Kennedy, M. Deki, S. Nitta, Y. Honda, H. Amano, "Low voltage high-energy α -particle detectors by GaN-on-GaN Schottky Diodes with record-high charge collection efficiency" Sensors, vol. 19, no. 23, p. 5107, 2019.
- A. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, P. Murmu, J. Kennedy, M. Deki, S. Nitta, Y. Honda, H. Amano, "Low leakage Mg-compensated GaN Schottky diodes on free-standing GaN substrate for high efficiency α -particle detection", EDTM-2020, Penang.

The contributions of the co-authors are as follows:

- I co-designed this project with Dr. Arul and Prof. Ng Geok Ing, performed all laboratory work including measurements, analysis and preparation of manuscript drafts.
- Prof. G.I. Ng provided valuable guidance, assisted in interpretation of results and edited the manuscript drafts.
- Dr S. Arulkumaran provided initial project direction, assisted with the analysis and edited manuscript drafts.
- K. Ranjan helped in the initial fabrication of devices, simulation of devices, establishing a measurement setup and edited the manuscript drafts.
- Dr. P. Murumu and Dr. J. Kennedy were our collaborators from GNS Science New Zealand who tested our α -particle detectors and provided us with measured data.
- Prof. Deki, Prof. Nitta, Prof. Honda and Prof. Amano were our collaborators from Nagoya University, who provided us GaN wafers and valuable guidance regarding the growth process along with help in editing the manuscript drafts.

14th Aug, 2019

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Date

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Abhinay Sandupatla

Acknowledgments

First I would like to express my sincere gratitude to my supervisor Prof. Ng Geok Ing for his guidance, support, and encouragement throughout the course of my PhD program. His continuous motivation has been a great positive influence on me to successfully complete this work.

I would like to thank my mentor Dr. S. Arulkumaran for imparting knowledge and guidance through his technical expertise. He has played a vital role in organizing and scrutinizing my work in order to make it worthy of publications in international journals and conferences.

My special thanks to Prof. S. Nitta, Prof. Y. Honda, Prof. M. Deki and Prof. H. Amano from Nagoya University, Japan, for their support in the growth of the wafers, timely response for our queries and for the preparations of journal and conference papers.

I would also like to thank Dr. J. Kennedy and Dr. P. Murumu from GNS, New Zealand, who have helped me with the radiation testing on the fabricated devices and the analysis of the test results. I would also like to thank them for offering technical advice and clarifications whenever I approached them.

My greatest gratitude extends to the staff of MMIC Design Center (MDC), Temasek Laboratories at Nanyang Technology University especially Kumud Ranjan for all his support and help in the fabrication and processing of the devices that form the very basis of my thesis.

In addition I would also like to thank my team members Matthew Whiteside, Dr. Li Yang, Dr. Weichuan, Dr. Alex and most importantly Dr. Liu Zhihong for their valuable help during this work.

I would also like to express my sincere gratitude to all lab staff in N2FC CR1 and CR2, especially Shamsul, Zulkiflee Abdullah, Dr. Gong Yih, Chung Kwok Fai and Ling Ling for their valuable help in the fabrication of my devices.

Above all, I would like to express my sincere gratitude to my wife Gayathree Karthikkeyan, parents S. Mahesh Kumar and S. Jyothsna, sister S. Amani and friends Prativa Das, Suki Roy and Ankur Sharma who have invested their trust in me and for standing beside me as the greatest moral support in difficult times

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Abstract

Gallium Nitride (GaN) with its large bandgap, high electron saturation velocity, and critical electric field has been widely applied in the fabrication of illumination, high frequency, and high-power devices. Recently, researchers are exploring radiation sensing as a probable application for GaN devices on the virtue of the high Displacement Energy (E_D) of GaN (20 eV) which is twice higher than any other semiconductors such as GaAs and Si. Up till now, different research groups have successfully fabricated GaN Schottky Barrier Diodes (SBD) and tested them in alpha particle detection. While SBDs with thin epitaxial layers ($<12\text{ }\mu\text{m}$) could only detect low energy alpha particles ($<4.5\text{ MeV}$) at -120 V, SBDs on bulk GaN substrate required very high voltage ($\sim 550\text{V}$) to detect higher energies (5.48 MeV). However, both bulk GaN SBDs and SBDs with thin epitaxial layers show extremely poor performance at low voltages. The poor performance of GaN-based radiation detector is due to high Threading Dislocation Density (TDD) and limited Depletion Width (DW). While high TDD increases leakage current (I_R) thus reducing the sensitivity of the detector, thin DW restricts the maximum energy which can be detected by a GaN detector.

In this thesis, the focus is to reduce I_R and increase DW by reducing TDD, Charge Carrier Density (CCD), and increasing Drift Layer Thickness (DLT). While TDD was successfully reduced by employing a GaN-on-GaN

structure, CCD was reduced by compensating the un-intentionally doped n-type (Si) dopants with p-type (Mg) dopants. In addition, multiple Drift Layers (DL) of different thicknesses were grown to study the impact on SBD performance. Finally, the fabricated SBDs were then tested as radiation detectors to detect 5.48 MeV alpha particles.

In this work, the employment of GaN-on-GaN structure reduces the lattice and thermal expansion coefficient mismatch which in turn results in ~ 3 orders of magnitude reduction of TDD. Approximately 2 orders of magnitude reduction in CCD was successfully achieved by compensating the unintentional n-type (Si) dopants with p-type (Mg) dopants. The reduced CCD results in 3 orders of magnitude lower I_R (3 pA) and ~ 3 times higher V_{BD} (1480 V), while having minimal impact on the forward current-voltage characteristics. It was also found that compensation also results in a change of conduction mechanism from barrier modified Thermionic Field Emission (TFE) to regular TFE due to thicker DW .

SBDs were fabricated on wafers with different DL thicknesses (2 μm , 5 μm , 15 μm , and 30 μm) to increase DW and enable high energy detection. While SBDs with thicker DL exhibited lower I_R , it also reduced forward saturation current. A linear increase in V_{BD} from 560 V to 2400 V, with an increase in DLT , was also observed. The measured V_{BD} of 2400 V in SBDs with 30 μm DLT is by far the highest reported V_{BD} . Increase of DLT has also resulted in a change of conduction mechanism from TFE to

Thermionic Emission (TE) due to a reduced probability of tunnelling in thicker *DLs*.

SBDs were tested for radiation sensing application by exposing them to Am-241 alpha particle source which releases 5.48 MeV alpha particles. These SBDs exhibited a near-ideal Charge Collection Efficiency (*CCE*) at 96% at -300 V. The detectors also exhibited 25% superior performance in low bias conditions (-20 V) with 3 times lower variation of efficiency as a function of applied voltage (-20 V to -80 V) in comparison with other reported GaN radiation detectors.

In summary, high-energy alpha particle detection at low voltages have been demonstrated in this work with the employment of compensated GaN-on-GaN SBDs to reduce the TDD, *CCD*, and increase the *DW*. The designed GaN detectors exhibited high *CCE* (65%) even at low voltages (-20V) thus shows the feasibility to realize compact and portability GaN-based radiation detectors.

List of Acronyms

BS	Breakdown strength
CCD	Charge carrier density
CCE	Charge collection efficiency
CL	Cathodoluminescence
CM	Conduction mechanism
DL	Drift layer
DLT	Drift layer thickness
DW	Depletion Width
E_d	Displacement energy
E_a	Activation energy
FP	Field plate
HVDC	High Voltage Direct Current
HVPE	Halide vapor phase epitaxy
ICP-RIE	Inductively coupled plasma – reactive ion etching
I_R	Reverse leakage current
I_{sat}	Forward saturation current
JBS	Junction Barrier Schottky
MOCVD	Metal-organic chemical vapor deposition
n	Ideality factor
SBD	Schottky barrier diode

SIMS	Secondary mass ion spectroscopy
TDD	Threading dislocation density
TE	Thermionic Emission
TFE	Thermionic Field Emission
UV	Ultraviolet
ϕ_B	Barrier Height

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1 Introduction

1.1 Gallium Nitride (GaN)

Among the III-V semiconductors, Ga and it's alloys have emerged as the best semiconductor materials for lighting, electronic and sensing applications due to their superior inherent material properties such as direct bandgap, higher energy bandgap (3.4 eV), critical electric field (3.3 MV/cm), electron saturation velocity ($\sim 2 \times 10^7$ cm/sec), and thermal conductivity (2.78 W/cm.K) when compared with other popular semiconductors (see figure 1.1).

Figure 1.1: Comparison of various properties of important semiconductors Si, SiC, and GaN [1, 2, 3, 4].

GaN is a direct bandgap semiconductor which has enabled its use in many modern-day optoelectronic devices like laser diodes and LEDs. GaN's large bandgap of 3.4 eV has resulted in the generation of ultraviolet, blue and green shades of light. The availability of these colour light sources has helped the realization of full-colour LED displays by complementing the color spectrum of available LEDs.

Other advantages of GaN such as high critical electric field, high bandgap, high mobility, and high saturated electron velocity have enabled GaN electronic devices to have high breakdown voltages (V_{BD}) which can support high current densities. Fig.1.2 shows the various applications of GaN-based devices presently being employed, ranging from lighting to high voltage direct current (HVDC).

Figure 1.2: Device blocking voltage and device current requirements for various application [5].

While the applications like lighting, power supply, and HVDC are well researched, GaN's application in sensing is still in its infancy. High bandgap and thermal conductivity have encouraged many researchers to explore the application of sensing using GaN Schottky barrier diodes (SBD). Researchers have reported GaN SBDs sensors such as ultra-violet (UV) sensor [6] and hydrogen sensor [7](see figure 1.3 below).

Figure 1.3: Schematic diagrams of GaN-based sensors for (a) UV light detection, and (b) Hydrogen detection

In both sensors, Hydrogen or UV light sensor detection happens in the depletion width (DW) where the presence of H atoms or UV light generate e-h pairs, which cause a change in I - V characteristics. This change is detected to signify the presence of H-atoms or UV light.

Other materials have also been utilized to develop similar sensors for a wide range of applications.

Table 1.1: Comparison of various parameters useful for sensing applications [8].

Parameters	Types of sensors			
	Electro-chemical cells	Polymers	Metal Oxide	GaN
Sensitivity	Moderate	High	Poor	High
Selectivity	Poor	Poor	Moderate	High
Response Time	Moderate	Fast	Moderate	Fast
Lifetime	Limited	Moderate	Long	Very long
Energy Consumption	Low	Low	High	Low

Table I compares sensors made of different materials based on their parameters like sensitivity, selectivity lifetime, etc. An understanding of these parameters indicates GaN is a better choice for highly efficient, sensitive, and reliable sensors.

Besides UV and gas sensing applications, GaN has also been used as radiation detectors because of its high displacement energy (E_d) [9](see figure 1.4 below).

Figure 1.4: Displacement energies of different semiconductors.

E_d is defined as the energy required to displace an atom from its crystal lattice. Once an atom is displaced from its lattice position it compromises the structural integrity of the material resulting in damage to the structure. High E_d implies higher energy is required to damage the crystal structure of GaN. This strength helps GaN-based detector to withstand higher dosage of particle radiation and increase the lifetime of a GaN detector. Researchers have previously explored semiconductor-based radiation detectors using GaAs (see figure 1.5) due to its mature growth process.

Figure 1.5: Alpha particle detector on a GaAs wafer [10].

Although GaAs has a superior and matured growth process, its application has been proven to be inferior to GaN-based detectors due to the lower E_d [11]. B.D. Weaver et al. in 2016 compared and proved that GaN could withstand 10 times higher dosage in comparison to GaAs (see figure 1.6).

Figure 1.6: Drain current vs. dose damage for GaN and GaAs

This capability of GaN to withstand 10 times higher dosage translates to 10 times longer lifetime than GaAs based detectors when both are exposed to a similar amount of radiation dosage. In addition to higher E_d , GaN also has higher critical electric breakdown field (3.3 MV/cm), which is ~8 times higher than GaAs (0.4 MV/cm). Higher electric breakdown field helps SBDs to withstand higher reverse voltages and generate thicker DW, which could help to detect higher radiation energy particles.

Fig. 1.7: State of the art GaN Schottky rectifiers with a performance limit of GaN, SiC, and Si [12]

Higher critical electric breakdown field also translates to a higher theoretical limit for the breakdown voltage in GaN devices. However, from

figure 1.7, we can observe that no research group has been able to achieve V_{BD} close to the theoretical limit of GaN. These reported V_{BD} of GaN SBDs have been primarily limited by high threading dislocation density (TDD) and charge carrier density (CCD) in their epitaxial layers. High TDD is generated due to the lattice mismatch between the GaN epitaxial layer and its substrate (Si, SiC, or Sapphire). To reduce this TDD, researchers have employed GaN-on-GaN structures.

1.2 Why GaN-on-GaN?

Difficulties in bulk crystal growth resulted in the delay in the development of native GaN substrate. As a result, GaN epitaxial layers are typically being grown on hetero-epitaxial substrates such as Si, Sapphire, and SiC. The high lattice mismatch and thermal expansion coefficient mismatch results in the generation of high TDD (see table II).

Table 1.2: - Lattice mismatch, thermal expansion coefficient mismatch, and TDD for GaN epitaxial layers grown on various substrates [13].

Parameter	Si	Sapphire	SiC	GaN
Lattice mismatch	-17%	-33%	3.5%	0
Thermal Expansion coeff. Mismatch	116%	-23%	24%	0
Threading Dislocation densities (/cm ²)	$\sim 10^9$	$\sim 10^9$	$\sim 10^7$	$\sim 10^4$

The high TDD in GaN epitaxial layer due to non-native substrates results in the generation of multiple low resistive current leakage paths. These low resistive paths not only increase the leakage current (I_R), but they also result in their coagulation. To reduce I_R and increase V_{BD} , it is necessary to minimize the TDD by growing GaN epitaxial layers on native GaN substrate, namely GaN-on-GaN structures.

The development of GaN-on-GaN has been limited due to difficulty in the growth of large GaN crystal. These crystals require high pressure (6 GPa) and high temperature (2200°C) during the growth [13], which pose difficulties in the traditional melt-solidification method for GaN substrate manufacturing. These difficulties were later overcome, and bulk GaN crystals with good quality can be realized by three different methods. The main GaN crystal growth methods include:

- The first method is an improvement of growth system, where adding of Sodium (Na) to Gallium (Ga) along with the increased concentration of Nitrogen (N) reduces the temperature and pressure requirement for GaN growth (800°C and 5 MPa) [14].
- In the second method, researchers employed the technology utilized for Quartz manufacturing to manufacture GaN, which is called the ammonothermal method. In this method, Ammonia is used as a solvent, KNH_4 , and NH_4Cl as a mineralizer. In this

method, GaN crystal is grown at 600°C with high pressure of 400 MPa. [15].

- Finally, the third method employed was borrowed from the developed and established method of growth for GaAs and InP and later used for the manufacturing of GaN based device structures. This method is called hydride vapour phase epitaxy (HVPE). HVPE provides us with the highest growth rate of several hundred micrometers per hr, which is high enough for the growth of GaN several millimeters in thickness. With the advancement of GaN growth by HVPE, free-standing GaN substrates are now available up to 4-inches in diameter.

The reduced defect density results in reduced tunnelling paths for electrons under reverse-biased conditions, which in turns reduces the I_R . Lower leakages and high forward currents result in diodes with improved V_{BD} . P. Zhao et al. had published comparison studies which show improvement from 0.9 eV to 1.1 eV in barrier height and 2.5 to 1.1 in ideality factor (n) of SBD when the substrate was changed from sapphire to GaN [16]. Similar results were also published by N. Tanaka *et al.*, who reported the lowest I_R at 26.5 $\mu\text{A}/\text{cm}^2$ at -400 V [17]. Lower TDD also results in devices being more thermally stable, have longer mean time to failure (MTTF), higher reliability, and improved performance consistency.

1.3 Motivation and Objective

Although significant improvement in SBD characteristics has been achieved by growing GaN epitaxial layers on the GaN substrate, the highest reported breakdown strength (BS) (2.2 MV/cm) [18] is still sub-par and significantly below the theoretical limit of GaN (3.3 MV/cm) [19]. Improvement in V_{BD} plays an essential role for sensing applications as resolution, sensitivity, and the upper limit of detectable energy of the detector are dependent on it. Higher V_{BD} helps generate and maintain thicker DW , which would help detect higher energies. Hence, for GaN to be a viable semiconductor material for radiation sensing applications, better-performing SBDs with higher V_{BD} and lower I_R are highly required. This thesis mainly focusses on the studies of SBDs to improve the V_{BD} and reduce I_R by optimizing CCD and drift layer thickness (DLT). A novel structure of compensated drift layer (DL) has been employed to reduce the CCD , which increases V_{BD} and reduces I_R . The physics behind these improvements was further analyzed in detail by extracting the conduction mechanism and activation energies of the I_R in the SBDs. To further improve the SBD characteristics, multiple wafers with different DLT were grown, on which SBDs were fabricated. The effect of DLT on SBD characteristics was thoroughly analyzed, and the physical reasoning behind the changes was explained. The optimization of CCD and DLT has

helped realize improved sensing performance of our SBDs with near-ideal CCE of 96.7% at -300 V and record-high CCE of 65% at -20 V.

Chapter 2 introduces the various material studies performed on our samples to ascertain the quality of GaN by extracting characteristics like threading dislocation density (TDD) by panchromatic cathodoluminescence (CL), elemental composition by secondary mass ion spectroscopy (SIMS), doping concentration by Hall measurements and GaN crystalline quality by XRD. The various material characterizations provide us with a physical understanding of the observed results. A description of the various steps involved in the fabrication process of SBDs is also introduced.

Chapter 3 introduces a novel idea of compensation of unintentional n-type (Si) doping in *DL* by p-type (Mg) to increase the *DW*. We performed a systematic comparative study between two similar wafers with and without compensation to analyze the effect of compensation on SBD characteristics.

Chapter 4 explores the idea of further increasing the *DW* by employing compensated *DLs* of different thicknesses along with the studies of the effects of variation in *DLT* on both the forward and reverse SBD characteristics.

In Chapter 5, we introduce the theory of different types of conduction mechanism (CM) and the physics behind the reduction in I_R and the increase in V_{BD} due to the impact of Mg compensation and the increase of DLT . The CM of SBDs with thicker DL s (15 μm and 30 μm) were studied in more detail by biasing them at high reverse voltages to understand the effects of high reverse voltages on compensated SBDs.

Chapter 6 presents the experimental results of the fabricated SBDs for α -particle detection. The variations in measured α -particle spectra as a function of applied voltage, detector dimensions, and test conditions (air versus vacuum) are also presented.

In chapter 7, the conclusion and the lifetime contributions are summarized. Recommendation and future research scope are also presented.

2 Material Analysis of GaN-on-GaN wafer and Fabrication of SBDs

In this chapter, we will discuss the various material characteristics of the grown GaN-on-GaN wafers and the fabrication process for Schottky barrier diodes (SBD). GaN substrates used in this work were grown by hydride vapor phase epitaxy (HVPE) technique [20] with a doping concentration of $1 \times 10^{18} / \text{cm}^3$. Different epitaxial GaN layers were grown by metal-organic chemical vapor deposition (MOCVD) [21] on these free-standing GaN substrates by Nagoya University in Japan. These epitaxial layers varied in thicknesses and doping concentration. Figure 2.1 shows the final cross-sectional schematic of the wafer used for the fabrication of SBDs.

Figure 2.1: Cross-sectional Schematic of the grown wafer

2.1 Material Characteristics

Fundamental material characteristics like dislocations, defects, crystallinity, etc. of a semiconductor govern the operating characteristics of the devices. These material properties are essential since they impose a technical restriction on the performance of the device. In this chapter, the various techniques such as CL, SIMS, Hall, and XRD are used to extract threading dislocation density (TDD), elemental composition and densities, doping concentrations and crystal structure, respectively.

2.1.1 Threading Dislocation Density –

Cathodoluminescence

TDD is the density of defects generated in the GaN Crystal structure due to lattice and thermal expansion coefficient mismatch. Figure 2.2 shows the creation of threading dislocation due to the lattice mismatch between GaN and Sapphire.

Figure 2.2 Lattice mismatch between GaN and Sapphire creates dislocation

These defects provide a low resistance leakage path for electrons to traverse through the *DW*, leading to an increase in leakage current (I_R), thereby severely affecting the performance of the device [22].

In this work, TDD was extracted by panchromatic cathodoluminescence (CL) [23]. In CL measurement the material is exposed to an electron beam resulting in different processes at beam-material interaction. Among these processes, few generate electromagnetic radiation in visible spectral range and are called CL. When an incident electron beam energizes electrons in the ground state to higher energy states, they return to their ground state after their lifetime. When these energized electrons return to their ground state, they emit optical energy leading to fluorescence (see figure 2.3).

Figure 2.3: Various material analysis can be performed based on the incident electron beam.

CL imaging collects and measures the optical energy generated by the e-beam interaction with the material. By moving the incident e-beam, one can scan a pre-defined area of the material with a single-pixel resolution. The emission of light is highly dependent on the material on which electron beam is incident. In case of a GaN layer, no light is emitted when an electron beam is incident on dislocation or crystal defect [23]. Therefore, by calculating the density of the dark spots, one can determine the TDD of the wafer.

CL imaging was performed using a FESEM 7600F* system at 30kV beam strength, 30000x magnification over a 30 μm x 30 μm area on all wafers used in this work to obtain the TDD.

Figure 2.4: Panchromatic CL images of wafers with (a) 0 μm , (b) 2 μm , (c) 5 μm , (d) 15 μm and (e) 30 μm *DLT*

Figure 2.4 shows a sample CL image of each wafer with each dark spot corresponding to a single threading dislocation. The measured TDD of $1.71 \times 10^6 / \text{cm}^2$ to $4.46 \times 10^6 / \text{cm}^2$ lies within the range of all other published values ($1 \times 10^6 / \text{cm}^2$ to $7 \times 10^6 / \text{cm}^2$) for GaN-on-GaN structures [24, 25, 26, 27].

Table 2.1: List of the average dark spot densities extracted by CL and the number of locations measured to obtain the average.

Sample ID	Drift Layer Thickness (μm)	Average TDD NTU by CL ($\times 10^6 / \text{cm}^2$)	No. of Locations measured by CL
J0120S	0	3.84	3
J0120	2	1.86	6
N0038	5	2.02	5
N0013	15	1.71	8
N0056	30	4.46	5

2.1.2 Elemental Composition – SIMS Measurements

An ideal GaN crystal has Ga and N in a 1:1 ratio. However, during growth, other elements like Carbon, Oxygen, Silicon, Iron, and Nitrogen can get introduced into the crystal lattice. These impurities affect the performance of a device fabricated on GaN material as they can provide electrons or holes depending on their valence electrons. To understand the impact of these impurities, their quantification is essential. In addition, in our designed structure, Magnesium (p-type) is also doped in the GaN epitaxial layer to reduce the n-type (Si) concentration. To quantify all the impurities present, secondary ion mass spectroscopy (SIMS) was performed by sputtering the surface of the material with focused primary ion beam and collecting the ejected secondary ions (see figure 2.5 below). The mass/charge ratio of the emitted secondary ions are measured with a mass spectrometer to determine the elemental, isotopic, and molecular composition up to 5 μm depth.

Figure 2.5.: Working Principle of SIMS analysis

In this work, SIMS measurements were performed using commercial vendor, and the obtained results have been plotted and tabulated below.

Figure 2.6: SIMS analysis results for various elemental concentrations for samples with (a) 2 μm *DLT*, (b) 5 μm *DLT*, (c) 15 μm *DLT* (d) 30 μm *DLT* and (e) 15 μm conventional *DLT*

From figure 2.6 the presence of Mg-ions was verified in the DLs of all compensated wafers. To study the effect of Mg-compensation a conventional wafer with a DLT of 15 μm was grown without presence of Mg-ions (see fig 2.6 e)

The data extracted from SIMS results have been tabulated in table 2.2.

Table 2.2: Extracted elemental concentration from SIMS analysis

Element	Detection Limit	Measured Concentration by SIMS [cm^{-3}]				
		<i>DLT</i> 2 μm	<i>DLT</i> 5 μm	<i>DLT</i> 15 μm	<i>DLT</i> 30 μm	<i>DLT</i> 15 μm Conv.
Si ($\times 10^{14}$)	1	30	40	150	60	400
C ($\times 10^{15}$)	3	20	20	25	12	10
O ($\times 10^{15}$)	3	2	2	3	2	3
Mg ($\times 10^{14}$)	2	30	10	150	10	8
Fe ($\times 10^{14}$)	6	70	20	70	10	9
CCD ($\times 10^{14}$)		12	22	7.6	41	400

As shown in Table 2.2, the measured oxygen concentration was always lower than the detection limit suggesting that no significant amount of O_2 was observed in the samples. The elemental concentrations in different wafers were measured to be in the expected range for all wafers. While Si in *DL* acted as n-type dopants, Mg was a p-type dopant leading to reduced charge carrier density (*CCD*) from $7.6 \times 10^{14}/\text{cm}^3$ to $4.1 \times 10^{15}/\text{cm}^3$, which is 1-2 orders of magnitude below the conventional wafer.

2.1.3 Charge Carrier Density – Hall Measurement

Although elemental concentration and CCD values were extracted from SIMS analysis, CCD was also measured by Hall Measurement to verify the carrier density obtained. Reduction in CCD plays a vital role in the improvement of GaN devices by increasing V_{BD} and decreasing I_R .

The Hall measurement is based on Lorentz force wherein static magnetic field applied perpendicular to current flow will introduce an electric field which is perpendicular to both the magnetic field and the current flow. On measuring the Hall voltages generated, it is possible to measure the resistivity, mobility, charge carrier type, and charge carrier density [28]. Van der Paw method is commonly used for electrical characterization of small flat samples. This technique requires samples to have four ohmic contacts on the outer perimeter and the wafer to be uniformly thick, as shown in figure 2.7 below.

Figure 2.7: Hall sample being measured by van der Pauw method.

In this work, Hall measurements were performed using the BioRAD Hall measurement system (see figure 2.8)

Figure 2.8: BioRAD Hall Measurement System

In this method, multiple measurements were taken by changing the terminals across which voltage and current were measured. This removes measurement and probing errors. On successful completion of the measurement, we can extract the sheet resistance, mobility, type, and concentration of charge density. Due to exceptionally low doping

concentration in our compensated wafers, extremely high resistivity was measured. This high resistance limited the extraction of most parameters.

Table 2.3: Measured doping concentration and sheet resistance using Hall measurements

	Doping Concentration (/cm ³)	Sheet Resistance (Ohm/sq)
0 μm	10^{18}	0.5
Compensated 15 μm	10^{14}	5×10^6
Un-compensated 15 μm	10^{16}	1.26×10^2

2.1.4 Crystal Structure - X-Ray Diffraction (XRD)

GaN crystal structure plays a vital role in determining the performance of the electronic devices. Poor crystal structure results in the change of important properties like thermal conductivity, electron saturation velocity, critical electric field, and electron mobility. To exploit all the advantages of GaN, the use of highly crystalline GaN is mandatory.

To obtain the crystalline quality of the MOCVD grown drift layer, XRD was performed using PANalytical X'Pert³ MRD XL with a beam voltage of 30 kV and 10 mA current in two orientations namely 002 and 102 on all wafers. Measurements on all samples resulted in similar FWHM, which indicates the similar crystalline quality of all GaN layers grown by MOCVD.

Figure 2.9: Sample XRD profile showing FWHM for (a) 002 and (b) 102 orientations

Measured XRD results are shown in figure 2.9, from which full width half maximum (FWHM) of 108.4 arc.sec and 260.6 arc.sec was extracted at 002 and 102 orientations, respectively. The extracted FWHM lies within previously published results, indicating the high crystalline quality of the GaN drift layer [29, 30].

2.2 SBD Device Fabrication

After all material analysis, the wafer is cleaned using piranha solution 1:3:: H₂O₂:H₂SO₄ to remove organic residue followed by organic cleaning with

acetone and Isopropanol. The samples were then rinsed with DI and blow-dried with N₂.

SBDs were fabricated by two different methods: (1) optical lithography and (2) Shadow Mask

2.2.1 SBD Device Fabrication – Optical Lithography

The SBD fabrication using Optical Lithography technique comprises of 3 steps, namely, mesa isolation, Ohmic contact formation, and Schottky contact formation.

The conventional process flow for SBD fabrication using optical Lithography has been shown in figure 2.10 below.

2.2.1.1 Mesa Isolation

Mesa isolation is used to isolate adjacent devices. Typically, it is achieved by dry etching such as inductively coupled plasma - reactive ion etching (ICP-RIE). Mesa step starts with a coating of 1.4 µm photoresist layer of AZ5214 using a spin coater and soft baking it for 2 min at 105°C. After soft bake, the pattern from the chrome-based optical mask for mesa stage is transferred onto the photoresist layer using UV light (405 nm) – contact mode mask aligner. This transferred pattern is developed by CD-26 developer. Once the Mesa pattern is developed, PR residue is removed by O₂ plasma descum. The wafer is then loaded into ICP-RIE for etching.

Pre-calibrated programs are used to etch 150 nm of GaN. GaN etching is carried out by Cl_2 and BCl_3 gasses. Etched wafers are then transferred for the next step once GaN etch depth of ~ 150 nm is measured by a Dektak Surface Profiler.

Figure 2.10 Four-step Schottky Barrier Diode fabrication process

2.2.1.2 Ohmic Contact Formation

Good Ohmic contact with low resistance helps increase the current flow. The contact resistance of the Ohmic contact is influenced by a lot of factors like doping concentration, metal stack used in making the ohmic contact, metal-semiconductor interface, annealing temperature, and duration, etc.

The mesa-etched sample is cleaned again organically with acetone and iso-propanol to remove any residues present on the surface after the mesa etching process. Organic cleaning is followed by surface treatment in buffered oxide etchant for 2 min. Surface treatment improves the metal-semiconductor contact leading to better ohmic contact. After surface treatment, the wafer is placed in an electron beam (e-beam) evaporator to deposit Ohmic contact metal stack consisting of Ti/Al/Ni/Au (20/120/40/50 nm). After deposition of the metal stack, the wafer is annealed in rapid thermal annealer at 775°C for 30 seconds.

2.2.1.3 Schottky Contact Formation

For Schottky contact formation, the Schottky metal stack plays a very crucial role. A high work function metal like Ni or Pt is generally preferred as a Schottky contact for GaN wafer. We have used 50nm of Ni followed by 1000 nm of Au to prevent oxidization of Ni and facilitate the subsequent wire bonding process.

Annealed wafers are again cleaned with Acetone and IPA after which Ga side of the wafer is coated with PR, and Schottky pattern is developed similar to mesa pattern. Unlike Mesa pattern after development, oxides on the surface of the wafer are removed by BOE. The wafer is then placed in e-beam to deposit Ni/Au (50/1000 nm) metal stack. After metal deposition, the wafer is dipped in either Acetone or AZ 300T PR stripper to lift off the

unwanted metal. Figure 2.11 below illustrates the basic principles behind the lift-off process.

Figure 2.11 Principles of lift off

One of the final fabricated SBDs is shown in figure 2.12, where the SBD is 250 μm in diameter.

Figure 2.12: Image of a fabricated diode of 250 μm diameter

2.2.2 SBD Fabrication – Shadow Mask

The second method of SBD fabrication utilized a metal shadow mask. While the initial steps of fabrication were similar to optical lithography, the only difference was in the formation of Schottky contact. In place of the complicated optical lithography, we fabricated the Schottky contact via a shadow mask which covered the wafer during e-beam deposition of Ni/Au. On completion of the deposition, SBDs were ready for measurements. Use of a shadow mask eliminated the need for lithography and lift-off process. Figure 2.13 below shows the SBD fabrication using a shadow mask.

Figure 2.13 Fabrication of SBD using a shadow mask

The final SBDs fabricated are shown in Fig 2.14, of which the smallest circles are of 0.5 mm diameter and the largest ones are 1 mm in diameter.

Figure 2.14 Top image of the fabricated SBDs

3 Enhanced Breakdown Voltage in

Compensated Vertical GaN-on-GaN SBD

3.1 Introduction

As discussed in chapter 1, GaN-based SBDs are excellent for radiation sensing applications as compared to other incumbent semiconductors such as Si and GaAs. The designing of a radiation detector is primarily dependent on three major parameters namely displacement energy, depletion width, and leakage current.

- Displacement Energy (E_d) – High E_d improves the lifetime of the detector, as discussed in chapter 1. GaN has the highest E_d among major semiconductors making it an optimum material choice for radiation detection applications [31].
- Depletion Width (DW) – thickness of DW plays an important role in radiation detection as it corresponds to maximum energy which can be detected. Thicker DW is required to detect higher radiation energy. For example, Q. Xu et al. has reported a requirement of 19 μm DW to detect 5.48 MeV of energy [32].
- Reverse Leakage Current (I_R) – Radiation detectors are mainly biased in the reverse bias region to increase DW . In an ideal detector, the current that flows through it should be due to the incidence of a charged particle into the DW , but in practical

detectors non-zero I_R exists. This I_R needs to be minimized for improved detection sensitivity and resolution [33].

In chapter 1, we have discussed how GaN-on-GaN structures help SBDs reduce reverse leakage current density (I_R) and increase breakdown voltage (V_{BD}) by reducing threading dislocation density (TDD). Another huge advantage of employing GaN-on-GaN structure is that it allows the fabrication of vertical SBDs. A vertical structure prevents current crowding at the edges as in the case of lateral devices, but instead distributes the electric field uniformly, thus increasing V_{BD} (see Figure 3.1).

Figure 3.1: Electric field distribution in reverse bias for (a) Lateral and (b) Vertical SBDs

This uniform electric field distribution helps to better exploit the high electric field strength of GaN (3.3 MV/cm) [34]. Various research groups have already fabricated vertical GaN-on-GaN SBDs with reduced TDD to improve V_{BD} [35], but the highest reported field strength is 2.2 MV/cm by Sumitomo Electronics [36], which is still quite low in comparison to the theoretical limit of 3.3 MV/cm. This difference in the highest achieved electric field strength and the theoretical limit of GaN implies that there is

a need for further improvement in V_{BD} . Even though many research groups have tried to improve V_{BD} , they have been unsuccessful due to the incorporation of unintentional n-type (Si) doping during the growth of GaN by Metal Organic Chemical Vapor Deposition (MOCVD). To increase V_{BD} and DW while decreasing I_R , we have employed two different methods-

1. Reduced CCD in DL by Compensation
2. Increased DL thickness (DLT)

3.2 Simulation – Effect of CCD and DLT

To first enhance our understanding of the effect of CCD and DLT on V_{BD} , Selbeherr's model of impact ionization was simulated using SILVACO to estimate the breakdown voltages of the diodes. Selbeherr's model is the most basic model of breakdown and takes a lot of time for compilation. Many other models like Grant's are simplified versions of Selbeherr's model to reduce processing time. Due to the simplistic structure of diodes the simulation of the device characteristics is easy and requires a low processing capability. Figure 3.2 shows the simulated variation in V_{BD} as a function of CCD for five different DLT .

Based on these simulation results, it is evident that thicker DL with low CCD will result in higher V_{BD} . This rise in V_{BD} with DLT and lower CCD is due to the increase in DW . The simulation also shows that at higher doping concentrations, the thickness of DL does not affect the V_{BD} . While

the effect of reducing doping concentration on V_{BD} is minimal in SBDs with 2 μm DL , it is more evident in thicker DL . Based on these simulation results, it is clear that CCD plays an important role in determining the V_{BD} for SBDs with thicker DL .

Figure 3.2 Effect of CCD for DL s of different thickness.

3.3 Reduced CCD in DL by Compensation

During MOCVD growth of GaN, Si impurities are unintentionally incorporated, leading to n-type doping. This unintentional doping leads to increase of charge carrier density (CCD) resulting in thinning of DW [37]. Figure 3.3 shows the band diagram schematic of an SBD with a thick and thin DW . Thin DW increases the probability of an electron tunnelling through, resulting in higher tunnelling current and increased I_R .

Figure 3.3: Band diagram representation of SBDs with (a) thick and (b) thin DW .

To achieve thick DW and low I_R , reduction of unintentional doping of Si is mandatory. However, the success in achieving this has been limited due to growth limitations [38]. Our approach of reducing CCD is by compensating the n-type (Si) doping with p-type (Mg) doping in the drift layers (DL). p-type doping results in the generation of holes which help trap electrons, thereby reducing the resultant CCD . The reduced CCD should, in turn, help reduce I_R and increase V_{BD} .

To experimentally study the effect of reduced CCD in DL s of SBDs, electrical characteristics measured from I - V and Breakdown Voltage Measurements were compared between SBDs with 15 μm compensated DL and 15 μm conventional DL . Fabrication of the SBDs has been covered in section 2.2, and their electrical characterization were performed using Agilent B5210A power device analyzer.

3.3.1 I-V Measurements

Figure 3.4 (a) and figure 3.4 (b) show both the reverse and forward current characteristics of SBD with 1mm in diameter. It can be observed in figure 3.4 (a) that compensation has resulted in a ~ 3 orders of magnitude decrease in I_R at -20 V due to the reduced CCD . Figure 3.4 (b) shows the effect of compensation on the forward characteristics. Although we observe a slight decrease in forward saturation current (I_{sat}) from 0.27 A/cm² to 0.11 A/cm², the drop is minimal in comparison to I_R . Increased series resistance due to a reduction in CCD is the primary cause of the decrease in I_{sat} .

Figure 3.4 (a) Reverse and (b) Forward I - V characteristics of compensated and conventional SBDs of 1mm dia.

From the measured forward I - V characteristics, Ideality Factor (n) and Barrier Height (Φ_B) were extracted using equations 3.1 and 3.2. [37]

$$\Phi_B = KTq \ln I_{sat} A A^* T^2 \quad (3.1)$$

$$I = (eqVnKT/-1) \quad (3.2)$$

where I_{sat} is the forward saturation current, A is the diode contact area, K is the Boltzmann's constant and A^* is the Richardson's constant with a theoretical value of $26.9 \text{ A/cm}^2\text{K}^2$ [39].

Average ideality factors of 1.03 and 1.05 were extracted from 10 SBDs with compensated and conventional DL , respectively. The near-unity

ideality factor signifies an excellent metal-semiconductor interface at the Schottky-semiconductor contact [40]. To ensure the formation of an excellent metal-semiconductor interface, the wafers were thoroughly cleaned by Piranha solution followed by organic cleaning and dipping in buffered oxide etchant for 2 minutes [41]. The similarity of values in n among the SBDs both with and without compensation shows that compensation does not affect n of SBDs. Similarly, the extracted Φ_B for both compensated (0.77 eV) and conventional (0.89 eV) SBDs are close and also similar to other reported Φ_B for Ni-based Schottky contacts [42, 43, 44].

Table 3.1: Comparison of measured and extracted parameters for SBDs with compensated and conventional DL .

Sample	R_{sh} (ohm/sq) (Hall)	I_{sat} (A/cm ²) (2V)	I_R (A/cm ²) (-20V)	n	Φ_B (eV)
Conventional	126	0.27	1×10^{-4}	1.05	0.89
Compensated	5×10^6	0.11	1.8×10^{-7}	1.03	0.77

From table 3.1, it can be observed that compensation also results in 4 orders of magnitude higher sheet resistance and three orders of magnitude reduction in I_R , which is primarily due to the reduction in charge carrier density. All other parameters are relatively unaffected by compensation.

3.3.2 Breakdown Characteristics

Breakdown characteristics help define the maximum voltage and power an electronic device can handle. These characteristics play a vital role in determining the electrical limitations of electronic devices. These measurements are essential as higher reverse voltages generate thicker DW and thicker DW is one of the primary requirement of a high performing radiation detector. GaN has a high bandgap and high electric field strength, which makes it an optimum material to fabricate devices with high V_{BD} .

For breakdown characterization, SBDs were exposed to increasing voltages until it reaches the set compliance of 1 A/cm^2 or when it reaches the catastrophic failure of the device. The SBDs were also dipped in Fluorinert FC-40 prior to the measurements to insulate the SBDs from atmospheric flashover [45].

Figure 3.5: Image of an SBD after the catastrophic breakdown

From figure 3.5, it can be observed that a crest is formed at the center of the SBD due to the burning of the metal-semiconductor stack. This breakdown pattern also implies that breakdown is not due to current crowding at the edge of the SBD.

Figure 3.6 shows the semi-log breakdown characteristics of fabricated vertical SBDs with both compensated and conventional *DLs*. Higher V_{BD} (1480 V) [46] was measured on SBDs with compensated *DL* in comparison to 430 V measured on conventional SBDs. This increase in measured V_{BD} was due to lower *CCD* leading to the formation of thicker *DW*.

Figure 3.6: Reverse breakdown voltage characteristics of conventional and compensated GaN SBDs of 1 mm dia.

Furthermore, the breakdown strength (BS) was also calculated using equation (3.3) [47].

$$BS = \sqrt{2q(CCD)V_R/\epsilon_0\epsilon_s} \quad (3.3)$$

where V_R is the applied reverse voltage, CCD is the carrier concentration, q is the electronic charge, ϵ_0 is the permittivity of free space and ϵ_s is the dielectric constant of GaN (8.9) [48].

SBDs with compensated DL s exhibit 3 times higher BS of 980 kV/cm in comparison to 350 kV/cm of the conventional SBDs. The calculated BS is still very low when compared to the theoretical limit of GaN (3.3 MV/cm). Further improvement in the breakdown characteristics is possible by employing better termination [49], field plate structures [50], and increasing DLT .

3.4 Effect of DLT on GaN-on-GaN SBDs

GaN-on-GaN SBDs are fabricated on wafers with a highly doped substrate and a lowly doped DL . Figure 3.7 shows the cross-section schematic of GaN-on-GaN wafer. Due to the high CCD in the substrate, DW cannot exceed the thickness of the DL .

Figure 3.7: Cross-sectional schematic of a GaN-on-GaN wafer.

Hence, in order to increase the DW further, we need to increase the drift layer thickness (DLT), which in turn would help to reduce I_R and to increase V_{BD} . To experimentally study the effect of compensated DL s with different thicknesses, multiple wafers of different DLT (0 μm , 2 μm , 5 μm , 15 μm , and 30 μm) were grown. Electrical characterization like I - V and breakdown measurements were performed on SBDs fabricated on these wafers to analyze the effect of DLT . The material characteristics of all wafers and the fabrication of SBDs on them have been covered in chapter 2.

3.4.1 I-V Characteristics

Figure 3.8 shows the (a) reverse and (b) forward current characteristics of the 500 μm diameter SBDs with different *DLTs*. The measured I_R of SBD decreased after incorporation of *DLT* on the free-standing GaN substrate. With reference to SBDs with 0 μm *DLT* (0.2 A/cm^2), about 5 orders of magnitude lower I_R (3 A/cm^2) was observed in the SBDs with *DLT* of 15 μm and 30 μm . No change in the I_R of SBDs with *DLT* greater than 15 μm was observed (see Fig. 3.6(a)). This could be due to the saturation of tunnelling current for *DLs* greater than 15 μm in the SBDs. Lower I_R with an increase in *DLT* could be attributed to the increased series resistance, improved crystalline quality, and improved surface morphology of the wafer [13]. Higher values of forward saturation current density (0.0226 A/cm^2) was observed in SBDs with *DLT* of 2 μm in comparison to SBDs with *DLT* of 5 μm , 15 μm and 30 μm (see Fig. 3.6(b)). This decrease in current density with the increase of *DLT* is primarily due to the reduction of *CCD* in the thick *DLs*, thus resulting in the increased series resistance.

Figure 3.8: Room temperature (a) reverse and (b) forward *I-V* characteristics of vertical SBDs of 500 μm diameter on free-standing GaN.

Furthermore, n and Φ_B were extracted from I - V characteristics using equation 3.1 and 3.2 for the fabricated vertical GaN SBDs. Figure 3.9 shows the variation in n and Φ_B for different DLT . For a good representation of the device performance, ten SBDs were measured on each sample. The observation of near unity n value for SBDs with $DLTs$ of 2 μm (1.1), 5 μm (1.02), 15 μm (1.03), 30 μm (1.09) indicates the formation of a high-quality interface between Ni and GaN [40].

Figure 3.9: Schottky barrier height and ideality factor of vertical SBD on free-standing GaN for different $DLTs$ (10 SBDs were used).

The observation of higher n value in SBD on a GaN substrate (without DL) is due to the increase of charge carrier density at the GaN side of the Schottky interface. The extracted Φ_B values of 0.73-0.81 eV for SBD with different $DLTs$ are typical for Ni/Au Schottky contacts on GaN. A similar range of Φ_B values was also reported by other researchers [42, 43, 44].

3.4.2 C-V Characteristics

To verify the reduction in CCD of the DL and to calculate the DW , C-V measurements were performed using B1505A power device analyzer. Variation in capacitance with a change in voltage from -5 V to +25 V was measured on all SBDs with different DLT (see figure 3.10). When the applied voltage was <0 V, no variation in capacitance was observed. While SBDs with the thinnest DLT of 2 μm exhibited a change in capacitance when applied voltage exceeded +2.5 V, SBDs with thicker $DLTs$ did not exhibit any change in capacitance till +25 V (equipment limit) (see figure 3.8).

Figure 3.10: Room temperature C-V characteristics of vertical SBDs of 500 μm diameter on free-standing GaN

To verify the complete depletion of DL , DW was calculated from the measured capacitance (at 0 V) using the following eq 3.4 and listed in the table below.

$$DW = \varepsilon_0 \varepsilon_s A / C \quad (3.4)$$

Table 3.2: Measured capacitance, DW and V_{BD} of vertical SBDs with different DLT s

DLT (μm)	Capacitance (pF) (at 0V)	DW (μm) (CV)	V_{BD} (V)
2	23	2.1	562
5	9.3	5.3	782
15	4.8	15.2	1480
30	2.5	30.1	2400

The CCD extracted from C-V of SBDs with $2\mu\text{m}$ was found to match well with results obtained through Hall measurements and SIMS analysis (see chapter 2).

3.4.3 Breakdown Characteristics

Figure 3.11 shows the semi-log plot of the breakdown characteristics of the fabricated SBDs with different DLT s. The SBDs with 2 μm , 5 μm , 15 μm , 30 μm DLT s exhibit V_{BD} of 562 V, 782 V, 1480 V, and 2400 V respectively. The measured V_{BD} of 2400 V on SBDs with 30 μm DLT is the highest ever reported breakdown voltage on the virtue of their thicker DLT resulting in thicker DW .

Figure 3.11: Semi-log plot of V_{BD} characteristics of SBD for different DLT s.

3.5 Benchmarking

Figure 3.12 shows the plot of V_{BD} vs. DLT for the state-of-the-art reported vertical SBDs. Saitoh *et al.* realized a V_{BD} value of 1100 V for the SBDs with DLT of 5 μm after the incorporation of a field plate (*FP*) [36]. However, our SBDs with 5 μm DLT exhibit similar V_{BD} without any additional edge termination or *FP*. D. Shibata *et al.* has employed junction barrier Schottky (JBS) with p-type termination and 13 μm -thick DL and realized a V_{BD} value of 1600 V [49]. Improved V_{BD} measured on our SBDs with different DLT is due to the reduction of CCD in the MOCVD grown GaN DL s.

Figure 3.12: Benchmarking of measured reverse breakdown voltages of vertical GaN SBDs with state-of-the-art results.

3.6 Summary

In this chapter, we have explored two different ways of improving SBD performance (in reverse bias conditions) by reducing CCD and increasing DLT . The effects of compensation of GaN DLs and change in DLT were studied from the $I-V$, and reverse breakdown characteristics. The extracted forward Schottky parameters such as n and ϕ_B were found to be independent of compensation and DLT . Reduction of 3 orders of magnitude in I_R and increase of V_{BD} by ~ 3 times in SBDs with compensation is primarily due to reduced CCD , leading to thicker DW . Similarly, increasing DLT from $2\ \mu m$ to $30\ \mu m$ reduces I_R by ~ 2 orders of magnitude and increases V_{BD} by ~ 4 times. The measured V_{BD} of $2400\ V$ on SBDs with $30\ \mu m$ DLT is the highest reported value. These results show that compensating a thicker DLs of vertical SBDs with p-type (Mg) could be a viable method to reduce I_R and improve V_{BD} by generating a thicker DW .

4 Conduction Mechanism

4.1 Introduction

Previously in chapter 3, we have discussed two different methods of reducing leakage current (I_R) and increasing breakdown voltage (V_{BD}). To further enhance our understanding of the physical causes behind I_R reduction, we have carried out an investigation of the possible conduction mechanisms (CM) to help identify the physical cause of the impact of compensation on I_R .

Figure 4.1: Different Conduction Mechanism possible in reverse biased SBD [51]

In general, there are three main types of CM, namely thermionic emission (TE), field emission, and thermionic field emission (TFE), which are shown in Figure 4.1 and explained in detail below.

4.1.1 Thermionic Emission (TE)

TE occurs when electrons flow over a barrier due to thermal excitation of electrons (shown in figure 4.1 in red). When thermal energy provided to electrons exceeds the energy required to cross the barrier, electrons can freely traverse leading to I_R . Mathematically TE is given by equation 5.1 [52]

$$I_R = A^* T^2 \exp\left(\frac{-\phi_B}{k_B T}\right) \quad (4.1)$$

where A^* is the Richardson's constant, ϕ_B is barrier height, T is temperature and k_B is Boltzmann's constant.

In the case of TE, I_R is only dependent on ϕ_B and temperature. In order to improve SBD performance by reducing I_R , it is necessary to increase ϕ_B or reduce operating temperature.

4.1.2 Field Emission

Semiconductors with high charge carrier density (CCD) can only form a very thin DW at a metal-semiconductor interface. The thin DW results in easier access for electrons to tunnel through the DW . This tunnelling of electrons through the barrier in the presence of reverse bias results in high I_R . (Field Emission is shown in black in figure 4.1.) To reduce I_R due to field emission, it is necessary to reduce CCD and increase DW .

4.1.3 Thermionic Field Emission (TFE)

TFE is the result of electrons traverse across the barrier both by tunnelling and over the barrier. TFE is shown in blue in figure 4.1. Mathematically TFE is given by [37]

$$I_R = I_S \exp \left(\frac{V_R}{kT} - \frac{V_R}{E_{00} \coth(E_{00}/kT)} \right) \quad (4.2)$$

where

$$I_S = \frac{A^* T \sqrt{\pi E_{00}}}{k} \sqrt{(V_R - \phi_B) + \frac{\phi_{BTFE}}{\coth^2(E_{00}/kT)}} \times \exp \left[\frac{\phi_{BTFE}}{E_{00} \coth^2(E_{00}/kT)} \right]$$

and

$$E_{00} = \left(\frac{qh}{4\pi} \right) \sqrt{\frac{CCD}{m^* \epsilon_0 \epsilon_s}}$$

where E_{00} is characteristic energy related to tunnelling probability of potential barrier and V_R is the applied reverse voltage.

To understand the physical mechanisms of reduced I_R and increased V_{BD} due to compensation and increase DLT , CM of I_R was extracted by comparing measured I_R with calculated I_R based on each type of CM. Similar method of extraction of CM has been employed by M.R. Hontz et al. in which by matching his measured data to the theoretically calculated values, he has extracted CM to be barrier modified TFE (See figure 4.2) [53].

Figure 4.2 Conduction Mechanism extracted and reported by M.R. Hontz et al [53].

4.2 Effect of Compensation on CM

To extract the effect of compensation, CM of I_R of both compensated and conventional SBDs was extracted at room temperature. Figure 4.3 shows the CM extraction of both compensated and conventional SBDs where the theoretically calculated lines are plotted in a dashed format along with the measured I_R (solid lines).

Figure 4.3: Reverse Leakage current conduction mechanism of SBDs with both compensated and conventional DL .

Figure 4.3 compares the variation of I_R with voltage for both compensated and conventional SBDs. A good agreement between measured and calculated I_R was observed for compensated SBDs which indicates that

the CM is TFE [53, 54]. While a suitable match for compensated SBDs was obtained with regular TFE model, in the case of SBDs with conventional DL , the measured I_R was comparable to calculated I_R with a higher CCD (see inset table in figure 4.3). This type of CM, where a good match is achieved only by considering increased CCD is quite typical and has been observed and reported by various research groups [53, 54] and is called barrier modified TFE.

Figure 4.4: Band diagram representation of (a) compensated and (b) conventional SBDs.

In TFE exhibited by compensated SBDs, I_R is dominated by tunnelling of electrons through the barrier (as shown in figure 4.4 (a)) and in barrier modified TFE model, high density of donor type deep surface traps cause narrowing of DW leading to the increase of I_R [54] as shown in figure 4.4 (b).

4.3 Effect of DLT on Conduction Mechanism

In chapter 3, we have studied the effects of DLT on SBD performance and observed the decrease in I_R by 1 order of magnitude along with ~ 5 times increase in V_{BD} with the increase in DLT of SBD. The study of CM of I_R for SBDs with different DLT will further enhance our understanding of the physical reasoning behind the improvement and also help optimize the SBD device structure for radiation sensing applications.

The extraction of the types of CM is carried out using current-voltage-temperature (I - V - T) measurements. These were performed using Keysight B1505A power device analyzer by varying voltage from 0 V to -20 V at the temperature ranges from 25°C to 150°C in steps of 25°C.

4.3.1 SBDs with 2 μm and 5 μm DL

Figure 4.5 shows both calculated and measured I - V - T characteristics of GaN SBDs with DLT of 2 μm . Similar I - V - T characteristics were also observed from the GaN SBDs with the DLT of 5 μm . A good fit has been observed between the measured I_R (solid lines) and calculated I_R (dashed lines) using the TFE equation (see equation 4.2).

Figure 4.5: Reverse leakage current at different temperatures of GaN SBD with 2 μm *DLT* compared with TFE model.

Figure 4.6: I_R vs. T of GaN SBDs with 2 μm and 5 μm *DLT* (at -20 V).

Figure 4.6 shows the calculated and measured I_R as a function of temperature for the GaN SBDs with DLT of 2 μm and 5 μm . From the figure, it is clear that GaN SBDs with compensated 2 μm and 5 μm DL s show that TFE is the dominating mode of conduction mechanism.

Figure 4.7 shows the schematic band diagram of the GaN SBDs with thin DL s of 2 μm or 5 μm . Thin DL s leads to the formation of thin DW and hence electrons have a higher probability of successfully tunnelling through the DW . When the I_R is dominated by tunnelling of electrons through the DW , the CM of I_R is called TFE [37].

Figure 4.7: Energy band diagram of GaN SBDs with 2 μm or 5 μm DLT .

4.3.2 SBDs with 15 μm *DLT*

Figure 4.8 shows the measured I_R of compensated SBDs with 15 μm *DLT* at 25°C, 75°C, and 150°C along with the theoretical I_R at the respective temperature.

Figure 4.8: Reverse leakage current at different temperatures of GaN SBD with 15 μm *DLT* compared with both TE and TFE model.

From figure 4.8 it can be observed that at lower temperatures of 25°C to 75°C with an increase in voltage, the measured I_R matches well with calculated I_R when TFE is considered as the dominant mode of CM. While at higher temperatures from 100°C to 150°C, the measured I_R exhibits no change in value with an increase in bias voltage and matches closely with

calculated I_R using equation 4.1 for TE. The transition of the CM from TFE to TE started from 75°C to 100°C which can be observed in figure 4.9.

Figure 4.9: Variation of measured I_R with temperature with theoretical variation in I_R for both TE and TFE CM (at -20 V).

Increase of DLT from 5 μm to 15 μm leads to the increase of DW (see figure 4.10), which reduces the probability of electrons tunnelling through the DW thus reducing I_R . At higher temperatures, the thermally excited electrons have easier access over the barrier accompanied with lower tunnelling probability, resulting in TE as the principal mode of conduction. From figures 4.8 and 4.9 it is clear that the vertical GaN SBDs with 15 μm DLT can exhibit both TFE at low temperatures and TE at high temperatures.

Figure 4.10: Energy band diagram of GaN SBDs with 15 μm *DLT*

4.3.3 SBDs with 30 μm *DL*

Unlike SBDs with thinner *DLTs*, SBDs with 30 μm *DL* exhibit no variation in I_R with the increase in reverse bias (see figure 4.11).

Figure 4.11: Reverse leakage current at different temperatures of GaN SBD with 30 μm *DLT* compared with TE model.

The measured I - V characteristics of GaN SBDs with 30 μm *DLT* match well with the theoretical I - V curves calculated using equation (4.1) at different temperatures, which proves that TE is the dominant mode of conduction. The CM was also verified by I_R versus temperature plot (see figure 4.12), where we observe the measured variation in I_R is similar to calculated variation from equation 4.1 with the change in temperature.

Figure 4.12: I_R vs. T of GaN SBDs with 30 μm DLT (at -20 V).

Fabricated GaN SBDs with 30 μm DLT have a large DW (See the band diagram in figure 4.13), which drastically reduces the probability of electron tunnelling through it. From this, it is clear that in vertical GaN SBDs with 30 μm DLT , CM is dominated by TE.

Figure 4.13: Energy band diagram of GaN SBDs with 30 μm DLT .

4.3.4 Effect of *DLT* on Activation Energy

Previously in chapter 1, we have discussed the difficulties in the growth of free-standing GaN. The solutions discussed to overcome these difficulties are still not optimized, resulting in the formation of point defects in GaN crystal. These defects can exist as donors which donate electrons to the conduction band or as acceptors which donate holes to the valence band. Either way, they play a significant role in determining the electrical characteristics of the devices. In theory, these defects activate when comparable thermal energy is provided to them. So the origin and type of the defect is determined from the thermal energy required to activate it, and it can be extracted from the IVT characteristics. This thermal energy required to activate these defects is called Activation Energy (E_a).

Figure 4.14 (a) shows the activation energy plot of GaN SBDs with 2 μm , 5 μm , and 30 μm *DLT*. Similar values of $E_a = 0.4 \pm 0.01$ eV were extracted for SBDs with different *DLT*. Since the GaN SBDs with 15 μm *DLT* exhibit a change in conduction mechanism with increase in temperature, the SBDs were biased over a wider temperature range from 0°C to 200°C to extract an E_a of 0.40 eV at high temperature (100°C to 200°C) and 0.39 eV at low temperature (0°C to 75°C) (see figure 4.14 (b)). The E_a of ~0.4 eV corresponds to the presence of Mg ions in the drift layer [55], which was verified by SIMS analysis (see table 2.2).

Figure 4.14: (a) Activation energy plot of SBDs with 2 μm , 5 μm , and 30 μm DLT (at -20V), (b) Activation energy plot for GaN SBDs with 15 μm DLT.

4.3.5 TFE to TE Transition in SBDs with 15 μm DLT

As observed in Fig 4.9, there is a change of CM from TFE at 75°C to TE at 100°C. To further analyze the cause of this change, more detailed measurements were performed between 75°C and 100°C in 5°C intervals. Settling time of 10 min was given between each measurement for a uniform rise in temperature. Based on these measurements, activation energy was extracted (see figure 4.15).

Figure 4.15: Activation energy plot for compensated SBDs within transition region of 75°C and 100°C.

The extracted E_a of -1.67 eV signifies activation of N-vacancies [56] in the DL. These N-vacancies are activated when the temperature exceeds

75°C and trap tunnelling electrons. As a result, the number of electrons which tunnel through the DW decrease, thereby reducing I_R . The trapping of tunnelling electrons changes the dominant CM from TFE to TE.

4.4 Effect of High-Voltage on CM

So far in this chapter, we have studied the CM at low voltage (< -20 V), but radiation detectors tend to work in higher reverse bias conditions and generate thicker DW . To obtain a better understanding of I_R , CM was extracted at these higher voltages for SBDs with $15\text{ }\mu\text{m}$ and $30\text{ }\mu\text{m}$ DLT .

4.4.1 High Voltage CM – $15\text{ }\mu\text{m}$ SBDs

Figure 4.16 shows the measured IVT characteristics, which have been divided into 3 zones for easier analysis (Zone-I: 0 V to -20 V , Zone-II: -20 V to -125 V , and Zone-III: -125 V to -300 V). As the IVT characteristics of zone-I have been explained previously, this section will mainly focus on Zone-II and Zone-III. In Zone-II, the I_R characteristics are similar to that in zone-I. In both Zone-I and Zone-II, CM is dominated by TFE for temperatures below 75°C and TE for temperatures above 100°C . In zone-III, when the applied voltage exceeds -125 V , CM changes from TE to TFE due to the high electric field across the DW , which increases the probability of tunnelling through the DW .

Figure 4.16: High voltage IVT characteristics of GaN SBDs of 1 mm dia. with 15 μm DL .

4.4.2 High Voltage CM – 30 μm SBDs

Similar to SBDs with 15 μm DL , SBDs with 30 μm DL exhibit multiple changes in CM with both change in voltage and temperature. Due to the increased thickness of DL , DW also increases, which leads to higher voltage requirement to observe a similar change in CM. From figure 4.17, it can be observed that the IVT characteristics can be again divided into 3 zones. While Zone-I of both SBDs are similar with voltage up to -20 V, Zone-II covers a larger voltage bias from -20V to -325 V and Zone-III from -325V to -800 V.

Figure 4.17: High voltage IVT characteristics of GaN SBDs of 1 mm dia. with 30 μm DL .

4.4.3 Variation in E_a with Voltage

To further understand the physical reason behind the change in CM in SBDs with 15 μm and 30 μm DLT , E_a was extracted and plotted as a function of voltage in figure 4.18. E_a of $\sim +0.4$ eV was measured at -20 V for both SBDs, which was due to Mg ions in the DL [55]. The presence of Mg ions was also confirmed by SIMS analysis on both samples (see table 2.2). From figure 4.18 (a) and 4.18 (b), a similar variation of E_a can be observed. At low temperatures (0 to 75°C), E_a gradually reduces from +0.4 eV to -0.01 eV for both SBDs.

Figure 4.18: Variation of E_a with voltage for low and high temperatures for SBDs with (a) 15 μm and (b) 30 μm DLT.

Due to its thick DL, SBDs with 30 μm DL require larger applied bias for a similar change in E_a . Similarly, at higher temperatures (100 to 150°C), E_a

increases to +0.69 eV (at -150 V for SBDs with 15 μm DL and -400 V for SBDs with 30 μm DL). This increase in E_a is due to the activation of carbon-traps, which may de-trap the electrons leading to higher tunnelling current and hence change of CM from TE to TFE. On further increasing of bias voltage, E_a reduces to ~ -0.01 eV, which signifies the presence of surface related imperfections [57].

4.5 Summary

In this chapter, we have analyzed the effects of compensation, DLT , and high voltage on CM. While compensation changes CM from barrier modified TFE to TFE, increasing the thickness of compensated DL changes CM from TFE to TE. Activation of N-vacancies ($E_a = -1.67\text{eV}$) at temperatures $>75^\circ\text{C}$ results in the trapping of tunnelling electrons, which reduces I_R and changes in CM. Similarly, activation of C-traps ($E_a = 0.69\text{eV}$) at high voltages (-150 V for SBDs with 15 μm and -400 V for SBDs with 30 μm DLT) de-traps electrons thus resulting in increased tunnelling current and the change of CM to TFE.

5 Radiation Detection

5.1 Introduction

As discussed in previous chapters, GaN-based SBDs are excellent for radiation sensing applications on the virtue of its high displacement energy (E_d), high bandgap and high thermal conductivity in comparison with other incumbent semiconductors such as Si and GaAs. These advantages led many research groups to explore GaN-based devices for radiation sensing applications [58, 59, 60, 61]. The different types of GaN-based SBD detectors are classified into three types namely double schottky contact (DSC) structure, mesa structure and sandwich structure.

5.1.1 Double Schottky Contact structure

DSC structure has two Schottky contacts on a thin GaN epi-layer (see figure 5.1). This GaN epi-layer was grown on a hetero-epitaxial substrate like sapphire using a highly conductive buffer layer to reduce threading dislocation density (TDD).

Figure 5.1: Double Schottky Contact structure alpha particle detector.

The first-ever GaN alpha particle detector was realized by Vaitkus et al. [58] with the DSC structure. The detector had a 2 μm GaN epi-layer, which resulted in the detection of 410 keV alpha particles with 92% charge collection efficiency (*CCE*).

DSC structure was predominantly popular during initial stages of GaN alpha particle detection due to its easier fabrication process which needs only one masking step without an optimized Ohmic contact. The main disadvantage of this structure is the use of a thin epi-layer ($<10\ \mu\text{m}$) which restricts the maximum energy which can be detected.

5.1.2 Mesa Structure

Mesa structure is also based on a thin film GaN (see figure 5.2 (a) and (b)). While Schottky contact is always fabricated on the GaN layer, ohmic contact is fabricated on either etched GaN or highly conductive buffer layer.

Figure 5.2 (a) Mesa-I and (b) Mesa-II structures of alpha particle detectors

These mesa structures shown in figure 5.2 have been implemented by different research groups to achieve higher *CCE* (~100%) due to lower trapping impurity concentration [59, 62]. Compared to the DSC mesa structure, mesa structure detectors exhibit superior performance with a lower noise level and fewer mobility fluctuations. These are primarily due to better transport properties of charge carriers flowing vertically. However, the disadvantages associated with DSC such as thin epitaxial layer and parasitic capacitance and resistance, are also applicable to mesa structures.

5.1.3 Sandwich Structure

The sandwich structure has GaN layer sandwiched in between the ohmic and Schottky contacts (see figure 5.3).

Figure 5.3: Sandwich structure of alpha particle detectors.

Compared to thin-film based structures discussed above, the sandwich structure has the potential to generate large depletion width (*DW*), thus capable of detecting alpha particle with higher energy. Furthermore, the vertical structure also helps reduce current crowding and improve charge carrier transport properties. Multiple research groups like Mulligan et al. [60] and Q. Xu et al. [61] have employed this vertical SBD or sandwich

structure to fabricate alpha particle detectors. While these detectors were able to detect comparatively higher energies (5.48MeV) [60], they required high voltage bias of -550 V to achieve 100% CCE, which increases both the complexity and size of the detector, thus severely affecting its portability.

5.2 Design of α -Particle Detector

To design an α -particle detector which works in low bias conditions and detect higher α -particle energies, we have employed a GaN-on-GaN SBD structure (see figure 5.4). The thin epitaxial GaN layer is very lowly doped resulting in a thick DW , while the highly doped substrate gives mechanical strength to the detector and forms a good Ohmic contact which helps to reduce the biasing voltage needed.

Diode Diameter: 500 μm – 1mm

Figure 5.4: GaN-on-GaN structure for alpha particle detectors

The thickness of the drift layer (*DL*) plays an important role in determining the maximum thickness of *DW* (discussed previously in chapter 3), thereby the maximum energy which can be detected. The *DL* required to detect 5.48 MeV emitted by ^{241}Am was calculated through SRIM simulations. Figure 5.5 shows the SRIM calculated range of the thickness required in GaN to absorb α -particles with energies between 10 keV and 6 MeV. From this graph, we found that we need a 14.54 μm *DW* to detect α -particles with 5.48 MeV. Hence, SBDs with 15 μm and 30 μm *DL* were used for α -particle detection.

Figure 5.5: α -particle (^{241}Am , 5.48 MeV) range in GaN calculated by SRIM.

5.3 Radiation Testing

5.3.1 Sample Preparation

A quarter of 2" wafer was diced into individual SBDs after their electrical characterization (see figure 5.6). After dicing, two SBDs were attached on dual inline package (DIP) using Silver paste. Highly conductive Ag paste helps connect the ohmic terminal with the ground pin of the package. The Schottky contacts were connected to other pins using an Au wire of 20 μm diameter. The packaged SBDs were then tested before exposing to α -particle radiation.

Figure 5.6: Three stages of sample preparation.

5.3.2 α -particle Measurement Setup

α -particle testing was performed at the National Isotope Center GNS in New Zealand. ^{241}Am was used as a source for the generation of 5.48 MeV α -particles with an active area of 7 mm^2 placed at 8 mm from the detector (as shown in figure 5.7). The α -particle source has radionuclides deposited

onto a stainless-steel disc of 16 mm diameter, which is held in place by a plastic holder. The GaN SBD detector was connected to a pre-amplifier, amplifier, and signal processing circuit to detect the change in the current flowing through the SBDs due to the interaction with an α -particle. A Si surface barrier detector from ORTEC was used as a reference along with ORTEC-671 amplifier for energy calibration.

Figure 5.7: Schematic drawing of Source-Detector measurement setup (not to scale).

5.4 Detection of α -particle Spectra

Performance of an α -particle detector is primarily defined by its *CCE*. *CCE* is the ratio of absorbed energy and incident energy, which is dependent on the *DW* of the detector. The acquired data was calibrated using a standard Si detector as a reference with the following formula [60].

$$E = E_0 + \frac{W_{GaN}}{W_{Si}} * k * Channel \quad (5.1)$$

where *E* is the absorbed energy, *E*₀ represents energy loss at the metal interface which was estimated based on SRIM analysis to be 183 keV for an Au/Ni (1000/50 nm) contact, *k* is a calibration factor for the reference Si detector. *W*_{GaN} (8.9 eV) and *W*_{Si} (3.6 eV) are the energies required to generate an electron-hole pair in GaN and Si, respectively.

5.4.1 Variation in α -particle spectra – Voltage

- **Low Voltage:** The α -particle energy spectra obtained under low bias conditions (-20 to -80V) are shown in figure 5.8. It can be observed that with the decrease in applied bias, the detected energy also decreases. The decrease in detected energy is due to the reduction in *DW* at lower bias conditions. Reduced *DW* decreases the path length of the α -particle, thereby limiting the ability to detect high-energy α -particles.

Figure 5.8: Acquired α -particle spectra of GaN SBDs for different applied voltages (-20 V to -80 V)

Figure 5.9 shows the variation of CCE with voltage of our detectors compared with other published bulk GaN detectors (sandwich structures). Our detectors exhibited very low variation in CCE (7%) with a change in voltage (-20 V to -80 V) when compared to the variation shown by 450 μm -thick bulk GaN detector (32.7%) [60] and 500 μm -thick bulk GaN detector (58.1%) [61]. This is mainly due to the presence of thick DW even at low bias conditions, which was achieved by compensation of DL and reduced CCD .

Figure 5.9: Comparison of measured *CCE* of SBDs vs. applied voltages (-20 V to -80V) with state-of-the-art reported values.

- High Voltage:** Our detectors were also biased at higher voltages to obtain thicker *DW* leading to a higher *CCE* similar in the range reported by others using bulk GaN detectors [60, 61]. Our detector performance improves from 72% at -80 V to 96.7% at -300 V (see figure 5.10), which is the lowest reported voltage at which 5.48 MeV α -particle was successfully detected.

Figure 5.10: Acquired α -particle spectra of GaN SBDs for different applied voltages (-100 V to -300 V)

High voltage performance of these detectors was compared with other published α -particle detectors. Of the many published reports, only Q. Xu et al. reported a high 100% *CCE* while detecting a 5.48 MeV α -particle. However, their detectors need to be biased up to -550 V, which is 250 V higher than our detectors that may be a limiting factor for some applications (see figure 5.11).

Figure 5.11: Comparison of measured CCE of SBDs vs. applied voltages (-100 V to -550 V) with state-of-the-art reported values.

The detector's energy resolution was extracted to be 71 keV from the FWHM of the α -particle spectra measured at -100 V. The measured energy resolution is 30% better than other reported bulk GaN-based detectors (121 keV) [60]. The improved energy resolution was due to the reduction in the dispersion of α -particle by placing the detector normal to the source. SRIM simulations were also performed to study the effect of incident angle on energy resolution [63] (see figure 5.12). Increase in the angle between the incident α -particle and the surface of the detector increases the full width half maximum (FWHM) of the detected spectral energy from 97.8 keV to 163.8 keV. This increase in FWHM is due to spectral widening

when the source is placed at an angle to the detector resulting in a reduction of spectral resolution.

Figure 5.12: Variation of energy resolution with a change of the incident angle.

5.4.2 Variation in α -particle spectra – Detector Dimension

SBDs of different sizes were exposed to α -particle of 5.48 MeV energy emitted by the ^{241}Am source to study the effect of detector size on the detected spectra. Figure 5.13 shows the observed variation in detected spectra at -100 bias conditions for SBDs with different sizes. From the

figure, it could be observed that the SBD dimension doesn't play any significant role in the detection of α -particle.

Figure 5.13: Detected α -particle spectra when SBDs of dia. 0.6mm and 1mm were biased at -100 V

5.4.3 Variation in α -particle spectra – Air vs. Vacuum

Figure 5.14 shows the comparison of the energy spectrum of GaN detectors biased at -100 V measured in vacuum and air. About 7% of reduction in *CCE* was observed when the detectors were measured under air. When an α -particle passes through the vacuum, all its energy gets transferred to the detector resulting in high-energy detection. When α -particles traverse through air, scattering results in loss of energy. This loss in α -particle energy results in lower % of *CCE*. For practical applications,

portability and cost are important factors and the need for vacuum restricts portability and also increases the cost of the system. While the presence of air results in a 7% drop in *CCE*, compensated SBDs could still be considered for practical applications.

Figure 5.14: Acquired α -particle energy spectra of GaN SBDs at -100 V under air and vacuum.

5.5 Benchmarking

Figure 5.15 compares the low voltage performance of GaN-on-GaN SBD detectors with the state-of-the-art α -particle detectors reported so far as a function of detected energies. About 30% higher *CCE* was observed in the compensated 15 μm -thick GaN *DL* based α -particle detectors at -20 V. In addition, our detectors also exhibited 96.7% *CCE* at -300 V which is 250 V lower than the published literature. These promising results pave the

way to achieve high CCE , low operating voltage, portable α -particle detectors.

Figure 5.15: Benchmarking of extracted CCE of our detectors with epitaxial grown GaN detectors (squares) and bulk GaN (triangles) detectors at low voltages.

5.6 Summary

In summary, GaN-on-GaN SBD based α -particle detectors were successfully fabricated and tested to demonstrate it is able to detect high energy (5.48 MeV) α -particles with a *CCE* of 65% even at low voltages (-20 V). The measured *CCE* is 30% higher than the previously reported values at -20 V. The detectors also exhibit 96.7% *CCE* at -300 V, which is 250 V lower than previously reported values. The measured spectral resolution of 71 keV is 30% better than the previously reported value. The improved performance in α -particle detection is due to the formation of thicker *DW* even at low voltages. In conclusion, we have demonstrated the great potential of vertical GaN-on-GaN SBD with compensated *DL* for portable α -particle detectors which can work even at low voltages.

6 Conclusions and Recommendations for Future Work

6.1 Conclusion

GaN SBDs have demonstrated great potential in radiation detection on the virtue of its high displacement energy, wide bandgap, high thermal conductivity, and critical electric field strength. Conventionally, GaN particle detectors employ either a thin GaN epitaxial layer on hetero-epitaxial substrate or thick free-standing GaN substrate to fabricate a radiation detector. While the thin epi-layer detector worked at low voltages (-28 V) with high *CCE*, they are only able to detect very low energies (< 1 MeV). On the other hand, free-standing GaN detectors required very high voltages to detect high energies with high *CCE*. The work in this thesis is centered upon incorporating the advantages of thin GaN film on free-standing GaN to realize high performance α -particle detector for high energy detection at low voltage with high *CCE*.

To design the particle detector, stopping range of ions in matter (SRIM) simulations were performed to measure the thickness of depletion width (*DW*) required in order to measure 5.48 MeV α -particle generated from ²⁴¹Am source. From the SRIM simulation, a minimum *DW* thickness of 14.54 μm was found to be necessary. To understand the effects of charge carrier density (*CCD*) and drift layer thickness (*DLT*) on the generation of

DW, multiple simulations were performed using TCAD provided by Silvaco. Based on TCAD simulations, design considerations of *DLT* and *CCD* were reached. *DLT* of 15 μm with *CCD* lower than $1 \times 10^{15}/\text{cm}^3$ was required to generate the required *DW* of 14.54 μm .

The simulated requirements were achieved by designing a thin compensated GaN drift layer (*DL*) grown by MOCVD on HVPE grown conducting GaN substrate. Compensation of thin *DL* by doping Mg (p-type) ions in *DL* reduces the *CCD* generated by unintentional Si (n-type) doping. Resultant *CCD* of $7.6 \times 10^{14}/\text{cm}^3$ in GaN *DL* was able to achieve in the grown GaN *DL*, which was lower than the required value from simulation. As a result, this low *CCD* has also helped to realize ~5 times thicker *DW* of 15 μm in compensated SBDs in comparison to 3.16 μm in conventional SBDs. The increase in *DW* reduced the reverse leakage current (I_R) by ~3 orders of magnitude and increased the breakdown voltage (V_{BD}) by ~3 times without affecting the ideality factor and barrier height of the SBDs. The improvement in reverse characteristics is expected to help improve the sensitivity of the detector. Similarly, SBDs were also fabricated with compensated *DLs* of different thicknesses (2 μm , 5 μm , and 30 μm) to study the effect of compensated *DLT* on SBD performance. Increase of *DLT* reduced I_R by ~1 order of magnitude and improved V_{BD} ~4 times. The measured V_{BD} of 2400 V on SBDs with 30 μm *DLT* is the highest reported V_{BD} so far.

The improvements in reverse bias characteristics were further analyzed by extracting the effects of compensation and *DLT* on conduction mechanism (CM). While compensation resulted in a change of CM from barrier modified TFE to TFE, increase in *DLT* changed conduction mechanism from TFE to TE due to the increase in *DW*. Activation energy (E_a) was extracted to be 0.069 eV for conventional SBDs, which corresponds to surface traps. E_a of ~0.4 eV was extracted for all compensated SBDs irrespective of their thickness. E_a of 0.4 eV corresponds to activation of Mg ions in the *DL*.

Finally, the fabricated SBDs were exposed to α -particle radiation of 5.48 MeV emitted by ^{241}Am source. Different studies like effects of bias voltage, area of the detector, and presence of air on the detector performance have also been presented. These compensated GaN-on-GaN SBDs exhibit 30% increase in *CCE* (65%) at low voltages (-20 V) in comparison to previously reported GaN α -particle detectors. High *CCE* of 96.7% was also measured at -300 V, which is 250 V lower than the previously reported bias requirement. The spectral resolution of 71 keV is also 30% better than the previous reports. The improved performance in α -particle detection is due to the formation of thicker *DW* at low voltages. By exposing α -particle radiation to multiple detectors of different sizes, it was verified that the size of the detector does not play an important role in determining its efficiency. Presence of air results in scattering of α -particle incident on the detector, which in turn reduced its efficiency by ~7%. In

conclusion, the studies from this work demonstrated the great potential of vertical GaN-on-GaN SBD with compensated DL for high-energy α -particle detection at low voltages with high CCE .

6.2 Key contributions of this work

The motivation of this work is to develop a GaN-based α -particle detector which can detect energies as high as 5.48 MeV at low voltages, which should help to increase the portability of such devices. The key contributions of this thesis include:

- To achieve the required CCD , Mg (p-type) compensation was implemented for the first time to reduce the unintentional Si (n-type) doping in MOCVD grown GaN. The p-type doping reduces the CCD in the DL , increasing the resultant DW and V_{BD} while reducing I_R .
- The effect of DLT on various characteristics like I - V , IVT, CV, and V_{BD} were compared for the first time. These studies provide a better understanding of GaN-on-GaN structure and could help researchers to design SBD detectors for different required α -particle energies.
- Effect of compensation and DLT on the CM of I_R was also studied, which helped analyze its physical effects and provide better insight on the effects resulting in reduced I_R and increased V_{BD} . Multiple changes in CM with an increase in voltage and temperature are reported for the first time. Due to the change in CM from TFE to TE, I_R suddenly reduces with increase in voltage resulting in the

observation of a negative differential resistance (NDR) region for the first time on GaN-based devices.

- Finally, the fabricated SBDs were exposed to α -particle radiation, and the detectors exhibited 30% improvement in low voltage performance and 30% improvement in spectral resolution compared to reported GaN-based α -particle detectors. High CCE of 96.7% was also measured at -300V , which is 250 V lower than the previously reported α -particle detectors based on bulk GaN. These improvements in the characteristics of α -particle detectors pave the way to realize a portable α -particle detector.

6.3 Recommendations for Future Work

So far, we have designed, fabricated, and tested a novel design for a portable α -particle detector which can work at low bias conditions. Although promising results have been demonstrated in this work, the following improvements are recommended:

- In this thesis, we have successfully reduced CCD by 2 orders of magnitude with Mg compensation. This reduction in CCD has helped realize thicker DW , higher V_{BD} , and lower I_R . Further optimization of DW is possible by the further reduction in CCD . Reduction in CCD can be achieved in two ways. Firstly, improvement in growth techniques, which could help reduce unintentional Si doping. Secondly, the optimization of p-type doping concentration to help reduce the resultant CCD even further.
- In this thesis, only Mg has been used for compensation of Si doping in DL . Many other elements, like Iron and Carbon can also act like p-type dopants and reduce CCD . While researchers have already used both carbon and iron to reduce CCD of GaN-buffer layers, no one has attempted to use them for compensation of a DL . It has been reported by K. Ko et al. [64], that both carbon and iron requires higher ionization energy for activation as electron traps in

comparison to Mg. Activation of C and Fe at higher temperatures may help these devices to operate at higher temperatures.

- α -particles emitted by any radioactive source are divergent in nature. This divergent nature limits the maximum distance detector needs to be placed for reliable detection. To increase the range of detection, detector surface area needs to be increased. As our GaN-on-GaN α -particle detectors exhibit no effect of detector dimensions on *CCE*, it would be recommended to connect multiple detectors in an array, creating a larger surface area. This method also helps increase the reliability of the device as even if one detector fails other detectors in the array would keep the device functioning.

Author's Publications

Journal Publications

1. A. Sandupatla, S. Arulkumaran, G. I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda and a. H. Amano, "*GaN drift-layer thickness effects in vertical Schottky barrier diodes on free-standing HVPE GaN substrates*" AIP Advances, vol. 9, p. 045007, 2019.
2. A. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, P. Murmu, J. Kennedy, M. Deki, S. Nitta, Y. Honda, H. Amano, "*Low voltage high-energy α -particle detectors by GaN-on-GaN Schottky Diodes with record-high charge collection efficiency*" Sensors, vol. 19, no. 23, p. 5107, 2019.
3. A. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda, H. Amano, "*Improved breakdown voltage in vertical GaN Schottky Barrier Diodes on free-standing GaN with Mg-compensated Drift Layer*" , JJAP-RC, vol. 59, no. 1, p. 010906, 2020.
4. K. Ranjan, S. Arulkumaran, G. I. Ng and A. Sandupatla, "Investigation of self-heating effect on DC and RF performances in AlGaIn/GaN high electron mobility transistors on CVD-Diamond," IEEE Journal of the Electron Devices Society, vol. 7, p. 1264-1269, 2019, doi: 0.1109/JEDS.2019.2947564

5. K. Ranjan, A. Sandupatla, S. Arulkumaran and G. I. Ng, "Low static and dynamic ON-resistance with high Figure-of-Merit in AlGaIn/GaN HEMTs on CVD Diamond", *Physica Status Solidi (a)*, doi:10.1002/pssa.201900815.
6. A. Sandupatla, S. Arulkumaran, G.I. Ng, S. Nitta, J. Kenney, and H. Amano, "Vertical GaN-on-GaN Schottky Diodes as a particle radiation sensor," Review article – *Micromachines* (Invited).

Conference Publications

1. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, S. Nitta, M. Deki, H. Amano, "Effect of GaN drift-layer thicknesses in vertical Schottky Barrier Diodes on free-standing GaN substrates" SSDM, 2018 Tokyo, Japan.
2. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, S. Nitta, Y. Honda, M. Deki, H. Amano, "Effects of Drift Layer Thicknesses in Reverse Conduction Mechanism on Vertical GaN-on-GaN SBDs grown by MOCVD", EDTM, 2019, Singapore.
3. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, M. Deki, S. Nitta, Y. Honda, H. Amano, "Enhanced breakdown voltage in vertical Schottky diodes on compensated GaN drift layer grown on free-standing GaN" ICNS-13, Bellevue, USA (2019).
4. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, P. Murmu, J. Kennedy, M. Deki, S. Nitta, Y. Honda, H. Amano, "Low leakage Mg-

- compensated GaN Schottky diodes on free-standing GaN substrate for high efficiency α -particle detection”, EDTM-2020.
5. Sandupatla, S. Arulkumaran, G.I. Ng, K. Ranjan, S. Nitta, Y. Honda, M. Deki, H. Amano, “Change of conduction mechanism in vertical GaN-on-GaN Schottky diodes at elevated temperatures” EDTM-2020.
 6. K. Ranjan, S. Arulkumaran, G. I. Ng, and - A. Sandupatla, “Low interface trap density in AlGaIn/GaN MIS-HEMTs on CVD-Diamond”, EDTM-2020.

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