Advanced polarization engineering of III-nitride heterostructures towards high-speed device applications

DISSERTATION

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By

Digbijoy Neelim Nath

Graduate Program in Electrical and Computer Science

The Ohio State University

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Dissertation Committee:

Professor Siddharth Rajan, Advisor

Professor Steven A. Ringel

Professor Wu Lu
Abstract

This thesis explores polarization-engineering in III-nitride heterostructures towards next generation high-speed GaN-based transistors.

GaN-based devices have found a wide range of useful applications such as high-speed RF transistors in wireless technology and as blue/green light emitters in opto-electronics. Due to superior material and electrical properties, GaN-based transistors offer much higher output power with increased efficiency than its rival technologies can offer. However, with aggressive scaling of device dimensions, conventional AlGaN/GaN HEMTs are now reaching the limit of their high-speed performance (maximum cut-off frequency, $f_T$) due to LO phonon-limited saturation velocity ($\sim 1-2 \times 10^7 \text{ cm/s}$) of electrons in GaN. To enable a high-power III-nitride device technology in the THz regime, unconventional transport mechanism and advanced channel engineering need to be explored. This thesis seeks to explore three approaches towards this – alternative channel material (In$_x$Ga$_{1-x}$N) for higher intrinsic electron velocity, lower dimensional transport (1D transistors), and unconventional tunnel-injected ballistic transport in a hot electron transistor.
The electron velocity in In$_x$Ga$_{1-x}$N ($x \approx 0.25$) is theoretically estimated to be at least 50-100% higher than in GaN which can lead to substantial increase in $f_T$; however, achieving high quality In$_x$Ga$_{1-x}$N with high In-composition presents significant epitaxial challenges. In the first part of this thesis, MBE growth of high composition InGaN is investigated, and a comprehensive growth diagram is developed.

Lower dimensionality can be promising for superior electron transport including better noise figure. Conventional approaches to nanowire fabrication including both top-down and catalysis-mediated bottom-up approaches have their own limitations. Besides, it has always been a challenge to achieve dense arrays of nanowire transistors required for technological applications. In the next part of the thesis, self-defined arrays of nanowires or 1-D channel transistors are demonstrated in vicinal N-polar GaN-based heterostructure by using polarization-engineering. High current densities up to 150 mA/mm is achieved in dense arrays ($>10^5$ nanowires/cm) of self-defined 1D transistors.

In the final part, a unipolar III-nitride device - tunnel-injected hot electron transistor (THETA) - is investigated which can theoretically provide $f_T > 1$ THz by exploiting ballistic transport of electrons over a thin base layer. However, all unipolar III-nitride vertical devices have been always found to suffer from unacceptably high leakage current densities. A comprehensive investigation into such vertical leakage mechanism is presented and is attributed to a ternary alloy-mediated percolation-based transport. By eliminating ternary alloys as leakage barrier, III-nitride THETA is demonstrated for the first time with output modulation in common-emitter configuration with a current transfer ratio up to 0.80 at 6 eV base-emitter bias.
Dedication

This document is dedicated to my parents and my sister.
Acknowledgments

The last five years of my stay in Columbus as a PhD student in the Ohio State University have been highly rewarding both in professional and personal experiences, and I would like to extend my sincere thanks to all who made it possible.

My advisor Prof. Siddharth Rajan (or Siddharth as we address him) must be thanked before anyone else. I am (was) his first student, and initially in the absence of any other student or post-doc in the group, he played multiple roles for me as an advisor, as a mentor, as a teacher and as a friend. He had taught me right from holding samples with tweezers to doing epitaxial growth of GaN heterostructures using MBE. He taught me to use AFM, XRD and Hall measurement equipments besides teaching me to analyze results obtained from such characterization techniques. I am indebted to him for various aspects of research which I have learned from him including writing technical papers, making slides for presentations, identifying & approaching the right problems to solve. He has been providing critical insights and directions into my research, brainstormed challenging issues in design and analysis of my devices and inspired me at times of my repeated failures. His enthusiasm for new device ideas and his positive attitude in everyday life are indeed infectious. He supported me completely when I faced unexpected and severe hardships at the beginning of my PhD. I extend my sincerest gratitude to him for everything.

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Vita

June 30, 1985 ............................................. Born - Assam, India

2004-2008 ................................................. B.E., Electrical & Electronics Engineering
                                  BITS, Pilani (India)

2008-2013 ................................................. Graduate Research Associate
                                  Department of Electrical Engineering
                                  The Ohio State University

Publications

Journal papers

Digbijoy N. Nath, Pil Sung Park, Zhichao Yang and Siddharth Rajan, “Demonstration of
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Declaration

The results and contents of this dissertation are primarily based on the following five journal publications which I have had authored based on work which I had carried out and obtained in my PhD. Hence there may be some overlap and similarities between the texts in this dissertation and the following publications (authored by myself).


Chapter 1

Introduction

The III-nitride family of semiconductors consisting of GaN, InN, AlN and their alloys has found a wide range of electronic and opto-electronic device applications in the last two decades. A set of unique material, electrical and optical properties of III-nitrides has enabled devices which are not viable with contemporary Si and GaAs/InP based technologies. III-nitrides span a direct band gap from beyond near-IR (0.7 eV, InN)\(^1\) to deep-UV (6.2 eV, AlN)\(^2\) which has enabled realizing high brightness, energy-efficient blue and green light emitting diodes (LEDs) as well as laser diodes. The first InGaN-based blue LED and laser diode were demonstrated by Nakamura et al in 1993\(^3\) and 1996\(^4\) respectively. Improvements in epitaxy of high quality, low-dislocation GaN wafers as well as understanding and progress in device designs have gradually led to the expansion of the GaN LED market which stands at $ 9 billion USD\(^5\) at the time of writing this thesis. This has revolutionized display, information storage (blu-ray) and energy-efficient lighting technologies. UV and deep-UV LEDs, solar cells and photo detectors are other promising applications of III-nitride opto-electronics which are being actively researched upon.
The formation of a polarization-induced high sheet density \(10^{13} \text{ cm}^{-2}\) 2-dimensional electron gas (2DEG) at the interface between GaN and strained AlGaN enabled realizing the first III-nitride high electron mobility transistor (HEMT) in 1993\(^6\) without modulation doping. Due to high breakdown field (~3 MV/cm) and high electron velocity in GaN, AlGaN/GaN HEMTs demonstrated much higher output power density\(^7,8,9,10,11\) at microwave and milli-meter wave frequencies than contemporary technologies could offer\(^12,13,14\). Fig. 1.1 shows a comparison between III-nitride and InP/InGaAs-based technologies in terms of output power density and frequency of measurement as demonstrated by various groups. It illustrates that III-nitride HEMTs (even on silicon substrate) deliver more than an order of magnitude higher power density than InGaAs based devices.

![Figure 1.1: Output power versus measurement frequency for III-nitride and InGaAs/InP device technologies](image)

Higher power density translates in to smaller device footprints, leading to reduced cost and size, reduced cooling requirements and lighter weight. Thus, GaN RF power
amplifier market, projected to reach $1.75 billion USD\textsuperscript{15} by 2022, has grown steadily, finding applications in wireless technology for both commercial and military purposes. Major industry players include Cree, Panasonic, Mitsubishi, RFMD, Triquint, Nitronex, International Rectifiers, etc. Besides, GaN RF devices hold great promise for space applications due to their radiation-resistant nature; in fact, the first GaN RF device (operating in X-band) went up in orbit aboard Proba-V satellite\textsuperscript{16} launched by European Space Agency in May 2013 which is expected to lead to 10x increase in signal strength. Fig. 1.2 shows the application space for GaN-based RF devices.

![Figure 1.2: Application space of III-nitride RF devices](image)

Although GaN-based HEMTs are delivering excellent power performance at microwave frequencies, yet they are far from reaching the THz regime. In fact, with
device dimensions being aggressively scaled down, it has become tremendously challenging to extend the current gain cut-off frequency \((f_T)\) for III-nitride HEMTs beyond 350-400 GHz\(^{17,18}\). Fig. 1.3 shows \(f_T\) versus gate length as reported by various groups\(^{19,20,21,22}\) in the recent past. Due to reduction of parasitic such as access region resistance, higher \(f_T\) is progressively being achieved at nearly the same sub-30 nm gate length. However, it has become tremendously challenging to push \(f_T\) beyond 400 GHz.

The reason GaN HEMTs are reaching this performance limit is because LO phonons limit the electron saturation velocity in GaN at around \(2\times10^7\) cm/s\(^{23}\). This saturation velocity poses a theoretical bottleneck in realizing \(f_T>500\) GHz for HEMTs with GaN as the transistor channel and thus has held back the development of a high-power III-nitride device technology in the THz range.

![Figure 1.3: \(f_T\) versus gate length reported for III-nitride HEMTs](image)

This thesis seeks to explore alternative approaches which hold promise to reduce the transit time in III-nitride transistors. To this end, engineering the energy band profile as well as polarization\(^{24,25}\) in such heterostructures is investigated which can enable novel
high-speed devices. Three approaches are identified which are promising to further increase the $f_T$ of GaN-based devices:

i. Use of In$_x$Ga$_{1-x}$N as alternate channel material

ii. Exploring reduced dimensional (1-D) transport

iii. Tunnel injection hot electron transfer amplifier (ballistic transport)

Fig. 1.4 provides an overview of the work presented in this thesis.

Figure 1.4: Overview of the work presented in this thesis

1.1 Motivation
1.1.1 Use of InGaN as alternate channel material

Barring a few reports\textsuperscript{26,27,28,29}, III-nitride HEMTs have always been demonstrated with GaN as the transistor channel. However, since the electron saturation velocity in GaN (1-2x10\textsuperscript{7} cm/s) is the primary factor limiting the maximum achievable $f_T$, the most obvious approach to push its limit is to explore alternate III-nitride alloys as transistor channel where electron saturation velocity can be higher than in GaN.

InN is one of the most promising channel materials where, based on Monte Carlo simulations\textsuperscript{30}, the electron velocity (3.3x10\textsuperscript{7} cm/s) had been predicted to be higher than in GaN. However, InN being 11% lattice-mismatched to GaN, relaxes in a few mono-layers and thus a pseudomorphic InN layer is extremely challenging to achieve. More recently, it was shown theoretically\textsuperscript{31} that alloy-disorder in In\textsubscript{x}Ga\textsubscript{1-x}N (x = 0.25-0.30) can reduce the peak phonon population in the channel and lead to a 50-100\% increase in electron velocity. Such an increase in electron velocity can enable $f_T > 500$ GHz in In\textsubscript{x}Ga\textsubscript{1-x}N (x = 0.25-0.30) channel HEMTs. However, it has been challenging to realize a HEMT with In\textsubscript{x}Ga\textsubscript{1-x}N (x>0.15) as the channel. The primary challenge lies in the epitaxy of In\textsubscript{x}Ga\textsubscript{1-x}N with high In-compositions such as 25-30\%, both by MBE and by MOCVD. If InGaN is grown at typical GaN growths temperatures, In-N bonds break and N\textsubscript{2} leaves leading to decomposition\textsuperscript{32} of InGaN layer during growth. In fact, in plasma-assisted MBE, GaN is usually grown at $> 700^0$C while above $\sim 550$-600$^0$C, it is challenging to obtain conventional Ga-polar InGaN. Hence, InGaN has to be grown at significantly lower temperatures such as 500$^0$C or lower to avoid decomposition. The higher the In-composition (x>0.2), the more challenging is the epitaxy. The lower growth temperature
leads to poor structural quality of InGaN. Besides, phase separation\textsuperscript{33} is another issue that affects epitaxy of InGaN.

Due to these challenges, only a few reports on In\textsubscript{x}Ga\textsubscript{1-x}N channel HEMTs exist in literature, and such devices have been reported with very low In-compositions such as x=0.05. Such low composition InGaN channel HEMTs have not shown superior performance compared to conventional GaN-channel HEMTs because a significant velocity enhancement is predicted only for In\textsubscript{x}Ga\textsubscript{1-x}N channel with x > 0.25.

Understanding the epitaxy of In\textsubscript{x}Ga\textsubscript{1-x}N (x = 0.25-0.30) in comprehensive details is therefore quintessential to realizing devices with such channels. Also, besides the conventional Ga-polar orientation of InGaN, the reverse polarity i.e. N-polar InGaN can be studied to explore feasibility of realizing high composition InGaN layers.

1.1.2 Reduced dimensional (1D) transport

Among many exciting application potentials, nanowires have been widely studied as a promising candidate to sustain downscaling\textsuperscript{34} of planar MOS transistors as per Moore’s law. This is because nanowires can be fabricated down to sub-10 nm dimensions with good electrostatic control\textsuperscript{35} which is very challenging to achieve using planar devices with 2-dimensional transport. Additionally, due to quantum-confined one dimensionality, nanowires also present an interesting platform to explore transport properties\textsuperscript{36} of carriers which may be useful for high-speed and high-performance transistors. For instance, due to significant change in phonon scattering rate associated with 1-D density of states, LO phonon limited electron velocity is theoretically predicted\textsuperscript{37} to be enhanced in 1-dimensional channels as compared to 2-D counterparts.
This holds promise for investigating III-nitride 1-D channel HEMTs to explore if higher electron velocity is achievable which can subsequently enable pushing its $f_T$ limit. Besides, nanowires are also shown to exhibit superior low-frequency noise properties\textsuperscript{38,39}.

However, achieving controlled assembly of high-density nanowire arrays for large-scale integration, which is crucial for practical applications, is still a major challenge for both top-down\textsuperscript{40,41,42} and bottom-up\textsuperscript{43,44} approaches. While achieving high quality nanowires with sub-20 nm dimensions becomes a challenge for top-down approach, the bottom-up approach suffers from issues such as poor surface control, poor longitudinal control of doping profiles and possible metal contamination due to requirement of metal as catalysts for growth initiation\textsuperscript{45}. Besides, reports on III-nitride nanowire transistors are few. In this thesis, a self-defined dense array of 1-D channel transistors is demonstrated combining advantages of both top-down and bottom-up approaches by exploiting polarization in N-face vicinal GaN/AlGaN heterostructures. This can enable investigation of transport properties such as electron velocity in III-nitride 1-D channels.

1.1.3 Tunnel injection hot electron transfer amplifier

To circumvent the LO phonon limited velocity saturation, ballistic transport offers an attractive alternative over conventional drift-diffusion transport in AlGaN/GaN HEMTs. In ballistic transport\textsuperscript{46}, electrons travel without collision over a very short distance which leads to ultra-fast transit times. Such devices are usually vertical since due to the very short dimensions (~5-10 nm) required for such collisionless transport, lateral transistors are extremely challenging to realize. Two primary vertical device
configurations used in such a ballistic transistor are hot electron transistor (HET) and tunnel injection hot electron transfer amplifier (THETA). In both types of devices, electrons with sufficiently high energy – hot electrons – are injected either thermionically (HET) or via tunneling (THETA) through a thin emitter barrier. These electrons then travel ballistically over a very short layer (base) and are collected in an n-doped collector. The device is operated by forward biasing the base and emitter junction (V_{BE}>0) so that electrons can be injected into the base, and reverse-biasing the base-collector junction (V_{CB}>0). For electrons to travel ballistically, the base has to be very thin – in the order of electron mean free path – which trades off with base conductivity. Besides, the height of the base-collector barrier needs to be traded off between a high transfer ratio ‘α’ corresponding to lower barrier height and low base-collector leakage requiring a higher barrier. Due to ballistic nature of transport, such a device in III-nitride system is theoretically estimated to exhibit $f_T > 1 \text{ THz}^{49}$.

For such unipolar vertical ballistic transistors to work, the ‘cold’ electrons in the base layer should not leak into the collector, such that the base and collector junction exhibits a rectifying behavior in reverse bias (V_{CB}>0). However, unipolar n-GaN/AlGaN/n-GaN heterostructures have been always found to exhibit unacceptably high vertical leakage current densities. Although reverse leakage in HEMT Schottky diodes and in bipolar III-nitride structures such as LEDs have been significantly less (<< 1 A/cm²), very high leakage currents (~ kA/cm²) in unipolar structures render them difficult to realize. All III-nitride vertical devices requiring a unipolar current barrier such as resonant tunneling diodes (RTD), current aperture vertical electron transistor (CAVET), THETA etc. are affected by such leakage. A comprehensive study of current
transport in unipolar heterostructures is therefore necessary to reduce this unacceptably high leakage which can enable novel and promising III-nitride vertical devices.

1.2 Overview of the thesis

This thesis is organized as follows: in chapter 2, the promises and challenges in realizing an InGaN channel HEMT with high In-compositions (>20%) are presented. A comprehensive plasma-assisted MBE growth study of both Ga-polar and N-polar In$_x$Ga$_{1-x}$N along with a growth model are presented. The growth model was found to fit well to the experimentally observed In-compositions in various In$_x$Ga$_{1-x}$N layers. The model allowed achieving In$_x$Ga$_{1-x}$N with high In-composition by using two growth parameters – Ga-flux and substrate temperature. Single phase N-polar In$_x$Ga$_{1-x}$N epitaxial films were achieved as verified by single peaks in X-ray diffraction (XRD) and photoluminescence (PL) measurements. This has enabled future work on achieving InGaN channel HEMTs as well as other devices based on high In-composition InGaN.

In chapter 3, transport properties of N-polar AlGaN/GaN HEMTs on vicinal substrates are studied and lateral electrostatic engineering is explored to achieve anisotropic transport. With advanced polarization engineering, pure 1-D transport is demonstrated in AlGaN/GaN HEMT structures where each nanowire channel corresponds to one atomic terrace (~7-14 nm) of the vicinal heterostructure. This translates into dense arrays (~100,000 wires/mm) of self-defined nanowires which carry technologically relevant current densities and combines advantages of both top-down and bottom-up approaches. This polarization-engineered approach to achieving 1-D transport eliminates conventional issues related to nanowire fabrication such as contamination,
issue with catalysis, good contact formation with wires, obtaining arrays of aligned nanowires, etc.

In chapter 4, vertical transport (I-V) characteristics in unipolar GaN/AlGaN/GaN heterostructures is investigated. Ternary alloy (AlGaN) mediated percolation-based leakage due to random alloy fluctuations of Al-composition is attributed to be the most likely reason for vertical leakage in such unipolar III-nitride structures. This is also supported by 2D Poisson and drift-diffusion modeling of percolation transport. Eliminating ternary random alloy as electron barriers, vertical leakage was found to be reduced by several orders of magnitude reduced reinforcing the percolation model of leakage.

In chapter 5, the development of a III-nitride tunneling hot electron transistor or THETA is discussed. The small-signal delay analysis of GaN-based THETA is presented showing that $f_T > 1$ THz is theoretically achievable. A Ga-polar THETA is designed using a 3 nm AlGaN (25%) as emitter barrier and a degenerately doped ($10^{20}$ cm$^{-3}$) GaN base layer. A polarization-engineered electrostatic barrier exploiting GaN was used to prevent ternary AlGaN mediated percolation-based base-collector leakage. Devices were found to exhibit negligible base-collector leakage and base contacts were found to be Ohmic in nature. Devices exhibited output modulation ($I_C$-$V_{CE}$) in common-emitter configuration, which is the first such report in any type of unipolar III-nitride transistor. A maximum current transfer ratio of 0.82 was measured in a device with 6 nm base thickness.
Chapter 2

Molecular Beam Epitaxy of InGaN

2.1 Introduction

This chapter describes the growth of high-quality N-polar In$_x$Ga$_{1-x}$N with high In-composition by plasma-assisted MBE.

The ternary In$_x$Ga$_{1-x}$N alloy system was primarily investigated towards enabling opto-electronic devices such as LEDs and laser diodes. Although it has attracted interest for possible multi-junction solar cells since its band gap (0.7 to 3.4 eV) encompasses the entire visible and near-IR spectrum, yet emitters remain the most important application of the InGaN material system. This is because InGaN is unique in providing a capability in reaching these energies since III-As/P system do not have high quality direct band gap materials in these wavelengths. InGaN-based blue LEDs and white LEDs (comprising of phosphor-coated blue LEDs) are now a multi-billion dollar industry. Green emission however, still poses significant difficulties due to epitaxial challenges in achieving high quality InGaN films on conventional Ga-face polarity with high In-compositions ~ 20-25% required for emitting green wavelength (510 nm and beyond). Extensive research in to non-polar (a-plane and m-plane) and semi-polar InGaN LEDs
have led to the demonstration of high brightness green LEDs and laser diodes in the recent past.\textsuperscript{51,52,53}

However, outside of the opto-electronic applications, InGaN has been far less explored. Only a few reports\textsuperscript{54,55,56} on InGaN channel transistors exist till date, and the In-compositions in all of these reports are 10\% InGaN or lower except for the first report\textsuperscript{57} where a 15\% InGaN channel was reported. However, band gap of InN was not known at that point, and therefore the composition of 15\% InGaN cannot be verified. More recently\textsuperscript{58}, a cutoff frequency of 260 GHz was reported for a highly scaled InGaN channel HEMT with 5\% In-composition.

2.2 Motivation for InGaN channel HEMT

The primary motivation for investigating InGaN channel HEMTs is a predicted higher electron saturation velocity\textsuperscript{59,60} compared to that in conventional GaN-channel HEMTs which is promising for III-nitride devices with $f_T > 500$ GHz.

At room temperature, interaction between electrons (in channel) and LO phonons limits the electron saturation velocity ($v_{sat}$) in GaN to about $2.5 \times 10^7$ cm/s\textsuperscript{61} as predicted theoretically although experimentally estimated values\textsuperscript{62,63,64} fall short of it. It is shown (ref. [59]) that in In$_x$Ga$_{1-x}$N, the alloy disorder induced scattering (of LO phonons) can increase the number of LO phonon modes interacting with electrons leading to a lower electron temperature. A lower electron temperature results in less hot phonon scattering which translates into a predicted 50-100\% higher electron saturation velocity in In$_x$Ga$_{1-x}$N than in GaN with about 30\% decrease in electron mobility for In$_x$Ga$_{1-x}$N ($x \sim 0.25-0.30$). Such a high $v_{sat}$ can boost the small-signal performance of devices significantly.
To estimate various RF device metrics of InGaN channel HEMT and to compare them with conventional AlGaN/GaN HEMTs, we propose a device epitaxial design as shown in Fig. 2.1. It consists of 3.8 nm of InGaN (25% In-composition) as the channel layer, which has 20 nm of n-doped GaN layer on the top separated by a thin (3 nm) UID GaN layer from the InGaN channel. The n-GaN layer on top is to form non-alloyed Ohmic contact to the channel while the gate can be formed by etching n-GaN layer in the intrinsic region and putting ALD Al$_2$O$_3$ as dielectric as shown in Fig. 2.1. The 2DEG density estimated by using a 1-D Schrodinger-Poisson solver (BandEng) is 7.6x10$^{12}$ cm$^{-2}$. The reason for a proposed non-alloyed contact is because the device is proposed to be grown on a low threading-dislocation density (TDD) free-standing GaN template which would give re-growth interface charge unlike heteroepitaxial growth of GaN buffer on SiC. Thin InGaN layers grown on heteroepitaxially grown GaN/SiC give rise to high TDD mediated island-like morphology which prevents achieving uniform 2DEG density (as will be discussed later in this chapter).

Figure 2.1: Epitaxial design of proposed HEMT with InGaN channel (25% In-composition). Recess gate can be formed by putting ALD Al$_2$O$_3$
To estimate the performance of such a proposed InGaN channel HEMT, we shall plot its power frequency (pf$^2$) limit compared to other conventional semiconductors technologies including GaN channel HEMTs. pf$^2$ limit shows the maximum operating voltage against maximum current gain cut-off frequency $f_T$ for a device technology. It is given by\textsuperscript{66}

$$V_{br} < \frac{E_{\text{max}} \, v_{sat}}{\pi \, f_T}$$  \hspace{0.5cm} (1)

Here, $E_{\text{max}}$ is the critical breakdown field for the given material. The critical breakdown field for InN is yet to be reported in literature, either theoretically or experimentally. For an N-polar InN based HFET reported by Lin et al\textsuperscript{67}, the breakdown of InN layer was observed prior to attaining saturation current at a drain bias of just 2.7 V. So to have a starting point as an estimate of InN breakdown field, we try to find an empirical relationship between breakdown field ($E_{br}$) and energy band gap of various semiconductors because there is few report on a mathematical relationship between $E_{br}$ and $E_g$. Figure 2.2 shows $E_{br}$ as a function of $E_g$ for five different semiconductors. The breakdown field $E_{br}$ depends on the \textit{square} of $E_g$ and the fitting has an $R^2 = 0.99987$. This square-law dependence comes out of tunneling theory. Following this trend, the InN breakdown field is ‘estimated’ to be about 100 kV/cm which is purely based on this square-law dependence. Thus for 25% InGaN, the breakdown is predicted to be $\sim 1.3$ MV/cm.
With a predicted breakdown field of 1.3 MV/cm and a 50-100% higher $v_{sat}$ than GaN, the $pf^2$ limit for InGaN (25% In-composition) can now be plotted as shown in Fig. 2.6. The $v_{sat}$ assumed is $4.38 \times 10^7$ cm/s which is 75% higher than the theoretical value for GaN. As seen in Fig. 2.3, the $pf^2$ limit for In$_{0.25}$Ga$_{0.75}$N is much better than that of InP and of course Si while being slightly below the limit for GaN. However, for very high frequencies such as $f_T > 500$ GHz which GaN has extremely less probability of achieving, In$_{0.25}$Ga$_{0.75}$N channel based HEMT with its high velocity can still be operated at much higher power than InP based HEMTs or HBTs can be operated.
The maximum output power from a device (HEMT) is limited by the maximum possible swing achievable in the output voltage and current is hence simply given by:

\[ P_{\text{out}}(\text{max}) < \frac{1}{8} V_{br} I_{\text{DSS}} \]  

(2)

The limits to \( V_{br} \) are known from eqn. (1) and observing that \( I_{\text{DSS}} = qn_s v_{\text{sat}} \), we can express the \( P_{\text{out}}(\text{max}) \) as:

\[ P_{\text{out}}(\text{max}) < \frac{E_{\text{max}} q n_s v_{\text{sat}}^2}{8\pi f_T} \]  

(3)

The maximum output power thus depends linearly on the 2DEG density but quadratically on saturation velocity. For various semiconductors heterostructures containing a 2DEG including our proposed design with 25% InGaN layer (Fig. 2.1), we can thus plot \( P_{\text{out}}(\text{max}) \) as a function of \( f_T \). To compare with contemporary non-nitride

Figure 2.3: \( pf^2 \) limit for InGaN (25% Indium mole-fraction) compared to other contemporary device technologies.
device technologies, we assume a 2DEG of \( \sim 4 \times 10^{12} \text{ cm}^{-2} \) in InP/InGaAs composite channel devices which is in fact a very high sheet density for such material systems. Also, we consider a standard AlGaN/GaN HEMT device with 2DEG \( \sim 1 \times 10^{13} \text{ cm}^{-2} \). Our proposed InGaN channel design mentioned earlier has a 2DEG of \( \sim 7.6 \times 10^{12} \text{ cm}^{-2} \). Figure 2.4 shows \( P_{\text{out}}(\text{max}) \) (theoretical) in dBm as a function of \( f_T \) for these three heterostructure systems.

![Figure 2.4: Output power available for three heterostructure systems as a function of \( f_T \).](image)

A few experimentally measured data points of output power (at measurement frequencies) for both AlGaN/GaN HEMTs and InP-based devices as reported in the literature\(^{68,69,70,71}\) are also shown in Fig. 2.4. It is observed that AlGaN/GaN and \( \text{In}_{0.25}\text{Ga}_{0.75}\text{N} \) channel HEMTs are predicted to deliver output power of similar magnitudes at all frequencies even though GaN has a breakdown field 2.5 times higher than that of \( \text{In}_{0.25}\text{Ga}_{0.75}\text{N} \). This is because the \( P_{\text{out}} \) is proportional to \( v_{\text{sat}}^2 \) – a 50-100\% increase in \( v_{\text{sat}} \).
for In$_{0.25}$Ga$_{0.75}$N pulls $P_{\text{out}}$ up by 2.25 to 5 times as compared to GaN. Of course, $P_{\text{out(max)}}$ is never measured at $f_T$ of the device and so this plot gives only an idea of how $P_{\text{out(max)}}$ behaves at cut-off frequency.

A significant promise for In$_{0.25}$Ga$_{0.75}$N channel HEMT is thus – it is promising for achieving $f_T > 500$ GHz due to higher saturation velocity than in GaN, and at the same time can deliver almost similar $P_{\text{out}}$ as compared to AlGaN/GaN HEMT.

2.3 Challenges in realizing InGaN channel HEMTs

An appreciable increase in electron velocity is predicted for InGaN with at least > 20% In-composition. The primary challenge in realizing it lies in achieving high quality InGaN with such high In-mole fractions (20% and above) in the conventional Ga-face polarity. This is because the optimal growth conditions for the alloy components InN and GaN are significantly different. While a steady-state Ga metal bilayer coverage at optimal growth temperatures (~ 710$^\circ$C) enhances adatom diffusion leading to superior surface and material qualities for plasma-assisted molecular beam epitaxy (PAMBE) growth of GaN$^{72}$, conventional In-polar InN growth by MBE is limited to ~ 500$^\circ$C because of its inherent thermal instability and decomposition temperatures lower than that of desorption of metallic In. $^{73}$ This is significantly lower than optimal growth temperatures needed for growth of GaN ( ~ 710$^\circ$C) which therefore deteriorates the structural quality of In$_x$Ga$_{1-x}$N films grown. Besides, high composition In$_x$Ga$_{1-x}$N layers are found to suffer from phase separation$^{74,75,76}$ and spinodal decomposition.

Recently, the reversed direction of polarization of GaN, i.e., N-polar orientation was explored to exploit advantages for high-speed performance of highly scaled transistors.$^{77,78}$ It was also demonstrated that PAMBE growth of N-polar InN can be done
at approximately 100°C higher than the thermal dissociation limit of In-polar InN.\textsuperscript{79,80,81,82} This implies that N-polar InGaN with higher In-compositions can be grown at higher growth temperatures than In(Ga)-polar InGaN, and films with lower point defect incorporation and better electrical and optical properties may be expected. In addition, the reversed direction of polarization may have other advantages from the device design perspective. However, N-polar InGaN growth reports have been few so far.\textsuperscript{83,84} This chapter seeks to provide a comprehensive understanding of In incorporation in N-polar InGaN as compared to Ga-polar orientation. A quantitative growth model is proposed that explains the variation of In mole-fraction in In\textsubscript{x}Ga\textsubscript{1-x}N with respect to change in growth temperatures and Ga-flux. There have been reports published earlier modeling the MBE growth of In\textsubscript{x}Ga\textsubscript{1-x}N\textsuperscript{85,86,87} but they were reported before the correct estimation of InN band gap as \(\sim 0.7\) eV. Thus the model proposed here is more accurate in light of a revised InN band gap.

2.4 MBE growth and characterization of InGaN

For epitaxy of InGaN, both N-polar and Ga-polar GaN templates were cleaved into \(\sim 1\) cm x 1 cm sized pieces and co-loaded on a single silicon wafer using indium-bonding to ensure identical growth conditions. This was to make sure that the difference in In incorporation for In\textsubscript{x}Ga\textsubscript{1-x}N of both polarities at a particular growth temperature could be studied. N-polar free-standing LED quality GaN templates were obtained from Lumilog\textsuperscript{88} (TDD \(\sim 10^8\) cm\textsuperscript{-2}) while Ga-polar GaN on sapphire template (TDD \(\sim 10^9\) cm\textsuperscript{-2}) were obtained from Kyma\textsuperscript{89}. Samples were grown by PAMBE in a Veeco Gen 930 system equipped with standard effusion cells for Ga and In. Active nitrogen was supplied using a Veeco RF Plasma source. Since sapphire has a lower thermal conductivity than
GaN, the surface temperature (using optical pyrometer) of the Ga-polar sample was found to be 3-5°C higher than that of the N-polar sample. All InGaN layers discussed in this work were grown for one hour with a standard GaN growth rate of 5 nm/min. However, due to decomposition of InGaN, the actual thickness of the films is expected to be less than expected from the nominal growth rate (i.e., 300 nm).

Three sets of growths were done at growth temperatures of 500°C, 550°C and 600°C in an In rich regime, the temperatures being stabilized prior to growth. The growth temperature was monitored by an optical pyrometer with readings calibrated against the melting point of Al. The In incorporation depends on the growth temperature and on the Ga/N flux ratio. The Ga-flux was kept constant at $9.5 \times 10^{-8}$ Torr which corresponded to ~0.39 times the stoichiometric GaN growth rate. An RF power of 350 W and N$_2$ flow rate equivalent to $1.9 \times 10^{-5}$ Torr of beam flux monitor (BFM) pressure corresponding to a stoichiometric growth rate of 5 nm/min was used throughout. All growths were done in In rich regime with an In-flux of $5 \times 10^{-7}$ Torr which is more than twice the stoichiometric Ga-flux. We assumed a “strong stoichiometric condition” (ref. [86]) which refers to the assumption that all impinging Ga atoms would be incorporated into the lattice and only those sites which have not been Ga-occupied would be available for In incorporation. This translates into the fact that a variation in In incorporation is simply dependent on growth temperature and Ga-flux in an N-limited growth regime.

Light emission from the N-polar and Ga-polar InGaN samples was collected by one meter long monochromator with a ruled grating 1200 gr/mm placed at surface normal and the signals were detected by Hamamatsu R2658 photomultiplier tube mounted exit slit of the monochromator. A Stanford Research System SR830 DSP lock-in amplifier
was used to analyze the data. An Ar ion laser with a wavelength of 488 nm was used as an excitation light source. The PL excitation density is 276 mW cm\(^{-2}\). A control sample was used to confirm that the measurements were performed in identical conditions so that PL intensity values between each measurement performed can be comparable. All measurements were done at room temperature. Triple axis ω-2θ X-ray diffraction (XRD) scans of the samples were performed symmetric around on-axis (0002) and (0002\(^{-}\)) for Ga-polar and N-polar respectively using a BEDE high resolution XRD system with Cu K\(_{\alpha 1}\) radiation (\(\lambda = 1.54056\) Å) and a Ge hybrid monochromator. The atomic force microscope (AFM) scans were performed using a Veeco DI 3000 AFM equipment in tapping mode configuration.

Figure 2.5 shows the ω-2θ triple axis scans of the N-polar films. All N-polar samples showed a single InGaN peak indicating the absence of phase segregation or compositional non-uniformity in the range of compositions (0-58%) explored here. Using the growth model (derived later in this work), the thicknesses of all N-polar and Ga-polar In\(_x\)Ga\(_{1-x}\)N films is at least 150 nm. Since this is much higher than the critical thickness\(^{90,91}\) corresponding to relaxation of In\(_x\)Ga\(_{1-x}\)N on GaN for compositions obtained in this study, all the films can be assumed to be fully relaxed. The In compositions for the N-polar In\(_x\)Ga\(_{1-x}\)N films as extracted from XRD data assuming complete relaxation are indicated beside each plot (Figure 2.5).
Figure 2.5: High resolution XRD $\omega$-$2\theta$ triple-axis scans of the N-polar InGaN films showing single peaks indicating no phase separation or compositional non-uniformity.

In Fig. 2.6, the variation of the In compositions of the $\text{In}_x\text{Ga}_{1-x}\text{N}$ films of both polarities as obtained from room temperature PL peaks and XRD scans as a function of growth temperature is shown. The energy band-gap values extracted from the room temperature PL peaks were used to determine the In-compositions in the films using bowing parameter of $b = 1.8 \text{ eV}^{92}$ with a GaN band gap = 3.4 eV. The wavelength corresponding to the lowest composition Ga-polar InGaN (~ 14% from XRD) grown at 600$^\circ$C was outside the range of the PL setup since its emission wavelength is expected to be lower than the excitation light source wavelength (488nm, >2.541 eV). The compositions determined from PL measurements are close to those obtained from XRD scans using linear interpolation of lattice constants (Vegard’s law). The small mismatch between the two ways of composition estimation can be attributed to uncertainty in bowing parameter as well as to the non-ideality of Vegard’s law. Also for PL, the energy band gaps have been extracted from room temperature PL peak positions and related
these to the In content. The PL peak position, however, cannot be related precisely to the band gap. Because of the typical higher energy of the PL peak positions with respect to the actual band gap, this may cause decreased In contents as derived from PL. From Figure 2.6, it is clear that for the same Ga-flux, In incorporation drops as growth temperature increases due to higher decomposition of InN at higher temperatures irrespective of the polarity. Besides, for a given growth temperature, In incorporation is higher for N-polar In\textsubscript{x}Ga\textsubscript{1-x}N than for Ga-polar In\textsubscript{x}Ga\textsubscript{1-x}N. This implies that N-polar In\textsubscript{x}Ga\textsubscript{1-x}N can be grown at a higher temperature for a specified In mole fraction than Ga-polar In\textsubscript{x}Ga\textsubscript{1-x}N.

![Graph](image)

Figure 2.6: In-composition as a function of growth temperature for both Ga-polar and N-polar InGaN as extracted from room temperature PL and XRD measurements.

2.5 Growth model

We developed a growth model\textsuperscript{93} for N-polar In\textsubscript{x}Ga\textsubscript{1-x}N based on InN decomposition to explain the growth temperature and Ga-flux dependent compositional
variation of In mole-fraction and later extend it for Ga-polar In$_x$Ga$_{1-x}$N as well. The model has been developed for the metal rich N-limited growth regime where the active N-flux available determines the nominal growth rate with an excess of In coverage on the surface. Thus, the composition of In in In$_x$Ga$_{1-x}$N samples is independent on In atoms impinging on or desorbing from the surface. It has been shown (ref. [82]) that N-polar InN decomposition in the metal rich growth regime can be considered to be N-atoms leaving the surface. If $F^N$ is the nitrogen-stoichiometric flux defining the growth rate in the absence of decomposition, then the actual stoichiometric flux $F^{N*}$ defining the true growth rate as InN decomposes is less than $F^N$ by a decomposition rate $F^D$:

$$F^{N*} = F^N - F^D$$  \hspace{1cm} (4)

The In-composition, $x$, in an In$_x$Ga$_{1-x}$N film is related to the effective (reduced) growth rate $F^{N*}$ and the incident Ga flux, $F_{Ga}$, by the equation (assuming ‘strong stoichiometric condition’)

$$x = 1 - \frac{F_{Ga}}{F^{N*}}$$  \hspace{1cm} (5)

We assume that the decomposition rate $F^D$ is proportional to the In mole fraction ‘$x$’ in the In$_x$Ga$_{1-x}$N film (so that for a pure GaN film, there will be no decomposition as expected). The decomposition rate $F^D$ is also shown to have an Arrhenius dependence on substrate temperature $T_{sub}$.

$$F^D \propto x \exp\left(- \frac{E_a}{kT}\right)$$  \hspace{1cm} (6)
Here, $E_a$ is the activation energy of decomposition of N-polar InN which has been calculated earlier to be 1.2 eV.\textsuperscript{33} Using (4) and (6) in (5), the In-composition ‘x’ in the In$_x$Ga$_{1-x}$N film can be expressed as a function of temperature as

$$x = \frac{\beta e^{\frac{-E_a}{kT}}}{2 \beta e^{\frac{-E_a}{kT}}} - \sqrt{(1 + \beta e^{\frac{-E_a}{kT}})^2 - 4 \beta e^{\frac{-E_a}{kT}} (1 - \frac{F^Ga}{F^N})}$$

(7)

Here, $\beta$ is the proportionality factor of equation (6) normalized to the value of N$_2$-flux.

The activation energy $E_a = 1.2$ eV obtained in ref. [82] is in the temperature range 590$^0$C-635$^0$C and so using this value of $E_a$ might not be accurate for a temperature range of 450$^0$C-650$^0$C modeled in our study. It has been pointed out that\textsuperscript{38} Indium loss cannot be accounted for simply by a single thermally activated process since the surface stoichiometric modifies the process behind it, implying a temperature dependence of $E_a$. However, the exact dependence of $E_a$ for InN decomposition on growth temperature is not yet well understood or derived and hence we shall use the value reported in ref. [82] for our work here with a room for better accuracy provided we know $E_a$ as a function of temperature. It is also noteworthy that in ref. [85], the activation energy for In$_x$Ga$_{1-x}$N decomposition was reported to be 3.5 eV as extracted from the plot of the ratio of InN loss to In composition vs. 1/kT. However, a value of activation energy of In$_x$Ga$_{1-x}$N decomposition reported in ref. [85] would require a revision now in the light of a revised and correct InN band gap of ~ 0.7 eV. From the data points obtained in this study, we plotted the ratio of $F^D/x^N$ vs. 1/kT (not shown here) and from the slope, derived $E_a \sim 1.5$ eV which is close to 1.2 eV reported in ref. [33]. The difference springs from various
factors like dependence of $E_a$ on growth temperature, value of 1.2 eV reported for 590°C-635°C range and uncertainty in precisely determining the In-composition (from either PL or XRD).

Using equation (7) and the data points of In composition corresponding to the three N-polar $\text{In}_x\text{Ga}_{1-x}\text{N}$ samples, a curve fitting was done to evaluate $\beta$. The resulting variation in ‘x’ as a function of substrate temperature as obtained from our model is plotted in Figure 2.7. The different curves correspond to different Ga/N flux ratios. As can be observed, In incorporation ‘x’ decreases as Ga/N flux ratio increases for a given growth temperature. Thus, using the curves as guidelines, a required In-composition ‘x’ can be achieved either by choosing the growth temperature and determining the Ga/N flux ratio from the plots or vice-versa. This growth model thus provides comprehensive flexibility in obtaining higher In-incorporation even at higher growth temperatures by choosing the required Ga/N flux ratio.

![Figure 2.7: Dependence of Indium mole-fraction on growth temperature for various Ga/N flux ratio as predicted by the growth model for N-polar $\text{In}_x\text{Ga}_{1-x}\text{N}$](image)

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To validate our growth model, we plotted the experimentally obtained data points (i.e. In-composition ‘x’) for N-polar In$_x$Ga$_{1-x}$N for a Ga/N flux ratio of 0.40 used in this work. As shown in Figure 2.8, the data points are found to be in good agreement with the curve predicted by our growth model.

![Figure 2.8: Experimental data points obtained in this work fitted to curves predicted by the proposed growth model for both N-face and Ga-face polarities of In$_x$Ga$_{1-x}$N. A few data points from literature are co-plotted to show that overall, N-face can incorporate higher In-composition than Ga-polar for same growth conditions.](image)

Besides, using the same approach as used for N-polar In$_x$Ga$_{1-x}$N, we use the same set of equations for modeling the growth of Ga-polar In$_x$Ga$_{1-x}$N. The $E_a$ for decomposition of In-polar InN however has been investigated earlier for lower growth temperatures only (< 500°C) and found to be 1.92 eV.$^{94}$ The pre-factor relating the decomposition rate to growth temperature and In mole fraction (eqn. (6)) is expected to be the same for growth kinetics of both Ga-polar and N-polar In$_x$Ga$_{1-x}$N since it accounts for any factor which is not temperature-dependent. More precisely, the pre-factor is
related to the number of planar sites containing N-atoms on the surface because that is what is assumed to define the decomposition of InN apart from temperature and In-composition. In simple words, with a different pre-factor for Ga-polar polarity, the higher incorporation of In in N-polar In\textsubscript{x}Ga\textsubscript{1-x}N at the same growth temperature can no longer be attributed to a difference in $E_a$ only. Borrowing the value of pre-factor from the growth model developed for N-polar polarity of In\textsubscript{x}Ga\textsubscript{1-x}N, we use a Ga/N flux ratio of 0.40 used in this work with $E_a$ as the unknown while fitting the data points for Ga-polar In\textsubscript{x}Ga\textsubscript{1-x}N. The activation energy for Ga-polar polarity is thus found to be 1.12 eV against 1.2 eV for N-polar polarity. Again, the data points are found to be in nice fit with the model as shown in Figure 2.8. Several data points showing In-compositions and growth temperatures for Ga-polar In\textsubscript{x}Ga\textsubscript{1-x}N by PAMBE from the literature\textsuperscript{95,96,97,98} have also been included in Figure 2.8 as a comparison. The higher In incorporation for N-face polarity is obvious from Figure 2.11.

The decomposition rate can be quantitatively estimated as $F^D \propto \chi \exp\left(-\frac{E_a}{kT}\right)$, and therefore the reduced growth rate, $F^{N*} = F^N - F^D$ as a function of growth temperature. Figure 2.9 shows the overall growth diagram for N-polar In\textsubscript{x}Ga\textsubscript{1-x}N growth by MBE calculated using experimental composition and temperature values from this study. The stoichiometric growth rate in the absence of decomposition is 5 nm/min; to ensure excess In coverage, an In-flux of approximately twice the stoichiometric (~ 10 nm/min) is used while the Ga-flux used is ~ 2 nm/min which is 0.4 times the usual growth rate of 5 nm/min. As seen, in the presence of decomposition, the growth rate no longer stays constant at 5 nm/min but drops significantly with increasing growth temperature. The
difference between the reduced nitrogen-stoichiometric (or reduced growth rate) and the Ga-flux, i.e. $F_{N*}^N - F_{Ga}^Ga$ in fact, corresponds to the amount of Indium incorporated. Thus from figure 2.9, the decreasing In-incorporation for a given Ga/N flux ratio with increasing growth temperature becomes clear.

The model developed above is valid in temperature and In-flux regimes where a stable excess Indium coverage is maintained. It has been established that in PAMBE growth of N-polar InN, metallic In accumulation (adlayer and droplets) on the surface due to In-flux from InN decomposition and impinging In atoms from the source is limited by maximum In-desorption rate $F_{des}^{des}$ up to a growth temperature of $\sim 610^0C$. However, at higher growth temperatures above $\sim 610^0C$, desorption rate of In exceeds decomposition rate of InN. In Figure 2.9, the shaded region above $\sim 630^0C$ has been indicated to have “no indium incorporation” as excess Indium can remain on the surface in the form of droplets only if the impinging In-flux is greater than $|F_{des}^{des} - F_{D}^{D}|$. If the surface is devoid of excess Indium but there is an excess of N, the growth will shift to In-limited regime instead of being N-limited thus invalidating our growth model. Since all our growths have been performed in an In-rich regime at temperatures below $\sim 610^0C$, the In-incorporation will depend only on the reduced N-flux $F_{N*}^N$ and the Ga-flux $F_{Ga}^Ga$ which remains unchanged.
To assess the optical quality of the N-polar InGaN films, we plot the PL intensity for the various N-polar and Ga-polar In$_x$Ga$_{1-x}$N samples in a linear scale (inset to Figure 2.10) with the intensities of Ga-polar samples multiplied 100x to bring them to a comparable level to the peak intensity of the N-polar sample grown at 600°C corresponding to 600 nm emission. Intensities of other N-polar InGaN samples are multiplied 10x as well. Figure 2.10 shows on its left axis the peak intensity corresponding to the PL measurements of each sample against the corresponding wavelength. The peak intensity for N-polar In$_x$Ga$_{1-x}$N samples show more than two orders of magnitude increase as wavelength decreases from ~ 900 nm to ~ 600 nm corresponding to a 100°C increase in growth temperature. Besides, the N-polar sample shows much higher intensity than the Ga-polar sample especially at shorter wavelengths.
Figure 2.10: Peak PL intensity of InGaN samples of both polarities as a function of wavelengths. The lines are a guide for the eyes. Inset: PL scans (normalized to the highest intensity obtained) of Ga-polar (G) and N-polar (N) InGaN samples, along with magnification factor and growth temperature.
However, the surface roughness or morphological difference plays a major role in PL intensity. Figure 2.11 shows (5 µm x 5 µm) AFM scans of both Ga-polar and N-polar samples grown at 550°C and 600°C. As can be seen, the N-polar samples have relatively higher rms roughness than that of the Ga-polar samples. Particularly, the N-polar sample grown at 600°C has a high rms roughness of ~ 15 nm. The surface morphologies of a
particular sample were found to be similar in various regions of the sample concerned. This might explain the relatively higher PL intensity of N-polar (bulk) InGaN samples. Besides, the In-compositions in the Ga-polar and N-polar samples grown at a particular temperature are different, and hence it would not be justified to comment on the optical qualities of the samples containing different In-compositions.

2.6 Growth of N-polar InGaN/GaN MQW for green LED

With a comprehensive growth model to guide the growth of N-polar InGaN layers including those with high In-compositions, an InGaN/GaN multiple quantum well (MQW) structure for green emission was grown at ~ 625°C. But such an LED structure would however be capped with p+ GaN layer and hence the surface morphology of thin (2-4 nm) In$_x$Ga$_{1-x}$N layers in the active region could not be observed.

Figure 2.12: AFM scan (2 µm x 2 µm) of 3 nm In$_{0.3}$Ga$_{0.7}$N layer capped with 2 nm In$_{0.05}$Ga$_{0.95}$N
Hence, under identical growth conditions a similar heterostructure was grown but with a single ~ 3 nm thick In$_{0.3}$Ga$_{0.7}$N layer covered by ~ 2 nm of In$_{0.05}$Ga$_{0.95}$N barrier to prevent the decomposition of the active layer as the sample was cooled down. This was done to observe the surface morphology of thin InGaN layer (30% Indium mole-fraction) which was found to be smooth with an rms roughness of ~ 0.5 nm for a 2 µm x 2 µm AFM scan (Fig. 2.12).
Based on our growth model, a Ga/N flux ratio was chosen to achieve 29% In-mole fraction in an In$_x$Ga$_{1-x}$N /GaN multiple quantum well (MQW) structure corresponding to green (~ 520 nm) emission. Figure 2.13(a) shows the epitaxial structure grown. The growth temperature for the growth of active regions was chosen to be ~ 625-
630°C which is fairly high for PAMBE growth of In$_x$Ga$_{1-x}$N in general. The growth of In$_x$Ga$_{1-x}$N and GaN successively for MQW without growth interruption with only one Ga-source posed severe challenges. Both the optimal growth temperature and the Ga-flux for the growth of In$_x$Ga$_{1-x}$N and GaN are significantly different. A pulsing scheme was employed to grow the GaN barrier: the In and Ga shutters were open throughout the barrier growth while the N$_2$-shutter was pulsed with a duty cycle equal to the Ga/N flux ratio, the Ga-flux being the same as used in the preceding In$_x$Ga$_{1-x}$N quantum well layer. Using our growth model, the decomposition rate was calculated for the given growth conditions to determine the actual growth time to achieve 3 nm thick quantum wells. A fitting of the dynamic simulation of triple-axis ω-2θ HRXRD scan with the actual scan data (Fig. 2.13(b)) indicated a close match of the In composition and thickness to that originally aimed for thus once again validating our growth model. Post growth, 3 x 3 reconstructions were observed (Fig. 2.14(a)) while sample was cooled indicating N-polar polarity; the top p+ GaN layer was found to have smooth surface morphology (Fig. 2.14(b)).
To test the optical quality of the MQW structure, Ni/Au/Ni and Ti/Au as top and bottom contacts respectively were deposited for p-GaN and n-GaN, and on-wafer continuous wave (CW) electroluminescence (EL) measurements were done. Fig. 2.15 shows normalized EL intensity as a function of wavelength of emission, showing green emission (~540 nm). This is the first demonstration of green emission from plasma-assisted MBE grown InGaN/GaN MQW (any polarity) and testifies the good optical quality of the N-polar thin In$_{0.3}$Ga$_{0.7}$N layers grown using the growth model proposed.
2.7 Growth of InGaN on heteroepitaxial N-face GaN on SiC

The growth model helped achieve green emission from In$_{0.3}$Ga$_{0.7}$N/GaN MQW and also enabled demonstration of record high inter-band reverse tunneling current densities$^{100}$ in III-nitrides using InGaN. All such growths were performed on free-standing LED quality N-face GaN templates available from Lumilog with TDD ~ $10^7$-$10^8$ cm$^{-2}$. However, for enabling InGaN channel HEMTs, the GaN buffer has to be semi-insulating which is difficult to realize on free-standing n-doped GaN templates. So a series of InGaN HEMT growths were done on N-face GaN heteroepitaxially grown on C-face SiC. N-polar GaN was grown using a 2-step buffer growth scheme$^{101}$ on SiC which would result in smooth surface morphology. Fig. 2.16 (a) and (b) show the epitaxial stack as well as XRD fittings of two such N-polar InGaN channel HEMT structures grown on GaN on SiC. The InGaN layers were grown at substrate temperatures of 550-590°C with Ga-fluxes adjusted (based on growth model) to achieve 15-25% Indium mole-fraction.
Based on energy band diagrams simulated using BandEng, a 2DEG density of ~3.8x10^{12} \text{ cm}^{-2} was predicted for the sample with 25% In-composition while for the sample with 13% In-composition, 2DEG density ~ 1.0x10^{12} \text{ cm}^{-2} was expected. Even if the mobility of 2DEG were very low ~ 100 \text{ cm}^2/\text{Vs}, yet a sheet resistance of a few tens of k\Omega/\text{sq.} was expected. However, all the InGaN channel HEMT samples grown on GaN on SiC exhibited insulating behavior indicative of absence of any 2DEG.
As seen from Fig. 2.17, AFM scans of the surface of the InGaN channel HEMTs grown on GaN on SiC show a very rough and TDD mediated island-type growth. This may be the reason for absence of a continuous charge sheet at the InGaN/GaN interface leading to an insulating behavior. Further work needs to be done on InGaN channel HEMT grown on low TTD substrates such as free-standing GaN with approaches to get rid of buffer leakage.
Chapter 3

1-dimensional transport in N-face GaN/AlGaN HEMT

3.1 Introduction

This chapter describes polarization engineering of N-polar GaN/AlGaN HEMTs to achieve self-defined, dense arrays of 1-dimensional channels. First demonstration of electrostatic tuning of the dimensionality of the electron gas between 1-D and 2-D is also explained.

1-dimensional transport channels or nanowires are an interesting system to investigate nanoscale phenomena owing to their quantum-confined one-dimensionality. Nanowires are increasingly explored for their several advantages to harness them for useful device applications such as nanowire based field effect transistors\textsuperscript{102,103}, future device applications\textsuperscript{104,105} as well as for nanowire photonic devices\textsuperscript{106,107} including microcavity lasers, LEDs, solar cells and photodetectors. Among many exciting application potentials, nanowires have been more widely studied as a promising candidate to sustain downscaling\textsuperscript{108} of planar MOS transistors as per Moore’s law. This is because nanowires can be fabricated down to sub-10 nm dimensions with good electrostatic control\textsuperscript{109} which is very challenging to achieve using planar devices with 2-
dimensional transport. Additionally, due to quantum-confined 1-dimensionality, nanowires also present an interesting platform to explore transport properties\textsuperscript{110} of carriers which may be useful for high-speed and high-performance transistors. However, few reports exist on exploring 1-D channels for their transport properties such as electron velocity with respect to device applications.

3.2 Motivation and challenges

With regard to high-speed III-nitride devices, the primary motivation of 1-D channels is to investigate if electron velocity in these nanowires is higher than in a 2-dimensional electron in a conventional HEMT. It would also be interesting to explore if other transport properties such as electron mobility, noise, etc. are superior in these 1-D channels.

It had been theoretically predicted\textsuperscript{111} that due to significant change in phonon scattering rate associated with 1-D density of states, LO phonon limited electron velocity would be enhanced in 1-dimensional channels as compared to 2DEG. Recently\textsuperscript{112}, an LO phonon based model was proposed to explain transport properties of 2DEG in AlGaN/GaN HEMTs such as current densities and transconductance. The model could be extended to the 1-dimensional case as well. The 1-D density of electrons $n_{1D}$, inclusive of both spins, is given by:

$$n_{1D} = 2 \times \frac{2k_F}{2\pi}$$  \hspace{1cm} (1)

$$k_F = \frac{n_{1D}\pi}{2}$$  \hspace{1cm} (2)
Here, $2k_F$ is the length of the Fermi line in 1-D which is analogous to the Fermi radius of $k_F = \sqrt{(2\pi n_{2D})}$ in the 2-D scenario. In a ballistic transistor, the applied drain bias $V_{DS}$ amounts the difference in the quasi-Fermi levels of the right-going and left-going electrons, which is locked by emission of LO phonons at $\sim 92$ meV (LO phonon energy). Fig. 3.1 (a) and 3.1 (b) show the electron distribution in terms of Fermi line (1D) and Fermi circle (2D) respectively. Fig. 3.1 (b) also shows how, below a critical electron density (for both 1D and 2D), electrons from the highest right-going state can emit an LO phonon and scatter to the bottom of the sub-band which is however not permitted at high densities due to Pauli’s principle.

![Diagram](image)

Figure 3.1: Electron distribution in terms of (a) Fermi line (1D) and (b) Fermi circle (2D) (from ref. [112]).

The critical electron density for 1D below which scattering in to bottom of sub-band is allowed is determined by $2k_F < k_{op}$, or the Fermi line being less than optical phonon scattering wave-vector $k_{op}$. Using eqn. (2), the $n_{1D}(\text{critical})$ can be written as:
The maximum 1D current density (in A) is given by:

$$J_{max} = q \hbar n_{1D} k_0 \frac{k_0}{m^*}$$  \hspace{1cm} (4)$$

Here, $k_0$ is the centroid of the electron distribution and its value depends on whether the 1-D channel electron density is above or below $n_{1D}(critical) \sim 2.18 \times 10^6$ cm$^{-1}$. A simple analysis involving scattering of carriers by LO phonons from highest right-going state would give $k_0$ as:

$$k_0 = k_{op} - \frac{\pi n_{1D}}{2}, \text{ for } n_{1D} \leq n_{1D}(critical)$$  \hspace{1cm} (5)$$

$$k_0 = \frac{k_{op}^2}{2\pi n_{1D}}, \text{ for } n_{1D} > n_{1D}(critical)$$  \hspace{1cm} (6)$$

The 1-D current densities can hence be estimated from equation (4), and velocity of saturation can be estimated by dividing the current density by the 1-D charge density. This gives:

$$v_{sat} = \frac{\hbar}{m^*}\left(k_{op} - \frac{\pi}{2n_{1D}}\right), \text{ for } n_{1D} \leq n_{1D}(critical)$$  \hspace{1cm} (7)$$

$$v_{sat} = \frac{2E_{op}}{\hbar n_{1D}}, \text{ for } n_{1D} > n_{1D}(critical)$$  \hspace{1cm} (8)$$

Here, $E_{op}$ is the LO phonon energy ($\sim 92$ meV for GaN). Estimates of electron velocity corresponding to 2D electron gas can be obtained from ref. [112]. To compare
the estimates of small-signal delays for 1D and 2D electron transport based on the LO phonon model as described above, we shall assume that 1-dimensional transport is achievable in a conventional AlGaN/GaN HEMT. In fact, later in this chapter, we shall demonstrate such a pure 1-dimensional system in an AlGaN/GaN HEMT obtained by polarization engineering. Also, to bring dimensional consistency between 1D and 2D, the 1D electron density (and hence current density) would be normalized to atomic terrace of 5 nm. The definition and concept of atomic terrace would be explained later in this chapter. A 2D density of $10^{13}$ cm$^{-2}$ and a 1D density of $2.5 \times 10^6$ cm$^{-1}$ (equivalent to $5 \times 10^{12}$ cm$^{-2}$) would be assumed for estimating the intrinsic $f_T$, which to a first order can be written as $f_T \sim v_{sat}/L_{gate}$, where $L_{gate}$ is the gate length of the HEMT.
Fig. 3.2(a) and (b) show $f_T$ vs drain current ($I_D$) for HEMTs with 700 nm gate and 100 nm gate respectively as estimated by the LO phonon model for 1D and 2D transport. For lower current densities ($I_D < 0.5$ A/mm), the velocity in 1D channels is predicted to be higher than in 2D as seen from Fig. 3.2. At higher current densities, $f_T$ for 1D is predicted to drop steeply since the LO phonon model yields a constant current density $J_{max} = 2qE_{op}/h$, independent of charge density. The LO phonon model over-estimates current densities because it takes into account only optical phonon scattering and single
sub-band occupation. Other scattering mechanisms, parasitic resistances, self-heating, two sub-band population, etc will change the intrinsic $f_T$ estimated here. However, on inclusion of parasitic components, this model is able to reconcile the observed peculiarities for 2D transport in AlGaN/GaN HEMT such as $g_m$ drop-off at higher current densities, current drives, etc. Thus, to a first order, based on LO phonon model, if 1D transport is achievable in a conventional AlGaN/GaN system, then it is expected to provide a higher $f_T$ as compared 2DEG in the same system.

However, reports on III-nitride nanowire FETs are few. Besides, achieving controlled assembly of high-density nanowire arrays for large-scale integration in any material system, which is crucial for practical applications, is still a major challenge for both top-down\textsuperscript{113,114} and bottom-up\textsuperscript{115,116} approaches. While achieving high quality nanowires with sub-20 nm dimensions becomes a challenge for top-down approach, the bottom-up approach suffers from issues such as poor surface control, poor longitudinal control of doping profiles and possible metal contamination due to requirement of metal as catalysts for growth initiation\textsuperscript{117}. A self-defined array of nanowires is thus highly desirable where challenges related to aligning these wires can be totally avoided. Such an array of self-defined wires would not only carry technologically relevant higher current densities but also present a viable system to explore transport characteristics such as electron velocity in 1-dimensional channels.

In the following sections in this chapter, anisotropic transport properties of 2DEG in vicinal AlGaN/GaN heterostructures will be explained, and it will be shown that such anisotropy can be engineered to achieve self-defined, dense arrays of 1-D channels.
3.3 Anisotropic transport in vicinal N-polar GaN/AlGaN HEMTs

3.3.1 Background

The reverse polarity of GaN, i.e. N-face GaN has increasingly attracted the interest of the III-nitride community both in terms of electronic and opto-electronic devices. Since the demonstration of N-polar GaN HEMT, state-of-the-art microwave performance has been achieved in this reverse polarity heterostructures. Particularly for highly scaled HEMTs, N-face polarity holds a lot of promises. Since growth of N-polar GaN by MOCVD presented challenges, most of the initial device results were by MBE grown N-face GaN HEMTs. Interestingly, MOCVD growth on vicinal GaAs led to naturally formed multi-atomic steps; similar step-ordering on vicinal <001> GaAs was also observed on growth of fractional layer super-lattice. By growing on vicinal sapphire substrates, surface instability issues were thus overcome in MOCVD grown N-polar GaN. Surface steps induced by the miscut of the vicinal substrate were found to improve surface mobility and mitigate three-dimensional growth and formation of hexagonal pyramids on the surface. This has led to excellent structural and surface quality for MOCVD grown vicinal N-polar GaN/AlGaN epitaxial layers with good DC and RF transistor performance.

In vicinal Ga-polar AlGaN/GaN heterostructures, mobility of the 2DEG was found to exhibit anisotropy in directions parallel and perpendicular to atomic steps and terraces. The difference in mobility in the two directions was attributed to the anisotropy in roughness, with an enhancement in the mobility along the step direction. With the development of N-polar GaN by MOCVD, mobility and device characteristics
of MOCVD-grown vicinal GaN/AlGaN/GaN structures were investigated (ref. [130]). Brown et al.\textsuperscript{134} studied conduction in the parallel direction and explained the vertical field dependence of the mobility. Although anisotropy in mobility and in transistor current ($I_D - V_D$)\textsuperscript{135} for vicinal GaAs-based heterostructures were attributed to probable step-related lateral potential modulation\textsuperscript{136}, yet a mathematical modeling of this potential landscape in the lateral direction was absent. Besides, anisotropy in the charge density of the 2DEG in such heterostructures was also not reported earlier.

### 3.3.2 Details of device fabrication

To study transport properties of 2DEG in vicinal AlGaN/GaN heterostructures, epitaxial structures (Fig. 3.3(a)) were grown by MOCVD on a sapphire substrate mis-oriented 4° towards the a-plane. Details of semi-insulating and smooth buffer growth can be found elsewhere (ref. [129]). The energy band diagram of the hetero-structure described here was obtained using self-consistent 1-dimensional Schrodinger-Poisson (BandEng) simulations (Fig. 3.3(b)).
Due to kinetics of step-flow growth, the atomic terraces and steps characteristic of the vicinal substrate replicate in the AlGaN/GaN epitaxial layers grown by MOCVD as shown by atomic force microscopy (AFM) of the surface of the sample after AlGaN deposition (Fig. 3.4). For a $4^\circ$ miscut in GaN, the atomic terraces are expected to be 8-16 nm wide (the variation is due to step-bunching). The SiN layer was added to improve surface stability and to simplify lithography and device fabrication.
Device fabrication was carried out on the epitaxial layer described above. Several transistors, Schottky diode, gated TLM, and Hall patterns were fabricated on the epitaxial layers. Standard i-line stepper lithography was used to define patterns including transistors with 700 nm gate lengths. Ohmic contact pads were fabricated using standard optical lithography by evaporating a metal stack of Ti(20 nm)/Al(120 nm)/Ni(30 nm)/Au(50 nm) and then subjecting to a rapid thermal annealing at 850°C for 30 seconds to enable the metals to spike through the top layers to the electron gas. Mesas were defined by using a BCl₃/Cl₂ based inductively-coupled-plasma/reactive ion (ICP/RIE) etch chemistry with 30 W of RIE power to etch 100 nm of the epitaxial layer so as to isolate the 2DEGs of individual devices. The Ohmic contacts were fabricated on the sample such that when a bias voltage is applied between two adjacent contacts, the direction of current flow between them would be either parallel or perpendicular (Fig. 3.5) to the atomic terraces characteristic of the vicinal surface. A contact resistance of 0.6 Ohm-mm was extracted from four point TLM measurements while sheet resistances
in the directions parallel and perpendicular to the atomic terraces were extracted to be 357 and 467 Ohms/square respectively. Schottky contacts were defined by evaporating Ni (30 nm)/Au (300 nm)/Ni (50 nm) metal stack to form gates for Schottky diodes to measure C-V.

Figure 3.5: Schematic showing measurement (and hence direction of current flow) in the direction parallel and perpendicular to atomic terraces on a vicinal substrate.

3.3.3 Observation and electrostatic model

In Fig. 3.6, typical transconductance ($g_m-V_{GS}$) profiles are shown for HEMTs with channels parallel and perpendicular to atomic terraces. The pinch-off voltage of transistor measured parallel to atomic terraces is higher in magnitude than that measured perpendicular to atomic terraces by approximately 1.5 to 2 V. We found that this difference in pinch-off voltage between perpendicular and parallel devices was maintained for all devices measured across all the dies in different samples, gate lengths from 16 µm down to 0.7 µm, and temperatures from 7 K up to 300 K. This 1.5-2 V difference in pinch-off voltage indicated that the charge density available for transport
along the parallel direction is higher than that available for transport perpendicular to the steps. This is further confirmed by capacitance-voltage (C-V) profiling done on Schottky diodes (fatFETs) whose gate to Ohmic alignment is parallel or perpendicular to the atomic terraces.

Figure 3.6: Transconductance ($g_m$) profiles of devices

Figure 3.7: Capacitance-voltage profiles in direction parallel and perpendicular to atomic terraces, confirming anisotropic 2DEG density in N-face vicinal HEMT.
From the C-V plot shown in Fig. 3.7, it is obvious that the since the capacitance corresponding to parallel direction ‘rises’ earlier (~ - 6V), the area under the C-V for parallel direction is more than that for the perpendicular direction, confirming that the net 2DEG available for transport in parallel direction is higher than that for perpendicular direction.

We developed a simple electrostatic model (Figure 3.8) to semi-quantitatively explain the anisotropic charge transport measured in this work. The model approximates the vicinal steps by uniform terraces of width d = 20 nm and height h = 1 nm (giving a miscut angle of approximately 3-4°). An infinite number of steps are assumed so that the potential profile corresponding to each step is the same. It provides calculation of an energy band landscape. Only the polarization charge has been considered; adding electrons in the form of 2DEG would change the profile.

The sheet charge at each vicinal step is assumed to be composed of line charges of infinitesimal thickness dx. In the x-z plane associated with each step where z-axis is the growth direction, at any point \((x_0,z_0)\), the electric field \(E\) due to \(\sigma_P\) (the net positive polarization charge at GaN/AlGaN interface) at the \(N^{th}\) step (from the step considered) is composed of x and z components given by

\[
E_x(N) = \int_{x=0}^{x=d} \frac{\sigma_P \cos \theta \, dx}{2\pi\varepsilon_r \varepsilon_0 r} 
\]

\[
E_z(N) = \int_{x=0}^{x=d} \frac{\sigma_P \sin \theta \, dx}{2\pi\varepsilon_r \varepsilon_0 r} 
\]

55
Here ‘r’ is the distance of the line charge considered from the point \((x_0,z_0)\). The net electric field in x and z directions are therefore obtained by summing \(E_x(N)\) and \(E_z(N)\) for a large number of steps \(N\). The contributions of the different charges at the different interfaces can be incorporated similarly. The energy band landscape associated with each step in the x-z plane can be plotted by evaluating potential \(V(x_0,z_0)\) as

\[
V(x_0,z_0) = \int_{(x=0,z=0)}^{(x=x_0,z=0)} E_x \, dx + \int_{(x=x_0,z=0)}^{(x=x_0,z=z_0)} E_z \, dx
\]  

(11)
Figure 3.8: Electrostatic model involving polarization charges at GaN/AlGaN interface to explain the observed anisotropy of 2DEG density.

The potential profile for a single step calculated using this model shows a lateral confinement potential (Fig. 3.9) in the x-direction at a vertical distance of $z_0 = 2$ nm from the GaN/AlGaN interface due to the step polarization charge for a GaN thickness of 10 nm and AlGaN thickness of 20 nm. The conduction band for the overall step structure assumes a saw-tooth profile (inset to Figure 3). As the channel density is reduced by applying a negative gate bias, the Fermi level of the electrons drops below the conduction band and no conduction can occur across the steps, while the channel is still conductive.
parallel to the steps. This explains the observation of anisotropic pinch-off and charge densities from $g_m-V_{GS}$ and C-V plots respectively. From our analysis, the magnitude of the confining potential was proportional to the step height and the polarization sheet charge density. The step length did not change the depth of the confining potential.

![Saw-tooth lateral energy profile](image)

Figure 3.9: Saw-tooth lateral energy profile corresponding to the atomic terraces

The lateral saw-tooth energy profile electrostatically modeled here can hence be used to create quasi 1-dimensional potential profiles without lateral patterning or epitaxy. The lateral confinement corresponding to each atomic terrace can thus enable one 1-D channel per terrace, leading to dense and self-defined arrays of nanowires or 1-D channels purely with electrostatic confinement, rather than quantum mechanical heterostructure-based confinement. Furthermore, the polarization charge density (alloy
composition) and vicinal miscut angles can be varied to achieve higher or lower confinement to engineer the spatial location, density, and other properties of the channel.

3.4 Towards demonstration of 1-D transport in N-polar vicinal HEMT

3.4.1. Probing dimensionality of electron gas by C-V profiling

The dimensionality of electron gas in a vicinal N-polar HEMT needs further investigation to gain insights into the anisotropy observed in preceding sections. Conventionally, the signature of 1-dimensionality for a nanowire is obtained through magneto-transport measurements at cryogenic temperatures or gated conductance measurements (where the conductance is quantized as a multiple of $e^2/h$ for each 1-D channel). However, in our system where each atomic terrace is expected to define one nanowire, we can expect to have a large ensemble ($\sim 0.5\ \text{million/cm}$) of self-aligned 1-D channels, and statistical fluctuations make it difficult to observe the traditional 1-D characteristics. However, the electron density populating the ensemble of 1-D channels in our system would still have a $1/\sqrt{E}$ dependence on energy $E$ due to 1D density of states. This can be investigated by probing the electron density as the Fermi level of the electron gas is tuned. For this, we performed C-V measurements in directions parallel and perpendicular to atomic terraces. The schematic of such devices (fatFETs) and measurement directions look similar to that shown in fig. 3.5 The C-V measurement was done as follows: on a Schottky or gate metal pad (200 $\mu$m x 200 $\mu$m), a sinusoidal signal of very small magnitude (30 mV) and a frequency between 100-500 KHz was applied, which rides on a large-signal DC bias also applied on the gate. An Ohmic pad (200 $\mu$m x 100 $\mu$m), situated 4 $\mu$m from the gate pad, is connected to the ground. The charge on the
gate metal is reflected in the electron gas populating the channel beneath the gate. For an incremental voltage $\Delta V$ on the gate, the increase in the channel charge $\Delta Q$ is measured. Thus, the small-signal charge flowing between the gate and the Ohmic metals through the electron gas channel provides the value of the capacitance at a particular gate bias as $C = \Delta Q/\Delta V$. However, only those electrons (or charge) whose wave-vectors are not quantized in the direction of gate-to-Ohmic can actually flow between the two contact pads through the channel and hence will contribute towards the capacitance value measured in that direction (i.e. parallel to or perpendicular to atomic terraces). For either direction (parallel or perpendicular), the density of electrons, $n_e$, ($\text{cm}^{-2}$) corresponding to a given gate bias $V_{g1}$ can be found by integrating the area under the C-V curve to $V_{g1}$ from pinch-off (i.e., the Schottky bias at which the capacitance starts to rise from zero indicating electrons are starting to populate the electron gas):

$$n_e(V_{g1}) = \frac{1}{q} \int_{V_{\text{pinch-off}}}^{V_{g1}} C(V_g) \, dV_g$$

(12)

Here $q = 1.6 \times 10^{-19}$ C is the charge of an electron. Therefore, irrespective of the actual charge that exists beneath the gate, the measured charge might be different depending on the dimensionality (or quantized state) of the electrons and the measurement direction.

The capacitance (normalized to the area) measured parallel and perpendicular to atomic terraces was shown in Figure 3.7. Using equation (12), 2DEG densities of $7.6 \times 10^{12}$ cm$^{-2}$ and $5.7 \times 10^{12}$ cm$^{-2}$ were extracted for directions parallel to and perpendicular to atomic terraces respectively. This anisotropy arises from the dependence
of the charge on the dimensionality of the electrons and the measurement direction as mentioned before.

### 3.4.2. Two sub-band model and tuning of dimensionality

To explain the direction-dependence of the C-V profile and the charge, as well as to demonstrate the presence of 1-dimensional transport in the system, we propose a 2-sub-band theory with a sub-band $E_0 < E_{\text{bar}}$ and a sub-band $E_1$ just above $E_{\text{bar}}$, where $E_{\text{bar}}$ is the lateral confinement energy corresponding to the saw-tooth profile (simplified representation in Figure 3.10). Electrons populating $E_0$ are quantized in two dimensions ($x$ and $z$) and can carry current in only one dimension (momentum wave-vector $k_y$) leading to 1-dimensional channel transport. The electrons populating $E_1$ have only wave-vector $k_z$ quantized due to heterostructure confinement in vertical direction but can carry current in the other two directions (momentum wave-vectors $k_x$ and $k_y$) (as shown in Fig. 3.10), thus contributing to pure 2-dimensional transport.

![Figure 3.10: Schematic of saw-tooth energy profile (simplified as triangular wells) in the lateral direction along atomic terraces, illustrating the two sub-band model](image-url)
When the gate voltage is lower than pinch-off voltage of the channel (-7 V in this case), the capacitance is zero indicating the entire charge is depleted. At pinch-off voltage which is ~ -6 V and ~ -5 V for transport parallel and perpendicular to atomic terraces respectively, the capacitance starts to rise indicating that electrons start populating the first sub-band. As gate-bias is increased, the Fermi level $E_F$ rises from below sub-band $E_0$ to above $E_1$ to account for the gradually increasing electron density populating the two sub-bands. At any given position of $E_F$, electrons populating only $E_1$ (or electrons with non-quantized wave-vector $k_x$) are sensitive to (or measured by) C-V profiling in the direction perpendicular to atomic terraces while C-V profiling in the parallel direction will measure electrons populating both $E_0$ and $E_1$ (or electrons with wave-vector $k_y$). Thus the capacitance shown in Fig. 3.7 corresponding to perpendicular direction is a direct measurement of a pure 2DEG density while that corresponding to parallel direction gives the total of 1DEG and 2DEG densities. The difference of the capacitances measured in the two directions is the capacitance for the 1-dimensional charge populating the $E_0$ sub-band only.

Thus we have:

$$n_{1D} (V_g) = n_{parallel} (V_g) - n_{perpendicular} (V_g) \quad (13)$$

Evaluating the area under this C-V curve gives the pure 1-dimensional charge density in dimensions of cm$^{-2}$ which can be converted to effective 1-dimensional charge density in unit of cm$^{-1}$ or m$^{-1}$ by multiplying it with the nanowire pitch or in this case, the average atomic terrace width.
Theoretically, at any position of Femi level $E_F$, the total number of electrons populating the $E_0$ sub-band, which are purely 1-dimensional, is given by the integration of the product of the 1-D density of states and the Fermi occupation function:

$$n_{1D}(E_F) = \int_{E_0}^{\infty} \frac{\sqrt{2m^*}}{\pi \hbar \sqrt{E}} \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \frac{1}{t_{terrace}} dE$$

(14)

Here, $m^*$ is the effective electron mass in GaN ($= 0.2$ times free electron mass), $k$ is Boltzmann constant ($= 1.38 \times 10^{-23}$ SI units), $T$ is room temperature ($= 300$ K) where measurements are performed and $\hbar$ ($= 1.054 \times 10^{-34}$ SI units) is the reduced Dirac constant. The expression is divided by the average atomic terrace width $t_{terrace}$ in order to normalize the 1-dimensional density of electrons ($cm^{-1}$) in units of $cm^{-2}$. Similarly, at any Fermi level, electrons occupying the $E_1$ sub-band, which are purely 2-dimensional, is given by the integrating the product of 2-D density of states and the Fermi occupation function:

$$n_{2D}(E_F) = \int_{E_1}^{\infty} \frac{m^*}{\pi \hbar^2} \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} dE$$

(15)

The choice of $E_0$ and $E_1$ is explained as follows: As a simplified approximation, let us consider $E_0$, the 1$^{st}$ sub-band, as reference, i.e. $E_0 = 0$. There is no absolute or universal relation between $E_0$ and $E_1$, because that depends on the total charge in the system. Depending on how much 1-dimensional and 2-dimensional charge exists in the system, the position of $E_1$ will be different. The further $E_1$ is from $E_0$, the more is the 1-
dimensional and less is the 2-dimensional charge for a given total charge. In our system investigated, we have a total 1-dimensional charge of \( \sim 2 \times 10^{12} \text{ cm}^{-2} \) and total charge (1-D + 2-D) of \( \sim 7.5 \times 10^{12} \text{ cm}^{-2} \) as obtained from C-V measurement. These charges will determine the position of sub-band \( E_1 \) relative to \( E_0 \). Of course, the total charge in the system will determine the position of Fermi Level (\( E_F \)) relative to \( E_0 \) (or to \( E_1 \), once \( E_1-E_0 \) is determined) at zero gate bias. The dependence of \( E_F \) on gate bias also needs to be calculated at this point to estimate the relative position of \( E_1 \). To do this, we calculate the total electron density of the system as a function of Fermi level, which is simply given by

\[
n_{\text{Total}}(E_F) = n_{1D}(E_F) + n_{2D}(E_F),
\]

where \( n_{1D} \) and \( n_{2D} \) are obtained from equations (14) and (15) respectively. Dividing the total charge \( Q_{\text{total}}(E_F) = q(n_{1D} + n_{2D}) \) by the zero-bias capacitance of the system gives the voltage shift needed to apply on the gate to achieve the given amount of charge. This voltage shift is required to be added to the pinch-off voltage to obtain the true gate bias corresponding to any given charge and hence the Fermi level. The normalized zero-bias capacitance is given by the ratio of the di-electric constant of GaN (\( \varepsilon \sim 8.9 \)) and the separation between gate and the electron gas (which is \( \sim 30 \text{ nm} \) in this case). For a total charge of \( \sim 7.5 \times 10^{12} \text{ cm}^{-2} \) in our system, we found that a position of \( E_F \) approximately \( \sim 0.18 \text{ eV} \) above \( E_0 \), is consistent with the total charge at zero gate bias. Subsequently, a position of \( E_1 \sim 0.09 \text{ eV} \) above \( E_0 \) gives a reasonably accurate value of pure 1-dimensional charge close to \( \sim 2 \times 10^{12} \text{ cm}^{-2} \) which we observe experimentally. Thus, the positions of \( E_1 \) and \( E_F \) relative to \( E_0 \) are purely dependent on the system under investigation and hence behave like fitting parameters.

It is noteworthy that while the 1-D density of states has an inverse dependence on \( \sqrt{E} \), the 2-D density of states is a step function and hence has no dependence on energy.
This implies that at higher energies, 1-dimensional electrons have a decreasing number of states of energy available for occupation while for 2-D electrons, position of the energy level is immaterial since its density of states is a step function of a particular sub-band. This fundamental difference in the dependence of 1-D and 2-D density of states on energy is clearly observable in Fig. 3.11 which shows the theoretically calculated variation of both 1-D and 2-D electron densities as the gate bias is increased. While 1-D electron density tends to increase very slowly at higher energies, 2-D electron density continues to increase sharply at higher energy. The experimentally obtained plots for variation of 1-D and 2-D electron densities as a function of gate bias for the same as extracted from equation (13) and preceding discussions are also plotted in the Fig. 3.11.

Figure 3.11: Pure 1-D and pure 2-D charge densities in the vicinal N-polar AlGaN/GaN HEMT: comparison between theoretical estimate based on two subband model and experimentally extracted values based on C-V.
It is interesting to note that till the Fermi level reaches the sub-band $E_1$, the total electron density in the system is mostly contributed by purely 1-D electrons (occupying sub-band $E_0$). As the Fermi level rises past $E_1$, the contribution from 2-D electrons starts to dominate as (1-D) electrons occupying $E_0$ have a decreasing availability of energy states on account of the $1/\sqrt{E}$ dependence of the 1-D density of states.

Two important observations are, firstly the theoretical and experimental values for both 1D and 2D electrons match up excellently, both in their bias-dependent behavior and in magnitudes. This proves the 1-dimensionality of the electrons existing in the system at room temperature besides providing a concrete proof to our 2-sub-band model. Secondly, depending on the position of the Fermi level, 1-D and 2-D electrons co-exist in the system. While for $E_F > E_1$, transport is purely due to 2-D electrons in direction perpendicular to atomic terraces, for $E_F < E_1$, transport is purely due to 1-D electrons in direction parallel to atomic step. This system therefore enables direct electrostatic tuning of the dimensionality of electron gases and can provide an excellent platform to explore physics of low-dimensional systems even at room temperature.

3.4.3 Demonstration of pure 1-D transport: Fermi Level engineering

To demonstrate pure 1-D transport in our system, we are required to reduce the total charge and thus ‘push’ the Fermi Level below $E_1$ sub-band so that only $E_0$ sub-band can contribute to transport. This can be achieved by etching the active layer (GaN) to some critical depth. Since it is not feasible to experimentally obtain the absolute position of $E_F$ with respect to $E_0$, we performed an etch-and-measure study. The region between two adjacent Ohmic pads was etched in steps of 15-30 seconds and the current between
adjacent Ohmic contacts was measured after every etch step. For this, an additional level of lithography was performed where photo-resist was exposed and developed to open a part of the spacing between two such adjacent pads. Thus, on exposing the sample to ICP-RIE chamber with standard plasma-etch recipe, only the region opened by photo-resist between two adjacent Ohmic pads would be etched. The idea is that etching of the active region to reduce the thickness of the GaN channel layer increases the vertical electric field in top GaN layer (due to constant Fermi pinning of the surface). This lowers the charge existing at the top interface of GaN and AlGaN and can ‘push’ the Fermi level down to between $E_0$ and $E_1$ subbands. Fig. 3.12 shows a schematic of the same.

![Figure 3.12: Engineering the Fermi level: etching the GaN layer to a critical depth reduces charge and pushes the Fermi level down below $E_1$ but above $E_0$ subbands, leading to pure 1-D transport parallel to atomic terraces.](image)

To investigate dependence of current levels in the two directions on etch depth, a controlled etch recipe which gives an etch rate of ~ 6 nm/min for N-face GaN was used to etch the sample in steps of 15-30 seconds. As the top GaN thickness starts to decrease with increasing etch time leading to a decreasing charge (in both directions), we would expect to measure a decreasing current level between two pads for the same applied bias. Since the exact epitaxial structure used in this study had a 5 nm SiN$_x$ passivation layer
and a 2 nm Al$_{0.6}$Ga$_{0.4}$N on top of the active GaN channel layer, the etching would initially result in a ‘dead’ time in which the SiN$_x$ and Al$_{0.6}$Ga$_{0.4}$N would be etched without any appreciable effect on the current levels. After 6 minutes of total etch time, current in the direction perpendicular to atomic terraces starts to drop significantly although that in the parallel direction stays nearly the same. With further etching, the current in both directions starts to decrease indicating a gradual lowering of the charge as expected. At a critical etch depth corresponding to a total etch time of 6 minutes and 45 seconds when the Fermi level has been ‘pushed’ below E$_1$ but above E$_0$ as shown in Fig. 3.12, we observe current up to 130 mA/mm in the parallel direction but negligible current in the direction perpendicular to atomic terraces (Fig. 3.13) implying achieving a 1-dimensional condition. This observation of 1D transport is consistent and repeatable for Ohmic contacts separated by various spacing levels (4 µm to 22 µm) and across various regions of the sample. To our knowledge, this is the first demonstration of 1-D transport without lithographically synthesized, designed or fabricated nanowire structures.
3.5 Conclusion

The co-existence of 1-D and 2-D electron gases in a polarization-engineered vicinal AlGaN/GaN hetero-structure system was demonstrated. It was shown that C-V profiling could be used as a tool to probe as well as to tune the dimensionality of electron gas between 1-D and 2-D. A two sub-band model was proposed to explain the dimensionality-dependence of electron gases on Fermi level position which was verified with experimentally measured data. Finally, using the proposed model, the Fermi Level was engineered to show clear and sharp signatures of pure 1-D transport (parallel to atomic terraces) at room temperature. Each atomic terrace, characteristic of the vicinal substrate, defines one 1-D channel at the GaN/AlGaN interface when transport is considered parallel to the terraces. The terrace width and hence channel dimension (~ 10-20 nm) is defined by the miscut angle of the vicinal substrate and these 1-D channels are not lithographically, but electrostatically defined. Since our approach using this novel
system enables us to achieve self-defined, regularly-spaced dense arrays of 1-D channels of electrons, it holds lot of promise for practical electronic and optical device applications and to provide a unique platform to probe low-dimensional systems. Making a good Ohmic contact to nanowires with low contact resistance has mostly been a challenge, and so another critical advantage of this system is that the contact to the 1-D channels would still be via the high density 2-D electron gas beneath the Ohmic regions.

The self-defined arrays of 1-D channels demonstrated here can be gated and 1-D HEMTs could be fabricated to investigate the transport properties and to explore if 1-D channels can offer higher velocity that can enable higher $f_T$ in such devices.
Chapter 4

Percolation-based vertical transport in unipolar III-nitride heterostructures

4.1 Introduction

This chapter describes vertical transport in unipolar III-nitride heterostructures and attributes the unacceptably high leakage observed in such structures to a percolation-based transport mediated by random alloy fluctuations in the ternary AlGaN barrier.

III-nitride electronics is primarily driven by HEMT which is a lateral device. While AlGaN/GaN HEMTs are available commercially and have found a variety of useful applications as RF amplifiers, progress in III-nitride vertical transistors has been very minimal. In the contemporary InP technology, heterojunction bipolar transistors (HBTs) have attained maturity having demonstrated $f_T$ up to 745 GHz$^{137}$ and $f_{max} > 800$ GHz$^{138,139}$. However in III-nitride HBTs, progress has been held back because of poor hole mobility$^{140,141}$ and lifetime$^{142,143}$ as well as challenges in achieving ultra-low contact resistances$^{144,145}$ in p-doped layers. Such issues related to holes in GaN have also prevented minority carrier opto-electronic devices such as solar cells and photodetectors from achieving success. Unipolar vertical electronic devices, though still in embryonic
stage, have attracted renewed interest recently. These include resonant tunneling diodes (RTDs)\textsuperscript{146,147,148}, hot electron transistors (HETs)\textsuperscript{149,150} and tunnel injection hot electron transfer amplifiers (THETA)\textsuperscript{151,152,153}. III-nitride unipolar vertical transistors are particularly interesting to investigate because of their ability to engineer electron velocity over very small distances (\(\sim < 10\) nm) and thus high transconductance. GaN-based THETA for instance, is a promising candidate for enabling III-nitride THz electronics as will be explained in chapter 5. Vertical III-nitride power devices might also benefit from developing a robust unipolar device technology.

However, unacceptably high vertical leakage current densities in n-GaN/AlGaN/n-GaN heterostructures have held back the development of unipolar III-nitride vertical electronic devices. Such a structure is shown in Fig. 4.1. An Al\(_x\)Ga\(_{1-x}\)N barrier is found to play no role in preventing leakage between the n-doped GaN layers above and below it.

![Figure 4.1: Unipolar n-GaN/AlGaN/n-GaN heterostructure which is always found to exhibit unacceptably high vertical leakage currents through the AlGaN barrier.](image)
High vertical leakage masks the true current densities in a device such as RTD and will hence degrade the peak-to-valley-current ratio (PVCR) significantly. In a vertical transistor such as THETA, such leakage will manifest itself as high base-collector leakage which will prevent any kind of output modulation and hence device operation. To enable the entire gamut of III-nitride unipolar vertical devices and/or to help them realize their full potential, understanding and reducing this leakage is of quintessential importance. The understanding about vertical leakage in unipolar III-nitride heterostructures presented in this chapter thus serves as one of the most critical aspects in enabling III-nitride THETA (to be discussed in the following chapter).

4.2 Vertical leakage in III-nitrides

In existing and commercially available III-nitride device technologies, the two most widely studied vertical leakage mechanisms correspond to leakage in bipolar LEDs and reverse bias leakage in Schottky diodes (or gate-drain leakage in HEMTs). Both these types of leakage are however much different from the leakage in unipolar GaN/AlGaN/GaN structures in that the leakage in LEDs and HEMTs are typically much smaller in magnitude. For instance, at a reverse bias of -5, even 0.1 A/cm$^2$ would be considered to be a very high leakage in typical LEDs while for unipolar GaN/AlGaN/GaN type of structures, even at 1 V of reverse bias, leakage would be in the order of a few kA/cm$^2$, which is many orders of magnitude higher than leakage in LEDs. Such small (<< 1 A/cm$^2$) vertical leakage current densities are still detrimental to device performance and are found$^{154,155,156,157,158}$ to be predominantly dependent on TD densities, particularly screw and mixed type dislocations for both HEMT and LEDs. Such
dislocation-mediated leakage has been proposed to be trap-assisted\textsuperscript{159} tunneling in HEMTs, and particularly hopping transport\textsuperscript{160} at low bias and Poole-Frenkel type of transport at high bias for LEDs.

However, no such study exists on unipolar vertical leakage in III-nitrides. The presence of a p-doped GaN in the bipolar LED structures and a metal-to-AlGaN Schottky contact in HEMT gates make such conventional leakage types fundamentally different in nature from unipolar leakage in n-GaN to n-GaN via AlGaN. In this chapter, we investigate this vertical leakage in GaN/AlGaN/GaN heterostructures and propose that percolation-based leakage due to alloy fluctuations in the ternary AlGaN barrier dominates such vertical transport. Our observation is supported by simulations performed using drift-diffusion model of transport incorporating such statistical fluctuations in Al-compositions. We also show that eliminating the random alloy barriers can provide control of vertical transport and reduces leakage by orders of magnitudes.

4.3 Investigation of vertical leakage in unipolar n-GaN/AlGaN/n-GaN

4.3.1 Experimental details

To study unipolar transport characteristic in III-nitride heterostructures, we investigate an epitaxial stack as shown in Figure 4.2 which consists of a 15-20 nm of GaN which is degenerately doped as n-type ([Si] = 4-5x10\textsuperscript{19} cm\textsuperscript{-3}) and serves as the top contact layer. It is separated from the bottom n-doped GaN template by an Al\textsubscript{x}Ga\textsubscript{1-x}N barrier 30-35 nm thick. The n-GaN template on which samples are grown serves as the bottom n-contact.
The epitaxial stacks for the devices were grown by plasma-assisted molecular beam epitaxy (MBE) using a Veeco 930 system equipped with a uni-bulb Veeco N$_2$ plasma source. Commercially available Ga-polar free-standing n-doped GaN substrates (TDD ~ 4x10$^7$ cm$^{-2}$) from St. Gobain$^{161}$ were used for the growths. Ga-rich conditions were used to grow the layers in an N$_2$-limited growth regime. Post growth, AFM scans showed smooth surface morphologies (Fig. 4.2(b)). High-resolution X-ray diffractometer scans were done to verify the thicknesses and compositions of epitaxial layers. Al (20 nm)/Ni (20 m)/Au (100 nm)/Ni (20 nm) were e-beam evaporated for top-contact metal stack. An inductively coupled plasma/re-active ion (ICP-RIE) etch recipe using 40 V RIE and 40 W ICP power with 50 sccm Cl$_2$/5 sccm BCl$_3$ was used to achieve a mesa isolation with a controlled etch rate. Depending on the device, mesa area was between 90 to 120 µm$^2$. Devices were probed using sub-micron probe tips and measured using an Agilent B1500 Semiconductor Parameter Analyzer.
4.3.2 Effect of heterojunction barrier height and TDDs

To investigate the effect of heterostructure barrier height on unipolar reverse bias leakage, a series of three samples with Al-composition of 16%, 27% and 37% in the AlGaN barrier were grown, with thickness fixed at 30 nm. As seen in the energy band diagrams (Fig. 4.3) obtained using self-consistent 1-D Schrodinger-Poisson simulator BandEng\textsuperscript{162}, AlGaN barrier with 16% Al-composition provides a heterojunction barrier in excess of 0.5 eV from the base Fermi level at equilibrium which should be sufficient to prevent thermionic leakage at room temperature. The reverse bias leakage current due to Fowler-Nordheim tunneling associated with such a heterostructure with 16% Al-composition was estimated theoretically using analytical calculations, and also by using Atlas Silvaco\textsuperscript{163} modeling. As seen in Figure 4.4(a), negligible leakage is expected up to reverse bias of 3 V from both analytical calculations and modeling. However, experimentally, the typical current density measured on devices fabricated on sample with the same AlGaN (16%) Al-composition barrier was found to be orders of magnitude higher.
Fig. 4.4(b) shows the measured vertical I-V characteristics of the samples with 16%, 27% and 37% Al-compositions in the barrier. The magnitude of leakage current in reverse bias was similar for these three samples despite a significant difference in their heterostructure barrier heights. While both thermionic and tunnel current would theoretically be expected to vary by orders of magnitude with such changes in the barrier height, experimental results showed that the AlGaN composition had negligible effect on the vertical current leakage in GaN/AlGaN/GaN heterostructures. Tunneling or thermionic emission based leakage mechanisms can be hence ruled out. Temperature dependence of the leakage characteristics (Fig. 4.5) revealed that vertical conductivity had weak dependence on temperature. Thus it can be concluded that the origin of leakage in unipolar GaN/AlGaN/GaN heterostructures is not a thermally activated mechanism such as trap-assisted tunneling\textsuperscript{159} or thermionic emission over the barrier.
Figure 4.4: (a) Comparison of leakage current density as analytically calculated, simulated and experimentally measured, in sample consisting of an AlGaN barrier with 16% Al-composition (b) Comparison of experimentally measured leakage current densities in samples consisting of AlGaN barriers with various Al-compositions.

Figure 4.5: Temperature-dependent leakage characteristics

The vertical leakage in unipolar GaN/AlGaN/GaN was hence found to be independent of heterojunction barrier height.
Since threading dislocations are widely believed to impact reverse bias leakage in AlGaN/GaN Schottky as well in bipolar devices such as LEDs, investigating the dependence of leakage in unipolar heterostructures on TDs is of paramount importance. Interestingly, the impact of TDDs on unipolar semiconductor heterojunction leakage has not been investigated till now. It has been pointed out in section 4.2 that unlike in metal/semiconductor and bipolar structures where reverse bias leakage is significantly small in magnitude (<< 1 A/cm$^2$ at a few volts), unipolar n-GaN/AlGaN/n-GaN heterostructures exhibit much higher vertical leakage current (~ a few kA/cm$^2$ at 1 V bias). To investigate the effect of dislocations, epitaxial structures were grown on a low-dislocation density bulk GaN substrate available from Ammono$^{165}$ (Sample LD, TDD < 10$^5$ cm$^{-2}$) and a higher dislocation density HVPE grown substrate from St. Gobain (Sample HD, TDD ~ 5x10$^7$ cm$^{-2}$). Both samples were indium bonded on 3” silicon carrier wafers, and co-loaded into the MBE chamber. Thus, they were grown and processed together to eliminate growth and process variations. Growths were done in usual Ga-rich conditions. It had been reported earlier$^{165,166}$ that plasma-assisted MBE growth of Ga-polar GaN does not lead to nucleation of new dislocations, and hence the TDDs in the epi-layers is determined by the TDDs of the substrate on which growth is done. AFM scans (Fig. 4.6(a)) with 5 µm x 5 µm scan area of the surface morphologies of the epitaxial stack for Sample HD showed ~30 black pits corresponding to screw-type dislocations indicating TDD ~ 10$^8$ cm$^{-2}$. No such pits were observed in the AFM scan (5 µm x 5 µm) for Sample LD as shown in Fig. 4.6(b) indicating TDD < 10$^5$ cm$^{-2}$. I-V characteristics for GaN/AlGaN/GaN structures (Fig. 4.7) revealed that despite three orders of magnitude difference in TDDs, the vertical currents observed in Samples LD
and HD were very similar. *This shows that TDDs are not the primary factor responsible for the anomalous high currents in unipolar GaN/AlGaN/GaN heterostructures.*

Figure 4.6: AFM (5 µm x 5 µm) scans of the surface of GaN/AlGaN/GaN heterostructures grown on (a) Ammono (TDD < 10$^5$ cm$^{-2}$) (b) St. Gobain (TDD ~ 10$^8$ cm$^{-2}$) substrates, showing difference in the density of ‘black pits’ corresponding to screw-type TDDs.

Figure 4.7: I-V characteristics showing that vertical leakage current density in GaN/AlGaN/GaN heterostructures does not depend on threading dislocation density.
4.3.3 Percolation-based transport as leakage mechanism

Since neither heterojunction barrier height nor a reduction in TDDs affects the behavior of GaN/AlGaN/GaN heterostructures and since there is almost no temperature dependence in the current density, our observations suggest that electrons see *almost zero effective barrier* to transport across the heterojunction. We propose that percolation-based transport through the Ga-rich regions of AlGaN is the dominant current mechanism in all the samples described earlier. Such percolation-based transport can be attributed to composition fluctuations in ternary alloy layer\(^{167}\) due to statistical distribution of Ga and Al atoms in group-III sites. To model this, a 2D finite element Poisson and drift-diffusion solver\(^{168}\) was applied to study the percolation-based transport behavior. The fluctuations in Al and Ga compositions (Fig. 4.8(a) and (b)) were generated by using a random number generator.
To compare with experimentally measured leakage data, the average Al-composition of the barrier layer was kept at 20% as the fluctuations in the compositions were generated. In every run, the program generated different Al distributions since it was fully randomized. They all showed similar trend. Therefore one such random fluctuation trend was chosen to present simulation results. The polarization charges, bandgap, effective mass at different locations were changed with the Al composition. A very small mesh size was applied to include this nanoscale fluctuation. After incorporating the statistical fluctuation of Al-composition in the AlGaN layer, the vertical current estimated from this simulation was found to be more than 5 orders of magnitude higher than that estimated without incorporating fluctuations in the layer (Fig. 4.9(a)), which indicated that percolation-based transport was most likely responsible for the
observed leakage in unipolar GaN/AlGaN/GaN samples. Fig. 4.9(b) shows comparison of leakage with and without percolation as predicted by the simulation with experimentally measured data for AlGaN barrier with 20% Al-composition.

Figure 4.9: (a) Leakage current predicted by percolation-model corresponding to AlGaN barrier layers with various Al-compositions (b) Comparison of leakage predicted by percolation-model for Al$_{0.2}$Ga$_{0.8}$N with measured data

The experimentally measured leakage is still higher than that predicted by simulation incorporating fluctuations. This could be due to the facts that tunneling transport due to Al-fluctuations wasn’t incorporated into the simulation model, and secondly, the simulation was 2D whereas the experimentally measured leakage corresponded to a 3D system. In this regard, the fluctuations shown in Fig. 4.8(a) and (b) correspond to one ‘slice’ of the real 3D AlGaN barrier. Modeling in 3D would provide one more dimension to the leakage path and hence can be expected to increase the percolation-based leakage substantially probably resulting in a closer match with experimental data.
4.4 Approaches to suppress leakage

A direct test of the percolation-based leakage hypothesis would be to investigate if vertical leakage in unipolar III-nitride heterostructure is indeed suppressed by eliminating the ternary alloy (AlGaN) barrier. To test it, two separate barrier configurations were explored that both eliminate random alloy fluctuations, and were compared with random Al$_{0.3}$Ga$_{0.7}$N barriers (Sample R). The first approach used was a digital AlGaN barrier (Sample D) with alloy barrier grown by repetition of 2 ML AlN/ 4 ML GaN digital periods. Such an approach eliminates the possibility of statistical fluctuations that could lead to Ga-rich regions in the AlGaN. Fig. 4.10 shows the energy band diagrams corresponding to Sample D showing that the effective barrier height in this case was similar to that for ternary AlGaN with 37% Al-composition (Fig. 4.3). The number of digital periods was such that the barrier corresponded to 25-30 nm of AlGaN with average composition 25% verified by dynamic XRD simulation (Fig. 4.11)
Figure 4.10: Energy band diagram of sample with non-random digital AlGaN as barrier: digital periods of 2 monolayers AlN/4 monolayers GaN are repeated to achieve ~30 nm AlGaN with 25% Al-composition.

Figure 4.11: Fitting XRD scan of the digital sample (D) with dynamic simulation (using BEDE Analysis software). Inset: Epitaxial stack.
Figure 4.12: Energy band diagram of sample E1 with an electrostatic barrier where electric field in the barrier opposes electron flow.

Figure 4.13: Fitting XRD scan of the sample E1 with a field-reversed profile in the barrier, with dynamic simulation (using BEDE Analysis software). Inset: Epitaxial stack.

A second non-random alloy barrier based on a polarization-engineered electrostatic barrier was explored. Such an electrostatic barrier can be of two types – first, where the electric field in the barrier \textit{opposes} the electron flow as shown in the energy
band diagram in Fig. 4.12 (Sample E1). Fig. 4.13 shows the XRD scan of the sample fitted with dynamic simulation. An unintentionally doped (UID) GaN layer is used above a thin AlGaN layer to provide the field as shown in the epitaxial stack (Inset to Fig. 4.13). A second type of electrostatic barrier was also investigated where a thin InGaN layer provided a polarization-induced dipole that would create an electrostatic barrier involving GaN which would be impermeable to percolation effects (sample E2). Using the growth model described in Chapter 2, the InGaN layer was grown in In-rich conditions using a Ga/N flux ratio of 0.40 at a temperature of 540°C. In the energy band diagram simulation, background density of $10^{16}$ cm$^{-3}$ n-type dopants for GaN layer was included. The AlGaN layer was used to further provide a dipole at the UID GaN/AlGaN interface which leads to a flat energy band profile at equilibrium as shown Fig. 4.14(a). The epitaxial stack is shown in Fig. 4.14(b)

![Energy band diagram and epitaxial stack](image)

Figure 4.14: Sample E2 with dipole-induced electrostatic barrier using a thin InGaN layer. (a) Energy band diagram (b) Epitaxial stack
Fig. 4.15 and 4.16 show the vertical I-V (leakage) characteristics in linear and log-scales respectively, of the random alloy barrier (R), the digital alloy barrier (D1) and the polarization engineered electrostatic barrier (E1 and E2). The samples with non-random digital (D1) and electrostatic barriers with field-reversal (E1) and dipole-induced barrier (E2) had more than 3 orders of magnitude lower leakage current density than the sample R (random alloy) for reverse bias in the range of < 2 V, even though the effective barrier height from the energy band diagram in these cases is nominally the same. In fact, for sample E2, the barrier is only 1 eV which ideally is sufficient to prevent leakage at room temperature. The low reverse bias leakage characteristic is not top-contact limited since the lateral current between two top-contact pads of a device exhibits linear Ohmic behavior. This significant reduction in vertical leakage using a polarization-engineered electrostatic and a digital alloy (Al$_{0.3}$Ga$_{0.7}$N) as barriers confirms our hypothesis that eliminating a ternary random alloy as the barrier does prevent percolation-based transport of electrons.
Figure 4.15: Vertical I-V characteristics (linear scale) measured on samples with different barrier profiles showing significant leakage suppression for samples with non-random alloy-based barriers.

Figure 4.16: Vertical I-V characteristics (log scale) measured on samples with different barrier profiles showing leakage suppression by orders of magnitude for samples with non-random alloy-based barriers, thus reinforcing the proposed percolation-based model.
4.5: Summary and conclusion

In conclusion, we investigated unipolar transport in GaN/AlGaN/GaN heterostructures and found the reverse bias leakage to be independent of TDDs as well as of heterojunction potential heights. It is hypothesized that random alloy fluctuations in the ternary AlGaN barrier lead to percolation-based transport which enables electrons to flow through the ternary barrier. This hypothesis is supported by simulations performed using a 2D FEM drift-diffusion transport model incorporating statistical fluctuations of Al-compositions in the AlGaN barrier. It was further tested experimentally by reducing the vertical leakage by more than 3 orders of magnitude by using non-random alloy based barriers based on digital Al\textsubscript{3}Ga\textsubscript{7}N and polarization-engineered binary GaN barriers. This understanding of unipolar transport characteristics and means of reducing the vertical leakage in GaN/AlGaN/GaN heterostructures hold promise for a variety of unipolar III-nitride devices, and for other devices such as HEMTs and LEDs that use random AlGaN alloy-based electron blocking layers.

The understanding of leakage investigated here are of great significance to vertical unipolar III-nitride devices since excess leakage in such structures had prevented them from achieving their theoretical performance. In addition, this work is also significant in understanding forward and reverse bias gate characteristics for III-nitride AlGaN/GaN HEMTs and metal-insulator transistor HEMTs, and electron barrier layers in III-nitride LEDs. In the case of MISHEMTs, forward bias on the gate has been found to create a large electron accumulation at the insulator/oxide interface even at low effective forward voltage where tunneling through the AlGaN should be minimal. This work on
understanding and eliminating percolation transport through the random alloy-barrier could help to eliminate these effects and enable normally off power transistors that operate at positive gate bias.
Chapter 5

Tunnel-injection hot electron transfer amplifier (THETA)

5.1 Introduction

This chapter describes the operation, design, fabrication and demonstration of III-nitride tunnel injection hot electron transfer amplifier (THETA) along with its delay analysis showing that it is theoretically promising for III-nitride THz electronics.

A transistor exploiting the ballistic nature of tunnel injection of hot electrons was first proposed by Mead\textsuperscript{170} in 1960, where the proposed device consisted of metal and oxide stacks for various layers (MOMOM: Metal Oxide Metal Oxide Metal). With epitaxial techniques such as MBE being available, the first semiconductor heterostructure THETA was proposed by Heiblum\textsuperscript{171} and subsequently demonstrated by Yokoyama et al\textsuperscript{172,173} in mid 1980s in the AlGaAs/GaAs system. More results on THETA in the same system including InAlAs/InGaAs were reported\textsuperscript{174,175,176,177} including spectroscopic studies\textsuperscript{178} of the ballistic nature of transport of hot electrons in such devices. However, almost all such results were reported to have been measured at low temperatures of 77 K and below because of the low $\Delta E_C$ available in GaAs-based material system which would result in thermionic carrier spillover between various layers. The first room temperature
report of a working THETA with both dc and RF gain was reported by Moise et al\textsuperscript{179}. Much of the work in hot electron devices such as THETA was inspired by their promise of delivering sub-picosecond delays\textsuperscript{180}; however, they suffered from three severe drawbacks:

i) high output conductance

ii) severe challenges in operating at room temperature and

iii) significantly lower current densities as compared to HBTs.

The contemporary InP-based HBTs were without these disadvantages of THETA, and soon started to mature rapidly, delivering power at RF frequencies. HBTs subsequently became a robust and mature technology and are a critical component of almost all cell phones in use today\textsuperscript{181}. Thus, III-V THETA failed to sustain the interest of the device community and subsequently became confined within the realm of condensed-matter physics.

In mid 1990s, III-nitrides started to generate a lot of interest in high electron mobility transistors (HEMTs). With the demonstration of the first III-nitride HEMT\textsuperscript{182}, significant amount of effort was directed towards demonstrating and increasing RF output power using AlGaN/GaN HEMTs. As explained in chapter 1 of this thesis, III-nitride HEMTs delivered much higher output power densities at microwave frequencies compared to the As/P material system and soon displaced InP-based HBTs from the high-power RF scenario. AlGaN/GaN HEMT, which is a lateral device, in spite of being highly successful, is reaching the limit of its high-speed performance due to LO phonon-limited finite electron saturation velocity. However, vertical transistors in III-nitrides are still at an embryonic stage as explained in section 4.1 in the preceding chapter. Unlike the
highly successful InP-based HBTs which removed III-V THETA from the scene, III-
nitride HBTs have been unable to mature even today because of poor hole mobility\textsuperscript{183,184} and lifetime\textsuperscript{185,186} as well as challenges in making ultra-low contact resistance\textsuperscript{187,188} to p-
type GaN. This makes unipolar vertical transistors in III-nitrides an attractive alternative to explore for high-speed applications particularly because of their ability to engineer electron velocity over short distances (< 10 nm) and high transconductance. This has re-
ignited interests in THETA and HET\textsuperscript{189} although in a different (III-nitride) material system. It will be explained in section 5.4 later in this chapter that theoretically, the intrinsic $f_T$ of III-nitride THETA can be expected to be over 1 THz.

The primary reason which has held back the progress of unipolar III-nitride transistors is the unacceptably high vertical leakage in n-GaN/AlGaN/n-GaN heterostructures. Such a leakage would manifest as base-collector leakage in a typical vertical device and prevent it from achieving output modulation and hence gain. Such high (a few kA/cm$^2$) leakage current densities in unipolar III-nitrides were attributed to percolation-based transport as described in chapter 4 due to random alloy fluctuations in the ternary AlGaN barrier. It was shown that by removing such a ternary barrier, vertical leakage could be suppressed by several orders of magnitude. In this chapter, such a non-
random alloy barrier will be explored to prevent base-collector leakage in III-nitride tunnel injection hot electron transistor. This subsequently enabled demonstration of the first III-nitride THETA.
5.2 Device operation

THETA\textsuperscript{190}, like any other vertical transistor such as HBT, has three terminals – emitter (E), base (B) and collector (C). The emitter consists of a thin barrier through which high energetic ‘hot’ electrons are tunnel-injected into the thin base region when the base-emitter is forward biased ($V_{BE} > 0$). A fraction of these hot electrons travels ballistically or with almost no collision over the thin base and are collected in the collector region when the base-collector junction is reverse-biased ($V_{CB} > 0$). Some of the injected electrons relax into the base due to various scattering mechanisms such as LO phonon scattering and electron-electron scattering. These relaxed electrons constitute ‘cold’ electrons which do not provide gain. The less the fraction of ‘cold electrons’ is, the higher the ‘$\alpha$’ is (which is current transfer ratio i.e. ratio of collector current to injected emitter current). For THETA to work, two critical conditions must be satisfied – firstly, the injected electrons have to travel ballistically, and secondly, the base and collector junction should be non-leaky. If the base-collector junction leaks, fraction of ‘cold’ electron in the base leaking to collector will be very high and the device would fail to exhibit any kind of output modulation. Fig. 5.1 shows a schematic of the epitaxial stack for THETA, showing the injected component of current, the cold or relaxed fraction and the ‘hot’ fraction of injected electrons which make it to collector. Fig. 5.2 shows a schematic of energy band diagram for THETA.
The base layer of THETA should very thin both to reduce transit delay and to reduce the fraction of injected electrons relaxing in to the base thereby increasing gain. However, the thinner the base is, the higher is its sheet resistance leading to higher parasitic voltage drops in the access region. This makes the intrinsic base-emitter potential very different from (or less compared to) the applied voltage and affects the device performance. To alleviate this problem, the base will need to be very highly doped.
to reduce its sheet resistance associated with a thin base. So the base thickness needs to be traded off between a low base sheet resistance and a higher gain and lower delay.

The height of the base-collector barrier height is another critical parameter which needs to be traded off. A low base-collector barrier height will lead to less quantum mechanical reflection of injected electrons at that interface and hence provide a higher $\alpha$. The injected electrons can ballistically make it to the collector only when the Fermi level in the emitter is at least equal to or higher than the height of the base-collector barrier. Hence for a low base-collector barrier, ballistic transport and gain can be expected at lower bias levels. However, a low base-collector barrier means a higher base-collector leakage. So the height of the base-collector barrier needs to be traded-off between lower leakage and a high gain.

5.3 Common-base versus common-emitter configuration

There are two common ways to test the transistor action of vertical devices such as THETA – common base (CB) and common emitter (CE) configurations. To test if the transistor is working as desired, what needs to be done is to observe if a change in the input actually changes the output in the desired manner. Fig. 5.3(a) and (b) shows the schematic of CE and CB measurements respectively.

Figure 5.3: (a) Common Emitter configuration (b) Common Base configuration
In CE configuration, the emitter is grounded and collector is fixed at a certain positive bias. The base Fermi level is now ‘pulled’ down by sweeping it with an increasingly positive bias ($V_{BE} > 0$). Due to a change in base-emitter Fermi level difference, the injected emitter current ($I_E$) will increase due to increased tunneling between emitter and base. For a working THETA, most of these injected electrons should be able to make their way to the collector and hence the collector current ($I_C$) should increase with an increase in $I_E$. In CB configuration, the base is kept at ground, and the collector is fixed at a certain positive bias. The emitter Fermi level is then swept ‘up’ by applying a negative bias on it ($V_{EB} < 0$). However, if the base contact is Schottky (or extremely resistive), then the electrons injected from the emitter will ‘see’ a resistor network as shown in Fig. 5.4 – an extremely high resistive path to the base contact and a fairly low resistance path to the collector.

Figure 5.4: Resistor network ‘seen’ by injected electrons: for a Schottky base contact, injected carriers will prefer to go to the collector due to the low resistance path.

The injected carriers will then preferably go to the collector and give the impression as if a very high current transfer ratio is observable. In other words, an
increasing $I_E$ will *still* lead to an increasing $I_C$ in spite of having a Schottky base. Hence, *common base is NOT a proper test of transistor action in THETA*. An increase in the output current $I_C$ with an increase in the input bias ($V_{BE}$) in common emitter configuration is the proper test for a working THETA.

It is to be mentioned that if the base contact is Schottky, then applying bias in emitter with respect to the base (with collector terminal floating) will lead to negligible change in injected current level. However, if the collector isn’t floating but kept at a certain positive bias, then with a Schottky base contact, THETA behaves as a two terminal device, i.e. resistor, with emitter and collector behaving as the only two terminals. Hence, in CE configuration where collector and emitter Fermi levels are fixed, changing the base bias will not affect the output current and thus it can be tested if the device is not working. But in a CB configuration where the base and collector Fermi levels are fixed, sweeping the emitter is similar to changing the potential at one terminal of a resistor, and hence output current $I_C$ will increase with increase in input current $I_E$ giving the (incorrect) impression that the device is modulating with a high gain.

### 5.4 Delay analysis

The motivation behind III-nitride THETA is its promise of delivering $f_T$ in the THz regime. To estimate its intrinsic $f_T$, the total delay associate with the device needs to be found out which can be done by adding the following time delays:

i) **Tunneling time** ($\tau_T$): time that electrons take to tunnel through emitter barrier

ii) **Charging time** ($\tau_{EB}$): time associated with charging the base-emitter capacitance ($C_{EB}$)

iii) **Base transit time** ($\tau_B$): time taken by carriers to transit over the base

iv) **Collector transit time** ($\tau_C$): time taken by carriers to transit over the collector
**Tunneling time** ($\tau_T$):

The time taken by an electron to tunnel through a barrier has been a quantum mechanical challenge, and there has been significant scatter in the literature regarding the same. Till date, there is no consensus regarding the tunneling time. Much of the theoretical work in this direction estimates tunneling time through a barrier to be *less* than the time an electron would take to move through the same region if there were no tunneling barrier$^{191,192}$ (also called ‘classical time’). This approach by physicists which predicts *shorter* tunneling time than classical time is based on transmission and reflection of ‘wave-packets’ of electrons across the tunneling barrier. If the impinging particle was a photon instead of an electron, it would imply superluminal (or faster than light) speeds. Indeed, it had been shown$^{193,194}$ experimentally that photon tunneling is superluminal (faster than light) but causal and doesn’t violate special relativity.

However, from the point of view of a device engineer, such a tunneling transit time *shorter* than the classical time is counterintuitive in that insertion of a barrier *increases* the speed of the electron. A charge control model analogous to that used in HBT is hence more appropriate to estimate the tunneling time of electrons. Based on this DC charge-discharge model$^{195}$, the tunneling time $\tau_T$ would be given by the steady-state charge stored inside of the tunneling barrier divided by the current flowing through it which is the tunneling current:

$$\tau_T = |t|^{-2} \frac{m}{\hbar} \frac{\int_{\text{barrier}} |\psi_b(z)|^2 \, dz}{\int_{\text{barrier}} \psi_b(z) \, dz}$$  \hspace{1cm} (1)

Here, ‘t’ is the transmission coefficient, and $\psi_b(z)$ is the wave-function of the electron inside of the barrier. For a rectangular barrier of height $V_B$ and thickness ‘a’
approximately corresponding to an emitter barrier in THETA, the tunneling time as a function of bias applied \( V \) is thus found to be (ref. [59]):

\[
\tau_T = \frac{a}{v_{\text{bal}}} \left[ 1 + \frac{mv_{\text{bal}}^2}{4V_B} \left( \frac{\sinh \left( \frac{8mV_Ba^2}{\hbar^2} \right)}{\sqrt{8mV_Ba^2/\hbar^2}} \right)^2 - 1 \right] \tag{2}
\]

Here, \( v_{\text{bal}} \) is the ballistic velocity of injection of electrons through the emitter barrier and in to the base. For collisionless transport along c-axis (\( \Gamma \rightarrow A \)), an electron group velocity of \( 8 \times 10^7 \) cm/s was predicted using Monte Carlo corresponding to an injection energy of 1 eV. Here, a conservative value of \( v_{\text{bal}} = 2 \times 10^7 \) cm/s is used. For designs of III-nitride THETA to be explained later, emitter barrier is typically 3 to 4 nm of AlGaN with 25-30\% of Al-composition. With Al or Ti as emitter contact, the barrier height can be expected to be between 0.2 to 0.4 eV. For such an emitter barrier, the tunneling time estimated using equation (2) is shown in Fig. 5.5 as a function of bias applied for different barrier heights.

![Figure 5.5: Intrinsic tunneling estimated by the charge-control model for different barrier heights as a function of distance](image)

Figure 5.5: Intrinsic tunneling estimated by the charge-control model for different barrier heights as a function of distance
Although the emitter barrier in the III-nitride THETA is 3-4 nm thick as shown in the equilibrium band diagram in Fig. 5.6, yet under application of bias when Fowler-Nordheim tunneling commences, the Fermi level of emitter metal will ‘see’ a less barrier thickness as the field in the barrier increases (Fig. 5.7).

![Figure 5.6: Equilibrium band diagram of proposed III-nitride THETA with 3.5 nm emitter barrier thickness. Barrier height is taken as 0.5 eV.](image)

As seen from Fig. 5.7, under -1 V bias on the emitter which corresponds to a typical device operation condition, the emitter Fermi level will ‘see’ a barrier 1 to 1.5 nm instead of 3.5 nm, assuming a barrier height of 0.5 eV. This value of 0.5 eV is however an over-estimate since Al contact on GaN provides a barrier height of 0 to 0.1 eV; so on Al$_{0.25}$Ga$_{0.75}$N, the barrier height can be expected to be 0.2-0.4 eV. Besides, using AlGaN with lower composition, an even lower barrier height is expected. From Fig. 5.6, tunneling time associated with such a barrier of 1-1.5 nm would be 10 fs or less.
Figure 5.7: Energy band diagram of THETA when -1 V bias is applied to emitter. The tunneling thickness ‘seen’ by emitter Fermi level would be 1 to 1.5 nm.

*Hence the intrinsic tunneling time corresponding to the proposed THETA with 3.5 nm of AlGaN barrier would be 10 fs or less.*

**Charging time** ($\tau_{EB}$):

Figure 5.8: Delay associated with charging-discharging of the base-emitter capacitance as estimated using equation (3).
The delay associated with charging-discharging of the emitter-base capacitance is given by the capacitance ($C_{EB}$) divided by the conductance:

$$\tau_{EB} = \frac{C_{EB}}{\frac{\partial J_{Tunnel}}{\partial V_{EB}}}$$  \hspace{1cm} (3)

Here, $C_{EB}$ ($= \varepsilon / d$, where $d$ = emitter barrier thickness) is the base-emitter capacitance and $J_{Tunnel}$ is the tunneling current density (or emitter current $I_E$) which can be estimated to a first order by a simple Fowler-Nordheim tunneling current calculation. Based on the proposed III-nitride THETA, a barrier height of 0.2 eV is assumed and using equation (3), the charging time associated with different barrier thicknesses are estimated as shown in Fig. 5.8. For the proposed THETA design with 3.5 nm emitter barrier, the charging delay is estimated to be around 75 fs as seen from Fig. 5.8.

**Base and collector transit times ($\tau_B$ and $\tau_C$):**

The transit times would be simply given by the thickness of the base layer and the collector barrier divided by the injection velocity. As explained in the preceding discussion on tunneling time, a value of injection velocity = $2 \times 10^7$ cm/s is assumed which is a highly conservative value and is *four times less* than what is predicted by Monte Carlo. For a scaled THETA with a base thickness of 5 nm and collector barrier thickness of 10 nm, a *total transit time of about 75 fs* is expected.

Thus, the total intrinsic delay associated with proposed III-nitride THETA can be found by adding the different delays estimated in the preceding discussions: 10 fs + 75 fs + 75 fs = 160 fs, which corresponds to an $f_T = 1$ THz. It is to be noted that a highly conservative value of injected electron velocity ($2 \times 10^7$ cm/s) has been assumed in these.
calculations. A slightly higher value of injected velocity (~3x10^7 cm/s) can lead to \( f_r \approx 1.2 \text{ THz} \).

Thus theoretically, III-nitride THETA has potential to enable III-nitride THz electronics.

### 5.5 Process flow of device fabrication

![Process flow diagram](image)

Figure 5.9: Process flow developed to fabricate THETA

The process flow developed to fabricate a 3-terminal vertical device, in this case THETA, is shown in Fig. 5.9. The process starts with evaporating emitter metal contacts after emitter lithography using i-line stepper projection aligner. The emitter metal is then used as an etch mask to blanket-etch the emitter layer from everywhere else and to stop at
the base layer. For the etch, a Cl₂/BCl₃-based controlled etch recipe is used with an etch rate of 10 nm/min. The reason for using the blanket etch instead of doing a base lithography and evaporating base metal is because the mask was designed for 1st generation devices with an n⁺-doped semiconductor emitter. As such, in absence of an emitter-metal based blanket etch, the top n-doped layer would short the emitter and base contacts. After etching down to the base layer, base lithography is done followed by base metallization. Thereafter, base and emitter contacts are covered with photo-resist and base mesa is isolated using the same controlled etch recipe to etch down to the collector layer. Since the collector is n-doped ([Si] = 3x10¹⁸ cm⁻³) GaN template (~500 microns thick), it behaves as an almost metallic layer (or equipotential). To form the collector contact hence, the backside of the sample is scratched with a diamond scribe and indium contact is formed to it by pressing it in the scribed regions. Test with multi-meter shows extremely low resistance between two such contacts on the backside indicating collector contact (on the backside of the sample) is excellently Ohmic in nature.
Figure 5.10: (a) Schematic of a typical device (top view) showing various dimensions of base and emitter fingers. (b) SEM scan of a fabricated device (Image by Dr. Camelia M.). The emitter finger is 0.7 µm wide.

Fig. 5.10(a) shows the schematic of the top view of a typical device with its various dimensions. Each device consists of one emitter finger and two base fingers. The two base fingers are useful to measure base-to-base current in the same device to check the linearity or Ohmic nature of the base contacts. Fig. 5.10(b) shows a scanning electron micrograph (SEM) of a device. The devices are probed using sub-micron manipulators available from Cascade Microtech, with probe tips 0.6 µm in diameter which allows good control in probing emitter pads 2.5 µm in width. Devices are measured using an Agilent B1500 Semiconductor Parameter Analyzer.

5.6 Various device generations

5.6.1 1st generation: resonant tunneling hot electron transistor (RTHET)

The 1st generation of devices to be explored was a special kind of THETA where two tunneling barriers were used as emitter barrier instead of one. The idea was to take advantage of resonant tunneling of electrons through the double-barrier system which
was expected to enhance the tunnel-injected current density. Fig. 5.11(a) shows the energy band diagram of such an RTHET as simulated by BandEng and Fig. 5.11(b) shows the epitaxial stack (Ga-polar). These were grown by plasma-assisted MBE in Ga-rich conditions using a Gen 930 Veeco system equipped with a unibulb plasma source. The N$_2$-limited growth rate was around 4 nm/min.

Fig. 5.12 shows the XRD scan of the stack fitted with dynamic simulation, which helped confirm the thickness and compositions of the various layers. Fig. 5.13 shows an AFM scan of the surface morphology post-growth showing smooth surface with atomic steps. This generation of devices had a degenerately n-typed doped GaN on top as emitter contact layer. Such a semiconductor layer would provide higher tunneling current density compared to a metal contact layer directly on barrier layer as in a THETA. However, etching precisely up to the base layer was a challenge especially because the thin 70% AlGaN layers (barriers) would alter the etch rate significantly. Multiple etches were done to reach the desired etch depth up to the base layer as confirmed through AFM scans of the etched interface.
Figure 5.11: (a) Energy band diagram of RTHET (b) Epitaxial of device grown by MBE

Figure 5.12: XRD scan of RTHET fitted with dynamic simulation.
Two terminal emitter-base measurements were done to check if resonant tunneling was observable whose signature would be appearance of negative differential resistance (NDR). It has been widely reported\textsuperscript{197,198,199} that achieving repeatable NDRs in forward and reverse sweeps in III-nitride RTDs has been a challenge – the position of the NDR shifts and/or the NDR vanishes away after a few sweeps.
Fig. 5.14 shows I-V characteristic of the base-emitter (resonant tunneling) diode of a device, showing repeatable NDR in forward sweeps with a record high peak to valley current ratio (PVCR) of 10.5. However, with reverse sweeps, the NDR disappears which is what has been most commonly reported in literature as the primary issue for III-nitride RTDs. In certain devices, the NDR was observed in both forward and reverse sweeps as shown in Fig. 5.15.

Due to issues with repeatability and reproducibility of NDRs (and hence resonant tunneling), RTHET was hence discarded since a 3-terminal transistor cannot be expected to deliver required performance (output modulation etc) when its input diode does not exhibit reproducible I-V characteristics. Further work on understanding resonant tunneling in III-nitrides and ways to address issues with NDR need to be investigated before a transistor based on resonant tunneling can be realized.
Figure 5.15: I-V characteristic of base-emitter (resonant tunneling) diode, showing NDR in both forward and reverse sweeps.

5.6.2 2nd generation THETA: ternary Al$_x$Ga$_{1-x}$N collector barrier

Semiconductor (n-GaN) emitter contact based double barrier RTHET was replaced by metal emitter contact based single barrier THETA. The design consisted of 3.5 nm Al$_{25}$Ga$_{75}$N emitter barrier with a very thin (~ 3-5 nm) of n+ doped GaN base ([Si] = 4E19 cm$^{-3}$). The base-collector barrier was a ternary Al$_{25}$Ga$_{75}$N barrier with 25-35 nm thickness. The n+ GaN template behaved as collector terminal. Energy band diagram of such a typical structure would be similar to the one shown in Fig. 5.6 but with a thinner base.

Devices were fabricated following the process flow described in section 5.5. However, due to a very thin base, the base contact was measured to be near-Schottky or extremely resistive. This prevented from observing any modulation. In common emitter configuration as outlined in section 5.3, with the emitter grounded and collector swept
from 0 to positive biases, the injected ($I_E$) current showed absolutely no change in change when base bias was changed in steps as shown in Fig. 5.16.

![Figure 5.16: 3-terminal common emitter characteristics of THETA with very thin base. Due to Schottky nature of the base contact, no change was observed in injected emitter current with change in input bias $V_{BE}$.](image)

Subsequently, the base thickness was increased to 10-15 nm, keeping thickness and composition of other layers the same. As shown in Fig. 5.17, the base-collector leakage was measured to be extremely high in all the devices, and on different samples with varying Al-compositions in the AlGaN barrier layer. This indicated the base-collector barrier was found to provide no barrier to electron flow.
Figure 5.17: Base-collector I-V, showing unacceptably high leakage ($V_{CB} > 0$).

Figure 5.18: Various current components in a device with leaky base-collector diode in common-emitter configuration with collector fixed at 4 V. Collector current decreases with increase in input bias $V_{BE}$ clearly indicating that the device doesn’t work.

Thus, in a 3-terminal common-emitter characteristic as shown in Fig. 5.18, the collector current was found to decrease with an increase in input bias $V_{BE}$, thus exhibiting an opposite trend of what is expected in a transistor. This was because when the collector is fixed at a certain bias (4 V, as shown in Fig. 5.18) and emitter is grounded, there is
severe leakage from base (which is initially at zero voltage) to the collector. Hence as base Fermi level is ‘pushed’ down by increasing $V_{BE}$ thereby bringing it closer to collector Fermi level which is at 4 V, leakage starts to decrease – $I_B$ decreases (in magnitude). Since output current is mostly leakage-dominated, $I_C$ also starts to decrease with increase in $V_{BE}$, thereby indicating that the device fails to work.

This unacceptably high leakage across a thick (25-35 nm) Al$_x$Ga$_{1-x}$N collector barrier was investigated rigorously as explained in chapter 4 of this thesis. It was found to be independent of heterojunction barrier height and of threading dislocation densities, but was rather attributed to a percolation-based transport mediated by alloy fluctuations in Al-composition in the ternary random alloy (Al$_x$Ga$_{1-x}$N). Replacing the random alloy Al$_x$Ga$_{1-x}$N barrier by digital AlGaN and with an electrostatic barrier by reversing the field in the barrier was found to reduce the leakage significantly.

5.6.3 3rd generation THETA: digital AlGaN collector barrier

The next generation of THETA consisted of digital AlGaN collector barrier, where 2 ML/4 ML of AlN/GaN were grown in digital periods such that the total thickness was 30-35 nm and the average composition corresponded to 25-30% AlGaN as confirmed by XRD scans. The base thickness was typically 15-25 nm of n+ GaN doped $[Si] = 5E19$ cm$^{-3}$. The band diagram of such a structure and its XRD fitting were shown in Fig. 4.10 and 4.11 respectively in the preceding chapter. The leakage was found to be suppressed by 2-3 orders of magnitude up to at least $V_{CB} = 2$ V, and base-to-base I-V of the same device exhibited linear Ohmic nature indicating that base contact was not limiting the low base-collector leakage.
With the base-collector being suppressed significantly, 3-terminal measurements were performed in common-emitter configuration keeping the collector fixed at 5 V. On sweeping the base bias (Fig. 5.19), the injected current ($I_E$) was found to increase slightly indicating that a change in base-emitter Fermi level difference changed the input current in the desired manner. However, the output current ($I_C$) was once again found to decrease with increase in input bias $V_{BE}$, indicating that the device failed to work. Similar characteristics i.e. non-leaky base-collector behavior and decrease in $I_C$ with increase in $V_{BE}$ were also observed in THETA where the field in the collector barrier was reversed using electrostatics (Band diagram in Fig. 4.12). The reasons attributed to the non-working nature of the devices were firstly, the collector barrier height was most likely too high (~2.5 to 3 eV) for injected ballistic electrons to overcome even with high $V_{BE}$ ~ 5 V, and secondly, the emitter to collector distance was 20-30 nm which maybe so long that ballistic electrons lost most of their energy and collimation due to collisions with phonon
and other electrons in the degenerately doped GaN base layer. For a collector barrier of 2.5 to 3 eV in height, $V_{BE} \sim 5$ V should ideally allow for injected electrons to be at a higher energy than the barrier height in the collector. However, as will be shown in section 5.7, due to finite sheet resistance of the base layer, voltage drop in the base access region is considerably high and leads to a very less $V_{BE}$ in the intrinsic region below the emitter layer. Thus, corresponding to an applied $V_{BE} \sim 5$ V, the intrinsic $V_{BE}$ below the emitter would be much less than 5 V and hence carriers can be expected to be unable to overcome the 2.5-3 eV high collector barrier. It is to be noted however that applying still higher input bias ($V_{BE} > 6$ V) was found to lead to permanent degradation of the device in the form of device breakdown or device burning.

5.6.4 4th generation THETA: dipole-induced electrostatic barrier (1 eV)

Since reducing the base-collector leakage alone couldn’t enable THETA to demonstrate output modulation in common-emitter configuration, in the 4th generation, the base-collector barrier height was reduced at 1 eV. A thin In$_x$Ga$_{1-x}$N ($x = 0.12-0.20$) in conjunction with GaN was used to provide a dipole-induced electrostatic barrier which (GaN) was non-permeable to percolation based leakage as explained in chapter 4. An Al$_x$Ga$_{1-x}$N layer downgraded from 20% to GaN was used to provide a flat energy band at equilibrium which would push the onset of Fowler-Nordheim tunneling to higher collector biases, allowing a wider window for collector swing before leakage starts to dominate. The epitaxial stack of such a structure and its corresponding energy band diagram as simulate using Silvaco are shown in Fig. 5.20 and 5.21 respectively. A series of such THETA samples were grown using plasma-assisted MBE with the base thickness being varied as 18 nm, 9 nm, 6 nm and 4 nm. A doping of [Si] = 1x10$^{20}$ cm$^{-3}$ was used in
the base layer for all the growths. Fig. 5.22 shows an AFM scan of the surface of a typical sample after growth showing smooth surface with rms roughness < 0.5 nm for 10 µm x 10 µm scan area.

![AFM scan of the surface of a typical sample after growth showing smooth surface with rms roughness < 0.5 nm for 10 µm x 10 µm scan area.](image)

**Figure 5.20: Epitaxial stack of 4th generation THETA**

![Epitaxial stack of 4th generation THETA](image)

**Figure 5.20: Epitaxial stack of 4th generation THETA**

![Energy band diagram of 4th generation THETA exploiting thin InGaN to provide electrostatic barrier, as simulated using BandEng.](image)

**Figure 5.21: Energy band diagram of 4th generation THETA exploiting thin InGaN to provide electrostatic barrier, as simulated using BandEng.**
Figure 5.22: AFM (10 µm x 10 µm scan) showing smooth surface of THETA post-growth.

Fig. 5.23 shows the input (base-emitter) characteristics of a device with an emitter area of 14 µm². High levels of current densities were achievable; in certain devices, input currents up to 60 kA/cm² (at 3 V) were measured.

Figure 5.23: Base-emitter I-V for 4th generation THETA (emitter area = 14 µm²)
The base-collector characteristic is shown in Fig. 5.24 and is overlapped with base-to-base I-V of the same device showing that the Ohmic or linear nature of the base contact is not limiting the very low leakage.

![Image](image_url)

Figure 5.24: Base-collector and base-to-base I-V of a device, showing non-leaky base-collector diode and an Ohmic base contact.

The base-collector characteristic is shown in Fig. 5.24 and is overlapped with base-to-base I-V of the same device showing that the Ohmic or linear nature of the base contact is not limiting the very low leakage ($V_{CB} > 0$). With the collector fixed at 5 V, 3-terminal measurements were done in common-emitter configuration by sweeping the base bias. Fig. 5.25 shows $I_C$-$V_{BE}$ plot analogous to a transconductance plot in a HEMT. With an increase in input bias $V_{BE}$, the output current $I_C$ was found to increase which implied that the THETA was able to modulate the output current in a desired manner. This indicated the working nature of the device. The collector was then swept for a family of output characteristics ($I_C$-$V_{CE}$) with the base bias being increased in steps of 0.5
V as shown in Fig. 5.26. Repeatable output modulation was observed for devices with varying base thicknesses and across different dies in all the samples.

Figure 5.25: Transconductance profile in common-emitter configuration, showing increase in output current $I_C$ with increase in input bias $V_{BE}$ (with collector bias fixed at 5 V), demonstrating the working nature of the device.

Figure 5.26: Output characteristics ($I_C$-$V_{CE}$) in common-emitter configuration for a 4th generation THETA device showing output modulation.
This is the first demonstration of III-nitride THETA, and the first demonstration of any type of hot electron transistor in III-nitride material system with output modulation in common-emitter configuration without subtracting base-collector leakage.

5.7 Device analysis

With THETA demonstrating output modulation in CE configuration, the next step was to measure its current transfer ratio or gain. For that, the base and collector are both grounded so that ideally, base-collector leakage is zero since the Fermi level difference between them is zero. The emitter is then swept to negative bias (V_{BE} > 0) so that electrons are injected from the emitter contact to the base, and the ratio of output to injected current (I_C/I_E) was measured. This gives \( \alpha \), the transfer ratio. The higher the \( \alpha \) is, the more is the fraction of injected electrons reaching to the collector and hence higher the gain.

![Graph showing \( \alpha \) vs. V_{BE}](image)

Figure 5.27: Transfer ratio measured for various devices in 4\textsuperscript{th} generation THETA with 9 nm base.
Fig. 5.27 and 5.28 show $\alpha$ corresponding to various devices on samples with 9 nm and 18 nm base thicknesses respectively. Since the InGaN is about 3.5 nm thick, the total emitter to collector distance would be 12.5 and 21.5 nm respectively. It can be seen that the transfer ratio $\alpha$ was measured to be very low (~0.1) and that too with high biases (~5-6 V) applied. With only 1 eV barrier in base-collector diode, $V_{BE} > 1$ should ideally provide a reasonable $\alpha$ when the emitter Fermi level is ‘above’ the base-collector barrier. Thereafter, $\alpha$ is expected to increase sharply with increase in $V_{BE}$ since injected ballistic electrons would see ‘no’ barrier to the collector in that scenario. As explained in section 5.6.3, this high applied bias was required due to finite base sheet resistance which resulted in significant parasitic voltage drop in the access region. Thus, the intrinsic potential in the region below emitter can be expected to be considerably less than the applied $V_{BE}$.

![Graph showing $\alpha$ vs $V_{BE}$](image)

Figure 5.28: Transfer ratio measured for various devices in 4th generation THETA with 18 nm base.
To increase $\alpha$, the base thickness was shrunk to 4 nm and 6 nm in subsequent THETA samples grown and processed. Fig. 5.29 shows $\alpha$ for some devices measured on two different samples with 4 and 6 nm base thicknesses. No definitive trend was observed with different base thicknesses, and $\alpha$ was found to be in a range of 0.25 to 0.8 (at 6 V applied bias) for both the samples. The significant scatter in the value of $\alpha$ could be attributed to non-uniformity in InGaN thickness and compositions across the sample leading to non-uniformity in emitter-to-collector distance. Interestingly, shrinking the base thickness did indeed help increase $\alpha$, and the highest $\alpha$ measured was 0.82.

![Figure 5.29: Transfer ratio measured for various devices in two samples (4th generation THETA) with 4 nm and 6 nm base thicknesses.](image)

To estimate the intrinsic $V_{BE}$ to a first order, the base sheet resistance ($R_{sh}$) and contact resistance ($R_{C}$) were extracted using TLM measurements (Fig. 5.30) and found to be 2 kΩ/□ and 4 Ω-, respectively. The $V_{BE}$ (intrinsic) can then be estimated by subtracting parasitic voltage drop – $I_B(R_C + R_{sh})$ in the access region from applied $V_{BE}$. 

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Figure 5.30: Extraction of base sheet and contact resistances from TLM.

Figure 5.31: Transfer ratio for a device with 6 nm base thickness, plotted against applied $V_{BE}$ and intrinsic $V_{BE}$.

A typical transfer ratio ‘$\alpha$’ plot corresponding to a device with 6 nm base thickness was chosen and the intrinsic $V_{BE}$ was estimated. The transfer ratio was then plotted for both intrinsic and extrinsic (or applied) $V_{BE}$ as shown in Fig. 5.31. It is interesting to observe that when plotted against intrinsic $V_{BE}$, the transfer ratio rises...
sharply at 1 V and reaches high value (~0.5) at fairly low bias (< 2 V) compared to the large values of applied bias > 5 V required for the same. The sharp rise of $\alpha$ at $V_{BE} \sim 1$ V corresponds to the emitter Fermi level ‘rising’ above the base-collector potential barrier of 1 eV at which, the injected electrons will ‘see’ no barrier and can ballistically transit to the collector. The stark difference in the plot of $\alpha$ against intrinsic and applied $V_{BE}$ as shown in Fig. 5.31 testifies the necessity of reducing the base sheet resistance and contact resistance to minimize the parasitic voltage drops in the base access regions.

Another important issue to address in the working generation of THETA is reduction of output conductance in $I_C$-$V_{CE}$ plot (Fig. 5.26). High output conductance had been also reported in almost all GaAs/InGaAs based THETA in 1980s and 1990s. It was attributed in ref. [177] to a reduction of base-collector barrier height as $V_{CB}$ was increased. However, that was most likely due to low $\Delta E_C$ available in GaAs-system. In III-nitride THETA demonstrated, the collector Fermi level ‘affects’ the current from the emitter contact in a non-local manner. If emitter and base are kept at certain fixed biases (say, $V_E = 0$, and $V_B = 2$ V), then the input current $I_E$ should be constant because $I_E$ should depend only on the input bias, i.e. the Fermi level difference between emitter and base ($V_{BE}$). However, it is always found that under a fixed $V_{BE}$, changing the collector bias does change the input current. An increase in $V_C$ leads to an increase in $I_E$, which is non-local effect. This prevents output current from saturating. Hence, to reduce output modulation, the collector and emitter terminals should be ‘separated’. This might be achievable by increasing the emitter barrier thickness as well as the collector barrier thickness.
5.8 Conclusion

In conclusion, III-nitride tunnel injection hot electron transfer was investigated. The motivation behind such a vertical unipolar transistor was outlined showing that theoretically an intrinsic $f_T > 1$ THz is achievable in such a device. Various device designs were explored starting with resonant tunneling based hot electron transistor. The most critical challenge preventing the realization of a unipolar vertical III-nitride transistor i.e. base-collector leakage through ternary random alloy ($\text{Al}_x\text{Ga}_{1-x}\text{N}$) barrier was identified and was overcome with energy band tailoring using dipole-induced electrostatic barrier. Finally the first III-nitride THETA exhibiting output modulation in common emitter configuration was demonstrated. Current gain transfer ratio was studied and found to increase up to 0.8 (at 6 V applied bias) for a base of 6 nm thickness. It was also shown that intrinsic potential was significantly different from that applied due to parasitic voltage drops in base access region. Importance of reducing the base sheet and base contact resistances, as well as the presence of output conductance in the devices and ways to reduce it was explained.
Chapter 6

Conclusions and future work

6.1 Conclusions

This thesis dealt with engineering polarization of III-nitride heterostructures towards potential high-speed device applications.

Epitaxy of N-polar In$_x$Ga$_{1-x}$N was studied and a growth model was developed to achieve desired In-composition by changing Ga-flux and growth temperature which was found to match with data. Achievability of higher Indium compositions in N-face polarity compared to Ga-face polarity for identical growths conditions was demonstrated. Good quality In$_x$Ga$_{1-x}$N showing single peaks in XRD and PL was grown with high In-composition (~30%) which enabled demonstration of the first PAMBE grown green LED. Initial studies on In$_x$Ga$_{1-x}$N grown on heteroepitaxially grown GaN on SiC was also presented and challenges were explained.

Lateral electrostatics was exploited in N-polar AlGaN/GaN HEMT on vicinal substrates, which when combined with polarization engineering, enabled tuning the dimensionality of the electron gas at the AlGaN/GaN interface between 1-D and 2-D. Self-defined and dense arrays of 1-dimensional channels were demonstrated which were
found to carry technologically relevant current densities and combined advantages of both bottom up and top down approaches. Such dense nanowire arrays self-defined in a HEMT could enable investigation of various transport properties such as electron velocity from the device point of view.

Unacceptably high vertical leakage current density, which has held back the progress of unipolar III-nitride vertical devices, was investigated and was found to be independent of heterojunction barrier height or TDDs. Rather, it was attributed to percolation based transport mediated by random alloy fluctuations in the ternary Al_{x}Ga_{1-x}N barrier. Replacing the ternary barrier separately with digital alloy and with polarization-engineered electrostatic barriers was found to suppress the leakage by orders of magnitude. Using such a ternary-free barrier, III-nitride tunnel-injection hot electron transistor (THETA) was demonstrated for the first time. The device demonstrated output modulation without subtracting base-collector leakage in common-emitter configuration with current transfer ratio up to 0.80 for base thickness of 6 nm. The base sheet and contact resistances were found to lead to significant parasitic voltage drops in the base access regions which affect the shape of the transfer ratio plot.

### 6.2 Future work

#### 6.2.1 Growth of In\textsubscript{x}Ga\textsubscript{1-x}N on heteroepitaxial GaN on SiC

The investigation of InGaN growth by MBE including the growth model explained in this thesis was done on free standing low dislocation density GaN substrates. However, such substrates are n-typed doped in nature. The GaN buffer layers grown on such n-doped substrates are always found to be leaky in nature. Growing p-doped GaN
barrier layer is found to reduce the leakage but not sufficient enough for viable HEMT technologies. Using semi-insulating GaN substrates (both Ga-face and N-face) also poses the challenge of regrowth interface which leads to a buffer leakage for annealed Ohmic contacts.

The most obvious approach to circumventing this problem is to grow GaN heteroepitaxially on SiC which leads to semi-insulating buffer layers. Such GaN on SiC grown by MBE yields extremely low buffer leakage current densities. The challenge in such an approach however as explained in section 2.7, lies in the island-type InGaN growth on heteroepitaxial GaN (Fig. 2.20(a) and (b), which was most likely mediated by a high threading dislocation density. InGaN channel HEMTs grown on heteroepitaxial GaN on SiC were found to exhibit insulating nature in spite of expecting 2DEG charge density in the 1-3x10^{12} \text{cm}^{-2} range based on band diagram simulations. The growths were typically done in 550-590^\circ \text{C} range. The future work in this direction could be to explore various growth regimes and conditions to study the achievability of a smooth and continuous InGaN epi-layer on heteroepitaxial GaN on SiC. High temperature growths in the 600-650^\circ \text{C} range can be investigated particularly for N-face InGaN since the first green LED demonstrated was grown at 625^\circ \text{C} on N-face polarity. Other approaches such as migration enhance epitaxy (MEE) and N-rich growth conditions could also be explored for growing such InGaN layers.

Also, very high composition N-face In_{x}\text{Ga}_{1-x}\text{N} (x > 0.40) growth on heteroepitaxial GaN on SiC could be explored in the future. Fig. 6.1 shows XRD scan and fitting with simulation of a thick InGaN layer on GaN on SiC, with 57\% In-composition, exhibiting single peak in both XRD and PL (not shown).
6.2.2 1-D channel HEMTs

Dense arrays of self-defined nanowires on vicinal N-polar AlGaN/GaN HEMTs were demonstrated in this thesis which exhibited pure 1-dimensional transport parallel to the direction of atomic terraces. However, such nanowires have not been gated till now and hence transistor operation ($I_D$-$V_D$, $g_{m}$-$V_G$) of such pure 1-D channel wires are yet to be demonstrated. As a future work in this direction, firstly, small-signal measurements can be done on highly scaled 1-D devices after putting down gate metals so that $f_T$ can be extracted. For a given charge density, $f_T$ for pure 1-D and pure 2-D transport-based transistors can be compared. Also, due to the unique nature of this 1-D/2-D hybrid system, only the intrinsic region will exhibit 1-D behavior while the access regions and Ohmic contacts will still be to 2DEG (Fig. 6.2). Hence contact resistance and parasitic drops can be expected to be same for both 1-D and 2DEG transistors. This will enable a direct comparison between 1-D and 2-D transport in terms of electron velocity.
Figure 6.2: Schematic of 1-D HEMT showing that only intrinsic region is 1-D in nature; access regions and Ohmic contacts will ‘see’ 2DEG.

Secondly, once 1-D HEMTs are fabricated, 1/f noise can also be studied in these nanowires and compared to noise performance of conventional 2DEG-based HEMTs.

Finally, it will be interesting to explore 1-D channel transistors with higher charge densities. In the work presented in this dissertation, the pure 1-D charge existing in the vicinal N-polar HEMT studied was around $2 \times 10^{12}$ cm$^{-2}$. For such low 1-D charge densities, fraction of 2DEG in the entire charge density is significantly high. As shown in Fig. 6.3, 1-D transport is achieved when Fermi level lies below the height of the lateral triangular barrier. Thus, the total amount of useful 1-D charge can be estimated by integrating the product of 1-D density of states with the Fermi function, with the limit of $E_F = E_{\text{barrier}}$: 
\[ n_{1D}(E_F) = \int_{E_0}^{\infty} \frac{\frac{\sqrt{2m^*}}{\hbar \sqrt{E}}}{1 + \exp\left(\frac{E - E_F}{kT}\right)} \frac{1}{t_{\text{terrace}}} \, dE \quad (E_F = E_{\text{bar}}) \quad (1) \]

Here, the expression is normalized by \( t_{\text{terrace}} \) - width of the atomic terrace (or pitch) to bring its units to \( \text{cm}^{-2} \) for comparison with 2DEG. Hence, the total 1-D charge available would strongly depend on the miscut angle of the substrate which defines the terrace width, and also on the lateral confinement barrier which would depend on the epitaxial design – the different polarization charges at the various interfaces.

Figure 6.3: Schematic of the saw-tooth energy profile in the lateral direction being approximated as triangular wells. Pure 1-D transport is achievable when Fermi level lies below the lateral confinement barrier.

Thus, future work in this direction could involve exploring HEMTs grown on substrates with various miscut angles and with carefully designed epitaxial stack to lead to a higher lateral confinement barrier. Estimates based on equation (1) are shown in Fig. 6.4. It can be seen that as the miscut angle is increased, net 1-D charge available also increases which also increases the fraction of 1-D charge out of the total 1-D + 2-D
charge densities existing in the system. With a miscut of $6^0$, 1-D charge up to $5 \times 10^{12} \text{ cm}^{-2}$ is achievable for a 120 meV lateral confinement barrier.

![Graph showing dependence of total 1-D charge available in a vicinal N-polar HEMT on angle of substrate miscut.](image)

Figure 6.4: Dependence of total 1-D charge available in a vicinal N-polar HEMT on angle of substrate miscut.

### 6.2.3 Further work on THETA

The first III-nitride THETA was demonstrated in this thesis. However, it requires significant amount of optimization and investigation to enable a viable RF technology.

#### 6.2.3.1 N-face THETA

THETA demonstrated and investigated in this thesis is on Ga-face polarity GaN. High base sheet and base contact resistances have been found to severely limit the device performance. One approach to investigate for reducing the sheet resistance is to explore the reverse polarity. Epitaxial stack and energy band diagrams for such an N-face THETA are shown in Fig. 6.5(a) and (b) respectively.
Figure 6.5: N-polar THETA (a) epitaxial stack (b) energy band diagram

The emitter barrier can be GaN with a thin InGaN to provide a ternary-free electrostatic barrier which will reduce percolation-mediated base-emitter leakage. With carefully designed emitter and collector profiles, the charge density in the base layer can be enhanced in N-face polarity which is promising for reducing base resistance.

6.2.3.2 Semiconductor emitter

THETA demonstrated in this thesis has a metal emitter contact, tunnel-injecting hot electrons through a thin (3-4 nm) AlGaN emitter barrier. However, metal to semiconductor tunneling had been calculated\textsuperscript{200} to exhibit high quantum mechanical reflection and lead to lower current transfer ratios. Hence, as a potential future work in THETA, a semiconductor (n\textsuperscript{+}-doped GaN) emitter layer can be investigated. Semiconductor to semiconductor tunneling can be expected to lead to increase in injection current density which is highly promising for reducing base-emitter capacitance delay for an RF device.
6.2.3.3 RF device

The THETA demonstrated in this thesis exhibited a highest $\alpha$ of 0.80 at -6 V of emitter bias. With significant reduction in base sheet and contact resistances by exploring N-polar THETA, intrinsic $\alpha$ can be expected to increase. Once $\alpha$ is $> 0.90$, it would be very interesting to perform RF measurements on such devices to extract $f_T$. For that, an RF mask layout needs to be designed with GSG (ground-signal-ground) contact pads. However, the contact pads would still need to have very small area (< 1 $\mu$m$^2$) to achieve high injection current densities. This would necessitate the use of air-bridge and polyimide$^{201,202,203,204}$ and/or benzocyclobutaene (BCB)$^{205}$ as passivation and planarization layers so as to make contact to extremely small area emitter and base pads. Standard RF device process layouts for highly scaled InP HBTs can be adopted for III-nitride RF THETA fabrication as well.


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