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On the subject

Simulation of analytical model for I-V characteristics of GaN based High Electron Mobility Transistors

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"الحمد لله الذي هدانا لهذا وما كنا لنهتدي لولا ان هدانا الله "

اللهم لك الحمد حتى ترضى

ولك الحمد اذ رضيت

ولك الحمد بعد الرضا

ولك الحمد على كل حال

dedicate

To the one who tired and raised and stayed up and sacrificed her money and beauty in order to get me to what pleases me, the source of tenderness my mother

To the one who took me to safety and made me proud of him, may God protect him and take care of him my dear father

To the one who brought me back my smile and my hope in life, the apple of my eye my dear husband

I dedicate this humble work to you all

Saliha

Dedicate

To my honorable parents, may God preserve and take care of them, to all those who helped me to accomplish this work, I dedicate this humble work.

Tarek

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ABREVIATIONS

AlGaN	aluminum gallium nitride
AlGaInN	aluminum gallium indium nitride
AlN	aluminum nitride
CGD	capacitance gateto to drain
DVD	digital versatile disk
eGaN	enhancementmode gallium nitride
Ev	Electronvolts
EPC	Efficient Power Conversion Corporation
EPM	Empirical Pseudopotential Method
FET	field effect transistor
FBL	First barrier layer
HEMT	High Electron Mobility Transistors
HVPE	hydride vapor phase epitaxy
HTCVD	high-temperature CVD
InAlN	indium aluminum nitride
SiC	silicon carbide
RF	radio frequency
LEDs	light-emitting diodes
MBE	molecular beam epitaxy
REBULF	reduced bulk field
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MESFET	MEtal-Semiconductor Field Effect Transistor
ZnO	zinc oxide
FBL	barrier layer
2DEG	Two Dimensional Electron Gas
InGaN	Indium Galuim nitride
PPE	piezoelectric polarization
PSP	spontaneous polarization
PVT	physical vapor transport
BV	Breakdown voltage
Vg	Voltage gate

Abstract :

semiconductors ' devices which are based on silicon have always been the best choice for communication purposes due to their decent physical properties but all of a sudden all this changed and wide gap semiconductors came into place to take over the market after showing better physical properties and features compared to silicon based devices which led them to quickly take the lead and become the most suitable for the future of communication.

AlGaN/GaN hemts are now the best candidate for future high frequency, high temperature electronics applications thanks to its physical properties (high critical field) which raised them to the fame and one of the most interesting features that they posses is its high mobility as well as the two dimensional electron gas

Understanding basic properties of these devices and the various factors that play a large role in the formation of 2DEG is crucial here .

In our thesis we introduce AlGaN /GaN transistor and study all possible parameters that can play a large role in improving its performance by varying gate length, spacer layer and barrier layer thickness in an attempt to examine their effects on the device's performance.

Key words : Substrates , AlGaN/GaN , HEMT, transistors , GaN , Sic , voltage

ملخص

لطالما كانت أجهزة أشباه الموصلات التي تعتمد على السيليكون هي الخيار الأفضل لأغراض الاتصال نظرًا لخصائصها الفيزيائية اللائقة ، ولكن فجأة كل هذا تغير وظهرت أشباه الموصلات ذات الفجوة الواسعة للسيطرة على السوق بعد إظهار خصائص وميزات فيزيائية أفضل مقارنة بالأجهزة القائمة على السيليكون ، مما أدى بهم إلى أخذ زمام المبادرة بسرعة وأن يصبحوا الأكثر ملاءمة لمستقبل الاتصالات.

تعد المقاحل عالية الحركة الإلكترونية المينيوم نتريد الغاليوم /نتريد الغاليوم الآن أفضل مرشح لتطبيقات الإلكترونيات عالية التردد ودرجات الحرارة المرتفعة في المستقبل بفضل خصائصها الفيزيائية (المجال الحرج العالي) التي رفعتها إلى الشهرة وإحدى الميزات الأكثر إثارة للاهتمام التي تمتلكها هي تنقل عالي بالإضافة إلى غاز الإلكترون ثنائي الأبعاد

يعد فهم الخصائص الأساسية لهذه الأجهزة والعوامل المختلفة التي تلعب دورًا كبيرًا في تكوين غاز إلكترون ثنائي الأبعاد أمرًا بالغ الأهمية هنا.

في عملنا نقدم مقحل الومينيوم غاليوم النتريد/ غاليوم النتريد وندرس جميع المعلمات الممكنة التي يمكن أن تلعب دورًا كبيرًا في تحسين أدائها من خلال تغيير طول البوابة وطبقة المباعد وسماكة طبقة الحاجز في محاولة لفحص تأثيرها على أداء الجهاز.

الكلمات المفتاحية : ركائز ، الومينوم غاليوم النتريد/غاليوم النتريد ، المقاحل عالية الحركة الالكترونية ، المقاحل ، نتريد الغاليوم ، كربيد السيليكون ، الجهد

Résumé :

les dispositifs à semi-conducteurs basés sur le silicium ont toujours été le meilleur choix à des fins de communication en raison de leurs propriétés physiques décentes, mais tout d'un coup, tout cela a changé et les semi-conducteurs à large écart sont apparus pour conquérir le marché après avoir montré de meilleures propriétés et caractéristiques physiques par rapport aux appareils à base de silicium qui les ont conduits à prendre rapidement les devants et à devenir les plus adaptés au futur de la communication.

Les ourlets AlGaN/GaN sont désormais le meilleur candidat pour les futures applications électroniques haute fréquence et haute température grâce à ses propriétés physiques (champ critique élevé) qui les ont élevés à la renommée et l'une des caractéristiques les plus intéressantes qu'ils possèdent est sa grande mobilité ainsi que le gaz d'électrons bidimensionnel.

Comprendre les propriétés de base de ces dispositifs et les différents facteurs qui jouent un rôle important dans la formation de 2DEG est crucial ici.

Dans notre thèse, nous introduisons le transistor AlGaN/GaN et étudions tous les paramètres possibles qui peuvent jouer un rôle important dans l'amélioration de ses performances en faisant varier la longueur de grille, la couche d'espacement et l'épaisseur de la couche barrière dans le but d'examiner leurs effets sur les performances du dispositif.

Mots clés : substrats, AlGaN/GaN, HEMT, transistors, nitrure de gallium, carbure de silicium, potentiomètre.

General Introduction

General Introduction :

all the great developpment that today's world has achieved so far in televisions, microwaves, lighting sources and smartphones is only the result of technological processes related to microelectronics such as transistors which were made up of silicon in the past and the main focus was always on achieving a decrease in both size and weight of the devices but these specifications are no longer that important for the device's quality and the improvement of reliability which led to the abandonment of silicon and search for another alternative semiconductor such as gallium nitride which was crowned as the best alternative for its impressive features and properties in our thesis , we investigate the characteristics and physical properties of GaN in comparison to its predecessors such as silicon as we finish off by digging deeper in our investigations to study the impact of varying doping concentrations and thicknesses of the various AlGaN/GaN hemt layers on the overall transistor's performance in an attempt to determine the proper parameters that best fit together to produce the highest performance possible for a GaN based transistor , the simulation process is carried out using the well known simulation software " silvaco atlas " and the great bunch of tools it offers in order to get the most accurate results possible, lastly we discuss and interpret the results obtained.

Chapter I:

gallium-nitride technology

Chapter I : gallium-nitride technology.

I.1 Introduction

Nowadays, one of the most important societal challenges is represented by the steady increase of the energy consumption in the world. In fact, the energy consumption is expected to increase by about 40% worldwide in the next 20 years , when the electricity will cover the largest fraction (up to 60%) of the used energy. In this context, power electronics is the technology devoted to the control and management of electric power. In fact, power electronics systems are used to provide the optimal characteristics of electric power (i.e., current, voltage, frequency, etc.) for any targeted application . [1]
For more than five decades, silicon (Si) has been the dominant semiconductor for power electronics devices. However, today the continuous demand for higher current, voltage and power density capability, as well as the need of a better energy efficiency to reduce the global energy consumption, are the driving forces to introduce new semiconductor technologies in power electronics and to overcome the inherent limitations of Si-based devices . [1]

You have no doubt heard “reduce, reuse, and recycle,” and over the past few decades, significant progress has been made in the recovery of electronics “end-of-life” products. While many of the metals used in electronic products have now achieved significant levels of recycling, such is not the case for minor metals like gallium. [2]

The material has the ability to conduct electrons more than 1,000 times more efficiently than silicon. It outstrips silicon in speed, temperature, power handling and is expected to replace it when silicon-based devices will reach their limits. [3]

Gallium nitride (GaN) is a very hard, mechanically stable wide bandgap semiconductor. With higher breakdown strength, faster switching speed, higher thermal conductivity and lower on-resistance, power devices based on GaN significantly outperform silicon-based devices . [4]
Gallium nitride has become a staple throughout the power electronics world, despite its emergence in the past few decades, So what is the history of gallium nitride?

Chapter I : gallium-nitride technology.

I.1 Brief History of GaN Technology

Gallium nitride was studied in the 1970s and then abandoned due to synthesis difficulties. In the 1990s, under the impetus of Japanese groups, notably S. Nakamura of the Nichia Company, enormous progress was made in the synthesis of gallium and indium nitrides. Rapid progress has spurred an extraordinary worldwide effort on this topic and brought these materials to the rank of among III-V semiconductors, indium nitride (InN). [5]

HEMT (High Electron Mobility Transistor) gallium nitride (GaN) transistors first started appearing in about 2004 with depletion-mode RF transistors made by Eudyna Corporation in Japan. Using GaN on silicon carbide (SiC) substrates, Eudyna successfully brought transistors into production designed for the RF market .[6]

The HEMT structure was based on the phenomenon first described in 1975 by T. Mimura et al. and in 1994 by M. A. Khan et al, which demonstrated unusually high electron mobility described as a two-dimensional electron gas (2DEG) near the interface between an AlGaN and GaN heterostructure interface . [6]

Adapting this phenomenon to gallium nitride grown on silicon carbide, Eudyna was able to produce benchmark power gain in the multi-gigahertz frequency range. In 2005, Nitronex Corporation introduced the first depletion mode radio frequency (RF) HEMT transistor made with GaN grown on silicon wafers using their SIGANTIC technology.

GaN RF transistors have continued to make inroads in RF applications as several other companies have entered in the market. Acceptance outside this market, however, has been limited by device cost as well as the inconvenience of depletion-mode operation.

In June 2009 Efficient Power Conversion Corporation (EPC) introduced the first enhancementmode gallium nitride on silicon (eGaN) field effect transistor (FET) designed specifically as power MOSFET replacements. These products were to be produced in high-volume at low cost using standard silicon manufacturing technology and facilities. The basic requirements for power semiconductors are efficiency, reliability, controllability, and cost effectiveness. Without these attributes, a new device structure would have no chance of economic viability. There have been many new structures and materials considered as a successor to silicon. [6]

I.2 Basic properties of GaN

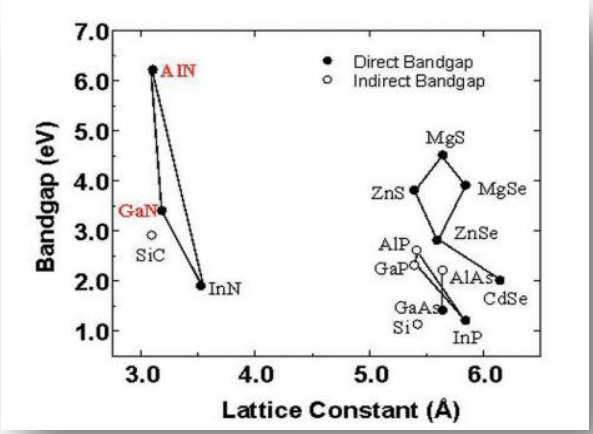
The characterization of a material as being wide bandgap pertains to the energy required for an electron to jump from the top of the valence band to the bottom of the conduction band within the semiconductor. Materials which require energies typically larger than one or two electronvolts (eV) are referred to as wide bandgap materials. SiC and GaN semiconductors are also commonly referred to as compound semiconductors because they are composed of multiple elements from the periodic table, The table below compares material properties for Silicon (Si), Silicon Carbide (SiC-4H1) and Gallium Nitride (GaN). These material properties have a major influence on the fundamental performance characteristics of the devices. Both SiC and GaN have material properties superior to Si for RF and Switching Power devices. [7]

The high critical field of both GaN and SiC compared to Si is a property which allows these devices to operate at higher voltages and lower leakage currents. Higher electron mobility and electron saturation velocity allow for higher frequency of operation. While SiC has higher electron mobility than Si, GaN's electron mobility is higher than SiC meaning that GaN should ultimately be the best device for very high. frequencies. Higher thermal conductivity means that the material is superior in conducting heat more efficiently. SiC has higher thermal conductivity than GaN or Si meaning that SiC devices can theoretically operate at higher power densities than either GaN or Si. Higher thermal conductivity combined with wide bandgap and high critical field give SiC semiconductors an advantage when high power is a key desirable device feature The relatively poor thermal conductivity of GaN makes heat management for GaN devices a challenge for system designers to contend with .[7]

TableI.1 physical properties of selected semiconductors [8]

	Si	GaAs	GaN	AlN	6H-SiC
Bandgap (eV) at 300°C	1.1 indirect	1.4 direct	3.4 direct	6.2 direct	2.9 indirect
Electron mobility ($cm^2/V{\cdot}s$) at RT	1400	8500	1000 (bulk) 2000 (2D-gas)	135	600
Hole mobility ($cm^2/V{\cdot}s$), RT	600	400	30	14	40
Saturation velocity (10^7 cm/s)	1	2	2.5	1.4	2
Breakdown field (10^6 V/cm)	0.3	0.4	> 5		4
Thermal conductivity (W/cm)	1.5	0.5	1.5	2	5
Melting temperature (K)	1690	1510	> 1700	3000	> 2100

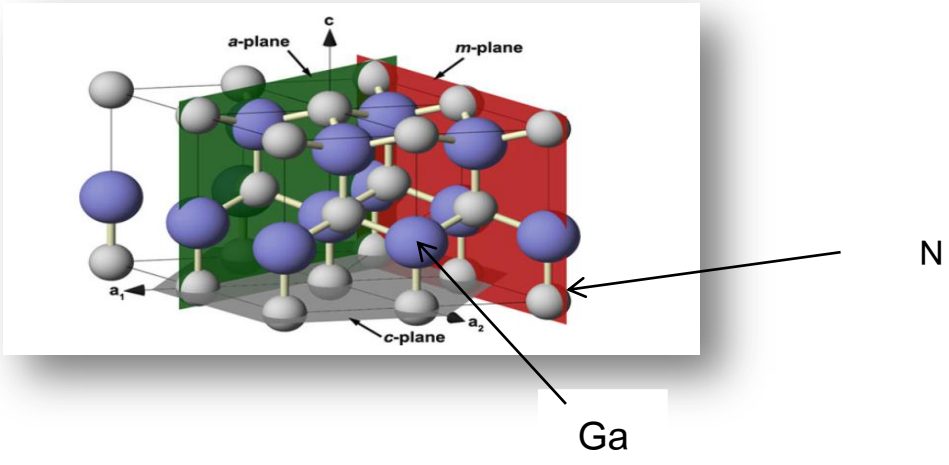
TableI.1 compares the physical properties of GaN and AlN with other well-known semiconductors. The nitrides are wellsuited to high temperature applications because of their wide bandgaps and low intrinsic carrier concentrations, The electron mobility in GaN is quite high considering the
magnitude of the bandgap and is even higher in selectively doped AlGaN/GaN heterostructures where two-dimensional electron gases may form, producing high sheet carrier densities3, These densities are enhanced by the strong piezoelectric and polarization effects present in the AlGaN/GaN structures. These properties make the nitrides well-suited to high-frequency applications. Finally, GaN possesses a very high breakdown field, allowing devices to support large voltages for high power operation. [8] .
SiC is also well-suited to these applications and has been developed for electronics over a much longer period than GaN. However, as shown in FigureI.1, GaN still has greater potential for these applications because of its larger bandgap and higher carrier velocity and mobility.
The top part of FigureI.1 shows theoretical and experimental data for the critical breakdown field of various semiconductors as a function of their bandgaps. While diamond supports the largest field



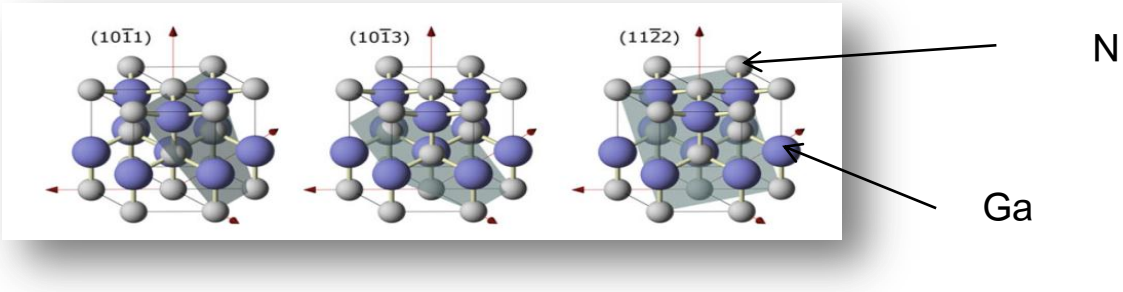
FigureI.1 Bandgap versus lattice constant for the nitrides and other technologically important semiconductors. [8]

I.2.1 Crystal structure :

Gallium nitride is a wide bandgap semiconductor that is most stable in the wurtzite structure, depicted in FigureI.2 . This structure is described by a hexagonal coordinate system having three equivalent basal plane lattice vectors, a1; a2, and a3, and a unique c translation vector. In three-index notation (a1; a2, c), gallium atoms are located at (0, 0, 0) and (1/3, 2/3, 1/2), while the nitrogen atoms sit on an equivalent sublattice at (0, 0, u) and (2/3, 1/3, 1=2Cu), where u D 0:377. Referring to FigureI.2, low-index planes in the wurtzite structure include f1120 N g a-planes, f1010 N g mplanes, as well as the .0001/ C c plane (also referred to the as the "Gaface") and the .0001/ N c plane (also referred to as the "N-face"). Other low-index planes include the so-called semipolar planes, such as f1011 N g; f1122 N g, and f1013 N g, which are inclined with respect to both the nonpolar planes and the c-plane, as shown in FigureII.2 . The potential utility of semipolar planes is discussed below,Unfortunately, attempts over 30 years of GaN epitaxy research repeatedly suggested that nonpolar and semipolar planes were "unstable" compared to the conventionally grown c-plane. One study after another yielded nonpolar films with surfaces too rough and/or faceted for device growth. In 2000, Waltereit et al. first demonstrated planar m-plane GaN growth via molecular beam epitaxy (MBE), This demonstration was followed by Craven et al.'s metal organic chemical vapor deposition (MOCVD) growth of planar a-plane GaN films in 2002. [9]



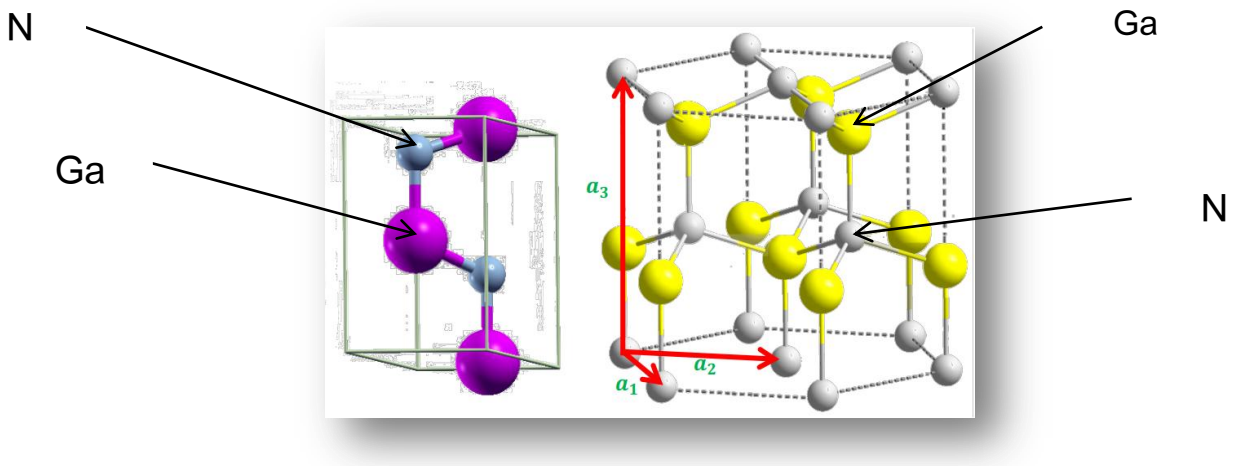
FigureI.2.a Scale representation of the GaN crystal structure in hexagonal coordinates. Ga atoms are shaded grey, with N atoms shaded blue [9]



FigureI.2.b Example schematics of low-index semi-polar GaN crystal planes [9]

While considerable progress was subsequently made in thin-film growth of nonpolar GaN, thick-film or bulk growth of nonpolar (and later, semipolar) orientations continued to be elusive until recently. The performance of the nonpolar GaN-based devices would therefore be limited by the lack of low-defect-density film and substrate options. This paragraph describes the progress achieved in thick-film nonpolar and semipolar GaN growth via hydride vapor phase epitaxy (HVPE), toward the ultimate goal of producing low-defect-density nonpolar and semipolar GaN thick films and substrates. As a well-established vapor-phase growth While considerable progress was subsequently made in thin-film growth of nonpolar GaN, thick-film or bulk growth of nonpolar (and later, semipolar) orientations continued to be elusive until recently. The performance of the nonpolar GaN-based devices would therefore be limited by the lack of low-defect-density film and substrate options.

The progress achieved in thick-film nonpolar and semipolar GaN growth via hydride vapor phase epitaxy (HVPE), toward the ultimate goal of producing low-defect-density nonpolar and semipolar GaN thick films and substrates. As a well-established vapor-phase growth technique, GaN HVPE currently offers the most attractive combination of low cost, high growth rate, and scalability for commercial production of GaN films and substrates. [9]



FigureI.3 Primitive unit cell and hexagonal conventional unit cell of GaN [10]

Lattice constant :

- a = 3,186 A˚
- c = 5,186 A˚

Unit lattice vector :

- a_1 = a(1,0,0)
- a_2 =a($\frac{1}{2}$, $\frac{\sqrt{3}}{2}$,0)
- a_3 = c(0,0,1)

The reciprocal lattice of a Wurtzite crystal is also a hexagonal lattice, with:

Reciprocal lattice unit vector:

$$b_1 = \frac{2\pi}{a}\left(1, \frac{1}{\sqrt{3}}, 0\right)$$

$$b_2 = \frac{2\pi}{a}\ (0, \frac{2}{\sqrt{3}}, 0)$$

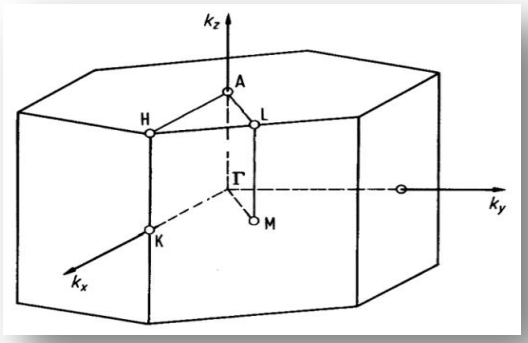
$$b_3 = \frac{2\pi}{c}\ (0,0,1)$$

High symmetry point:

Γ=(0,0,0) k= $(\frac{4\pi}{3a}, 0,0)$

H=$(\frac{4\pi}{3a}, 0, \frac{\pi}{c})$ L=$(\frac{4\pi}{3a}, 0, \frac{\pi}{c})$

A=$(0,0, \frac{\pi}{c})$ M=$(\frac{\pi}{a}, \frac{\pi}{\sqrt{3}}, 0)$



FigureI.4 The reciprocal lattice of a Wurtzite crystal with labeled high symmetry point.[10]

I.2.2 Electronic band structure :

Method: Empirical Pseudopotential Method (EPM)

Due to the periodicity of the lattice, the Schrodinger Equation is expressed in an algebra matrix equation:

$$\left[\frac{\hbar^2(\vec{k}+\vec{G})^2}{2m}\right]U(\vec{G}) + \sum_{\vec{G}'} V(\vec{G}-\vec{G}')U(\vec{G}') = E \cdot U(\vec{G})$$

Where:

E is the allowed electron energy states

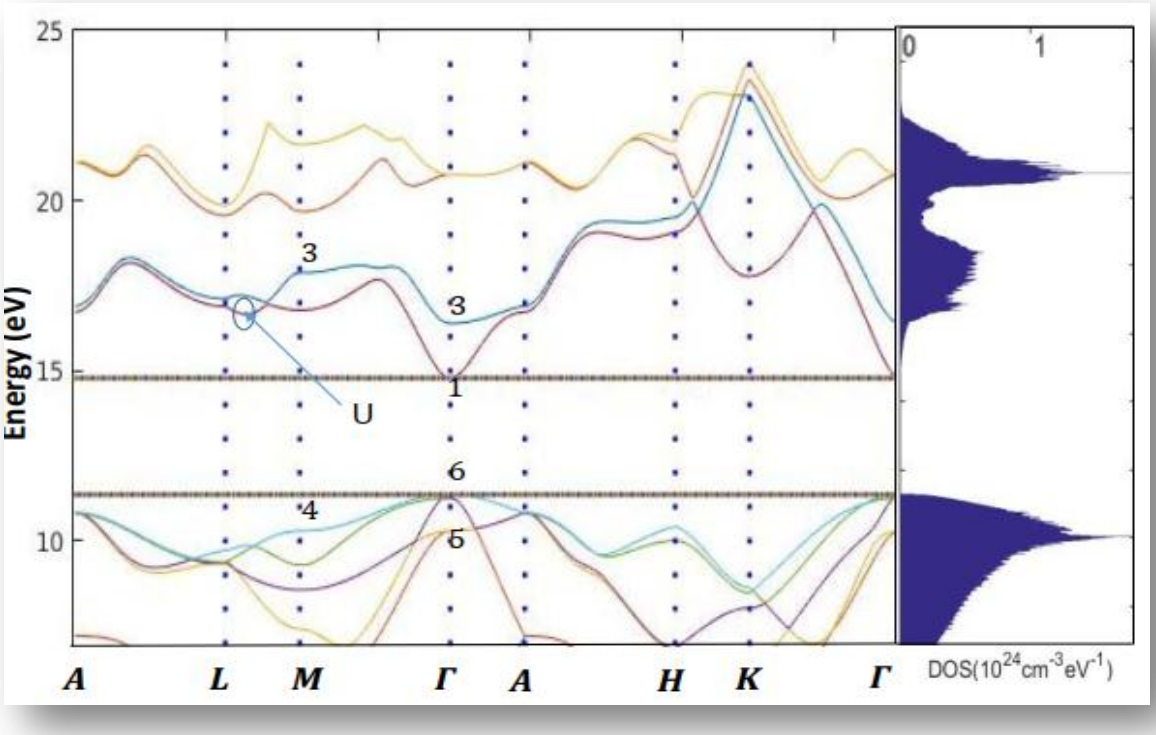
$\vec{G}$ is the reciprocal lattice vectors

$U\ (\vec{G})$is the Fourier transformation constant for Bloch functions

$V\ (\vec{G})$is the Fourier transformation constant for V(r)

$$V(\vec{G}) = \frac{1}{\Omega}\int_{\Omega} d\vec{r} \cdot V(\vec{r}) \cdot e^{-i\vec{G}\cdot\vec{r}}$$

V(r) is the periodic lattice atomic potential Band Structure for Mobility and Transport Properties including Velocity Overshoot. [10]



FigureI.5 Calculated band structures and Density of States using EPM [10]

I.3 Application Areas of GaN

GaN-based visible light-emitting diodes and laser diodes are already commercialized for a variety of lighting and data storage applications. This materials system is also showing promise for microwave and high power electronics intended for radar, satellite, wireless base stations, and utility grid applications; for biological detection systems; and for a new class of spin-transport electronics (spintronics) in which the spin of charge carriers is exploited. [8]

The explosive increase of interest in the AlGaInN family of materials in recent years has been fueled by the application of blue/green/UV light-emitting diodes (LEDs) in full-color displays, traffic lights, automotive lighting, and general room lighting (using so-called white LEDs) In addition, blue/green laser diodes can be used in high storage-capacity digital versatile disk (DVD) systems.

AlGaN-based photodetectors are also useful for solar-blind UV detection and have applications as flame sensors for control of gas turbines or detection of missiles . [8]

I.3.1 GaN Material System :

Most commonly used semiconductor materials are crystalline inorganic solids. These materials are classified according to the periodic table groups of their constituent atoms . [11]

For the current application of devices, monocrystalline GaN material is generally prepared on a heterogeneous substrate (e.g., sapphire, silicon carbide, and silicon) through MOCVD method . Due to the lattice mismatch and thermal expansion coefficient mismatch, GaN grown epitaxially on these heterogeneous substrates generally have a high defect density (10^8–10^{10} cm^{-2}), which would, to some degree, reduce the device performance and cause the poor heat dissipation. [12]

To date, the most promising direct-gap candidate materials for high-power, high-frequency device applications are the binary compounds and ternary alloys of the III-nitride materials system ,Their attractive intrinsic properties include high saturated electron drift velocity, small dielectric constant, and wide-band-gap energy which, besides obvious advantages in optoelectronics applications, enables higher

junction operating temperatures and implies breakdown electric-field strengths several times larger than in either silicon or GaAs. Two additional features further enhance the high-power electronics potential of the III nitrides over other wide-gap semiconductors, such as the various polytypes of SiC. First, GaN can form type-I heterojunctions with the ternary alloys AlGaN and InGaN, enabling the use of modulation doping techniques and the realization of modulationdoped field-effect transistors (MODFETs). In addition, the lattice mismatch between GaN and AIN can be exploited to alter the carrier concentration near the heterointerface through the action of the piezoelectric effect. Strain-induced polarization can increase the free-carrier concentration in the channel region of a heterojunction FET well beyond the den sity achievable by modulation doping alone, providing an additional degree of freedom by which device behavior may be engineered. [13]

In this context, it becomes very important to have access to all the information about the band structure details and transport parameters necessary for device design and optimization. Because of the relative technological immaturity of the III-nitride materials system, theoretical calculation of these properties is an important aid, and it becomes essential for the ternary alloys . [13]

I.4 Gallium Nitride Power Semiconductors Market :

The production of power devices includes the costs of substrate, epitaxy, device fabrication, packaging, support electronics and development.

The viable economic based limit of about $ 3 / cm^2 for substrate and epitaxy cost set by the power device marketplace is exceeded by all substrate choices except silicon wafers. Multi-wafer MOCVD tools provide the required throughput and cost of ownership, Next to the cost of substrate and epitaxial layers, device fabrication costs are the most critical. In fact, currently, substrate diameters of at least 150 mm are required to achieve widespread commercial viability for power device fabrication. It has been typical in compound semiconductor device fabrication to use specialized processes such as e-beam and lift-off lithography, as well as to utilize gold metallization. These techniques are understandable for military and RF applications, where markets will support costs of more than $ 10,000 for finished 100 mm wafers for discrete devices. The broad power device market will not support this order of magnitude

fabrication costs. In fact, to gain broad adoption of alternative material based power devices, fabrication costs must approach that of silicon based power devices. In fact, the device fabrication costs are only acceptable if high volume, high yielding standard (silicon compatible) semiconductor fabrication lines are used. Similarly, the volume necessary to support the broad power device market (10 million 150 mm wafer equivalents per year) requires scalability in device manufacture provided most readily by existing silicon device. [15]

In 2021, the global gallium nitride semiconductor devices market was valued at $12,084.6 million, which is likely to reach $72,813.1 million by 2030, growing at a CAGR of 22.1% from 2021 to 2030, according to P&S Intelligence. In 2021, the highest-revenue-generating category was opto-semiconductors, due to the numerous applications of these variants, mainly in consumer electronics and aerospace & defense sectors. Moreover, gallium nitride (GaN) is a mechanically stable wide-bandgap semiconductor with a faster switching speed, higher breakdown strength, and higher thermal conductivity . [14]

Many factors lead to the gallium nitride semiconductor devices market growth, for instance, the rising focus of internet service providers on incorporating high-capacity and low-latency networks using optical cables. As a result, the demand for energy-efficient GaN components and power semiconductors in wired communications will rise . [14]

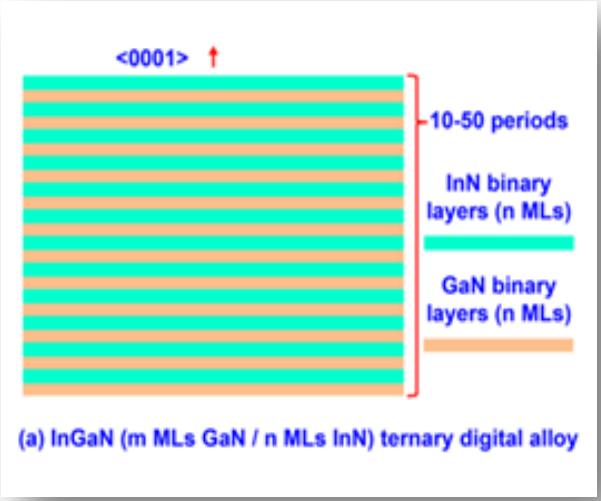
I.5 The III-nitride alloys :

III-nitride materials possess a number of properties that are simply not accessible in any other semiconductors, which will continue to make them an active area of scientific and technological development. The unique capabilities of the III-nitrides include a high dielectric breakdown voltage and a bandgap that spans from the infrared to the deep ultraviolet.

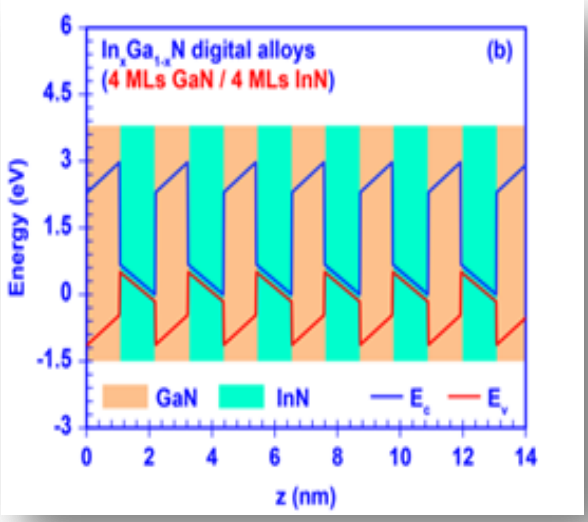
However, there are some unique processing challenges related to the crystal structure and bonding. They have long been of interest for implementation in applications ranging from high-power transistors to a solid-state replacement for traditional lighting. [16]

In specific, changing the Indium composition in InGaN ternary alloy from very low In-content to InN alloy allows large bandgap tunability from ~3.4 eV (GaN) to ~0.64 eV (InN), which yields excellent compatibility for various optoelectronic applications. [17]

Particularly, the InGaN ternary alloy with high In-content has been recognized for its importance in achieving optical emitting and absorbing devices in longer wavelength covering red color regime and beyond. However, the experimental realization of such material system has been limited by the challenges in growing high In-content InGaN ternary alloy. Specifically, the conventional epitaxy of InGaN alloy with high In-composition results in a phase separated material system, which leads to detrimental issues on the electronics and optoelectronics properties of this alloy. The phase separation issue in InGaN alloy system is attributed to the present epitaxial growth conditions in the state-of-the-art epitaxy tools, metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE).



FigureI.6 (a) Schematic illustration of InGaN digital alloy formed by m MLs GaN and n MLs InN ultra-thin binary layers.[17]



FigureI.6 (b) Band diagram of InGaN digital alloy formed by 4 MLs GaN and 4 MLs InN binary layers.[17]

I.6 $Al_xGa_{1-x}N$/GaN heterostructure :

AlGaN/GaN heterostructures have attracted much attention in recent years because of their potential for high temperature, high-power devices as well as for optoelectronic devices. [19]

The $Al_xGa_{1-x}N$/GaN heterostructure (HS) is prepared by metalorganic vapor phase epitaxy (MOVPE) at atmospheric pressure on sapphire substrate. The surface morphology of the $Al_xGa_{1-x}N$/GaN HS is investigated. When the $Al_xGa_{1-x}N$ layer is thinner than a certain thickness (hc), the surface is smooth and has no cracks. While when the layer is thicker thanhc, many cracks and V-shaped grooves appear in the $Al_xGa_{1-x}N$ and GaN layers, and their densities increase with increasingx. For the preparation of the $Al_xGa_{1-x}N$/GaN HS with a smooth surface free from cracks, it is important to control the thickness and the composition of the $Al_xGa_{1-x}N$ layer . [18]

GaN-based high electron mobility transistor (HEMT) has enormous potential to replace its counterparts such as Si and GaAs based transistors for high speed, high power, and high temperature applications. Currently, $Al_xGa_{1-x}N$/GaN heterostructures are usually grown on silicon (Si) and silicon carbide (SiC) substrates for power electronic applications. Although the quality of GaN grown on Si is not yet as good as that on SiC, epitaxy scale up on 200 mm diameter Si would eventually reduce the cost of GaN HEMT processing. Furthermore, with Au-free contacts, $Al_xGa_{1-x}N$/GaN HEMT on Si can be processed in existing Si foundries, hence, further reducing the cost of such high power transistors. Due to these benefits, $Al_xGa_{1-x}N$/GaN HEMT on Si has drawn much attention in recent years and the performance of such HEMTs has been improving. Medjoub et. al.1 have demonstrated 100 nm gate GaN HEMT on 100 mm Si with a output power density of 2.5 W/mm at 40 GHz. Hahn et. al.2 have reported the enhancement mode 1.0 μm gate $Al_xGa_{1-x}N$/GaN HEMT on 150 mm Si with the extrinsic transconductance of 366 mS/mm using a recessed gate process. In order to make GaN HEMTs more economical in an industrial foundry, researchers have been trying to grow $Al_xGa_{1-x}N$/GaN on 200 mm

diameter Si substrates. Although there are still challenges such as the wafer bowing induced electrical inhomogeneities, and the presence of a high density of point and line defects to be addressed for HEMT structures on 200 mm Si, a few groups have recently reported on the realization of $Al_xGa_{1-x}N$/GaN heterostructures on Si(111) using Aubased contacts or Au-free contacts.3^{-9} However, the gate leakage of

Schottky HEMT is still a problem for high power and high temperature applications. For instance, Ni/Au gate contact suffers from high gate leakage when annealed above 600◦C[10,11] Therefore, researchers are currently using metal-insulator-semiconductor type HEMT or O2 plasma surface treated gate to lower the leakage current. However, these steps often reduce the transconductance (gm) due to the reduction in the gate capacitance. [20]

Summary

In this chapter, we gave a general idea about semiconductor materials, talked about the technology of gallium nitride as well as the general properties of III-V compounds , As we have clarified some concepts about the types of polarization,

In the next chapter we will clearly introduce HEMT transistors and how GaN and AlN substrates work, and how to breakdown

Chapter II:

AlGaN /GaN High Electron Mobility Transistors (HEMTs)

Chapter II: AlGaN /GaN High Electron Mobility Transistors (HEMTs)

II.1 Introduction

Thanks to the recent advancements in the growth and fabrication processes, the performance of high electron mobility transistors (HEMTs) based on GaN has significantly improved. The main advantages of using GaN as a material for the realization of HEMTs are the high sheet charge density (>10^{13} cm^{-2}) of the two-dimensional electron gas (2DEG), which results in a low on-resistance of the transistors; the high thermal conductivity of GaN (>2 W cm^{-1} K^{-1}), which permits to reach high levels of power dissipation while keeping the channel temperature low; the high breakdown field (3.3 MV/cm)), which allows to fabricate devices with breakdown voltages in the order of hundreds or thousands of volts, depending on gate–drain spacing and on buffer thickness.

These unique features make GaN an almost perfect material for the manufacturing of high power transistors: thanks to the recent efforts of the scientific and industrial communities, GaN-based transistors with breakdown voltages in excess of 1.5–1.9 kV have been recently demonstrated,) thus clearing the way for the adoption of HEMTs in power electronics. Moreover, thanks to the low (on-resistance) × (device capacitance) product, GaN-based power HEMTs can reach high switching frequencies (>40 MH)), and can therefore be used for the fabrication of high efficiency power conversion system. [21]

Power electronic systems demand high blocking voltage in OFF-state and high current in ON-state for efficient switching performance. Specific transistors called HEMTs made of aluminium gallium nitride/gallium nitride (AlGaN/GaN) provides an edge over silicon-based transistors as they allow the systems to operate at very high voltages, switch ON and OFF faster, and occupy less space . [22]

In addition to the very high frequency performance. [23] , Commercially available AlGaN/GaN HEMTs use techniques to keep the transistor in normally OFF state, which affects the stability .[22]

II.2 High Electron Mobility Transistors (HEMTs)

The HEMT or High Electron Mobility Transistor is a type of field effect transistor (FET), that is used to offer a combination of low noise figure and very high levels of performance at microwave frequencies. This is an important device for high speed, high frequency, digital circuits and microwave circuits with low noise applications. These applications include computing,

telecommunications, and instrumentation. And the device is also used in RF design, where high performance is required at very high RF frequencies. [24]

AlGaN/GaN HEMTs devices also have been used as switching devices, These devices have a high breakdown field, high voltage , and high electron velocity, The high electric field and high electron velocity of the AlGaN/GaN HEMTs devices allows the fabrication of low ON resistance, high breakdown voltage, and high switching frequency. On the other hand, the AlGaN/GaN heterostructures HEMTs based devices have a great performance comparing with typical HEMTs devices. Moreover, most of the AlGaN/GaN HEMTs are depletion type.

The AlGaN/GaN HEMTs have been the driving tool for many research investigations in the recent years. The AlGaN/GaN HEMTs are very promising devices for high frequency, voltage, power, and temperature applications. [25]

This is due to the excellent material's properties of GaN. These properties include the wide band gap energy of 3.4 eV, the high electron mobility of 2000 cm^2/Vs, the thermal conductivity of 160 W/Km, and the high breakdown field of 3.3 MV/cm . The GaN properties plays an important role in improving the saturated drain current and the DC transconductance of these devices. The AlGaN/GaN based HEMTs are also attractive for microwave wave applications leading to a high power density performance, as well as the electron saturation velocity. These devices have other applications including the cellular handset, high broadband. [25]

They are considered the best candidates for wireless communication system applications. On the other hand, The AlGaN/GaN HEMTs have becoming a very attractive some advanced application. These applications include the satellite communications, weather forecasting, and military systems . The AlGaN/GaN HEMTs have recently used for biosensing based devices. These devices require a high sensitivity for certain applications. Recently, the AlGaN/GaN HEMTs devices are becoming very essential for wireless, radars, and power amplifiers applications. [25]

One of the challenging issues of the AlGaN/GaN HEMTs is the normally ON behavior of the device. Some of the proposed solutions for this issue including using different structures for the device gate. Other solutions include the usage a thin barrier layer of AlGaN and p-type GaN . Furthermore, these devices have an additional challenging issue of a limited gate voltage . The gate voltage is limited to 6 volts. This is due to the device gate contact resistive behavior. Other issues of

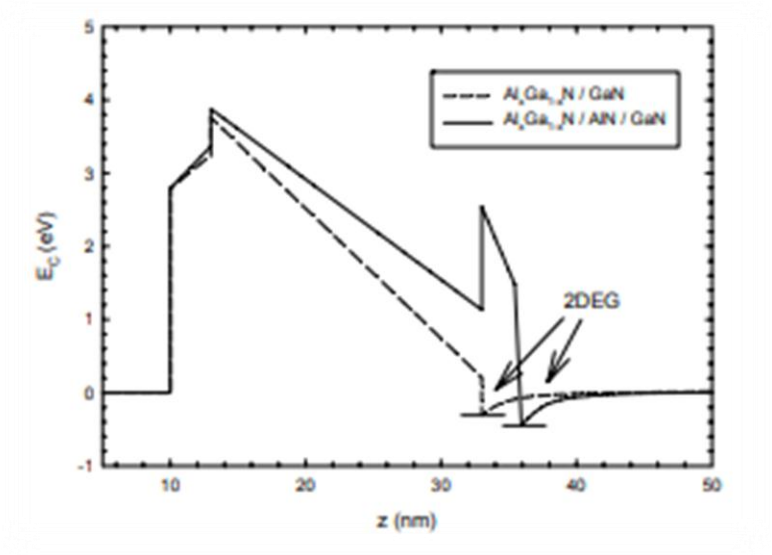
the AlGaN/GaN based HEMT is that the gate contacts required a minimum current to keep the transistor ON. [25]

II.2.1 Background

In recent decades, novel semiconductor materials, such as GaN, metal oxides, and 2D materials, have been widely studied to further enhance the energy conversion and storage efficiency, owing to their superior material and device properties. Among them, GaN-based AlGaN/GaN high electron mobility transistors (HEMTs) are good candidates for high power, high frequency, and low loss applications because of high critical breakdown field and high electron mobility ,The breakdown voltage (BV) is one of the most important design targets, and the reported values are still far below the theoretical limit ,Therefore, it is of great importance to further improve the BV, especially not at the cost of increasing the device size. Several termination techniques have been proposed to improve the BV, such as field plate ,fluorine ion implantation , and recessed gate-edge termination , Fluorine ions implanted in the thin AlGaN barrier layer (FBL) has a simple fabrication process without inducing an additional parasitic capacitance; however, the peak position of the fluorine profile and vacancy distributions is near to the two-dimensional electron gas (2DEG) channel, which would inevitably cause significant static and dynamic characteristic degradation. [26]

II.2.2 $Al_xGa_{1-x}N$/GaN HEMTs structure

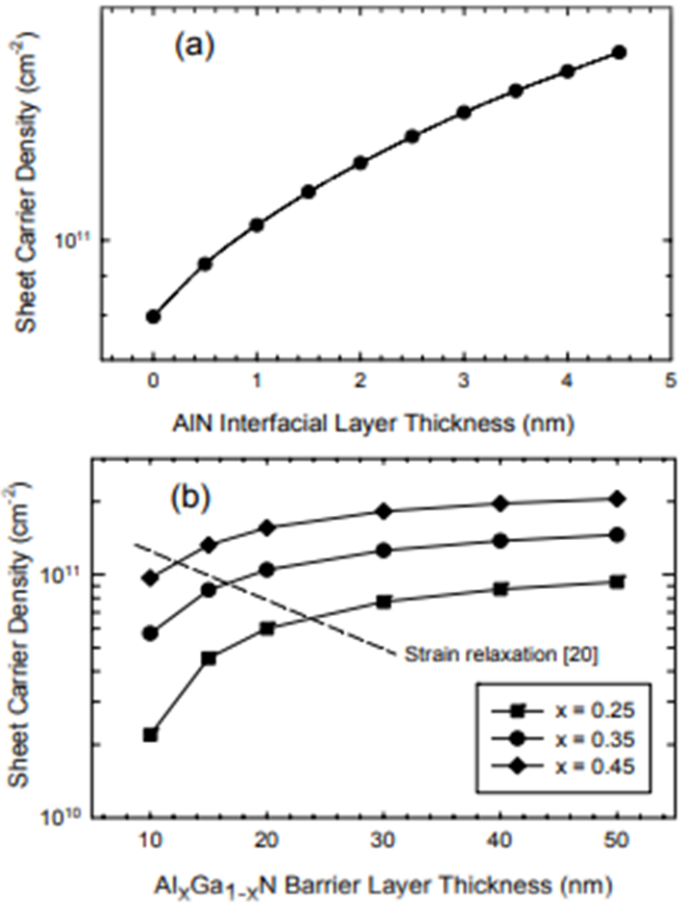
Conduction band structures of $Al_xGa_{1-x}N$/GaN HEMT structures with and without AlN interlayer are shown in Figure.1 Both simulated structures have a 3 nm GaN cap layer which provides enhancement of the effective Schottky barrier and provides smaller gate leakages and causes reduction in sheet carrier density in the channel . GaN cap layer is thin to form 2DEG at the GaN/$Al_xGa_{1-x}N$ interface. The addition of the AlN interlayer increases the conduction band offset ΔEc in the $Al_xGa_{1-x}N$ barrier layer. Thicknesses of the simulated AlN interlayers are in the limit of the strain relaxation mechanism ,The 2DEG formation at the AlN/GaN interface is deeper than the $Al_xGa_{1-x}N$/GaN interface which will supply better localization of the electrons in the well . [27]



FigureII.1 The band structure of $Al_xGa_{1-x}N$/GaN and of $Al_xGa_{1-x}N$/(AlN)/GaN structures for x = 0.35, Z-axis begins from the surface. [27]

Future investigations of the $Al_xGa_{1-x}N$/(AlN)/GaN HEMT systems depend on the structure designs as well as material quality. To increase 2DEG conductivity and breakdown field, higher Al-mole fraction at barrier layer is required ,However, the growth process of high-Al mole fraction layers on GaN is a problematic due to large lattice parameter mismatch which can cause defects due to strain relaxation , Because the transport properties of the 2DEG of the HEMT structures are limited by the strain relaxation, the number of reports about transport properties of the HEMT structures with a barrier layer having an Al-mole fraction of x > 0.5 is also limited .[27]

Inserting an AlN interlayer between $Al_xGa_{1-x}N$-GaN interface and increasing the mole fraction of the $Al_xGa_{1-x}N$ barrier. in FigureII. 2(a), effect of the AlN interlayer thickness on sheet carrier density is shown for the structure with Al0.35Ga0.65N barrier. Sheet carrier density is increasing with increasing AlN interlayer thickness. Due to large lattice mismatch between GaN and AlN layer, investigation of pseudomorphic growth of AlN layer on GaN above 5 nm is senseless . With increasing interlayer thickness, sheet carrier density approaches to 2 x 10^{11} cm^{-2}. In FigureII. 2(b), Sheet carrier density due to $Al_xGa_{1-x}N$ barrier thickness is shown for x=0.25, 0.35 and 0.45. Sheet carrier density is increasing with increasing $Al_xGa_{1-x}N$ barrier thickness. it is important to investigate the values consistent with AlN thickness. More AL fraction, increases sheet carrier density, but increases alloy disorder scattering, too. To prevent this, thicker AlN is needed, but it is hard to grow thicker AlN on GaN without strain relaxation.[27]



FigureII.2 (a) Sheet carrier density versus AlN interlayer thickness for a structure with a Al0.35Ga0.65N barrier layer. [27]

FigureII.2 (b) Sheet carrier density versus AlxGa1-xN barrier layer thickness for x=0.25, 0.35 and 0.45. Strain relaxation according to Bykhovski. [27]

II.3 Growth techniques and substrates choice .

The choice of substrate for growth of GaN-based HEMT structures aiming for high-power and high-frequency applications primarily depends on two critical parameters .

Thermal conductivity and in-plane lattice structure. A high thermal conductivity of the substrate is very desirable in the HEMT structures to alleviate the self-heating effect of the device, which considerably shortens the device lifetime and limits the device performance, but the merit of the

thermal property cannot be taken without considering the extent of the substrate's lattice mismatch with GaN, Moreover, the substrate used for the HEMT applications has to be semi-insulating (SI) to prevent parallel conductions in the device. Four commonly used substrates in the HEMT. [28]

II.3.1 Silicon Carbide Substrates (SiC)

Semi-insulating silicon carbide is one of the most attractive substrate materials for electronic applications, due to the favorable combination of lattice mismatch, isolation, and thermal conductivity . It is available with increasing quality and diameters up to 4 in. Both polytypes 4H- and 6H–s.i. SiC are used. On the contrary, III-N optoelectronic applications use conductive SiC substrates with similar diameters. Most of the outstanding electronic device results have been reported on semi-insulating SiC materials. [29]

II.3.2 Sapphire Substrates

epitaxial growth are listed in the Table I for comparison.[28]

Table II.1 Common substrates used in GaN-based HEMT epitaxy [28]

Substrate	Saphire	Si	SiC	Bulk GaN
In-plane lattice mismatch with GaN (%)	16	17	3.4	0
Thermal conductivity (W/mm-k)	35	150	490	260

Sapphire substrate is fundamentally not suitable due to its very low thermal conductivity. Its ratio of performance over cost will be no longer attractive since there has been enormous progress made in GaN-on-Si technology. However, GaN-on-Si epitaxy requires transition layers to accommodate the large lattice mismatch between GaN and Si ,This ultimately limits the usefulness of GaN-on-Si technology for high-end power electronics, because the region of the transition layers has a very low thermal conductivity, as a result of the many interfaces, alloy nature and its poor structural quality, all of which greatly impede the heat dissipating from the GaN device down to the substrate .

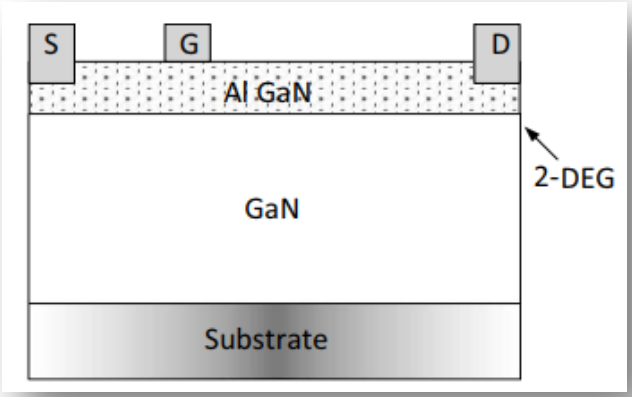
Fortunately, all the issues just mentioned above could easily be resolved with the use of bulk GaN substrates. Besides a better thermal conductivity than Si, GaN substrate enables homoepitaxial growth of GaN-based HEMT structures, which means no interlayer is needed so that one can expect the HEMT structure inherits the superior crystalline quality of the substrate. Despite the advantages of GaN substrates, they still trade off with high price and lack of large wafer size (up to 2″ to date). SiC substrates therefore become a good alternative. [28]

II.3.3 GaN and AlN Substrates

Native GaN and AlN substrates have been only recently developed and used for electronic applications, although they are most important for optoelectronic applications. However, native substrates face increasing attention to the expected improvement in electronic device reliability, For native GaN substrates are only recently available in n-conducting and semi-insulating form with diameters suitable for electronic device fabrication, Free-standing GaN substrates are available based on two growth processes. First of all, GaN templates on sapphire can be used to reduce the defect density for optoelectronic devices. The defect density is 8×10^7 cm^{-2} for this kind of technique for a 10 μm layer grown by MOCVD. This kind of quasibulk approach can be used in a variety of ways, ELO or related approaches. In some approaches, the host substrate such as sapphire is removed leaving free-standing GaN. The second method is the growth of GaN boules, in by HVPE. Si-based n-doping is used for conductive substrates, while Fe doping is used to obtain s.i. substrates. Free-standing GaN substrates based on a similar procedure are provided by Sumitomo, e.g., in . Impressive results of AlGaN/GaN HEMTs on free-standing GaN substrates have been demonstrated.[29]

II.4 HEMTs operation

A conventional Schottky gate GaN HEMT device structure is shown in FigureII.5. The source and drain metals constitute an ohmic contact, and the gate metal constitutes a Schottky contact. With a voltage stress VDS on the drain . [33]



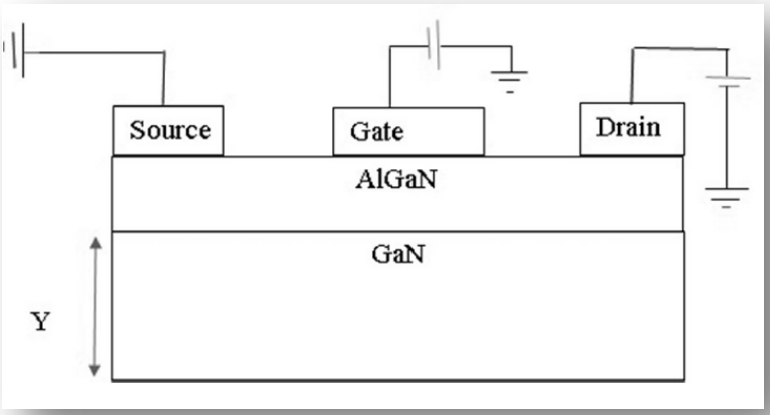
FigureII.3 Schematic diagram of an AlGaN/GaN HEMT. [33]

II.4.1 DC characteristics

AlGaN/GaN High Electron Mobility Transistors (HEMTs) are popular in power amplifier systems and offer advantages over another III-V semiconductor heterostructures, such as a large bandgap energy, a low dielectric constant, and a high critical breakdown field. These qualities make GaN a prime candidate for high-power and radiation hardened applications using a smaller form-factor [30]

DC characteristics of HEMT is very similar to the operation of MESFET. FigureII.8, shows the operation of depletion mode HEMT common source configuration. The gate is reverse biased and used as input to the device. The drain is forward biased, and output is taken at the terminal. The depletion region is formed under the gate due to reverse bias. The rectifying effect of depletion region on the channel will affect the electron transport from the source to drain end. Drain voltage varied and gate voltage is fixed, cause current flow from drain to source. MESFET is behave like a

resistor at low drain voltage. Depletion width at the drain increases with drain voltage and saturates when the channel could accommodate the maximum velocity of the electrons. [30]



FigureII.4 Cross-sectional view of AlGaN/GaN MESFET [30]

II.4.2 Degradation of HEMT performance .

Nowadays, GaN HEMT devices still cannot reach the theoretical brilliant performance due to reliability issues. Firstly, though GaN is a high-temperature-tolerant material, for a Schottky contact device, the semiconductor–metal contact suffers degradation under high temperature. The performance of GaN devices also varies with different temperatures. Secondly, the current collapse effect significantly limits the current performance, which is mainly reflected in the fact that current performance of a GaN HEMT deteriorates after stress or at an AC condition compared to a DC condition. Finally, the prebreakdown phenomenon of a GaN HEMT limits further improvement of the breakdown voltage in a high-power field, which can be attributed to an electric field peak, bulk leakage, and the reverse piezoelectric effect. [33] ,The GaN HEMTs can be categorized into normally-on and normally-off devices. [31], While the OFF-state reliability of AlGaN/GaN HEMTs has been widely studied, there are only a few reports on the ON-state reliability. [32]

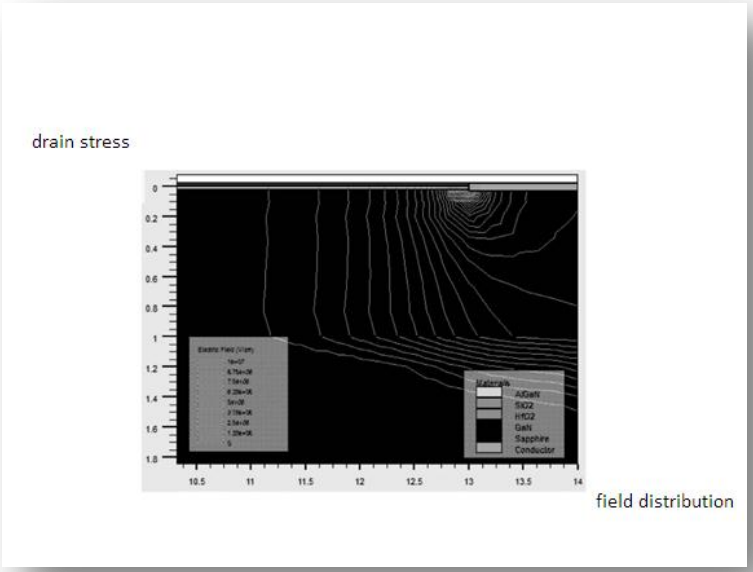
reported that for ON-state degradation of AlGaN/GaN HEMT devices on Sic, pits formed at the GaN cap layer and the gate edges. These pits were associated with the device degradation and their formation was thermally activated. showed that ON-state and OFFstate stressing results in similar

structural degradation and concluded that the same degradation mechanism operated under both stressing conditions . Recently, reported six trap energy levels in the GaN buffer layer of AlGaN/GaN HEMTs on Si stressed under different ON-state conditions. However, there is no report showing the characteristics of physical damage that occur during ON-state degradation of AlGaN/GaN HEMTs on Si. In contrast, OFF-state studies of AIGN/GaN HEMTs on Si show a correlation between threading dislocations (ID) and pit formation, This correlation has not been reported in studies with other substrates. The threading dislocation density is higher for devices grown on Si than on other substrates . Therefore, this correlation may not be as readily observed, or so strong on other substrates. Nevertheless, this correlation may influence the ON-state reliability, especially on Si substrates. [32]

II.4.3 Breakdown mechanisms

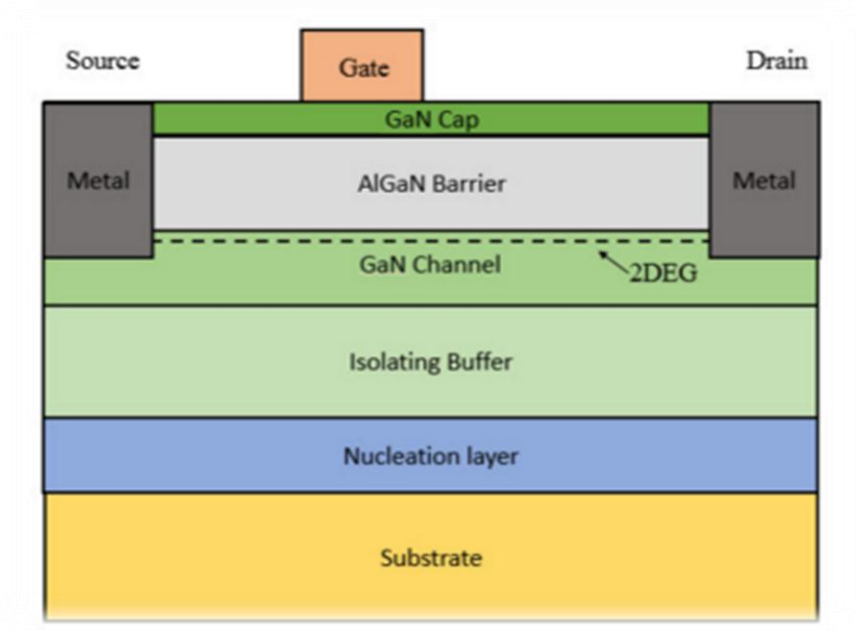
If the gate voltage is below the threshold voltage and the drain is stressed with high voltage, the GaN HEMT device gets into the block region. In this case, the GaN region is depleted from the drain to the gate. The depletion region helps to sustain the high voltage. As the GaN material has a much higher critical field Ecrit (3.3 MV/ cm) than silicon (0.3 MV/cm), the GaN HEMT device has very good high-voltage ability and can be designed for high-efficiency power devices. [33]

Under drain voltage stress, if the local electric field in the device is higher than the critical field Ecrit, the device will break down. The contour lines are closer at the junction edge than in other region, such as the edge of the gate at the drain side and the edge of the drain contact FigureII.9. These regions have a higher electric field and are much more susceptible to breakdown. If the breakdown occurs in the GaN or AlGaN regions, the electrons generated can destroy the 2DEG in the heterojunction. In this case, the on-resistance of the device would increase sharply, and the device is a failure . Because of the Schottky gate contact, a GaN HEMT device has a 10^3–10^6 level higher leakage current than conventional silicon devices with reverse bias , and this leakage current would cause an early breakdown. To restrain the early breakdown phenomenon and to increase the breakdown voltage . [33]



FigureII.5 Electric field distribution with drain stress [33]

II.5 Device HEMT Structure



II.6 The basic structure of GaN HEMT. [34]

The substrate: as explained above, we use substrates of materials other than Gan, and the materials often used are: silicon, sapphire, silicon carbide. The nucleation layer: is to minimize the lattice mismatch between the buffer layer and the substrate, and to ensure good crystallographic quality to grow the GaN crystal layer. [35]

The buffer layer: This layer is made of the GaN material, it is in the upper part of this layer that the two-dimensional gas will be formed, it is also called Buffer. [35]

The channel: The channel is located in the unintentionally doped small gap material layer. This is the most important part of the HEMT: this is where the two-dimensional electron gas is created. It is the layer that determines the performance of the component through the electron transport properties in the material. The spacer: made in our case by the gallium-aluminum nitride material AlGaN.

Its role is to minimize electron-donor interactions between the two-dimensional gas and the donor layer. It is subject to a compromise with respect to its thickness, the thinner it is, the more the concentration of charges in the channel increases, thus presenting a high current density, also reducing the source resistance. The thicker it is, the more the density of charge carriers decreases, thus increasing the mobility of electrons.[35]

The donor layer: It is in this layer that the charge space zone forms at the gate Schottky junction as ell as around the heterojunction. it is a layer of doped AlGaN large gap material which supplies free electrons to the structure. Its doping is generally high, using silicon which plays an important role in it because it contributes to the increase in the concentration of the electrons supplied.

The Cap layer: it is a thin layer of Gallium nitride, On which ohmic and schottky contacts are made.[35]

II.6 Summary

We have written in this chapter, AlGaN /GaN High Electron Mobility Transistors (HEMTs) Heterogeneous structure material and transistor dimensions in order to improve transistor performance. As we also described, $Al_xGa1_{-x}N$/GaN HEMTs structure , We also talked about the hemt process, and how A lateral electric field is constructed, and 2DEG flows across a heterogeneous interface to form an IDS .

Chapter III:

Simulation results and discussion

Chapter III: Simulation results and discussion

III.1 Introduction

Simulation is the process of imitation of a real device, or a physical or biological process. Simulations attempt to present the characteristics of the behavior of an abstract or physical system by the behavior of another system, which simulates the first, it is an attempt to repeat a process under artificial conditions that are somewhat similar to natural conditions.

Or we can say, simulation is one of the important means of solving problems, and it is the means the only and last solution to any problem, which is difficult to solve by analytical methods or numerical , The simulation is based on sampling methods And generate numbers and random variables, which have certain characteristics. [36]

We will first start by defining the simulation program that we will use in this experiment , which is the SILVACO program.

III.2.1 About SILVACO (Silicon Valley Corporation)

SILVACO (Silicon Valley Corporation) is an American company, "Silvaco International" headquartered in Santa Clara, California. it is one of the main professional finite element simulation software chain suppliers and computer-aided design for electronics technologies TCAD. These tools are employed by microelectronics companies in the field of research, device development and design Historically the company was founded in 1984 by Dr. Ivan Pesic to meet the needs of analog integrated circuit (IC) designers for SPICE (Simulation Program with Integrated Circuit Emphasis) models increasingly precise and linear. [37]

III.2.2 Presentation of the TCAD-SILVACO software

Silvaco TCAD can be applied to a breadth and depth of applications useful in the development of semiconductor technologies. TCAD has been proven to be a powerful tool to provide in-depth understanding of device fabrication and operation. When applied by engineers to their Semiconductor R&D needs, TCAD can provide insights difficult or even impossible to achieve empirically. TCAD can help enhance device performance, increase yield and reduce time to market.

However applying TCAD is a complex learned skill and engineers must apply their own skill and experience as a solid-state physicist, electrical engineer or circuit designer. Applying that knowledge to harness the TCAD infrastructure so that their simulation goals can be achieved. TCAD software

combines industry and academic physics knowledge, advanced numerical methods, user interfaces, and automation to allow engineers to get the answers they need . [38]

And it is a software environment that allows to design and predict the performance of semiconductor devices. This tool is used for modeling of semiconductor devices prior to fabrication. The modules of TCAD-SILVACO can be used for:

- Simulation of technological manufacturing steps such as ATHENA, SSupreme3, SSupreme4, etc.
- Electrical simulation of devices such as diodes, MOSFETs, transistors bipolar, carried out by the ATLAS module.

-Virtual Wafer Fab to automate Wafer fabrication simulation. In our study, the simulations are carried out by the two tools ATHENA, and ATLAS. [37]

III.2.2.1 ATLAS simulation software

ATLAS software allows the analysis of differential and physical equations of compounds such as the equations for diffusion or transmission charges, and thus is able to predict the electrica properties of most semiconductors in the two continuous systems and alternating. In addition to the "external" electrical behavior. It consists of two parts: the digital processing part and the physical modeling part Most common semiconductor compounds.

ATLAS has been designed in a way that enables the use of other tools, which facilitate its use, and these tools are as follows . [39]

III.2.2.2 DECKBUILD

It is the main window of SILVACO through which all simulators can be controlled, which is the environment in which the simulation program is defined, by defining the necessary structure, network, and electrical properties.

DECKBUILD is the interface between the user and the simulators, consisting of two windows. Input window in which emulators can be called up and controlled Using the DECKBUILD commands. While the second window displays the runtime output, the outputs and results of the emulators, including It programming errors and alerts after assembly. [39]

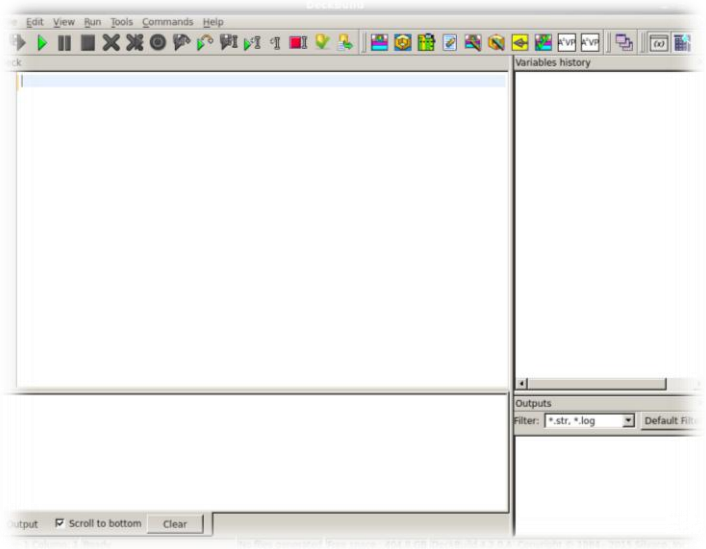


Figure III.1 DeckBuild Graphical User Interface [42]

III.2.2.3 TONYPLOT

It is the tool in which simulation results are plotted. Provides complete capabilities to visualize and analyze the output properties of the component's electronic structure, doping and electrical properties. Depending on the simulation software use, TONYPLOT can give Output properties in one, two or three dimensions. [39]

III.3 Analytical Current Model in AlGaN/GaN HEMT

Symbol	Definition	Units
n_s	Sheet electron density in 2-DEG	m^{-2}
$\varepsilon_{Al_xGa_{1-x}N}$	Dielectric constant of AlGaN	$C^2/J.m$
q	Elementary charge	C
k	Boltzmann's constant	J/K
T	Temperature	K
E_F	Fermi level	V
φ_B	Schottky gate barrier height	V
ΔE_C	Conduction band discontinuity	V
N_D	Donor concentration in n-AlGaN	m^{-3}
σ	Polarisation induced electron density	m^{-2}
d_d	Thickness of the n-doped AlGaN layer	m
d_i	Thickness of the undoped AlGaN layer	m
d	Total AlGaN thickness ($d_d + d_i$)	m
D_S	Conduction band density of states	m^{-2}/V
E_0	Lowest allowed energy level	V
u_1	Triangular well coefficient for E_0	$V.m^{4/3}$

TableIII.1 liste of simble [41]

III.3.1 Electrostatics and 2-DEG charge density

This section describes electrostatics and quantum effects of the device and calculation of the 2-DEG sheet charge density. The equations of electrostatics are obtained by solving the Poisson equation in the approximation of fully ionized impurities. By solving the Schrödinger equation in 2D triangular approximation, the total system of equations becomes:[41]

$$n_s = \frac{\varepsilon_{Al_xGa_{1-x}N}}{q\,d}\left(Vg - V_{off} - E_F\right) \quad (1)$$

$$V_{off} = \varphi_B - \Delta E_C - \frac{q\,N_D\,d_d^{\,2}}{2\,\varepsilon_{Al_xGa_{1-x}N}} - \frac{q\,\sigma}{\varepsilon_{Al_xGa_{1-x}N}}(d_d + d_i) \quad (2)$$

$$n_s = D\,kT\,Ln\left[1 + exp\left(\frac{E_F - E_0}{kT/q}\right)\right] \quad (3)$$

$$E_0 = u_1\,n_s^{\,2/3} \quad (4)$$

where Vg and V_{off} are gate voltage and offset voltage respectively. Voff could be either calculated from available literature or introduced as a parameter. This system of equations is solved traditionally by a self consistent numerical method. However, such a resolution is not suitable for a circuit simulator as it is too costly in computation time. Following the work of Cheng and Wang this system could be solved analytically. Analytical determination of E_F ($E_F = \eta + \omega$) is done in two steps:

1- Approximate solution **(η)** for two asymptotic cases: (a) for high ns and (b) for low ns

2- Small refinement **(ω)**, important for medium **ns** Refinement is done several times to ensure good accuracy for medium ns. We obtain different analytical expressions than and check that our expressions are valid even for very high Vds, up to 1 kV .

Knowing the Fermi potential, the surface potential is given by: [41]

$$\Phi_s = E_F + V_{ch} \tag{5}$$

Where Vch is the channel voltage which varies between VS at source and VD at drain.

III.3.2 Mobility

The following mobility model is adopted :

$$\mu_{LF}(E_T) = \frac{\mu_0}{1+\alpha|E_T| + \beta E_T^2} \tag{6}$$

where ET is the transverse electrical field obtained from Gauss theorem at AlGaN/GaN interface:

$$\varepsilon_{GaN} E_T = \varepsilon_{AlGaN}(Vg - V_{off} - \Phi_{sm}) / d \tag{7}$$

Where Φsm = 0.5 (Φsd + Φss) is known as the SP midpoint and where Φss and Φsd are surface potentials calculated at source and drain, respectively. [41]

III.3.3Velocity saturation

The following velocity saturation model, where EL is the longitudinal electrical field and Ec the critical field, is adopted [41]

$$v_{drift}(E_L) = \mu_{LF}(E_T)\frac{|E_L|}{1+\left(\frac{|E_L|}{E_c}\right)} \quad (8)$$

III.3.4 DIBL Short channel effect

Drain-Induced Barrier Lowering (DIBL) effect is modeled as a shift of V_{off} with drain voltage Vds: [41]

$$V_{off}(Vds) = V_{off}(0) - DIBL\,(Vd - Vs) \quad (9)$$

III.3.5 Temperature modeling

Some HSP model parameters, such as mobility μ_0, critical field E_c and thermal resistance R_{th}, are recalculated in temperature using the following law, where T_{ref} is a reference temperature and PEX an exponent: [41]

$$P(T) = P(T_{ref})\left(T/T_{ref}\right)^{PEX} \quad (10)$$

For Voff, temperature modeling is: [41]

$$V_{off}(T) = V_{off}(T_{ref}) - TCV\,(T - T_{ref}) \quad (11)$$

III.3.6 Self-heating effect

Two models of the self-heating effect (SHE) are included:

1 – A simple model where an empirical thermal resistance Rth is assumed as a lumped element for the power dissipation P_{diss},

2 – A more physical approach that models the heat diffusion from channel through a substrate of thickness tsub whose backside is held at constant temperature T0 (heat sink). Assuming the following general law for thermal conductivity (KEX=-1.4 for GaN, -1.5 for SiC and -1.25 for GaAs):

$$\kappa(T) = \kappa(T_{ref})\left(T/T_{ref}\right)^{KEX} \tag{12}$$

and following the approach of Canfield to solve heat diffusion generated under the gate near the drain in a simple half-cylinder whatever the value of the KEX exponent, the temperature increase is given by: [41]

$$\Delta T = T_0 \frac{1-\left(1-\frac{1}{\theta}\frac{P_{diss}}{P_0}\right)^{\theta}}{\left(1-\frac{1}{\theta}\frac{P_{diss}}{P_0}\right)^{\theta}} \tag{13}$$

$$with \quad \theta = -(KEX+1)^{-1}$$

$$and \quad P_0 = \pi\kappa(T_0)\,W T_0 \Big/ ln\left(\frac{8t_{sub}}{\pi L}\right) \tag{14}$$

Where W and L are gate width and length, α is a correction factor ($\alpha \leq 1$) allowin g calculating the effective channel length from which heat dissipation occurs. A new channel temperature is calculated ($T' = T + \Delta T$) and all parameters depending on temperature are recalculated. Drain current is then updated. This process is repeated iteratively until convergence of drain current is attained. Less than 10 iterations are necessary for a less than 300 °C temperature increase. [41]

III.3.7 Drain current model

Following the work of Gildenblat et al. and using the concept of symmetric charge linearization introduced during development of the SP model, the drain current is calculated by: [41]

$$I_{ds} = \beta\ \mu_{LF} \frac{\left(V_{gs} - V_{off} + V_t - \Phi_{sm}\right)\Phi}{r_L + \delta_0\ \Phi / V_c} \tag{15}$$

$$r_L = 1 / \left(1 + \Delta L / L\right) \tag{16}$$

with $\beta = W/L\ Cg$, $Cg = \varepsilon_{AlGaN} / d$, $\Phi = \Phi_{sd} - \Phi_{ss}$, R_I allows modeling of the channel-length modulation (CLM) effect and $V_c = E_c\ L$. [41]

III.3.8 charge model

The gate charge Qg, neglecting velocity saturation and CLM, is first calculated using the SP model formalism: [41]

$$\frac{Q_g}{W\ L\ C_g} = q_{im} + \frac{\Phi^2}{12\ H} \tag{17}$$

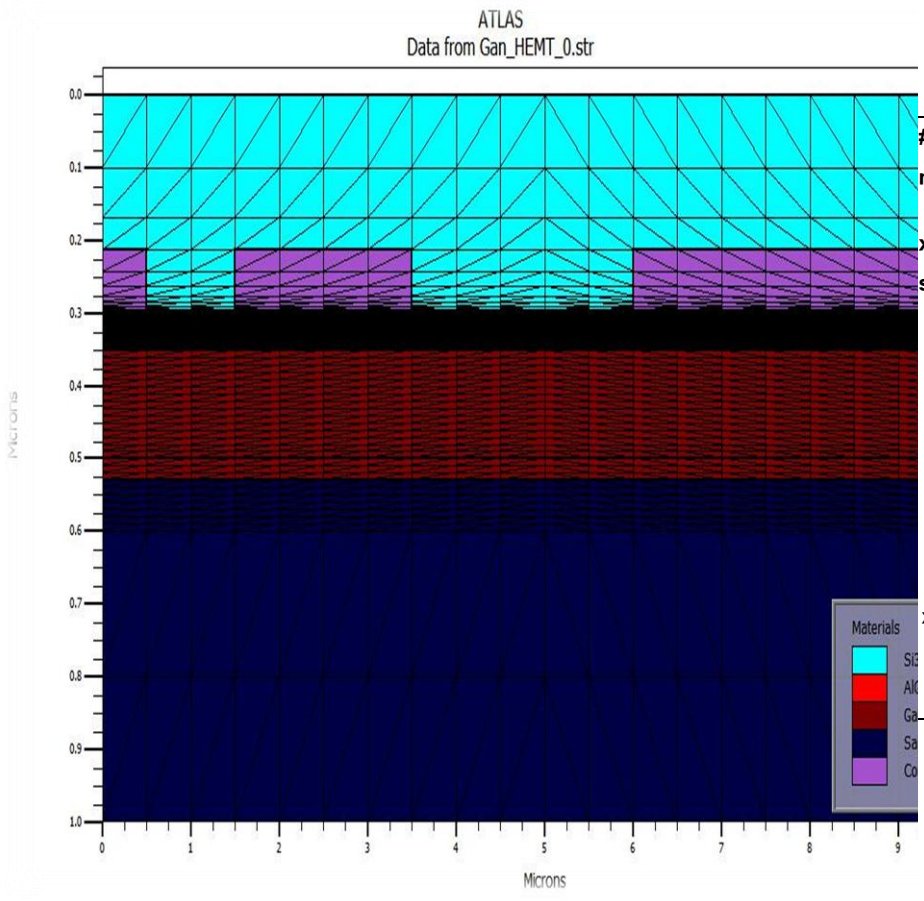
$$q_{im} = V_g - V_{off} - \Phi_{sm},\ H = q_{im} + \frac{kT}{q}$$

Source and drain charges are then evaluated using the Ward-Dutton partitioning scheme. If needed, intrinsic capacitances will be calculated as derivatives of the terminal charges: Cij = – dQi/dVj (i≠j) and Cii = dQi/dVi (i=j). Nine transcapacitances can be defined, six of them being independent. This treatment allows strict charge conservation during circuit simulation and requires no fitting parameters. [41]

III.4 HEMT device structure

III.4.1 MESH :a mesh is a network that is formed of cells and points. It can have almost any shape in any size and is used to solve Partial Differential Equations. Each cell of the mesh represents an individual solution of the equation which, when combined for the whole network, results in a solution for the entire mesh.

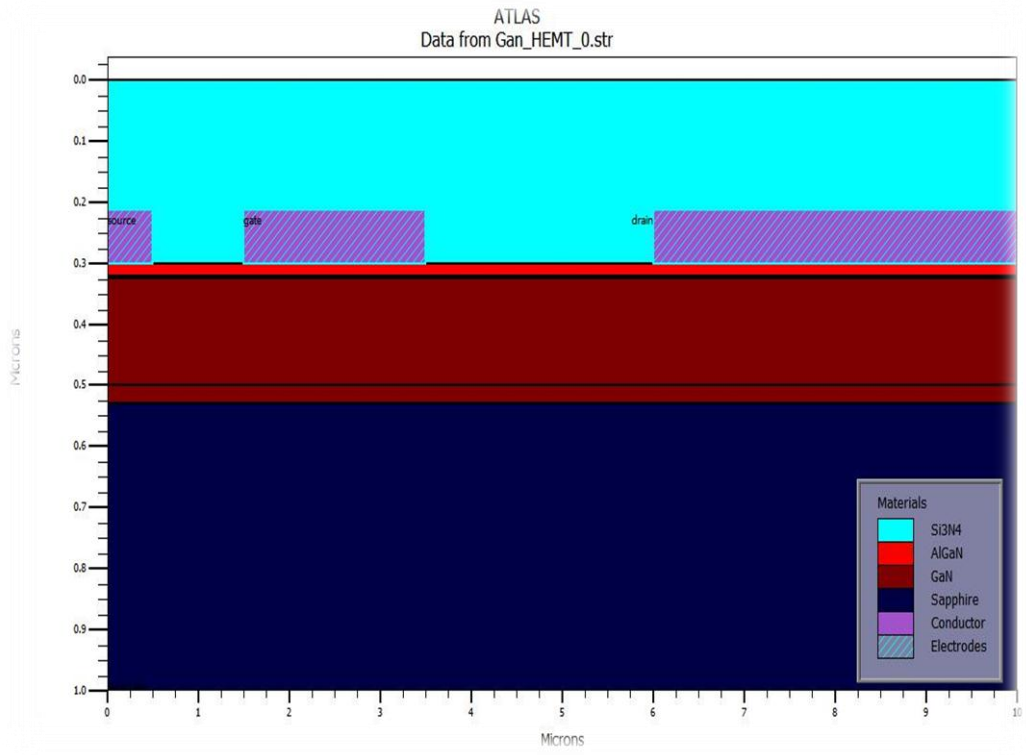
Solving the entire object without dividing it into smaller pieces can be impossible because of the complexity that is within the object. Holes, corners and angles can make it extremely difficult for solvers to obtain a solution. Small cells, on the other hand, are comparably easy to solve and therefore the preferred strategy. [40]



#x plane meshing	# y plane meshing
x.m l=0.0 s=0.25	y.m l=0 s=0.25
x.m l=2 s=0.25	y.m l=0.03 s= 0.001
x.m l=5 s=0.01	y.m l=0.028 s=0.001
x.m l=8 s=0.01	y.m l=0.525 s=0.05
x.m l=9 s=0.25	y.m l=0.550 s=0.1
x.m l=12 s=0.5	y.m l=1 s=0.2

Figure III.2 Mesh of Our structure

III.4.2 LECTRODE: In silvaco , our simulation code must contain at least one electrode to function properly an electrode can be defined either through a graphical user interface window or using a command line .



elec num=1
name=source
x.min=0.0 x.max=0.5
y.min=-0.5
y.max=0.0

elec num=2
name=drain
x.min=3.0 x.max=3.5
y.min=-0.5
y.max=0.0

elec num=3
name=gate
x.min=1.5 x.max=2.0
y.min=-0.5
y.max=0.0

elec num=4 substrate

Figure III.3 LECTRODE

III.4.3 REGION : regions have to be defined in our structure by specifying each region's material as well as its dimensions in microns **.**

region num=1 mat=nitride insulator
region num=2 x.min=0 x.max=12 y.min=0.0 y.max=0.20 mat=AlGaN x.comp=0.3
region num=3 x.min=0 x.max=12 y.min=0.020 y.max=0.025 mat=AlGaN x.comp=0.3
region num=4 x.min=0 x.max=12 y.min=0.025 y.max=0.525 mat=GaN
region num=5 x.min=0 x.max=12 y.min=0.525 y.max=0.550 mat=GaN
region num=6 x.min=0 x.max=12 y.min=0.550 y.max=1 mat=sapphire substrate

III.4.4 DOPING:

Doping is cruical in our structure as it serves to increase the conductivity of semiconductors in their intrinsic state , we have a variety of doping types ,from which we mention the uniform , gaussian and in our structure we particulary use the uniform one , doping can be either an N type (increased free electrones) or a P type (increased holes)

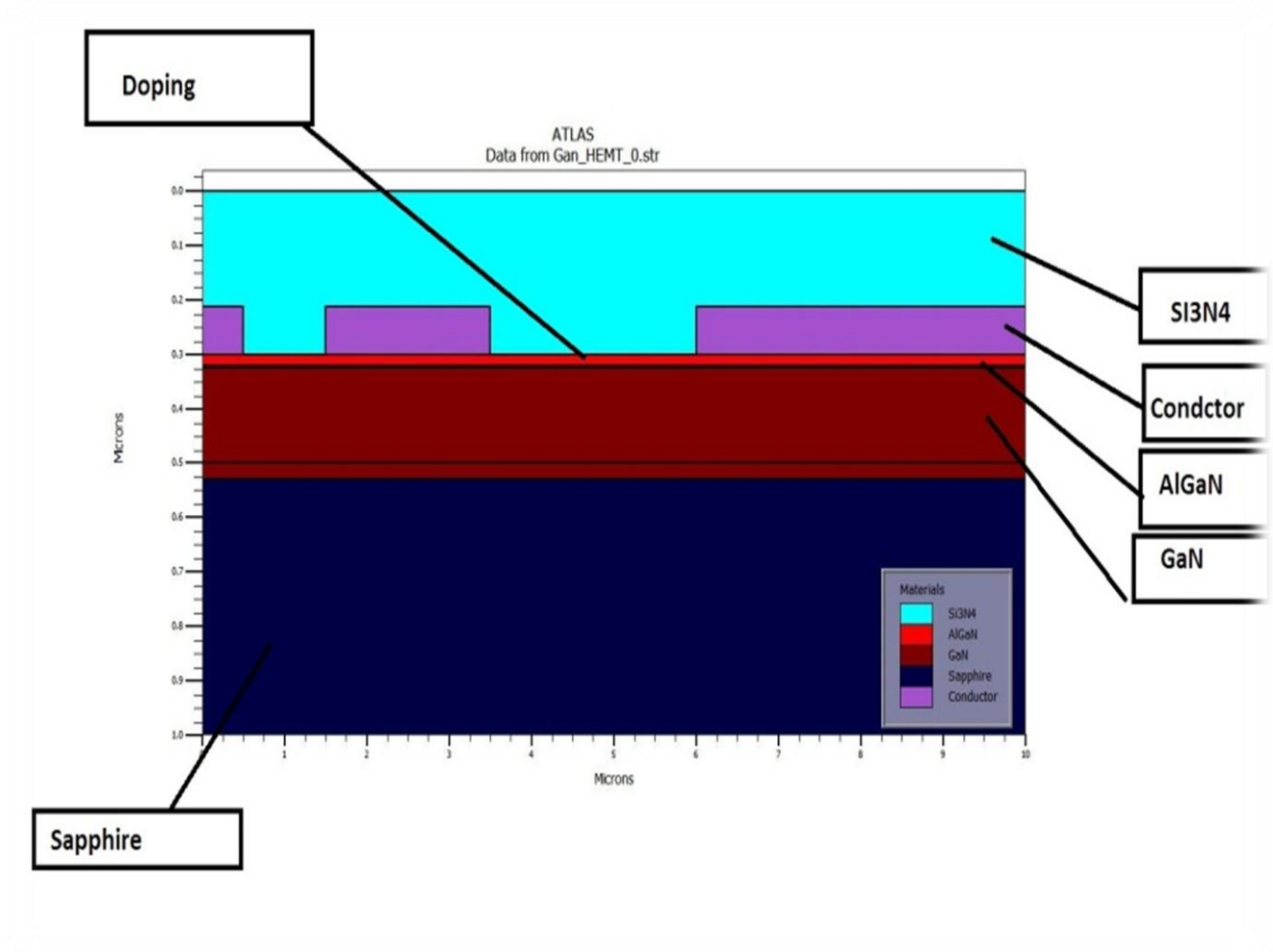


Figure III.4 The structure of HEMT $Al_{0.30}Ga_{0.70}N$ / GaN simulated by Atlas-Silvaco

III.5 Results and discution

III.5.1 Description of the simulated structure

Our topology is that of GaN/AlGaN HEMT transistor on a sapphire substrate with a size of 473 nm The structure is made up of 5 layers , the upper AlGaN layer is divided into two layers(spacer and barrier) of different size , we doped the barrier layer with an N type doping then comes the GaN area that will contain two dimensional electron Gaz then a second GaN layer to fix the lattice mismatch issue caused when using a sapphire substrate the distance from source to gate , gate to source are respectively 1 µm and 2.5 µm , The work function values for the schottky contacts are (5ev for gate , 3.93 for both drain and the source) .

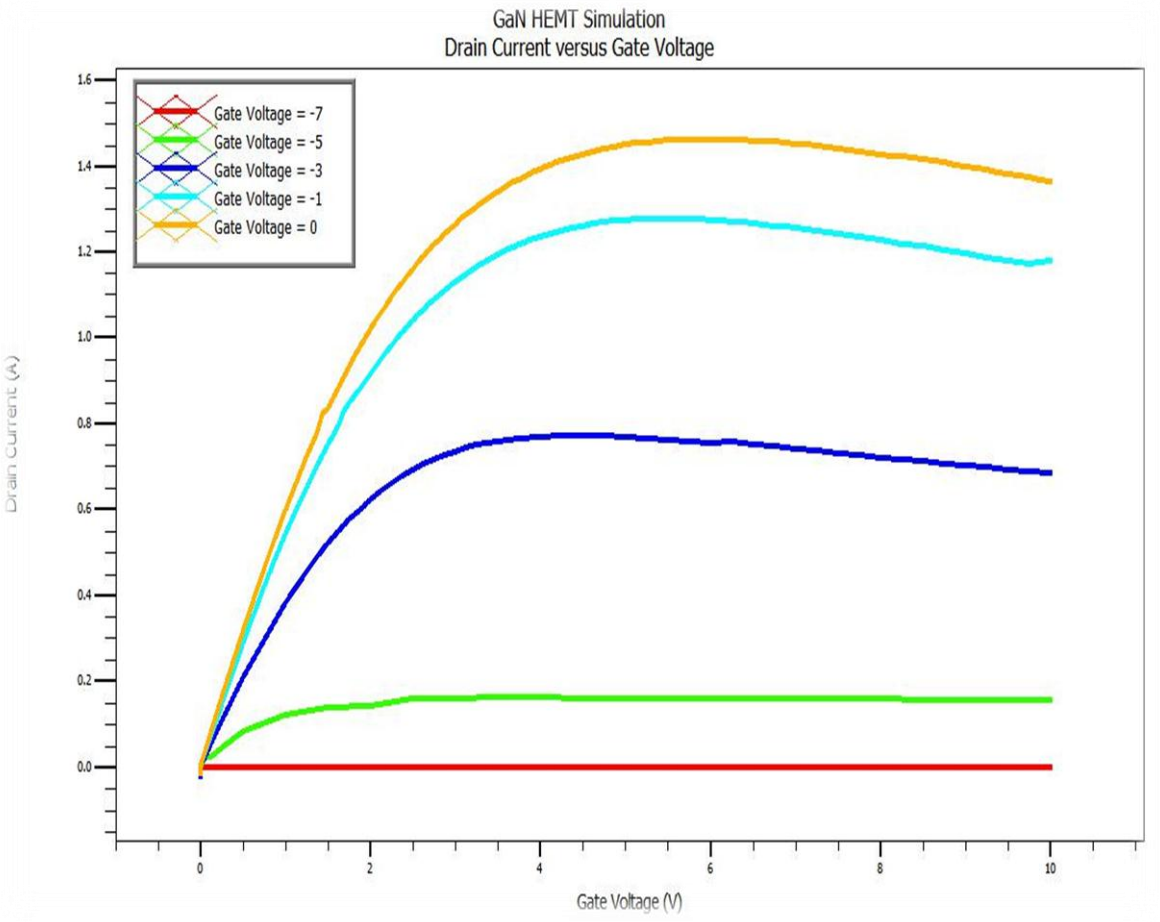
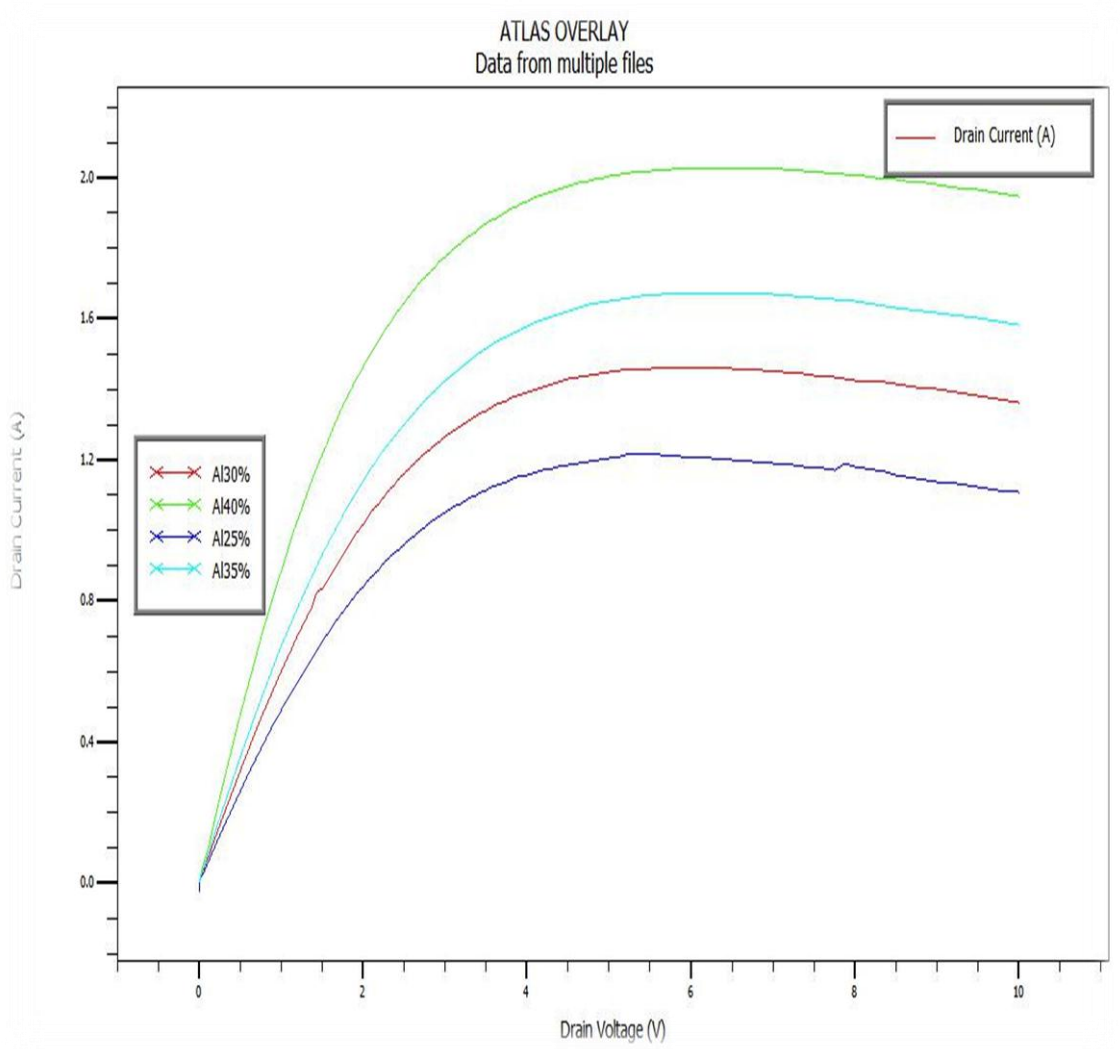


Figure III.5 the drain current characteristics measured at various gate voltages

As the above figure shows , it's noticed that as we varied gate voltage values from -7 all the way up to 0 ,the drain current increases as a result (the Ids current rises as Vg increases)



FigureIII.6 drain current characteristics measured at different aluminum concentration values

The figure above represents the drain current as it's measured by varying the aluminum mole fraction in both the barrier and the spacer layers equally and fixing the gate voltage at 0 , as it's shown on the curve above ,the highest electrical characteristics are obtained when aluminum concentration is at 40% this means that the higher Al concentration the better .

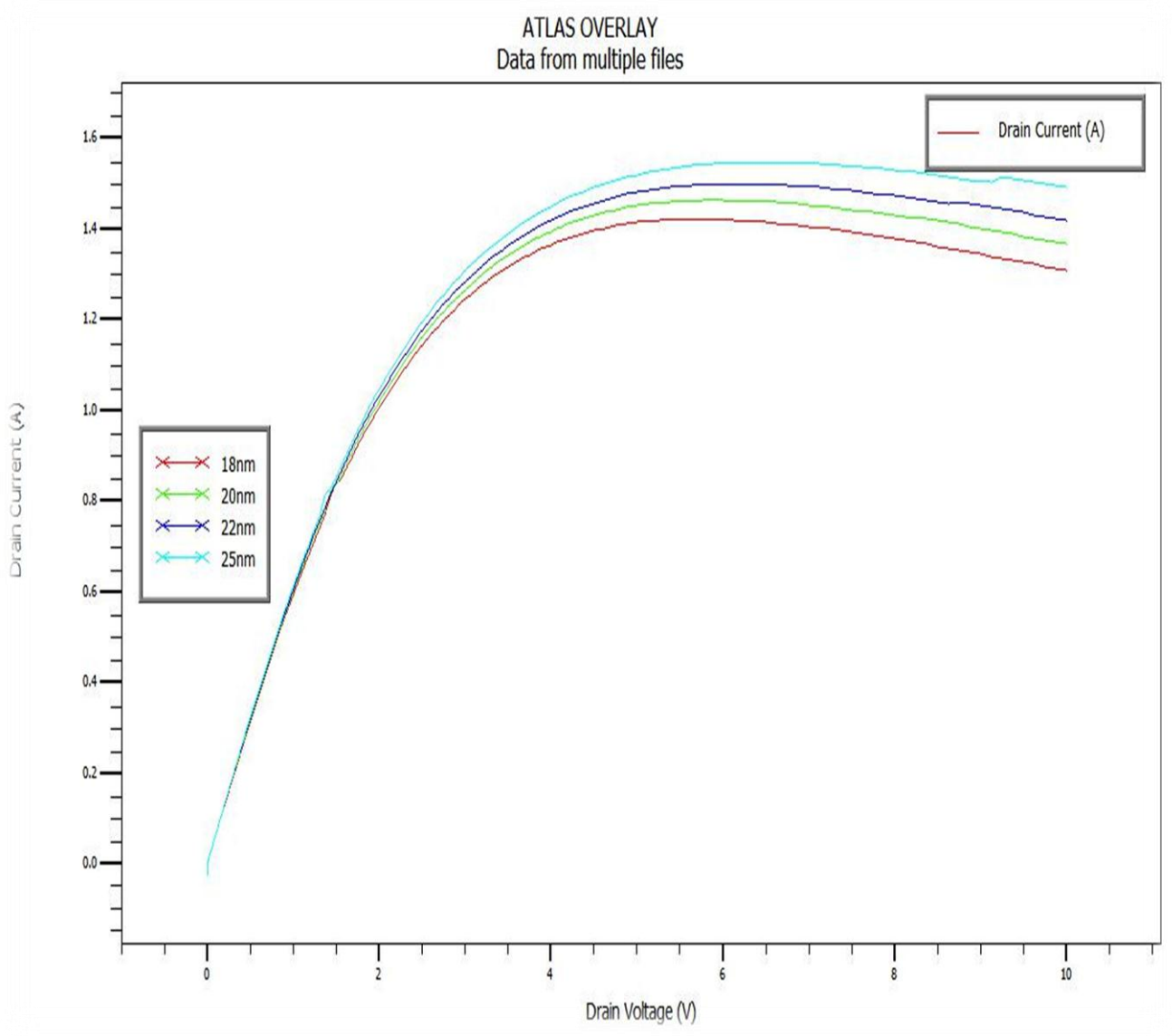


Figure III.7 drain current characteristics measured at various barrier layer's thickness values

The barrier layer is the the doped one and its role is to provide the gan layer with electrons (2DEG) , we measured electrical characteristics for different bthickness values as shown in the figure above and as a result we noticed that the thicker this layer in our strucutre is , the higher the drain current will be .

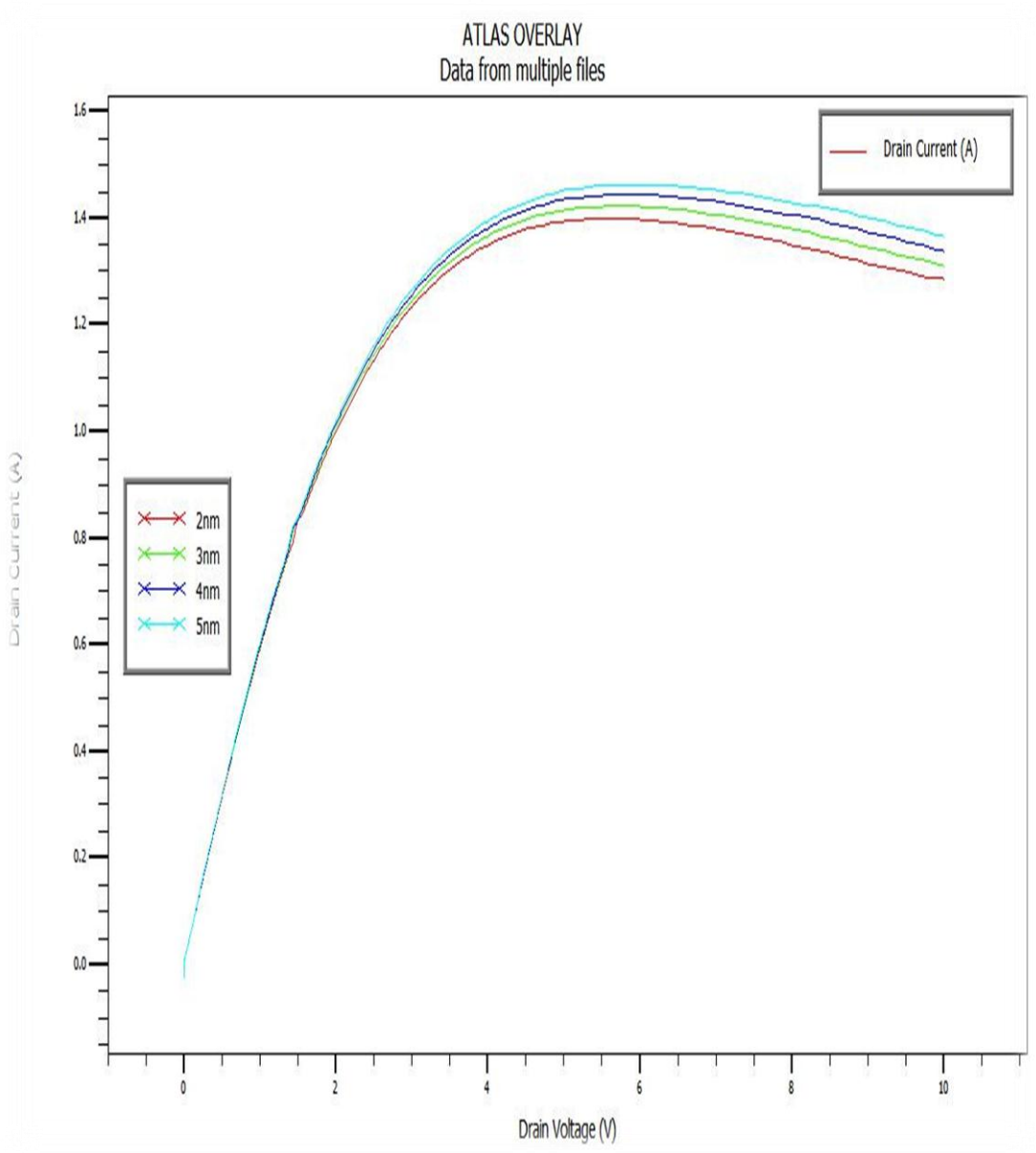


Figure III.8 drain current characteristics measured at various spacer layer's thickness values

The spacer layer is the undoped part of our structure that stands in between the barrier layer and the two dimensional electron gaz and the results shown above indicate that a thicker spacer layer is always better for higher current(5nm in our case) which will result in an increased electron mobility overall .

III.6 Summary :

As we went through the entire simulation process in this chapter, we examined various factors influencing GaN/AlGaN hemt on-current (aluminum concentration,barrier layer and spacer layer thickness) that were measured at a gate voltage of 0 since was the main goal we aimed at in our thesis, Our results indicate that our GaN/AlGaN will produce the highest current when the concentration of aluminum in both the spacer and barrier layers is at 40 per cent , the barrier layer thickness is 25nm and the spacer layer is 5 nm .

These resuts we obtained prove indeniably that gan technology used in gan/algan hemt structures will be the breakthrough in the future of high power switching applications four its unique properties and the best candidate for futur high power amplificators.

General Conclusion

General Conclusion:

as we travelled back in history of electronic devices manufacturing , many semiconductors were in use at some point in the past as they were thought to be the best and most suitable for high power eelectronic devices fabrication and no other component could ever come close to their quality and performance but all that changed due to the emergence of the newcomer "GaN based technology" ,a new competitor that soon took the lead and revolutionized the market of semiconductors used in high power eletctronic devices for exhibiting a wide range of the great features and physical properties compared to its predecessors in particular "silicon" that was the dominant material in that era in our thesis we went through AlGaN/GaN transistor's simulation to examine the influence of various factors on its performance We started off by introducing the GaN and the variety of its unique physical properties that make it stand out from the rest of widespread semiconductors in that era particulary its ability to produce ternary alloys such as the well known AlGaN and that's crucial in manufacturing field effect transistors with much higher performance thanks to the high mobility that heterojunctions can offer , we then investigate the differences between GaN material and the other semiconductors that are present in the market such as gallium arsenide allowing it to excel and shine up as the future of high power devices manufacturing We then moved on to the next chapter to dig even deeper in the high electron mobility transistor structure and the multiple layers that make it up ,we shed light on the materials that each layer is made up from, furthermore we took a closer look at the hemt 'substrate and compared the most common substrates available (sapphire,Sic,si) for the purpose of selecting the most suitable one that produce the highest performance possible Afterwards we finished off our thesis by simulating our gan/algan hemt model to extract the results and give detailled interpretations of the different curves we obtained and for this purpose we were eqquiped with the well known simulation software "silvaco atlas" to use its powerful tools to investigate the impact of distinct aluminm concentration values and various thicknesses of both the spacer and barrier layer on the transistor 's performance to produce a device with highest characteristics possible and we noticed that our simulated device will be at its peak performance at the following values (spacer layer thickness= 5nm, barrier layer thickness = 25nm, the aluminum concentration in both algan layers should be at 40%). By the end of our investigation journey we reach a conclusion that algan/gan hemt devices have made a significant breakthrough in the field of microelectronics and can be byond a shadow of a doubt destined to produce better and faster switching and amplification devices of a much smaller size yet a higher performance compared to their predecessors .

Future prospects

Gan technoloy has been proven to be the future of power electronics applications due to the exceptional properties of its material that allowed it to excel over silicon such as its wide bandgap compared to that of the silicon as well as its unique ability to resist high temperatures and being able to operate at high switching frequencies Thanks to all its previously mentioned strengths and outstanding properties ,GaN was proposed to be an alternative to Si in the field of the motor control owing that to its high switching frequency besides that Gan is nowadays indispensable in the future 5G mobile technologies since it offers a very promising future in RF sector for its great amplification ability of high frequencies Gan's applications extend even beyond that to include the most innovative wireless charging technology, Data centers as well rely heavily on Gan as they require more power and a reduction in space simultaneously Yet despite of all its advantages , Gan still present few challenges and more work and research needs to be conducted in the future to overcome the two main challenges that hold Gan from achievieng an increasing diffusion forever "price and reliability" which are major issues faced by this technology even though tthe elia ility issue has been resolved , we still however face the price issue therefore more attempts and efforts need to be done to further achieve more reduction in GaN manufacturing cost making it more competitive.

" GaN is indeniably and beyond a shadow of a doubt the future of microelectronics " .

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