

**Treatment of the Impacts of Transport Inflexion Points and  
Charge Trapping at the Surface  
States on Drain Current of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs**

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## **ABSTRACT**

### **Treatment of the Impacts of Transport Inflexion Points and Charge Trapping at the Surface States on Drain Current of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs**

Alireza Loghmany

During the past two decades AlGa<sub>N</sub>/Ga<sub>N</sub> Heterostructure Field Effect Transistors (HFETs) have been the target of much attention in high power microwave applications. Crystal imperfections in AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs have been pointed out as the cause of many reliability concerns such as drain-current collapse, gate lag, and excessive gate leakage-current. Current collapse and reliability degradation due to electron trapping at the surface layer of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs are major impediments for commercialization of these devices. Even though there have been remarkable improvements in crystal growth and device fabrication technology, trapping effects in AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs, specially under high drain-voltage conditions, have not been completely removed. Therefore, an assured simulation of HFET with incorporation of trapping effects is needed. In this thesis, in order to substantiate the hypothesis of electron trapping at deep surface states as the cause of semi-permanent current collapse this phenomenon is studied with the use of CADtool Medici.

Monte Carlo simulation of electronic transport at AlGa<sub>N</sub>/Ga<sub>N</sub> channels reveals that in addition to the steady-state velocity overshoot there exists a pronounced kink in the low electric-field region of the drift-velocity versus electric-field characteristics of these channels. Existence of the inflexion points attributed to this kink and the large width of the overshoot pattern in conjunction with the large electric-fields conventionally

applied to these wide band-gap semiconductors, make the modeling of electronic devices fabricated in this technology different than those of other III-V semiconductors. An analytical model for drain current/voltage characteristic of AlGaN/GaN HFETs with incorporation of steady-state drift-velocity overshoot and the inflexion points in the electronic drift transport characteristics is also presented in this thesis. The wide peak and pronounced inflexion points in the transport characteristics of AlGaN/GaN heterojunctions are modeled through considering a drift-diffusion channel rather than a drift-only transport channel. Simulation results have been compared to a non-diffusion type channel implemented with the assumption of Ridley's saturating transport model. The model is based on applying an iterative approach between Poisson's equation and current-continuity equation, which relieves the results from the burden of the choice of fitting parameters. With the advancement of this technology, development of a versatile analytical model with incorporation of these considerations is vital for understanding the full range of capabilities of III-Nitride material system.

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# Chapter 1

## Introduction

### 1.1 III-Nitride material systems

Good transport properties, widely tunable band-gap, superb bond-strength, and high breakdown electric-field in III-Nitride semiconductors (including InN, GaN, AlN, and their ternary alloys) make them suitable for realization of high-power, high-frequency and high-temperature RF-circuitry [1], [2]. With the room temperature band-gap of 0.7 eV for InN [3] and the band-gap of 6.2 eV of AlN [4], III-Nitride alloys can cover a very broad range of band-gaps and emission wave-lengths from infrared to the deep ultraviolet, which is currently employed in the making of Light Emitting Diodes (LEDs), Laser Diodes (LDs), and photo detectors.

Suitability of the application of III-Nitride heterostructures to electronic devices is not only due to their transport properties, but also due to the polar properties of their heterostructures which allow the formation of two-dimensional channels of extremely high carrier concentrations ( $\geq 10^{13} \text{ cm}^{-2}$ ), without the need for intentional doping. Gallium nitride (GaN) is the most investigated semiconductor of the III-Nitride material system. Although, low-field electron mobility of GaN is much less than that of GaAs (i.e. the main contender in the active microwave device market), its larger peak electron velocity,

wider velocity overshoot pattern, and higher thermal stability have been deemed sufficient for turning the table on GaAs, specially at the lower frequency ends and higher power levels [5], [6]. Figure 1.1 compares electron drift-velocity versus electric-field characteristics of GaN with two other major semiconductors (i.e. Si and GaAs), and also to SiC as another wide band-gap semiconductor.

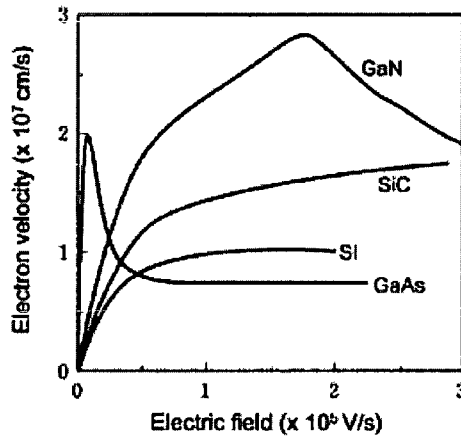


Figure 1.1: Electron velocity versus electric-field for Si, SiC, GaAs and GaN [7].

## 1.2 AlGaN/GaN Heterostructure Field-Effect Transistor

Heterostructure Filed-Effect Transistor (HFET) is a promising candidate for low noise microwave power applications [8], [9], [10]. A traditional AlGaAs/GaAs HFET is illustrated in Fig. 1.2. Traditional HFET technology improves the carrier mobility of two-dimensional electron gas (2DEG), formed at the vicinity of the heterointerface of the channel/buffer layer and the doped barrier, by resolving the ionized-impurity scattering problem via spatially separating the channel from these scattering sources. At the cost of reduction of the gate-transconductance, impurity scattering can be further reduced by

increasing the spatial separation of the electrons and ionized impurities through incorporation of a thin undoped spacer layer between barrier and the channel.

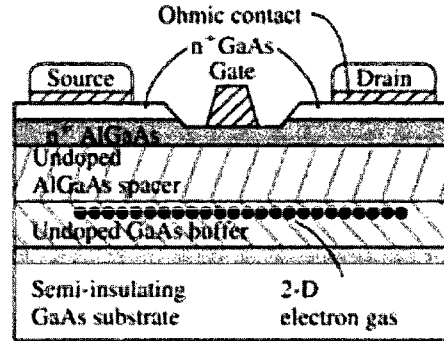


Figure 1.2: AlGaAs/GaAs HFET device structure [11].

HFETs are suitable structures for high frequency low noise amplifiers and now are widely used as extremely low noise devices in terrestrial and space telecommunications systems, space radio telescopes, Direct Broadcasting Satellite television (DBS) receivers, microwave and high power amplifiers, cellular phones and car navigation receivers.

Over the past two decades, AlGaN/GaN HFETs grown on sapphire and SiC have demonstrated much larger output power and temperature tolerance than AlGaAs/GaAs HFETs, which were previously the primary HFET candidates for high power applications. This is primarily due to the application of wider band-gap materials and the ability to achieve outstanding 2DEG densities without the need for intentional doping of the barrier in the polar AlGaN/GaN heterostructures. The first AlGaN/GaN HFET was demonstrated by Khan *et al.* in 1994 [12].

## 1.2.1 Device structure

Figure 1.3 shows the typical device structure of an AlGa<sub>N</sub>/Ga<sub>N</sub> HFET. Not unlike AlGaAs/GaAs HFETs, in these structures due to difference in energy band-gap of the two materials forming the heterojunction, there is a band-gap discontinuity at the heterointerface. This discontinuity creates a triangular quantum well which leads to the formation of a two-dimensional electronic channel in the undoped Ga<sub>N</sub>. However, unlike AlGaAs/GaAs HFETs existence of strong polarization at the heterointerface of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs causes an extra band-bending and reversal of the curvature of barrier's conduction band-edge which result in boosting the 2DEG concentration even in absence of intentional barrier doping [6]. Figure 1.4 shows the conduction-band diagram of AlGa<sub>N</sub>/Ga<sub>N</sub> HFET.

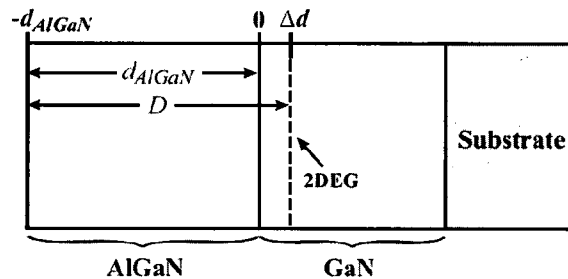


Figure 1.3: AlGa<sub>N</sub>/Ga<sub>N</sub> HFET structure [11].

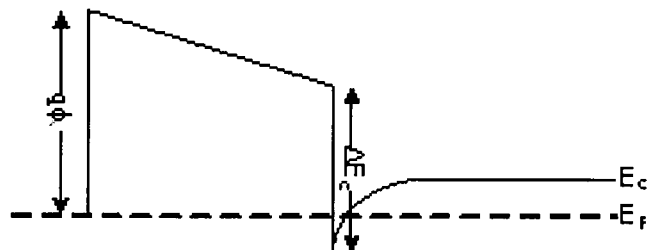


Figure 1.4: Conduction-band diagram of AlGa<sub>N</sub>/Ga<sub>N</sub> HFET.

## 1.2.2 Polarization in AlGaN/GaN HFETs

III-Nitrides semiconductors can be grown in two different crystalline forms: Zinc blende (Zb) and Wurtzite (Wz). Wurtzite which is the most common structure in III-Nitride materials has a hexagonal structure as shown in Figure 1.5 [13]. Non-centro-symmetric nature of Wurtzite structure leads to formation of spontaneous polarization in III-Nitrides even in absence of external strain and/or electric-field.

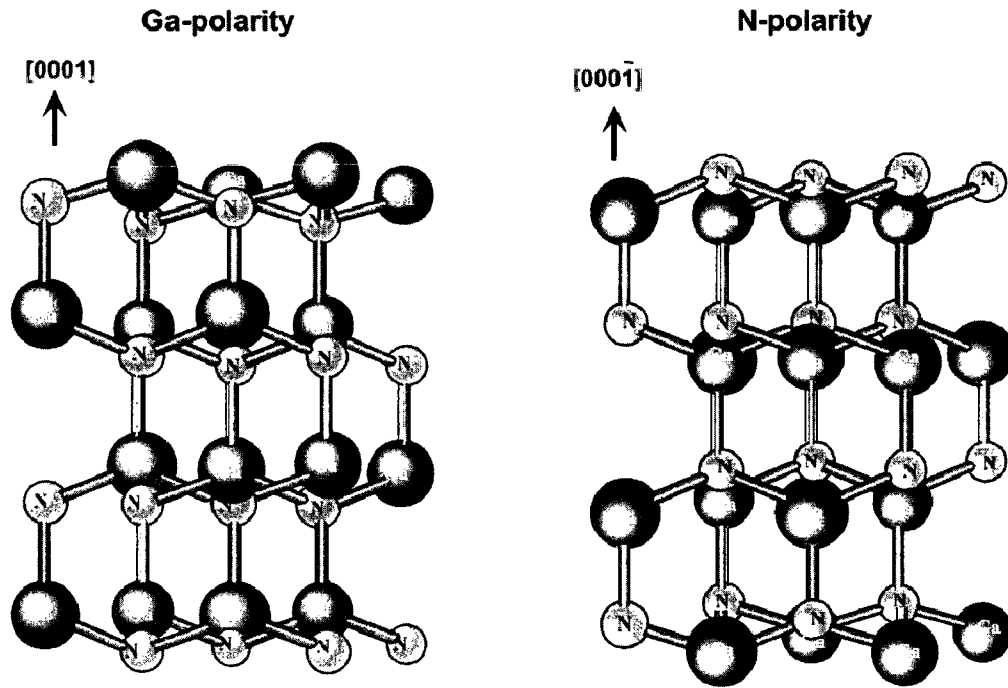


Figure 1.5: Schematic drawing of the crystal structure of Wurtzite Ga-face and N-face GaN [13].

Furthermore, a sizable piezoelectric polarization term exists in the strained pseudomorphically-grown III-Nitride heterojunctions. This is due to induction of strain through coherent growth of two lattice-mismatched crystals and the large value of piezoelectric coefficients of the III-Nitride material system [6]. Piezoelectric effect in addition to the difference between spontaneous polarization of GaN channel and AlGaN



barrier-layer causes the formation of a sizable polarization sheet charge at the AlGa<sub>x</sub>N<sub>1-x</sub>/GaN heterointerface. Figure 1.6 shows the spontaneous and piezoelectric polarizations in the AlGa<sub>x</sub>N<sub>1-x</sub>/GaN HFET [14]. In this figure, spontaneous polarization in each material is shown as  $P_{sp}$  and piezoelectric polarization in the tensile-strained AlGa<sub>x</sub>N<sub>1-x</sub> barrier is represented by  $P_{pz}$ . The value of spontaneous polarization increases along the material order of GaN to AlN, and to InN [4], [6].

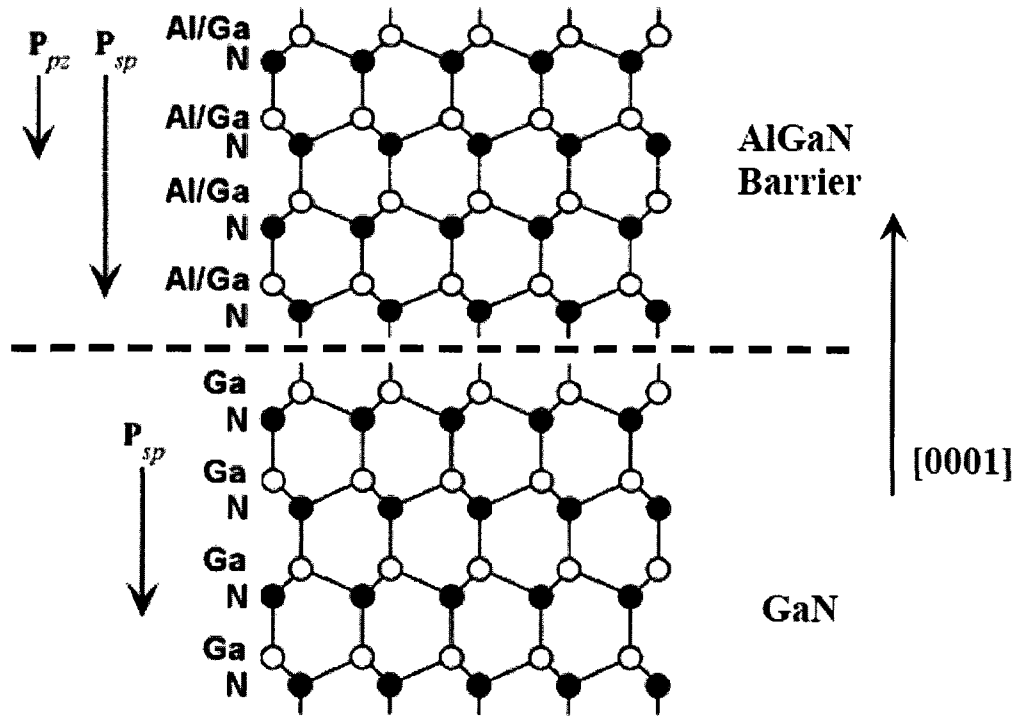


Figure 1.6: Spontaneous and piezoelectric polarization in AlGa<sub>x</sub>N<sub>1-x</sub>/GaN HFET [14].

### 1.3 Microwave performance of AlGa<sub>x</sub>N<sub>1-x</sub>/GaN HFETs

Due to high breakdown voltage of AlGa<sub>x</sub>N<sub>1-x</sub>/GaN HFETs, these transistors can be operated under high drain-voltages and high peak efficiencies satisfying the needs of commercial systems such as wireless base stations. Over the years, significant progress has been

made in terms of power density and total available power of AlGaIn/GaN HFETs. Figure 1.7 shows the historical progress diagram of GaN-based transistors during their first few years of development. Recently, Cree Inc. has reported GaN based transistors with output power of 240 W and gain of 11.5 dB for S-band (i.e. 2-4 GHz) applications [15].

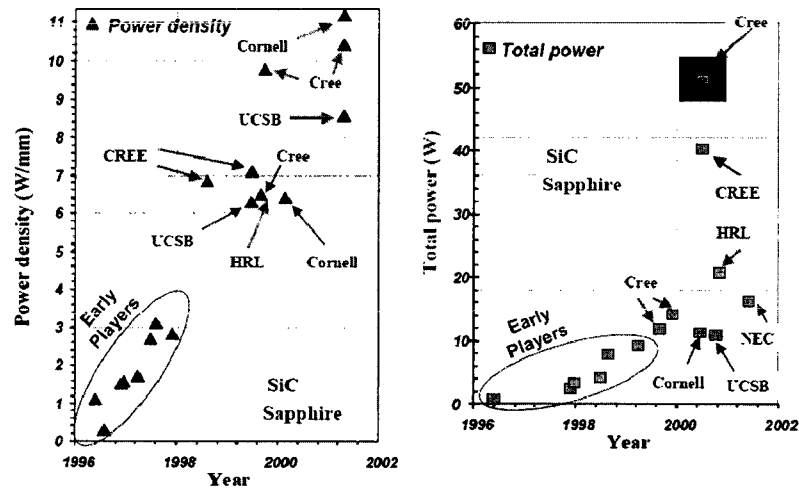


Figure 1.7: Historical progress in GaN-based transistors technology. (a) Power density of AlGaIn/GaN HFET versus year. (b) Total power of AlGaIn/GaN HFETs versus year [16].

## 1.4 Reliability of AlGaIn/GaN HFETs

Although AlGaIn/GaN HFET is a promising device for high power applications, at the present time the key issue which prevents this transistor from being fully commercialized is the issue of long-term reliability. The main reliability concerns of AlGaIn/GaN HFETs are drain-current collapse, gate leakage, and leakage through substrate.

### **1.4.1 Current collapse**

The microwave output power of an AlGa<sub>N</sub>/Ga<sub>N</sub> HFET has been observed to considerably deteriorate after long-term application of large DC voltages or under nominal microwave operating conditions [17], [18]. It has been speculated that these stressing schemes lead to the injection of hot carriers from the channel to the deep surface states in the high electric-field regions of the channel [18]. Trapping of these hot carriers leads to reduction in drain current of the device, which consequently degrades the microwave output performance. This phenomenon is referred to as current collapse or current slump and is described further in chapter 2.

Through improvement of crystalline quality of the HFET structure and electrically satisfying the surface traps by incorporation of a surface passivation layers it has been attempted to reduce these effects [19], [20]. Silicon nitride passivation has been shown to possess the ability of reducing the effects of these surface states [20-25]. Recently, a new technique has been investigated to suppress the current collapse by using polycrystalline AlN passivation layer [26]. The larger thermal conductivity of AlN, is also enticing due to its capability of boosting the maximum operating conditions dictated by the channel temperature [26], [27], [28].

### **1.4.2 Gate leakage**

High gate leakage-current is another drawback for AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs which should be reduced to suppress their power consumption and noise. Mechanisms of gate leakage current of these devices are not fully understood yet. Different mechanisms such as trap-

and defect-assisted tunnelling, barrier-thinning caused by charge trapping, and hopping through dislocations among others have been counted responsible for this excessive gate leakage. According to these explanations, existence of a distributed band of traps located within the barrier height of the AlGa<sub>N</sub> barrier acts as the facilitator in tunnelling through the barrier [29], [30], [31]. Surface roughness has also been shown to be a major player in this regard [32].

### **1.4.3 Leakage through substrate**

Lattice mismatch and difference between thermal expansion coefficients of epitaxially-grown III-Nitride layers and common substrates such as sapphire, Si, and SiC lead to high defect densities within these structures [13]. This is a limiting factor on the performance of these devices. The impacts of these imperfections are often observed in terms of unintentional doping of the buffer layer which results in soft pinch-off and leakage through this layer. Better device performance is expected when using the lattice-matched GaN substrate. Commercially available GaN substrates are currently being grown by Hydride Vapour Phase Epitaxy (HVPE) [33], [34]. However, still on these substrates presence of oxygen impurities causes n-type conductivity and substrate leakage. Transition metal doping can be used to change the conductive substrate into a semi-insulating substrate which can suppress the leakage current through substrate [35].

## **1.5 Overview of thesis**

Current collapse is one of the most important reliability concerns of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs,

which degrades the output performance of the device. Thus, incorporation of the impacts of the surface trap states in modeling these devices is vital. Furthermore, incorporation of full transport characteristics of GaN plays an important role in modeling these devices. My motivations for this study have been the incorporation of these features in an analytical model.

In chapter 2 of the thesis an assured simulation of AlGa<sub>N</sub>/Ga<sub>N</sub> HFET including the impact of electron trapping at deep surface states with the use of CADtool Medici® is performed. Medici® in its present form is not programmed for modeling the behavior of polar Ga<sub>N</sub> based heterostructures, as a result material parameters of Ga<sub>N</sub> and AlGa<sub>N</sub> and polarization terms are manually defined and can be found in appendix A.

In chapter 3, an analytical model for drain-current characteristic of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs with incorporation of inflexion points and steady-state velocity overshoot is presented. The wide peak and pronounced inflexion points in the transport characteristics of AlGa<sub>N</sub>/Ga<sub>N</sub> heterojunctions are modeled through considering a drift-diffusion channel rather than a drift-only transport channel. Simulation results have been compared to a non-diffusion type channel implemented with the assumption of the transport model in which manifestations of these transport characteristics have been neglected. The proposed model is based on applying an iterative approach between Poisson's equation and current-continuity equation. This relieves the results from the burden of the choice of fitting parameters.

Conclusions of this work and some suggested future works are presented in chapter 4.

# Chapter 2

## Impacts of Charge Trapping at the Surface States on Drain-Current of AlGaN/GaN HFETs

### 2.1 Introduction

GaN crystals suffer from a large variety of imperfections caused by contributing factors such as residual impurities [36] and presence of screw and threading dislocations among other factors [37]. The major cause of these non-idealities is the lack of a viable native substrate. While GaN substrates are currently being developed, the small size of these substrates has so far prevented them from becoming commercially viable [16], [38], [39], [40]. The lattice mismatch between GaN and commercially used substrates of this technology, such as SiC, sapphire, and Si, is the main reason for the defect formation in AlGaN/GaN HFETs. Lattice mismatch for GaN on SiC, sapphire, and Si are 3.5%, 14.5%, and 17%, respectively [41].

Crystal imperfections have been pointed out as the cause of many reliability concerns in this technology such as drain-current collapse, gate lag, and excessive gate leakage current. Drain-current of these devices is often observed to either lag behind the gate pulse (which is referred to as gate lag) or to undergo a collapse after application of bias and/or microwave signal to the gate (which is referred-to as current collapse). Current collapse and reliability degradation due to electron trapping at the surface layer of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs are major impediments for commercialization of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs [42].

Current collapse is a trap-related phenomenon which was first reported in an AlGa<sub>N</sub>/Ga<sub>N</sub> HFET grown on a sapphire substrate by Khan *et al.* [43]. Current collapse reduces the maximum drain-current and increases the knee voltage often after the application of a high drain-source bias. This phenomenon leads to reduced microwave output power performance of the device [44], [45]. Hot carrier migration from the channel to surface and trapping at deep acceptor-type surface states is often discussed as one of the causes of drain current collapse of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs [46]. Trapping of hot carriers can also happen at the AlGa<sub>N</sub>/Ga<sub>N</sub> interface or within the Ga<sub>N</sub> buffer [47]. To reduce the extent of current collapse, it has been shown that by properly introducing a surface passivation layer, current collapse can be significantly reduced [24], [25], [26], [27]. This is indicative of the role of surface traps of the gate drain access region in this process [48].

Due to negative charging of the acceptor-type surface states, surface potential in the gate-drain access region becomes negative, which leads to a loss of carriers concentration in the channel and eventually results in extension of the gate depletion

region [48], [49]. This phenomenon can be seen as the creation of a virtual secondary gate in tandem with the main gate of an HFET. In this analogy, electron accumulation in trap centers forms a negatively biased virtual gate in the drain access region immediately after the gate electrode. Pinching impact of this virtual gate on the channel causes the drain-current to reduce. The potential of this virtual gate is decided through the concentration of trapped charges in the surface of the gate-drain access region. In this case drain-current is controlled not only by the applied voltage to the metallic gate but also by the charge trapping/de-trapping process of the virtual gate.

Depending on the energy depth of these surface state, it has been reported that current collapse can either be a transient (i.e. due to shallow traps), or a semi-permanent phenomenon (i.e. due to deep traps) [17], [50]. In the first form, it has been observed that depending on the frequency response of these transients, they can have very decisive impacts on extensively reducing the microwave power gain of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs through shrinking their dynamic load line while having almost no impact on their DC current characteristics [51].

Even though there have been remarkable improvements in crystal growth and device fabrication technology, trapping effects in AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs, under high drain voltage conditions, have not been completely removed. Therefore, an assured simulation of HFET including trapping effects is needed. In this part of the thesis, impact of electron trapping at deep surface states which is based on a steady-state model is studied with the use of CADtool Medici®.



## **2.2 Medici simulation and modeling of AlGa<sub>N</sub>/Ga<sub>N</sub>**

### **HFETs**

This chapter is focused on simulating the drain current-voltage characteristics of AlGa<sub>N</sub>/Ga<sub>N</sub> HFET with the use of CADtool Medici. These characteristics are studied with and without consideration of charge trapping at the surface of drain access region. Medici is a two-dimensional numerical based device simulator from Synopsys [52]. While this software in its present form is not programmed for modeling the behaviour of polar AlGa<sub>N</sub>/Ga<sub>N</sub> heterostructures, the polarization terms and other material parameters of Ga<sub>N</sub> and AlGa<sub>N</sub> are manually defined by incorporating fixed charge concentrations at the surface and the heterointerfaces and also by replacing the material parameters of AlGaAs/GaAs system with those of AlGa<sub>N</sub>/Ga<sub>N</sub>. The definition of polarization through incorporating layers of fixed charge at surface and heterointerface is performed according to the reported strategy of Ambacher *et al.* [53]. Appendix A of the thesis contains the material-parameter files used for the re-definition of AlGaAs/GaAs system with AlGa<sub>N</sub>/Ga<sub>N</sub> parameters. These data are chosen from semiconductor characteristics data base of the Ioffe Physico-Technical Institute [4].

#### **2.2.1 Introduction to Medici**

Medici, through numerically solving of Poisson, current-continuity, and transport equations, models the two-dimensional (2D) distributions of potential and carrier concentrations in a device and can be used to predict the electrical characteristics for

arbitrary bias conditions [52]. In a Medici simulation through the definition of the following parameters a 2D device is represented:

- Mesh definition with regards to cross-sectional dimensions of the device.
- Definition of the doping types and profile in each region.
- Contact placement with regard to mesh point.
- Definition of metal work function.
- Definition of charge trapped profiles.
- Recalling the appropriate mobility model with regard to the expected type of simulation.
- Defining the tolerance for convergence.
- Application of bias and generation of the desired output characteristics.

In representing the polar AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs, as it was mentioned earlier, a few more steps should be taken in order to define a device:

- Define a fixed charge layer to have appropriate polar 2DEG electron concentration at AlGa<sub>N</sub>/Ga<sub>N</sub> heterointerface.
- Re-define the parameters of another material system such as AlGaAs/GaAs to represent AlGa<sub>N</sub>/Ga<sub>N</sub>, by recalling the material parameters for their binaries.

In order to guarantee the convergence of the numerical simulation, denser grid points should be defined in areas that electric-field has the greatest variation. In a FET, this happens at the drain edge of the gate.

The other deficiency of Medici is in defining Ohmic contacts to an AlGa<sub>N</sub>/Ga<sub>N</sub> HFET. This is partly due to the lack of concrete information on the tunnelling behaviour of AlGa<sub>N</sub>. The other contributing factor is that the Ohmic contacts of III-V technologies,

unlike silicon, rather than being of tunnelling type are created through alloy formation caused by Rapid Thermal Annealing (RTA). Full representation of this chemical process is not possible in Medici. However, assumption of a highly doped GaN layer between the metallic contacts of source and drain and AlGaN barrier is assured enough for the definition of Ohmic contacts. The device structure is further elaborated in section 2.2.3.

## 2.2.2 Numerical simulation using Medici

After defining the mesh for every grid point a set of fundamental semiconductor equations (i.e. Poisson's equation, current-continuity equations, and transport equations) will be solved. The electric behaviour of the device is governed by Poisson's equation (2.1) and continuity equations (2.2 and 2.3):

$$\nabla^2\phi = -\nabla \cdot \mathbf{E} = -\frac{\rho}{\epsilon} = -\frac{q}{\epsilon_s}(p - N_A^- - n + N_D^+) \quad (2.1)$$

where  $\phi$ ,  $\mathbf{E}$  and  $\rho$  are intrinsic Fermi potential, electric-field, and charge density, respectively. In this equation  $q$  is the charge of an electron,  $\epsilon_s$  is the permittivity of the semiconductor,  $p$  and  $n$  are free hole and electron concentration,  $N_A^-$  and  $N_D^+$  are the acceptor and donor ionized impurity concentrations. The continuity equations are given by:

$$\frac{\partial n}{\partial t} = \frac{1}{q} \vec{\nabla} \cdot \vec{J}_n - (R_n - G_n) \quad (2.2)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \vec{\nabla} \cdot \vec{J}_p - (R_p - G_p) \quad (2.3)$$

$G$  and  $R$  are generation and recombination rates, respectively (subscripts  $n$  and  $p$  refer to electrons and holes).  $J_n$  and  $J_p$  are the current density of electrons and holes, respectively.

Transport equations based on Boltzmann's transport theory are expressed by:

$$\vec{J}_n = q\mu_n \vec{E}_n n + qD_n \vec{\nabla}n \quad (2.4)$$

$$\vec{J}_p = q\mu_p \vec{E}_p p - qD_p \vec{\nabla}p \quad (2.5)$$

where  $\mu_n$  and  $\mu_p$  are the electron and hole mobilities and  $D_n$  and  $D_p$  are the electron and hole diffusion coefficients, respectively. Through self-consistent numerical solution of these equations according to the finite element technique, the current characteristic of each electrode, electric-field, and band diagram at any given location across the device can be plotted among any number of other electrical parameters [52].

In this simulation, an AlGa<sub>N</sub>/Ga<sub>N</sub> HFET has been investigated under two situations: (1) Before stress and (2) After stress. It has been attempted to re-produce the experimental observation of Valizadeh *et al.* [46] concerning the role of electron trapping of hot carriers at the surface states in semi-permanent collapse of drain-current. Their observations on electron trapping, resulted by long-term bias stressing, were supported by the recovery of drain current only upon illumination of the surface of HFETs with UV light [54]. Electron de-trapping from the surface states is caused by the energizing impact of the UV light. Because of the deep energy level of these observed traps, they had not observed any recovery in room light which has a low UV content [55].

## 2.2.3 Device structure

Although in polar AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs barrier doping unlike other III-V HFETs is not required [53], presence of moderate levels of unintentional doping (i.e. in the order of high  $10^{15} \text{ cm}^{-3}$ ) in the barrier and Ga<sub>N</sub> buffer will leave their signatures on the device characteristics such as sub-threshold current and output resistance. As a result, in order to

provide the best match to the experimental drain current-voltage characteristics, experimentation with a range of unintentional doping levels has been carried out.

In addition, in definition of fixed polar charge layers at the heterointerface, fine tuning of the charge concentration have been required to provide the best match. The key point in this definition is avoiding the pinning of Fermi level due to the high concentration of these 2D charge concentrations.

The other factor that requires tuning is the thickness of the buffer layer. While, the maximum number of grid point in Medici is 2400, the scale difference between the thick buffer layer (i.e. of micron size) and region of the device with highest variation of electric-field (i.e. of nano size) prevents us from having sufficient number of point in the buffer layer, if the full thickness of it is considered. To avoid this issue, a balance needs to be maintained between the reduced thickness of this layer in simulation and reduction of its doping level from what these values are in reality. This will essentially maintain the same resistance between the channel and the back contact of the device.

Different devices have been investigated to create the best agreement with the experimental results. The experimental results have been borrowed from the work of Valizadeh *et al.* [46]. As shown in Figure 2.1, the device structure is defined by a 0.68  $\mu\text{m}$  thick GaN buffer/channel layer, followed by a 2.5 nm AlGaIn spacer layer, and a 15 nm AlGaIn barrier layer. In definition of polar charge at the GaN-side of the AlGaIn/GaN heterointerface, rather than a 2D sheet charge a more assured Gaussian profile is defined to incorporate also the impact of quantum capacitance [56]. Effective thickness of 2DEG is assumed to be 2 nm [57]. The device has a gate length (i. e.  $L_G$ ) of 0.25  $\mu\text{m}$  and gate

width (i.e.  $W$ ) of 200  $\mu\text{m}$ . The gate to drain spacing (i.e.  $L_{GD}$ ) and gate to source spacing (i.e.  $L_{GS}$ ) are 1.875  $\mu\text{m}$  and total length of the device is assumed to be 25  $\mu\text{m}$ . Most of this length is provided to create acceptable drain and source Ohmic contacts to the 2DEG. Figure 2.1 shows a cross sectional view of the simulated device with source, gate and drain on top. Table I shows the device parameter used in simulation, unless identified otherwise.

According to the predictions of Valizadeh *et al.* [46], charge trapping at the surface states of the gate side of drain access region is responsible for reduction of drain-current upon bias stressing. This region is also identified on Figure 2.1. Trapping parameters that are later used in this chapter for inclusion of this effect are identified in Table 2.1. In this table the values for body doping, body thickness, delta doping, channel doping, barrier doping, trap layer thickness, trap layer length, trap layer doping, trap concentration are chosen on trial and error basis.

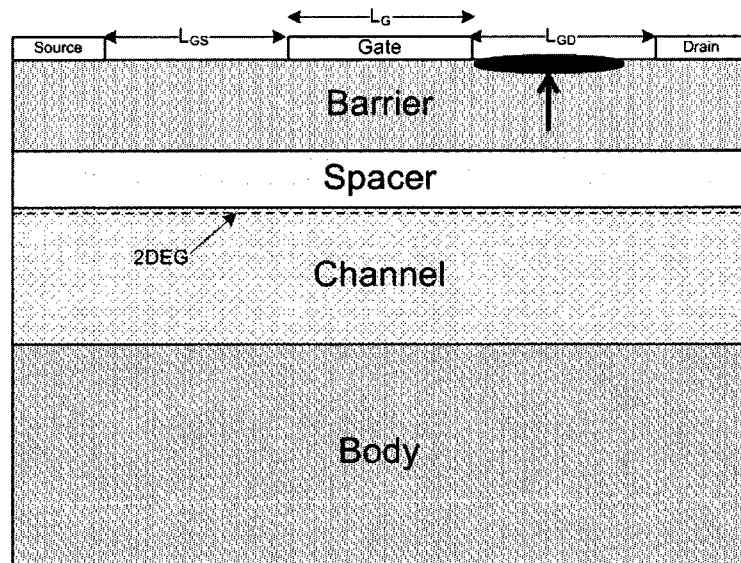


Figure 2.1: Schematic cross section of the presented AlGaIn/GaN HFET. Region of the surface with charge trapping is marked with the oval (figure is not in scale).

Table 2.1: Parameter used in simulation.

Simulation parameter	Value
Body thickness	0.68 $\mu\text{m}$
Channel thickness	0.002 $\mu\text{m}$
Barrier thickness	0.015 $\mu\text{m}$
Spacer thickness	0.0025 $\mu\text{m}$
Channel length	0.25 $\mu\text{m}$
Total length	25 $\mu\text{m}$
Gate drain spacing	1.875 $\mu\text{m}$
Body doping	$10^5 \text{ cm}^{-3}$
Channel doping	$10^{15} \text{ cm}^{-3}$
Barrier doping	$6 \times 10^{17} \text{ cm}^{-3}$
Spacer doping	$10^{16} \text{ cm}^{-3}$
Maximum 2DEG electron concentration	$10^{13} \text{ cm}^{-2}$
Delta doping	$3.1 \times 10^{20} \text{ cm}^{-3}$
Trap layer thickness	0.011 $\mu\text{m}$
Trap layer length from gate-edge	0.056 $\mu\text{m}$
Trap layer doping	$10^{15} \text{ cm}^{-3}$
Trap concentration	$5.5 \times 10^{14} \text{ cm}^{-2}$
Gate metal work function	5.17 eV

As it was mentioned earlier in chapter 1, due to spontaneous and piezoelectric polarization effects, a high concentration 2DEG exists at the AlGa<sub>N</sub>/Ga<sub>N</sub> interface even without intentional doping of the barrier. In order to take this effect into account and have an assured prediction of the drain current characteristic of the device, a fixed positive sheet charge profile at the barrier side of the AlGa<sub>N</sub>/Ga<sub>N</sub> heterointerface has been defined in conjunction with the 2DEG which is defined at the Ga<sub>N</sub> side of this heterointerface. Density of the positive fixed charge is assumed to be  $1 \times 10^{13} \text{ cm}^{-2}$ .

In this simulation, a longitudinal field dependent mobility is used. This is done by using “Analytic” expressions for the drift-velocity as a function of the electric-field in the direction of current flow (i.e.  $E_{||}$ ) which is given by:

$$\mu(E_{||}) = \frac{v(E_{||})}{E_{||}} \quad (2.6)$$

A “gallium arsenide-like” mobility model is used with the use of appropriate changes in electron transport parameters to provide the maximum similarity with GaN electric-field vs. drift-velocity relationship [52]. These parameters have been redefined through importing the two input files of Appendix A to Medici. These data are taken from the database of Ioffe Physico Technical Institute [4].

## **2.2.4 Simulation results and conclusions**

Medici input files of these simulations are provided in appendix B. File 1 has been used for simulating the fresh output characteristics and file 2 is used for simulation of the output characteristics of the stressed device.

### **2.2.4.1 Before stress**

Figure 2.2 illustrates the cross sectional view of the device simulated by Medici including the current flow of the device before stress for a set of  $V_{GS}$  and  $V_{DS}$  values. The inset of this figure, illustrates a magnified view of the current flow lines in the 2DEG channel. Compression of flow lines in the 2DEG and not in the barrier and buffer layer is indicative of the acceptable formation of an HFET channel. This simulation is run by the use of input file 1, which is reported in Appendix B.



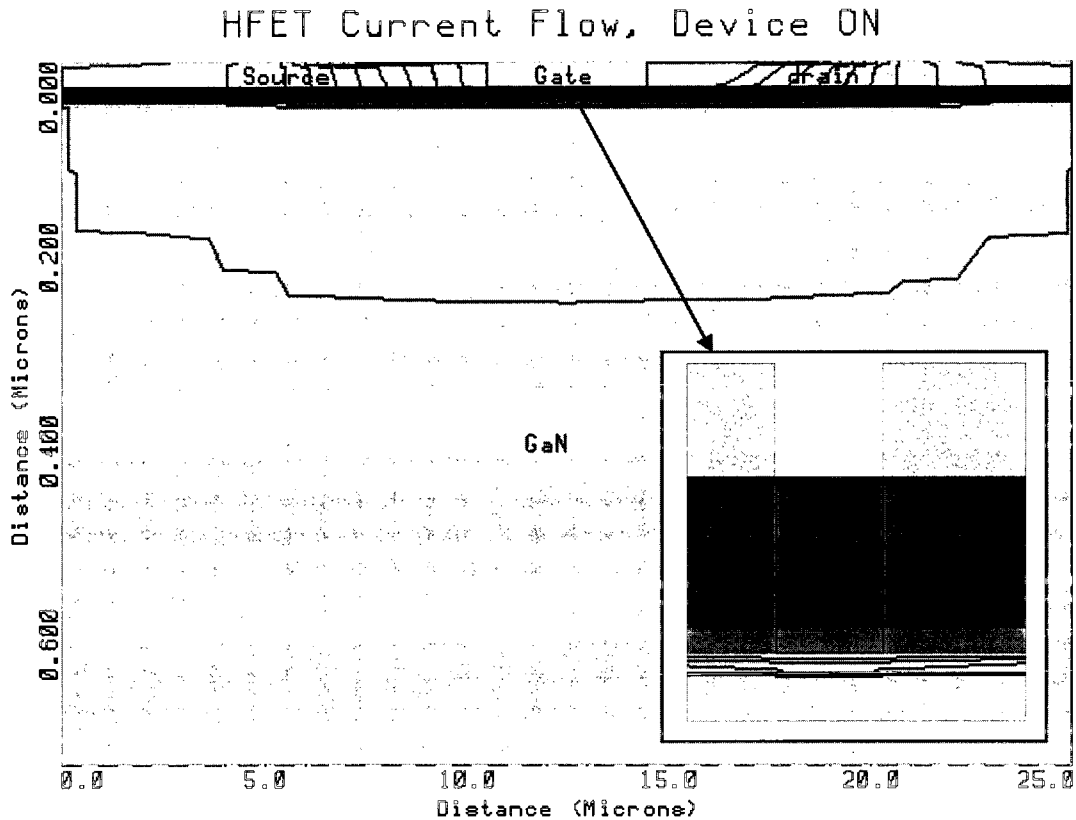
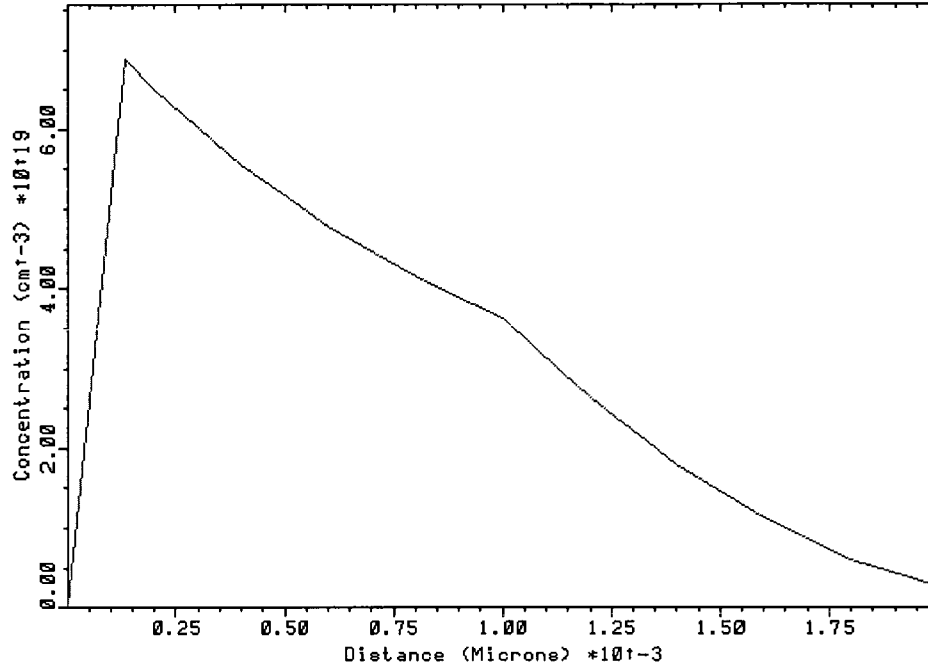


Figure 2.2: Schematic cross section of the presented AlGaIn/GaN HFET illustrating current flow before stress for  $V_{GS}=0$  V and  $V_{DS}=0.05$  V.

In support of the formation of an HFET-type channel at AlGaIn/GaN heterointerface, Figure 2.3 show the electron concentrations in the channel under the gate-drain access region (a) and gate electrode (b) along the direction normal to the heterointerface. These concentrations are provided at the same bias points as the data of Figure 2.2. Reduced peak of concentration in Figure 2.3(b) is indicative of the depleting effect of the metal gates. Oftentimes, by shrinking the thickness of the barrier, this depletion effect of the Schottky barrier on 2DEG charge is used to turn the normally depletion-type (i.e. negative threshold voltage) characteristics of AlGaIn/GaN HFETs to enhancement type (i.e. positive threshold voltage) [58].

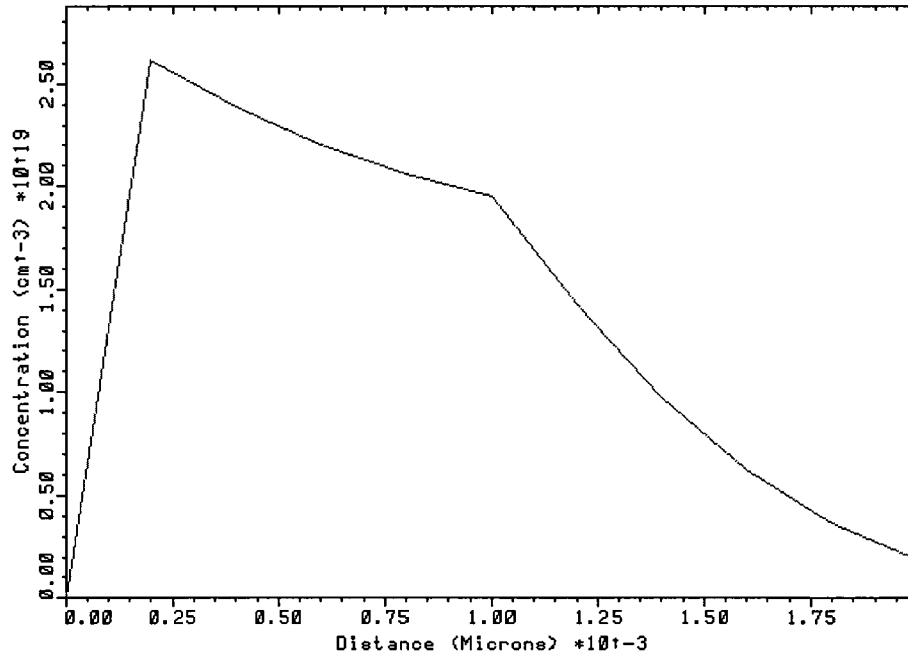
Unlike inversion type n-Metal Oxide Semiconductor Field Effect Transistor (n-MOSFET), the channel of an HFET is not normally formed due to the positive biasing of the gate. The origin of the channel charge concentration in HFETs is either the modulation doping or for the case of AlGa<sub>N</sub>/Ga<sub>N</sub> HFET is the polarization nature of the heterointerface. As a result, HFETs are normally “on” at zero gate voltage (i.e. depletion-type), unless the 2DEG is depleted either by the depleting effect of the gate Schottky contact or engineering of the polarization terms and barrier doping.

AlGaN/GaN HFET before stress



(a)

AlGaN/GaN HFET before stress



(b)

Figure 2.3: Electron concentration (cm<sup>-3</sup>) of the channel under the gate-drain access region (a) and gate (b) along the direction perpendicular to device surface for  $V_{GS}=0$  V and  $V_{DS}=0.05$  V. Device surface is assumed to be at  $x=0$ .

Figure 2.4 illustrates energy-band diagram before stress under the gate-electrode, along the direction normal to the heterointerface. The inset shows the zoomed-in view of this band diagram at the vicinity of the heterointerface.

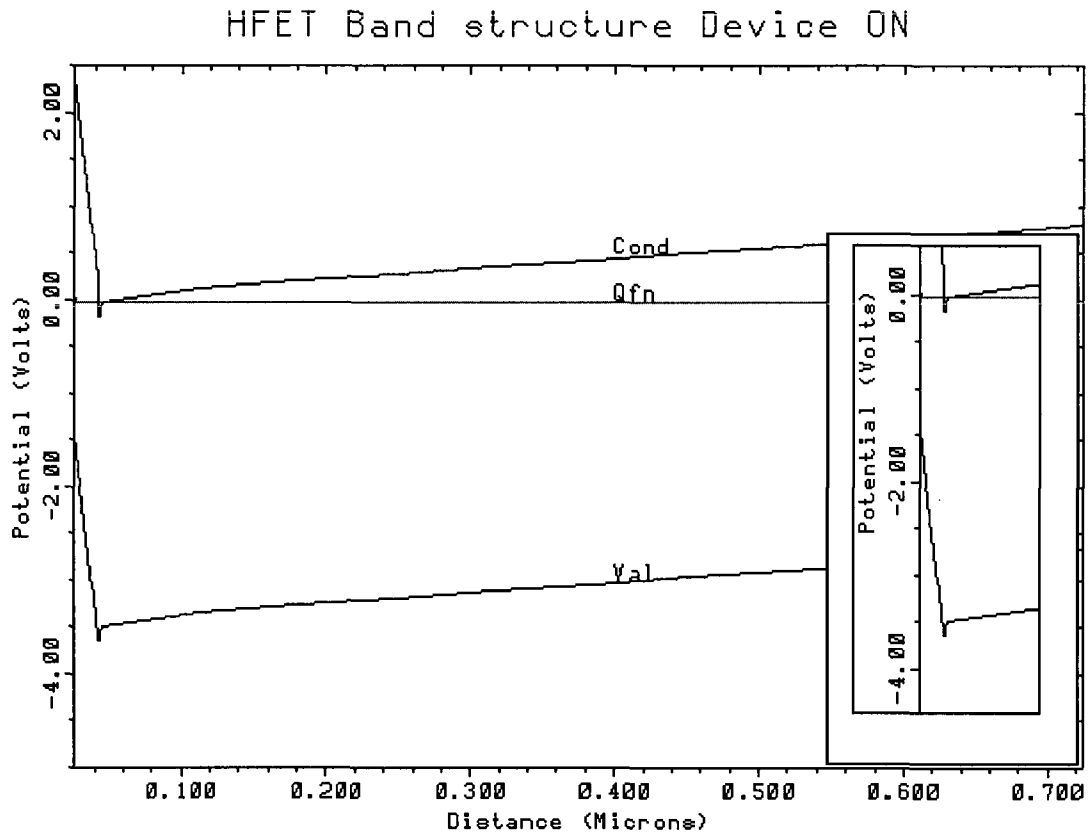


Figure 2.4: Energy-band diagram under the gate along vertical direction for  $V_{GS}=0$  V and  $V_{DS}=0.05$  V.

Inset: The zoomed-in view of this energy-band diagram at the vicinity of the heterointerface.

Figure 2.5 illustrates the comparison between the simulation results and an experimental set of drain  $I/V$  characteristics for the device before stress. Measurements data are from an AlGaIn/GaN HFET grown by molecular beam epitaxy (MBE) on a SiC

substrate [46]. The device had two gate fingers with a gate length of  $0.25 \mu\text{m}$  and a gate finger width of  $100 \mu\text{m}$ . As shown in this figure, a good match is achieved to the experimental values. In the next section, this agreement is used as the basis for the validity of the prediction of surface-charge trapping in substantiation of the post bias-stress characteristics of the same AlGaIn/GaN HFET [46].

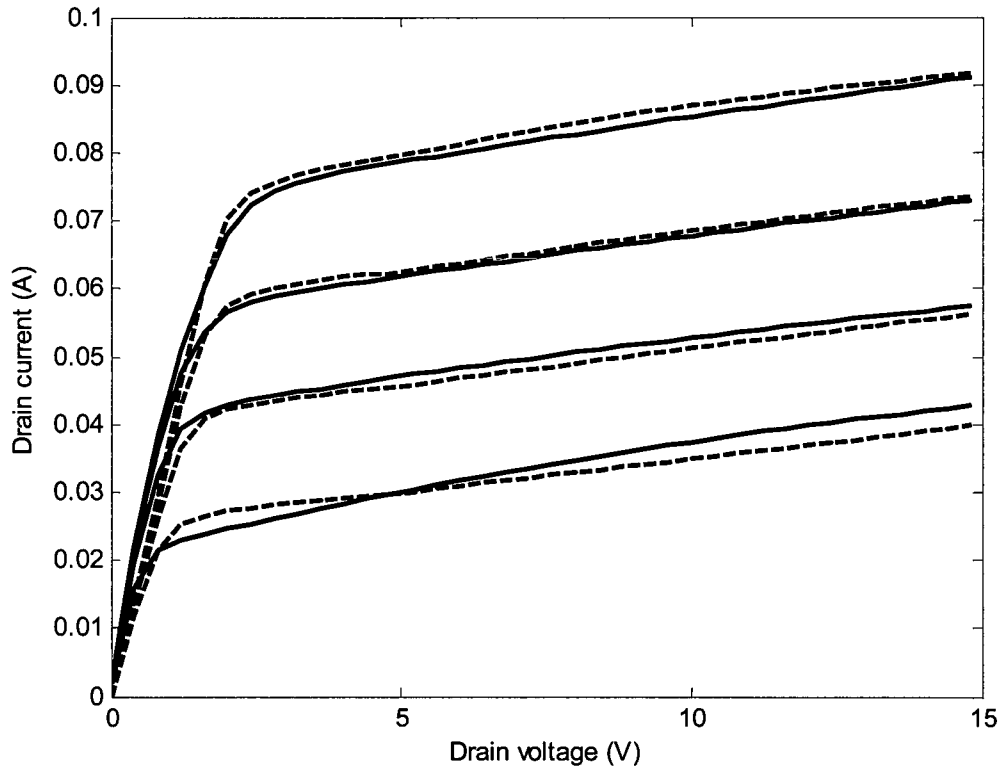


Figure 2.5: I-V characteristics of simulation result (solid line) versus experimental data (dashed line) with the assumption of  $L_G=0.25 \mu\text{m}$  and  $L_{GD}=1.875 \mu\text{m}$  for  $V_{GS}=-1.8 \text{ V} \sim -3 \text{ V}$  with the step of  $0.4 \text{ V}$  (before stress).

### 2.2.4.2 After stress

To incorporate the surface charge-trapping effect in the form proposed by Valizadeh *et al.* [46], a thin uniformly doped acceptor-type trap layer has been assumed at the surface of the drain access region. Through trial and error, appropriate values for length,

thickness, doping profile, and interface trap concentration have been chosen to create the best agreement with experimental drain I/V characteristics. This simulation is run by the use of input file 2, which is reported in Appendix B. As it is shown on Figure 2.6, incorporation of this negatively charged surface layer at the gate-side of the drain access region causes the pinching of current flow lines. This can be better seen through comparing the flow lines of this figure to flow lines of this region on Figure 2.2. Figures 2.2 and 2.6 are produced at the same bias point.

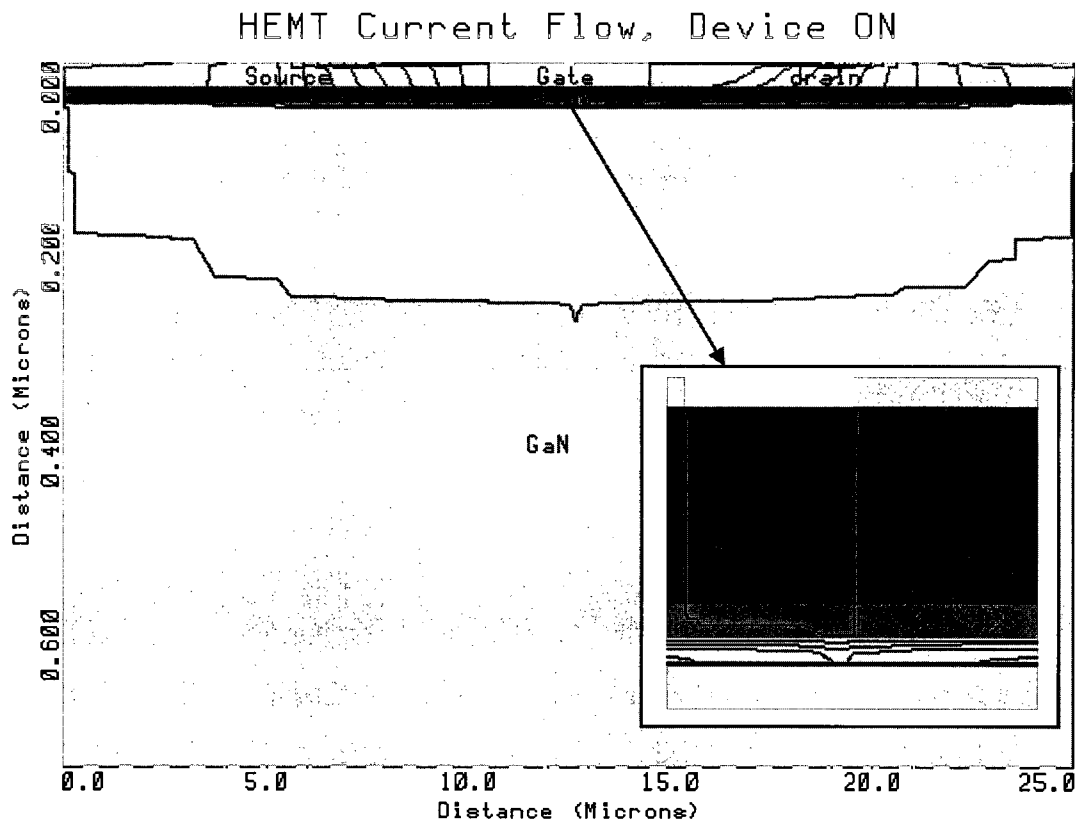
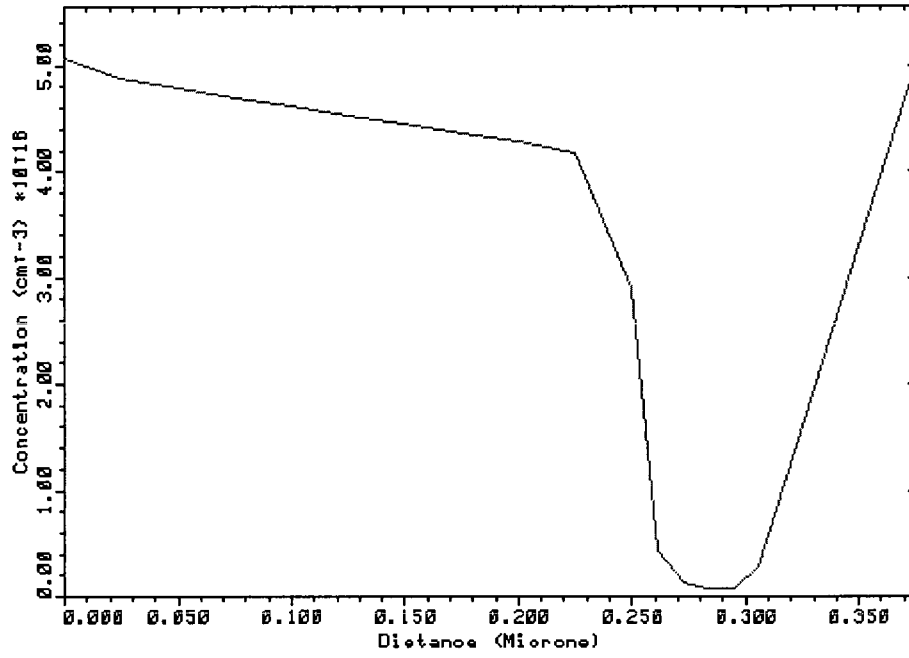


Figure 2.6: Schematic cross section of the presented AlGaIn/GaN HFET illustrating current flow after stress for  $V_{GS}=0$  V and  $V_{DS}=0.05$  V.

Figure 2.7 illustrates the electron concentration along the channel for different gate voltages and  $V_{DS}=5$  V. These concentrations are calculated at the peak position of the 2DEG concentration. Results show a significant loss of carrier concentration under

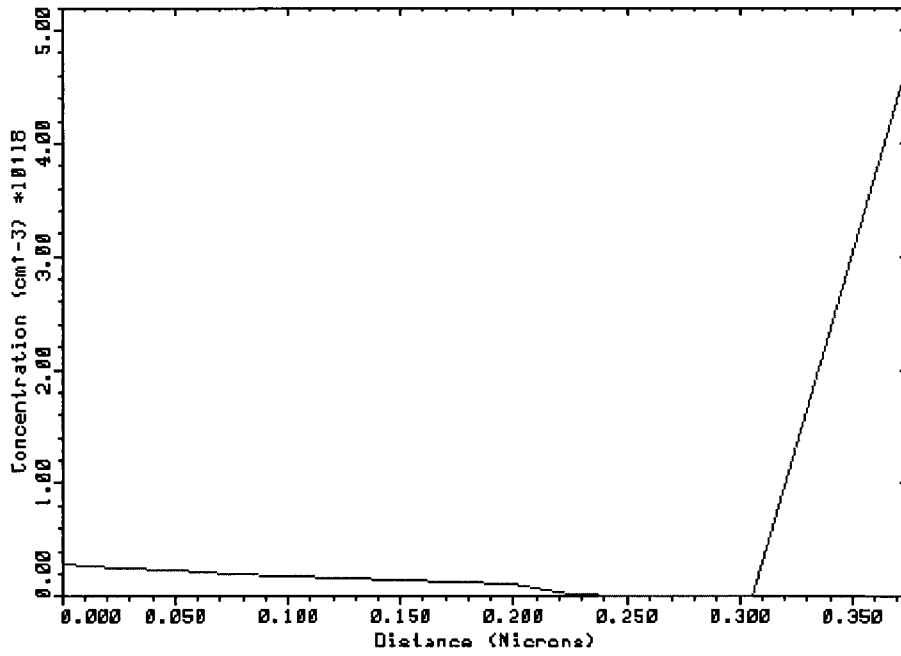
the gate-drain access region. This is due to the incorporation of the negatively charged surface trap layer at the surface of AlGaN barrier in this region. It can be seen that the charge depletion under the gate which was earlier observed on Figure 2.3(c), due to this effect extends towards the drain electrode as the gate voltage approaches the pinch-off voltage. This impact is often reported in terms of the formation of a secondary virtual gate in tandem with the main gate [59].

AlGaIn/GaN HFET after stress



(a)

AlGaIn/GaN HFET after stress



(b)

Figure 2.7: Electron concentration in the channel of the device for  $V_{GS} = -0.15$  V (a) and  $V_{GS} = -3$  V (b) along the longitudinal direction.  $V_{DS}$  is equal to 5 V. Source edge of the gate is assumed to be at  $x = 0$ .



Figure 2.8 illustrates the electric-field along the channel for the device after stress.

As is expected the peak electric-field occur at drain edge of the gate.

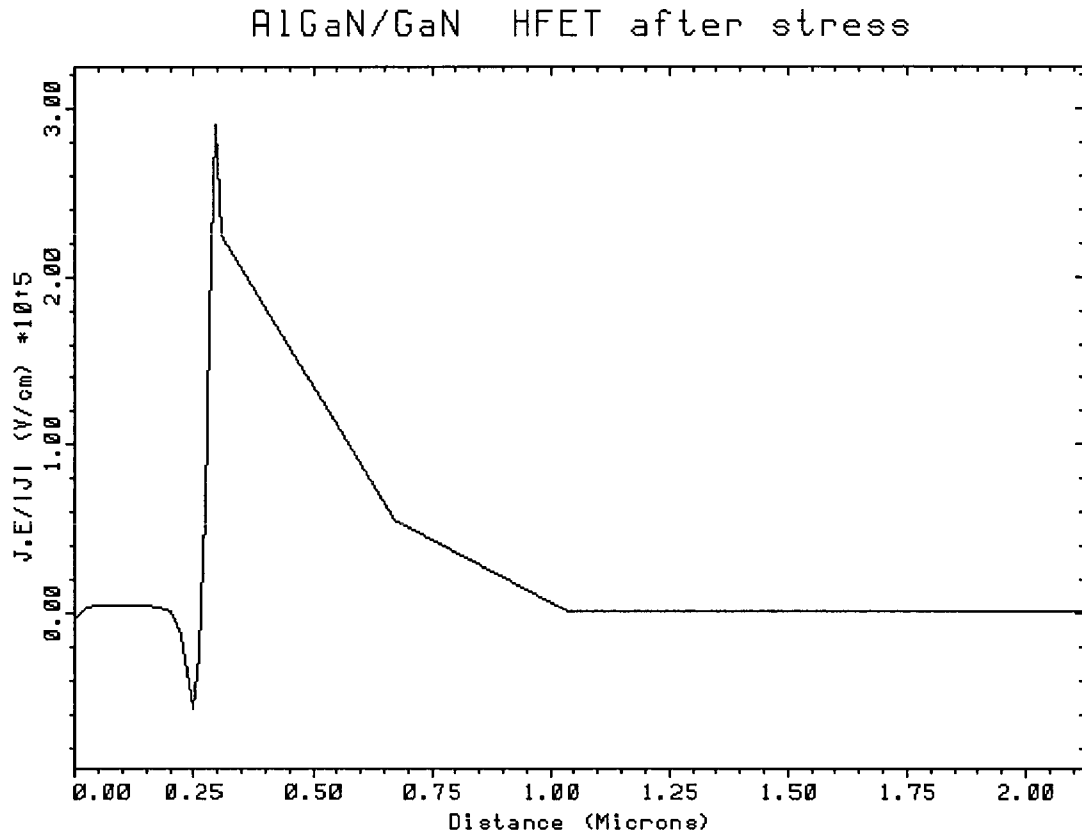


Figure 2.8: Electric-field along the channel after stress for  $V_{GS}=-1.8$  V and  $V_{DS}=5$  V. Source edge of the gate is assumed to be at  $x=0$ .

In Figure 2.9, simulation results for I-V characteristic of the device after stress have been compared with experimental data borrowed from [46]. The acceptable agreement between the simulation and experiment validates the speculations of Valizadeh *et al.* [46] on the role of acceptor-type surface traps on drain-current collapse of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs.

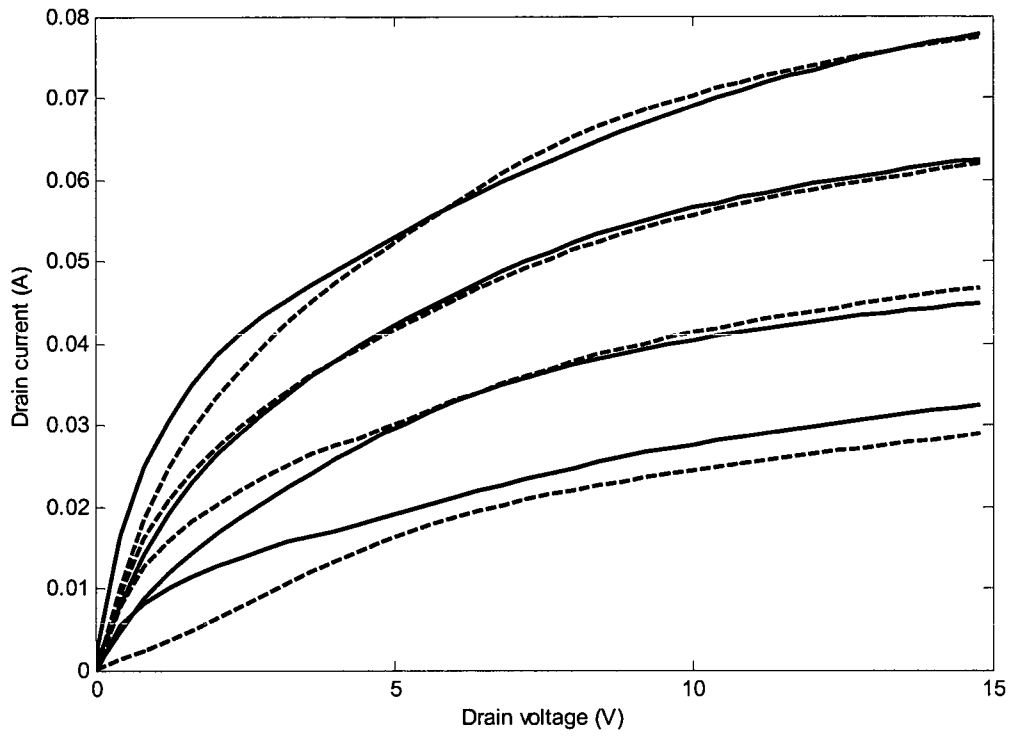


Figure 2.9: I-V characteristics of simulation result (solid line) versus experimental data (dashed line) with the assumption of  $R_s=0 \Omega$ ,  $R_d=0 \Omega$ ,  $L_G=0.25 \mu\text{m}$ , and  $L_{GD}=1.875 \mu\text{m}$  for  $V_{GS}=-1.8 \text{ V} \sim 3 \text{ V}$  with the step of  $0.4 \text{ V}$  (after stress).

# **Chapter 3**

## **Analytical Modeling of Drain-Current Characteristics of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs with Incorporation of the Impacts of Inflexion Points and Steady-State Velocity Overshoot**

### **3.1 Abstract**

An analytical model for drain-current characteristic of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs with incorporation of steady-state velocity overshoot and the inflexion points in the electronic drift transport characteristics is presented. Manifestations of these transport characteristics are usually neglected in modeling the drain-current of III-V HFETs. However, significance of these features in AlGa<sub>N</sub>/Ga<sub>N</sub> material system compared to other III-V technologies requires re-evaluation of this policy. Although for the current

state of the art these features are masked by the parasitic features such as the drain and source contact resistance, by further improvement in the device fabrication technology and reliability of these devices they will deserve further attention. The wide peak and pronounced inflexion points in the transport characteristics of AlGa<sub>N</sub>/Ga<sub>N</sub> heterojunctions are modeled through considering a drift-diffusion channel rather than a drift-only transport channel. Simulation results have been compared to a non-diffusion type channel implemented with the assumption of Ridley's mobility model. The current model is based on applying an iterative approach between Poisson's equation and current-continuity equation. This relieves the results from the burden of the choice of fitting parameters.

## 3.2 Introduction

Polar III-Nitride semiconductors, including AlGa<sub>N</sub>/Ga<sub>N</sub> heterojunction, due to their superb 2DEG concentration, high peak and saturation electron velocity, and wide band-gap have been the target of much attention over the past two decades. With improvements in material growth techniques [60], [61], device fabrication [62], and long-term reliability [63], an increasing need is being felt for development of models that will accurately incorporate particular features of this material system.

The study of Bhapkar *et al.* reveals that in addition to the steady-state velocity overshoot there exists a pronounced kink in the low electric-field region of the drift-velocity versus electric-field characteristics (i.e.  $v_d - E$ ) of Ga<sub>N</sub> [64]. Existence of the inflexion points attributed to this kink and the large width of the overshoot pattern in conjunction with the large electric-fields conventionally applied to this wide band-gap

semiconductor, make the modeling of electronic devices fabricated in this technology different than those of other III-V semiconductors.

In the present work, the influence of the particular  $v_d - E$  characteristics of GaN on drain-current characteristic of an AlGaIn/GaN HFET is modeled. Presence of these features dictates the formation of consequential electron bunching across the 2DEG channel, especially at high drain voltages. In the present model, variation of electron concentration across the channel is gauged with regards to Poisson's equation and current-continuity equation. The impact of the gradient in electron concentration is modeled by considering the diffusion current component in regions of the channel with electric-field values corresponding to low electric-field inflexion points and high electric-field negative differential mobility in the  $v_d - E$  characteristics.

The degree of complexity of the mobility model employed in a drift-diffusion transport problem is a determinant factor to the possibility of yielding either an analytical or a numerical solution. So far, several mobility models have been proposed or adopted for AlGaIn/GaN heterojunctions [65], [66], [67]. Simpler transport models such as Ridley's mobility model [66], which do not incorporate the steady-state velocity overshoot and inflexion points, yield easily solvable analytical models for drain current characteristics of HFETs [68]. However, more elaborate mobility models despite the burden of numerical solutions are worth studying for better projection of the impacts of transport properties on future-generation devices. To incorporate further details of the electronic drift transport of the AlGaIn/GaN 2DEG, such as inflexion points in low electric-field region and steady-state velocity overshoot under higher electric-fields, mobility model previously reported by Polyakov *et al.* [67] has been employed in the

present model. Due to the complexity of this mobility model, the analytical model only yields to numerical solutions.

The influence of parasitic contact resistance on drain-current characteristic of an AlGa<sub>N</sub>/Ga<sub>N</sub> HFET is also investigated. While, an ongoing research effort is pursued by many researchers to improve the Ohmic contact quality of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs [69], [70], the current state of the art of this technology still shows masking of transport features in the drain-current characteristics. In this study, the effectiveness of the present model in unveiling these features is revealed. The importance of these considerations is separately gauged for HFETs with self-aligned and non- self-aligned gates.

In section 3.3 details of the implementation of proposed model are presented. In section 3.4 results of the application of this mobility model to the AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs are presented with respect to the variation of source and drain parasitic contact resistance. These results have been compared to the outcome of the application of the model if Ridley's mobility model was implemented. Conclusions are presented in section 3.5.

### **3.3 Description of the model**

So far, drift transport characteristics of Ga<sub>N</sub> channels, predicted by Monte Carlo simulations [64], [71], [72], [73], to different degrees of approximation have been presented by a few analytical representations [65], [66], [67]. Among these models, Ridley's mobility model provides the most manageable framework for development of an analytical model for drain-current of HFETs [66]. For the current state of the art of this technology, shortcoming of this model in incorporating the steady-state overshoot of

drift-velocity has been deemed acceptable [68]. According to Ridley's drift transport model, electron drift-velocity (i.e.  $v(E)$ ) is determined in the form of a two-section model (in which  $v_s$  and  $E_s$  are the saturation velocity and electric-field at the onset of velocity saturation and  $v_0$  is the knee velocity):

$$v(E) = \begin{cases} v_0 E \frac{E + E_1}{E_1(E + E_0)} & E \leq E_s \\ v_s & E > E_s \end{cases} \quad \text{where } E_0 = \frac{v_0}{\mu_0} \quad E_1 = \frac{v_0}{\mu_1} \quad (3.1)$$

where  $\mu_0 = 1000 \frac{cm^2}{V.s}$ ,  $\mu_1 = 50 \frac{cm^2}{V.s}$ ,  $v_s = 1.4 \times 10^7 \frac{cm}{s}$

Figure 3.1, illustrates the drift-transport characteristics according to this model alongside with the predictions of the mobility model previously investigated by Polyakov *et al.* [67].

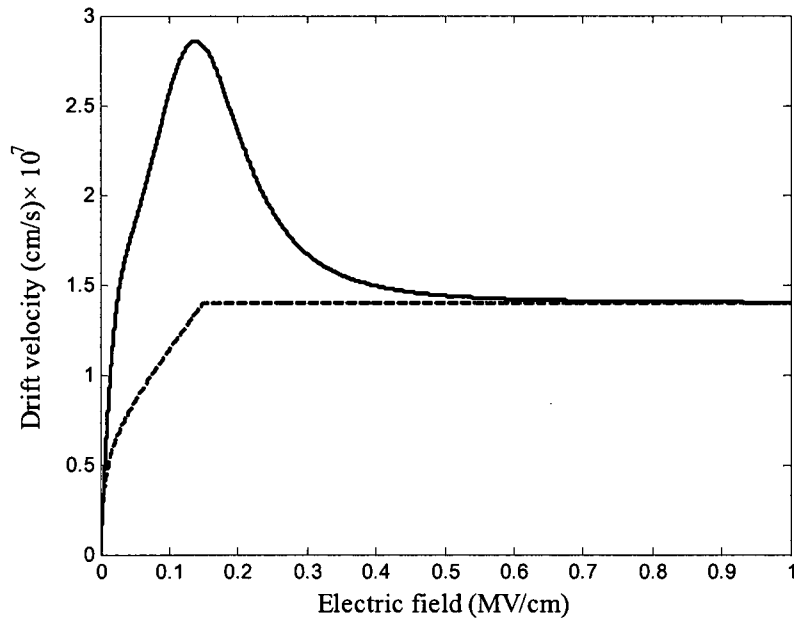


Figure 3.1: Drift-velocity vs. electric-field characteristic of the adopted mobility model (solid line) and Ridley's model (dashed line).

The latter model has been shown to correctly follow the inflexion points and steady-state velocity overshoot patterns envisioned by Monte Carlo simulations for this material system. Drift-velocity according to this mobility model is given by:

$$v(E) = \frac{\mu_0 E + \mu_1 E \left(\frac{E}{E_0}\right)^\alpha + v_{sat} \left(\frac{E}{E_1}\right)^\beta}{1 + \left(\frac{E}{E_0}\right)^\alpha + \left(\frac{E}{E_1}\right)^\beta} \quad (3.2)$$

where:

$$\mu_0 = 720 \frac{cm^2}{Vs}, \mu_1 = 234 \frac{cm^2}{Vs}, E_0 = 3.36 \times 10^4 \frac{V}{cm}, E_1 = 9.8 \times 10^4 \frac{V}{cm}$$

$$\alpha = 2.44, \beta = 7.45$$

The parameters of the model have been chosen to provide the maximum similarity to Monte Carol -based predictions of O'Leary *et al.* [73].

In the present work, the  $v_d - E$  relationship presented by (3.2) has been adopted to engage in studying the impact of the steady-state velocity overshoot and inflexion points observed in Figure 3.1, on drain-current characteristics of AlGaIn/GaN HFETs. This investigation has individually targeted devices with self-aligned gates and non- self-aligned gates in subsections 3.3.1 and 3.3.2 of this section, respectively. To extend the breakdown voltage of the device, AlGaIn/GaN HFETs, unlike inversion MOSFETs, are traditionally fabricated with non- self-aligned gates. To model an HFET with non- self-aligned gate, the device is broken into an un-gated HFET placed in tandem with an HFET of self-aligned gate. The influence of parasitic contact resistance is also included in this model through incorporation of contact resistance terms of source and drain (i.e.  $R_S$  and  $R_D$ , respectively). Table 3.1 shows the device parameters used for simulation, unless identified otherwise.



Table 3.1: Parameters used in simulation.

Symbol	DESCRIPTION	Value
$R_S$	Source contact resistance	5 $\Omega$
$R_D$	Drain contact resistance	5 $\Omega$
$L_{GD}$	Gate-drain spacing	1 $\mu\text{m}$
$L_G$	Gate length	0.25 $\mu\text{m}$
$W$	Device length	200 $\mu\text{m}$
$V_T$	Threshold voltage	-3.75 V
$d$	Barrier thickness	17.5 nm
$\Delta d$	2DEG thickness	2 nm
$\epsilon_r$	$\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ relative dielectric constant	8.78

### 3.3.1 Drain-current simulation of self-aligned HFET

Figure 3.2 schematically shows the cross section of the self-aligned AlGa<sub>0.3</sub>N/GaN HFET considered in modeling. The approach adopted in modeling the drain-current characteristic of a self-aligned HFET involves splitting of the channel into two regions:

- 1) Region I is referred to as the linear-region of the channel, along which the electric-field is smaller than the threshold electric-field corresponding to drift-velocity overshoot (i.e.  $E_{v\text{-max}}$ ).
- 2) Region II is referred to as the saturation-region of the channel, along which the electric-field is beyond  $E_{v\text{-max}}$ .

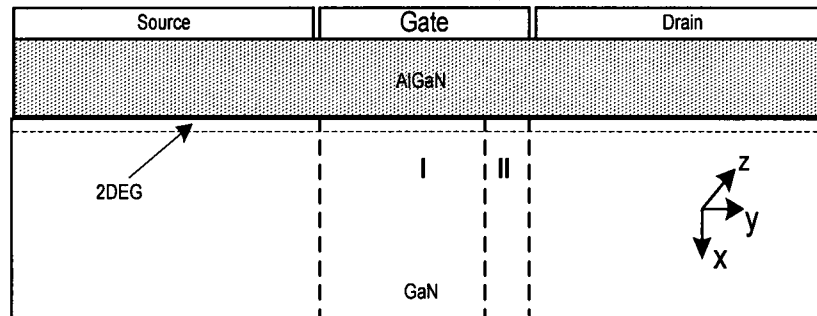


Figure 3.2: Schematic cross-section of a self-aligned AlGa<sub>0.3</sub>N/GaN HFET. Sections identified by I and II are explained in the text.

Under low drain voltages, as the maximum electric-field is smaller than  $E_{v\text{-max}}$ , region I will cover the entire length of the channel. With increasing the drain voltage, region II will start to form and expand at the cost of retraction of region I. Regions I and II are treated in sections 3.3.1.1 and 3.3.1.2, respectively.

### 3.3.1.1 Linear-region characteristics (i.e. $E < E_{v\text{-max}}$ )

In this region, by neglecting the gate leakage and leakage through the buffer layer, the drain-current density at any given point along the channel can be written as:

$$J = qn_s(y)v(E(y)) \quad (3.3)$$

In which, in presence of a gate bias (i.e.  $V_G$ ), the 2DEG density at the AlGaIn/GaN heterointerface can be expressed in terms of threshold voltage  $V_T$ :

$$qn_s(y) = C_{ch}(V_G - V_T - V(y)) \quad (3.4)$$

$V(y)$  is the channel potential and  $C_{ch}$  is the gate capacitance per unit area.  $C_{ch}$  is calculated by:

$$C_{ch} = \frac{\epsilon_0 \epsilon_{AlGaIn}}{d + \Delta d} \quad (3.5)$$

where  $\epsilon_{AlGaIn}$  is the relative dielectric constant of the barrier,  $d$  is the barrier thickness, and  $\Delta d$  is the effective thickness of the 2DEG, which is typically 2-4 nm for an AlGaIn/GaN 2DEG [74].

By substituting (3.2), (3.4), and (3.5) in (3.3), the following relationship between the drain-current density, longitudinal electric-field, and channel potential at any given point in region I will be resulted:

$$\left(1 + \left(\frac{E}{E_0}\right)^\alpha + \left(\frac{E}{E_1}\right)^\beta\right)J = \left(\mu_0 \cdot E + \mu_1 E \left(\frac{E}{E_0}\right)^\alpha + v_{sat} \left(\frac{E}{E_1}\right)^\beta\right)C_{ch}(V_{GT} - V(y)) \quad (3.6)$$

in which  $V_{GT}$  is the effective gate voltage. Replacing  $E(y)$  with the spatial derivative of channel potential in (3.6) leads to the following expression in terms of channel potential (i.e.  $V(y)$ ) and drain-current density (i.e.  $J$ ):

$$\begin{aligned} & \frac{1}{E_0^\alpha} \left( J - C_{ch}(V_{GT} - V(y))\mu_1 \frac{dV}{dy} \right) \left( \frac{dV}{dy} \right)^\alpha \\ & + \frac{1}{E_1^\beta} \left( J - C_{ch}(V_{GT} - V(y))v_{sat} \right) \left( \frac{dV}{dy} \right)^\beta - C_{ch}(V_{GT} - V(y))\mu_0 \frac{dV}{dy} + J = 0 \end{aligned} \quad (3.7)$$

Equation (3.7) requires numerical solution and can be solved by using the finite difference technique. To obtain the characteristics between the drain-current density and channel potential at the end of region I, for each gate voltage,  $J$  is swept from zero to 1 A/mm in very small increments. Continuity of the electric-field along the channel, current continuity in the drift-only channel, and boundary condition of the grounded source electrode are applied in this solution. In solving this equation longitudinal electric-field should be monitored. This equation is valid as long as this electric-field is smaller than  $E_{v-max}$ . The channel potential recorded at the end of region I (i.e.  $V_{D-v-max}$ ), is imported to section 3.3.1.2 for each value of gate voltage.

### 3.3.1.2 Saturation-region characteristics (i.e. $E > E_{v-max}$ )

Early reduction of carrier drift-velocity in region II and later saturation of drift-velocity (depending on the maximum value of drain voltage) in conjunction with current continuity dictate the materialization of electron bunching in this part of the channel.

Consequences of this phenomenon on the carrier drift characteristics of FETs have been considered on all the viable models presented for these devices after the seminal work of Grebene *et al.* [75]. These models have been based on silicon-like purely saturating  $v_d - E$  characteristics. While the model of Grebene *et al.* purely addresses this phenomenon through incorporation of the impact of the vertical electric-field in this region, in the current work presence of the steady state drift-velocity overshoot and creation of non-zero gradient in carrier concentration also demand the incorporation of a diffusion current term in region II.

According to the model of Grebene *et al.*, to incorporate the impact of electron bunching in region II, Gauss's law has been applied to the rectangular Gaussian box shown in Figure 3.3.

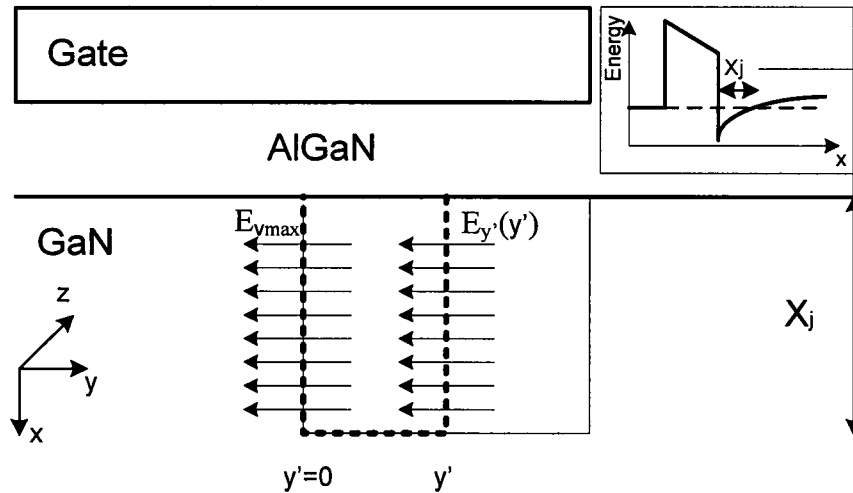


Figure 3.3: Schematic cross-section of a self-aligned AlGaN/GaN HFET, illustrating the Gaussian box used in the analysis of saturation-region. The inset shows the conduction band-edge at the AlGaN/GaN heterointerface.

This box fully extends throughout region II. In this figure,  $X_j$  marks the depletion layer thickness in GaN which is unintentionally doped to  $N_{\text{GaN}}$ . According to this:

$$\oint \vec{E} \cdot \vec{dS} = \frac{Q_{tot}}{\epsilon_s} \quad (3.8)$$

where  $E$  is the electric-field,  $\vec{dS}$  is the surface element, and  $Q_{tot}$  is the total charge enclosed by the Gaussian box. The absence of a Z-directed electric-field reduces (3.8) to a two dimensional equation:

$$\begin{aligned} - \left( \int_0^{y'} \frac{Q_n(y'')}{\epsilon_{GaN}} dy'' + \frac{qN_{GaN}X_j}{\epsilon_{GaN}} y' \right) \\ = -E_y(y')X_j + E_{v-max}X_j - \frac{\epsilon_{AlGaN}}{\epsilon_{GaN}} \int_0^{y'} E_{\perp}(0, y'') dy'' \end{aligned} \quad (3.9)$$

Here,  $X_j$  is assumed to be large enough so that the normal electric-field on the bottom surface of the Gaussian box is negligible. The normal electric-field to AlGaN/GaN heterointerface (i.e.  $E_{\perp}$ ) is given by:

$$E_{\perp}(0, y') = \frac{1}{d + \Delta d} \left( V_{GT} + \frac{Q_B}{C_{ch}} - V(y') \right) \quad (3.10)$$

where  $Q_B$  is the total bulk charge in GaN region enclosed by the Gaussian box.

$Q_n$  in (3.9) is the sheet charge density and unlike the assumption of Grebene *et al.* for the mobility model of the current work (i.e. (3.2)) it is not assumed to be constant:

$$Q_n(y') \simeq C_{ch} \left( V_{GT}' - V(y') \right) \quad (3.11)$$

In this form, the position dependency of the sheet charge density along the length of region II is incorporated through the variation of channel potential (i.e.  $V(y')$ ) and the threshold voltage  $V_T'(y')$ , which has been taken into account in  $V_{GT}'$  which is defined as  $V_G - V_T'(y')$ . In the model of Grebene *et al.* the constant profile of sheet charge density

has been maintained by assuming the same position dependency for the threshold voltage and channel potential. Although this is correct for a saturating  $v_d - E$  profile, it will not be acceptable for the mobility model of (3.2). As it is explained later in this section, the profile of threshold voltage will be calculated through iteratively solving (3.9) with the current-continuity equation.

By inserting (3.10) and (3.11) in (3.9), the following relationship between the device threshold voltage (i.e.  $V_T$ ) and the effective-threshold voltage of region II (i.e.  $V'_T(y')$ ) is achieved:

$$X_j \frac{\partial E(y')}{\partial y'} = -\frac{C_{ch}}{\epsilon_{GaN}} (V_T - V'_T(y')) \quad (3.12)$$

In solving for the position dependency of the threshold voltage in region II, the channel-potential and electric-field distributions of [75] can be taken as initial assumptions:

$$E(y') = E_{v-max} \cosh\left(\frac{y'}{\lambda}\right) \quad (3.13)$$

$$V(y') = V_{D-v-max} + \lambda E_{v-max} \sinh\left(\frac{y'}{\lambda}\right) \quad (3.14)$$

In which,  $V_{D-v-max}$  is the channel potential at the end of region I and has been imported from the calculations performed in that region. In this work, initial value of the parameter  $\lambda$  is taken equal to 30 nm which is in the range of values reported in literature for modeling the behavior of AlGaIn/GaN HFETs [68]. Adoption of these initial profiles to (3.12) will result in an initial guess for  $V'_T(y')$  which according to (3.11) will result in a position dependent profile for  $Q_n(y')$ . Variation in sheet charge density in region II is

then used for calculating the diffusion current component in this region. After this step, the assumption of the drift-only channel which was inherited from (3.3) should be revisited by deducting the position dependent diffusion current density at any given point along the channel in region II from the total value of the drain-current density (i.e.  $J$ ). This correction for achieving a revised profile for  $V_T'(y')$  is described below:

$$J_{drift} = J - J_{diff} \quad (3.15)$$

$$V_T'(y') = V_G - V(y') - \frac{J_{drift}(y')}{C_{ch} v(y')} \quad (3.16)$$

Plugging this new profile of effective threshold voltage in (3.12) will result in revised profiles for the channel-potential and electric-field along the length of region II. Continuity of electric-field should be maintained at the boundary of regions I and II. For every value of gate-voltage (i.e.  $V_G$ ) and drain-current (i.e.  $J$ ) this procedure is repeated until convergence. For iterative solution and convergence visual examination was used. The aforementioned correction of the drift current component is applicable to that portion of region II in which  $E(y')$  is smaller than the velocity-saturation electric-field. Beyond this point, assumption of Grebene *et al.* in the form of (3.13) and (3.14) will be valid. The values of  $\lambda$  and  $V_{D-v-max}$  should be appropriately chosen to maintain continuity of electric-field to the point immediately located before this point in the channel. This procedure is illustrated in Figure 3.4.

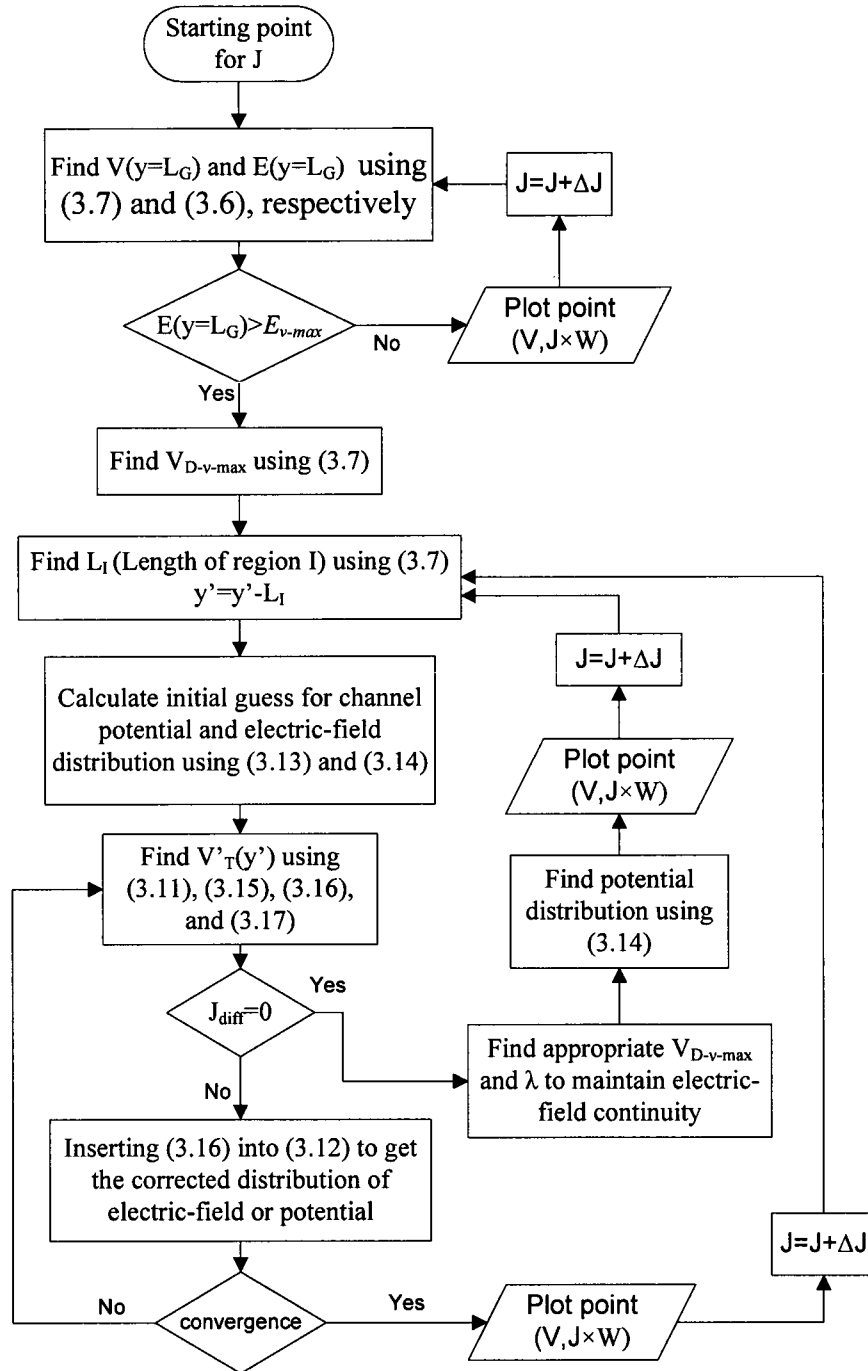


Figure 3.4: Simulation flowchart for the self-aligned AlGaIn/GaN HFET.



Diffusion component of current is calculated by using following expression:

$$J_{diff}(y') = \frac{k_B T}{q} \frac{v(y')}{E(y')} \frac{dQ_n(y')}{dy'} \quad (3.17)$$

where,  $k_B$  is the Boltzmann constant,  $T$  is the temperature in Kelvin and  $q$  is the charge of an electron. In this expression the simple form of Einstein's relationship for a non-degenerate semiconductor is employed. Later in section 3.4, it is demonstrated that despite the fact that this form is not fully applicable to a degenerate 2DEG, the impact of the full incorporation of Einstein relationship will be negligible.

### 3.3.2 Drain-current simulation of non- self-aligned HFET

Figure 3.5 schematically shows the cross section of the simulated non- self-aligned AlGaIn/GaN HFET. As it is apparent from this figure, this device can be envisioned as the tandem connection of a self-aligned HFET with an un-gated HFET.

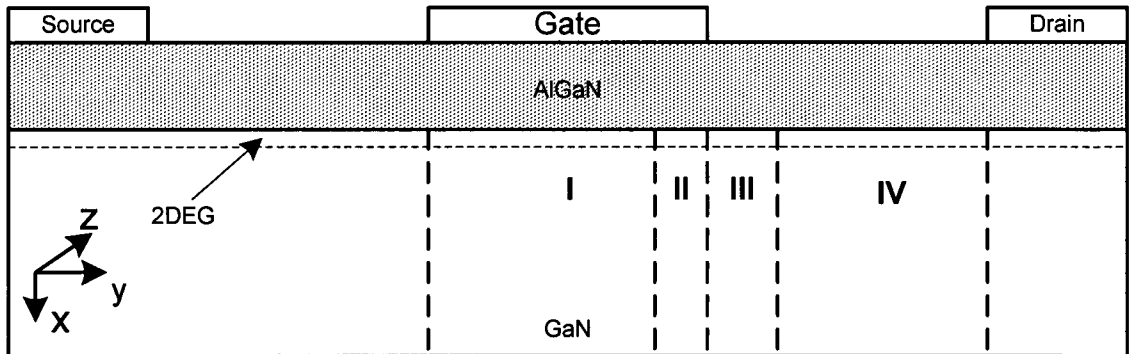


Figure 3.5: Schematic cross-section of a non- self-aligned AlGaIn/GaN HFET. Sections identified by I, II, III and IV are explained in the text.

The approach adopted in the present model for a non- self-aligned HFET is based on splitting of the channel into four regions: linear region (region I) and saturation region (region II) of the gated HFET, and saturation region (region III) and linear region (region

IV) of the un-gated HFET. In this analogy, form of the profile of the electric-field in the drain-access region of a FET requires the charge carrier of the un-gated HFET to be considered of opposite polarity. As a result, the role of source and drain is reversed in the un-gated HFET.

While the relationship between the current and voltage at the drain edge of gate for each value of gate voltage can be calculated according to the procedure explained in section 3.3.1, the potential drop across the drain access-region is accounted for by implementing a procedure very close to that of Figure 3.4 on this un-gated HFET. The only difference in this implementation is that in this region in the absence of a metallic gate, a surface potential term should instead be considered. In support of this argument, it should be reminded that the theory of metal semiconductor junction, due to lack of consideration of surface states, has the tendency to overestimate the role of metal work function. In this implementation, the current continuity and continuity of electric-field between regions II and III is maintained. In absence of an actual gate voltage, the role of the apparent spatial variation of the surface potential can be lumped into the variation of threshold voltage. This is a valid strategy as in the calculation of charge concentration along the channel the difference between  $V_G(y')$  and  $V_T'(y')$  and not their individual values is of interest. The value of the constant part of surface potential (used in place of  $V_G$  in equations of section 3.3.1) is set by swiping  $V_G$  and finding the proper value for which the electric-field continuity is maintained at the boundary of regions II and III.

### 3.4 Simulation results and discussions

Figure 3.6 illustrates an example of convergence of threshold voltage, diffusion current density, and electric-field in saturation region of the channel (i.e. region II). Acceptable levels of convergence after 6 steps of iteration have been observed to reduce the burden of choosing the fitting parameter (i.e.  $\lambda$ ).

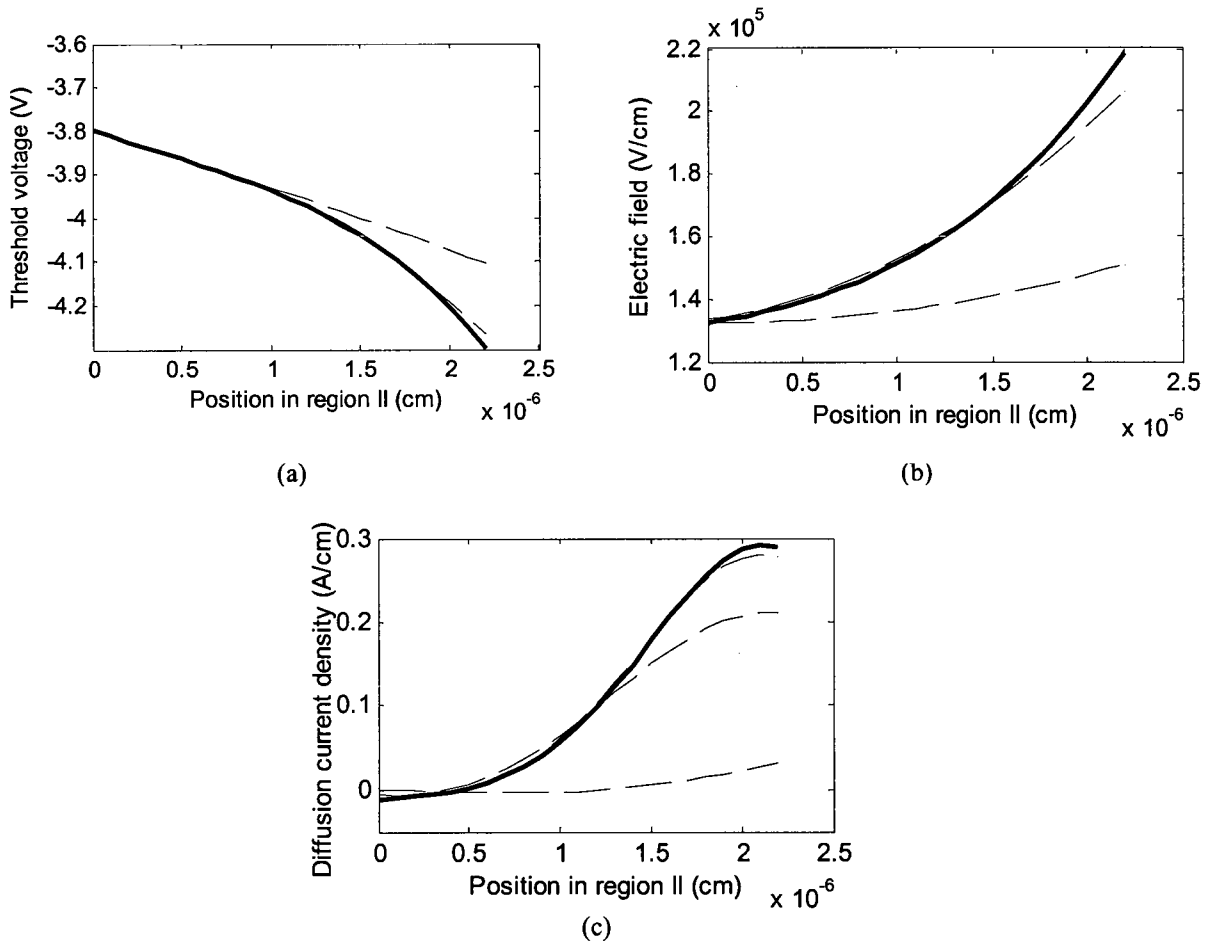
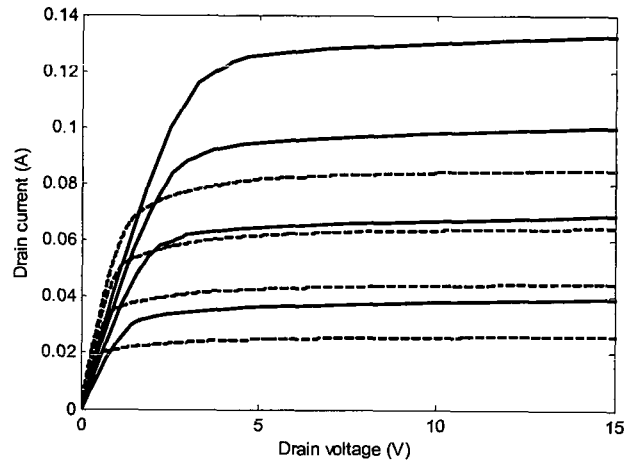


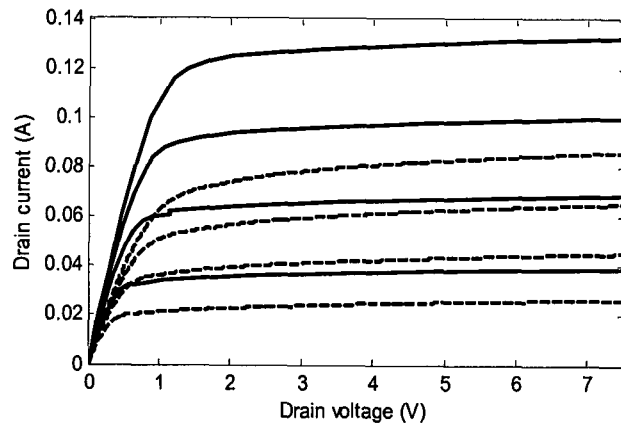
Figure 3.6: Convergence of threshold voltage distribution (a), electric-field distribution (b), and diffusion current density (c) in region II after 6 steps of iteration for  $V_{GS}=-1.8$  V,  $I=124$  mA. Convergence is achieved to the curve shown in solid line.  $R_S$  and  $R_D$  are equal to  $5 \Omega$ .

Figure 3.7(a) and (b) illustrate two sets of calculated drain-current versus drain-source voltage characteristics of a self-aligned and a non- self-aligned AlGaIn/GaN

HFET for gate-source voltages of -1.8, -2.2, -2.6, and -3 V, respectively. Two different mobility models have been used in the implementation of the proposed model. Continuous curves show the result of adoption of (3.2) while broken curves are representative of adoption of Ridley's saturating mobility model (i.e. (3.1)).



(a)

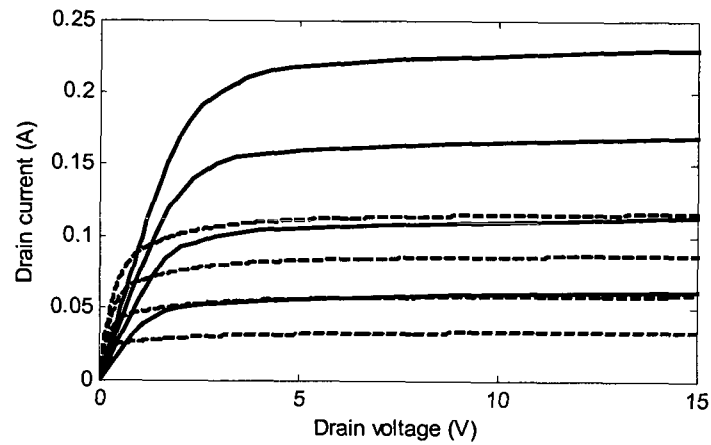


(b)

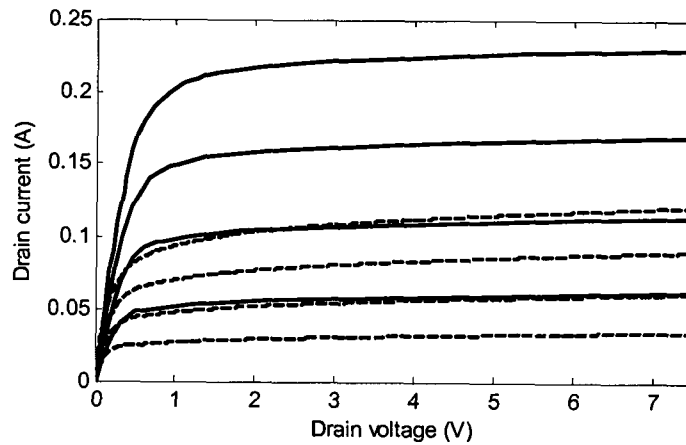
Figure 3.7: Drain I-V characteristics based on mobility model of (3.2) (solid curve) versus Ridley's mobility model (dashed curve) for  $V_{GS} = -1.8 \sim -3.0$  V with steps of 0.4 V for a non-self-aligned HFET (a) and a self-aligned HFET (b).  $R_S$  and  $R_D$  are equal to  $5 \Omega$ .

On Figures 3.8, 3.9, and 3.10, these data are presented for drain/source contact resistance of 0, 20, and  $35 \Omega$ , respectively. Due to higher drift-velocity at the low electric-field region predicted by (3.2), which is illustrated in Figure 3.1, the drain-current

calculated for this model is higher than the predictions of Ridley's mobility model. As it is demonstrated in Figures 3.8-3.10, by increasing the contact resistance the two sets of data will further mimic one another, especially at higher drain voltage. This observation is valid for both the self-aligned and non-self-aligned HFETs. This is due to the masking effect of the parasitic contact resistance on features such as inflexion points and steady state velocity overshoot that are present in the mobility model of (3.2).

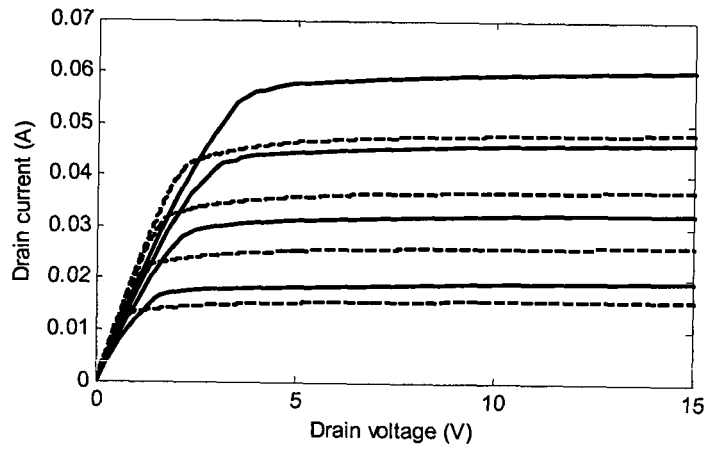


(a)

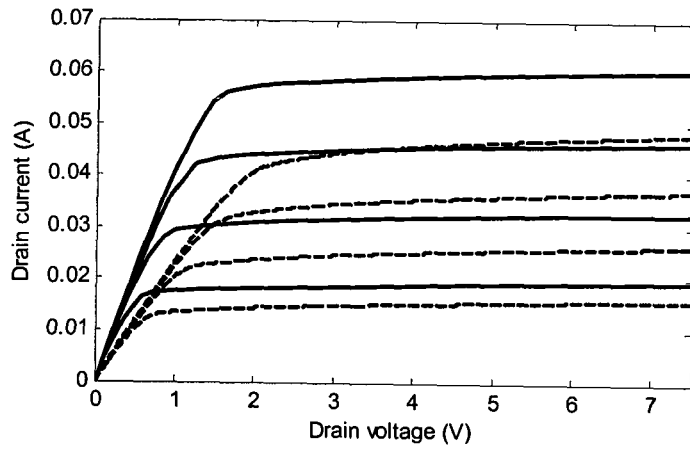


(b)

Figure 3.8: Drain I-V characteristics based on mobility model of (3.2) (solid curve) versus Ridley's mobility model (dashed curve) for  $V_{GS} = -1.8 \sim 3.0$  V with steps of 0.4 V for a non-self-aligned HFET (a) and a self-aligned HFET (b).  $R_S$  and  $R_D$  are equal to  $0 \Omega$ .

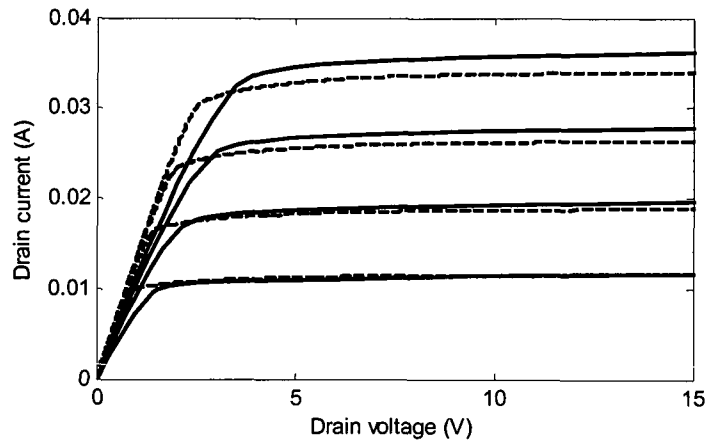


(a)

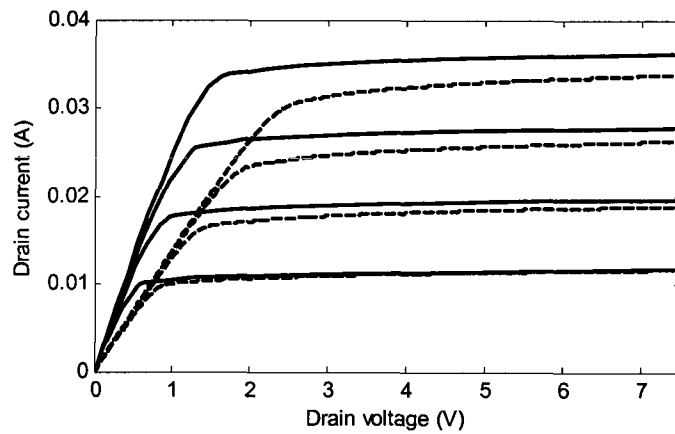


(b)

Figure 3.9: Drain I-V characteristics based on mobility model of (3.2) (solid curve) versus Ridley's mobility model (dashed curve) for  $V_{GS} = -1.8 \sim -3.0$  V with steps of 0.4 V for a non-self-aligned HFET (a) and a self-aligned HFET (b).  $R_S$  and  $R_D$  are equal to  $20 \Omega$ .



(a)



(b)

Figure 3.10: Drain I-V characteristics based on mobility model of (3.2) (solid curve) versus Ridley's mobility model (dashed curve) for  $V_{GS} = -1.8 \sim -3.0$  V with steps of 0.4 V for a non-self-aligned HFET (a) and a self-aligned HFET (b).  $R_S$  and  $R_D$  are equal to  $35 \Omega$ .

Figure 3.11 demonstrates the matching between the calculated drain I-V characteristics based on Ridley mobility model (with assumption of drain-source contact resistance of  $5 \Omega$ ) and borrowed measurement results from an AlGaIn/GaN HFET [46]. Measurements have been performed on an AlGaIn/GaN HFET grown by molecular beam epitaxy (MBE) on a SiC substrate. The device has two gate fingers with a gate length of  $0.25 \mu\text{m}$  and a gate finger width of  $100 \mu\text{m}$ . The closely-matched characteristics are indicative of high value of contact resistance of the measured devices. These observations indicate that contrary to the traditional assumptions of negligible impact of steady-state

velocity overshoot on drain-current characteristics of III-V HFETs, for AlGaIn/GaN HFETs the exact nature of the drift-transport can have very substantial impacts on the drain-current among other characteristics. This is due to the broader overshoot pattern and also larger value of electric-field normally applied to these wide band-gap HFETs.

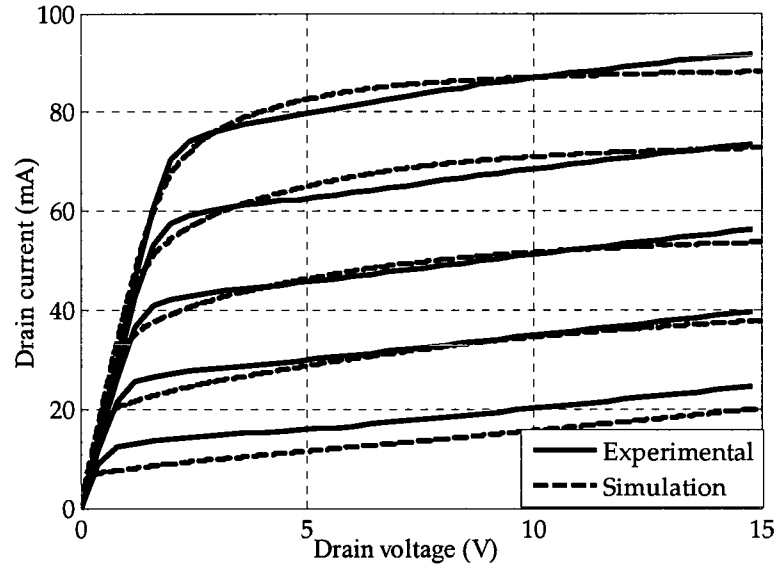


Figure 3.11: Drain I-V characteristics based on Ridley's mobility model (solid curve) versus experimental measurements (dashed curve) for  $V_{GS}=-1.8\sim-3.4$  V with steps of 0.4 V. The simulated device is a non-self-aligned HFET with  $R_S$  and  $R_D$  of  $5\ \Omega$ , and  $L_{GD}=1.875\ \mu\text{m}$ . The mismatch close to threshold voltage is due to the lack of consideration of leakage through buffer layer.

Despite the fact that these features are masked by parasitic effects such as contact resistance in the current state of technology, with the constant technological improvement of III-Nitride HFETs [70], [76], a more complete inclusion of transport characteristics in the fashion presented in this thesis, becomes a necessity.

The degeneracy of the 2DEG has been neglected in (3.17). In order to more accurately study the impact of the degenerated channel on drain-current characteristic of AlGaIn/GaN HFETs, the maximum correction factor (based on the maximum carrier kinetic energy in the channel) in the full form of Einstein relationship has been



calculated. As the worst case scenario, neglecting the position dependency of this correction factor, Figure 3.12 illustrates the results with respect to incorporation of this correction factor in (3.17). The inset of Figure 3.12 shows the variation of the correction factor versus the reduced Fermi level [77]. Due to negligible difference between the results with and without incorporation of this correction factor, the implementation of the presented model based on the simple form of Einstein relationship is deemed sufficient.

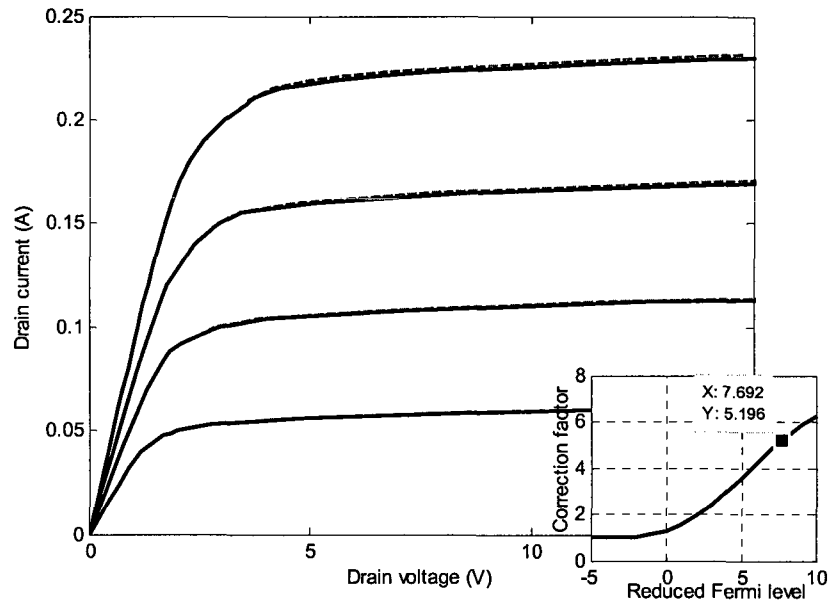


Figure 3.12: Drain I-V characteristics based on simple Einstein's relationship (solid line) versus corrected Einstein's relationship (dashed line) for a non-self-aligned HFET with the assumption of  $R_S=R_D=0 \Omega$ ,  $L_G=0.25 \mu\text{m}$ , and  $L_{GD}=1.0 \mu\text{m}$  for  $V_{GS}=-1.8\text{V}\sim 3.0\text{V}$  with the step of  $0.4 \text{V}$ . Inset: Correction factor as a function of reduced Fermi level  $\eta = \frac{E_F - E_C}{k_B T}$ .

In order to demonstrate the importance of inclusion of inflexion points of the  $v_d - E$  characteristics of AlGaIn/GaN channel, impacts of these features via comparing the outcomes of the proposed model versus the result of adoption of a mobility model incapable of representing the inflexion points are studied. Figure 3.13, shows the  $v_d - E$  characteristics according to the model earlier presented by Shey *et al.* [65]. This model is presented as:

$$v(x) = \frac{\mu_0 E(x) + v_s \left(\frac{E(x)}{E_1}\right)^5}{1 + \left(\frac{E(x)}{E_0}\right)^5} \quad (3.18)$$

Constant of this model, have been chosen as a best match to Monte Carlo predictions of O'Leary *et al.* [73]. These constants have been reported as [78]:

$$\mu_0 = 260 \left( \text{cm}^2/\text{V}\cdot\text{s} \right), \quad v_s = 2.10 \times 10^7 \text{ (cm/s)},$$

$$E_0 = 15.9 \times 10^4 \text{ (V/cm)} , \quad E_1 = 17.2 \times 10^4 \text{ (V/cm)}$$

This model has been used for studying the drain I/V characteristics of non- self-aligned AlGaIn/GaN HFETs with parameters indicated in Table 3.1, unless identified otherwise.

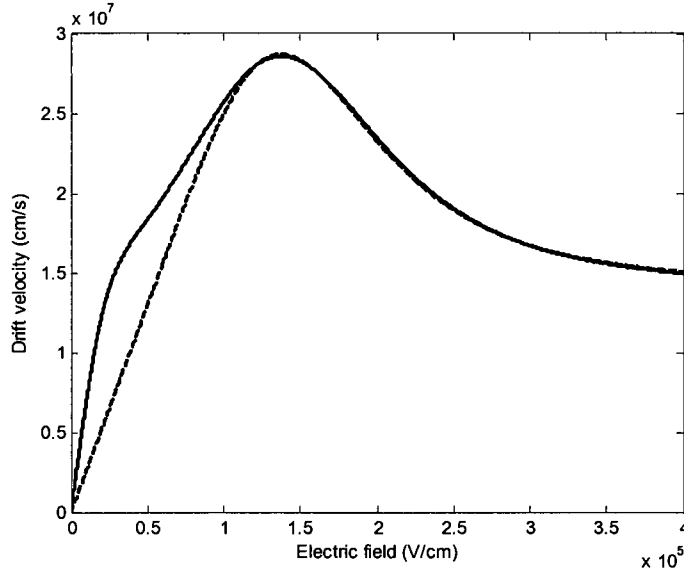


Figure 3.13:  $v_d$ -E characteristics according to (3.2) and (3.18).

Figure 3.14, illustrates the result of the adoption of this mobility model to the model presented in section 3.3.2, versus the outcome of that model based on mobility

model of (3.2). On Figure 3.14(a), (b), and (c) the gate length has been taken as  $0.25 \mu\text{m}$ ,  $0.5 \mu\text{m}$ , and  $1 \mu\text{m}$ , respectively. All other parameters of these devices are the identical.

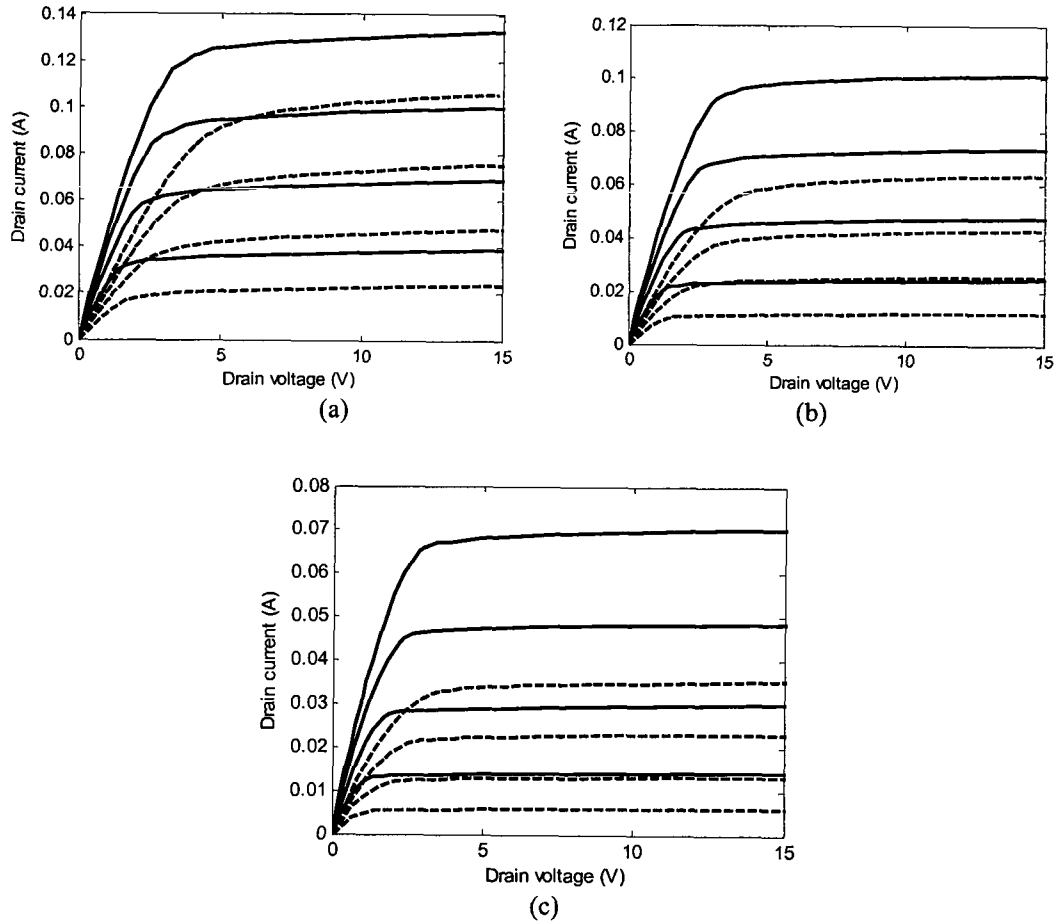


Figure 3.14: Drain I-V characteristics based on mobility model of (3.2) (solid line), versus (3.18) (dashed line) for  $L_G=0.25 \mu\text{m}$  (a),  $L_G=0.5 \mu\text{m}$  (b), and  $L_G=1 \mu\text{m}$  (c), for  $V_{GS}=-1.8\sim 3.0 \text{ V}$  with steps of  $0.4 \text{ V}$ .

Figure 3.15, illustrates the result of the adoption of mobility model of (3.18) to the model presented in section 3.3.2, versus the outcome of that model based on mobility model of (3.2). On Figure 3.15(a), (b), and (c) the gate-drain spacing has been taken as  $1 \mu\text{m}$ ,  $2 \mu\text{m}$ , and  $3 \mu\text{m}$ , respectively. All other parameters of these devices are the identical.

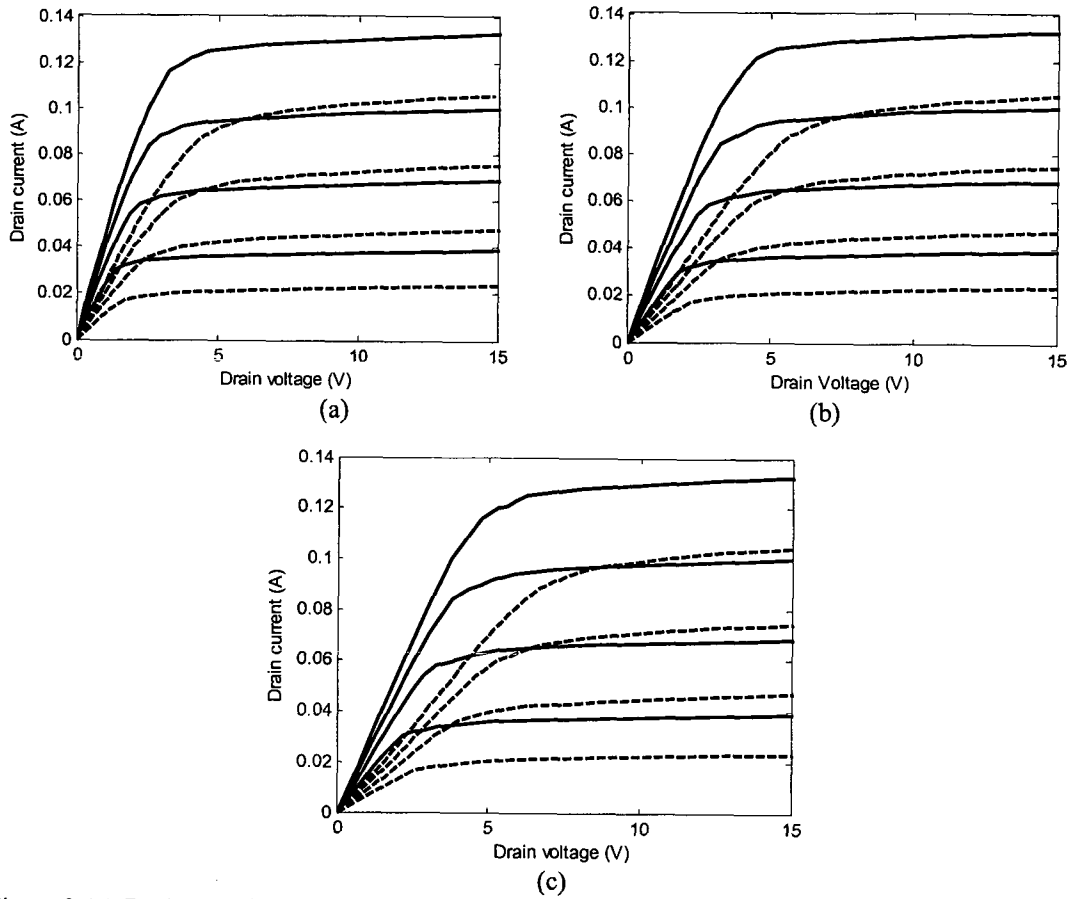


Figure 3.15: Drain I-V characteristics based on mobility model of (3.2) (solid line), versus (3.18) (dashed line) for  $L_{GD}=1 \mu\text{m}$  (a),  $L_{GD}=2 \mu\text{m}$  (b), and  $L_{GD}=3 \mu\text{m}$  (c), for  $V_{GS}=-1.8\sim 3.0 \text{ V}$  with steps of  $0.4 \text{ V}$ .

As it is observed on Figure 3.14 and Figure 3.15, the similarity between the outcomes of the two mobility models grows as the gate-length and gate-drain spacing are reduced. This is due to the fact that for short channel devices, under a proportionally longer part of the channel carriers are exposed to higher electric-fields for which the two models, as presented in Figure 3.13, predict identical drift velocities. This argument can be applied both to gated and the ungated HFETs of Figure 3.5.

### **3.5 Conclusion**

An analytical model for drain-current characteristic of AlGaN/GaN HFETs with incorporation of inflexion points and steady-state velocity overshoot is proposed. The application of this model to HFETs, with and without self-aligned gates, reveals the tangible impact of these features on drain-current characteristics of HFETs. The presented model, which is based on iterative solution of current-continuity and Poisson's equations, is quite independent of the choice of fitting parameters. It is shown that by technological improvement of the Ohmic contacts in III-Nitride technology, the effects of transport features such as inflexion points and steady-state velocity overshoot gains further relevance in producing highly reliable models for these devices. It has been observed that the inflexion points of drift transport characteristics will play a more prominent role in the drain characteristics of devices of longer gate length and gate-drain spacing. This is specially highlighted by the improvement in quality of Ohmic contacts to AlGaN/GaN heterojunctions.

# Chapter 4

## Conclusion and Future Works

### 4.1 Goals and contributions of the thesis

This thesis had the main goal of modeling the drain-current characteristic of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs with incorporation of electron trapping at deep surface states and detailed drift transport characteristics. To demonstrate the validity of the models, results have been compared with experimental data.

### 4.2 Conclusions

Current collapse and reliability degradation due to electron trapping at the surface layer of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs are the major concerns in this technology. Current collapse suppresses microwave output power performance of the device. Even though considerable improvements have been made in this technology trapping effects in AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs have not been removed.

In chapter 2, an assured simulation of AlGa<sub>N</sub>/Ga<sub>N</sub> HFET including trapping effects was presented using CADtool Medici®. The simulation has been performed for

the device before stress and after stress and the results have been compared with experimental observation of Valizadeh *et al.* [46]. After stress results show a significant loss of carrier concentration under the gate-drain access region which is due to the incorporation of the negatively charged surface trap layer at the surface of AlGa<sub>N</sub> barrier in this region. The acceptable agreement between the simulation and experimental data validates the speculations of Valizadeh *et al.* [46] on the role of acceptor-type surface traps on drain-current collapse of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs.

In chapter 3, an analytical model for drain-current characteristic of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs with incorporation of inflexion points and steady-state velocity overshoot is proposed. The application of this model to AlGa<sub>N</sub>/Ga<sub>N</sub>, with and without self-aligned gates, reveals the significant impact of these features on drain-current characteristics of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs. The model is quite independent of the choice of fitting parameters due to iterative nature of this approach. It is shown that by technological improvement of the Ohmic contacts in III-Nitride technology, the effects of transport features such as inflexion points and steady-state velocity overshoot gains further relevance in producing highly reliable models for these devices. It has been observed that the inflexion points of drift transport characteristics will play a more prominent role in the drain characteristics of devices of longer gate length and gate-drain spacing. This is specially highlighted by the improvement in quality of Ohmic contacts to AlGa<sub>N</sub>/Ga<sub>N</sub> heterojunctions.

### **4.3 Future works**

This research concludes with specific direction to future work. Extension of the present model to accommodate the impacts of gate leakage and leakage through substrate is

suggested as a viable future direction. Also it is suggested that implementing a more accurate charge trapping profile at AlGa<sub>N</sub> layer with incorporation of the impact of the traps in other locations of the device such as barrier and buffer layer will improve the matching between experimental data and simulation results. Study of the time constant of these trapping/de-trapping mechanisms in regards to the energy-level, emission rate, and capture cross-section of the traps can cast light on the frequency response of these processes.

In addition, incorporating the thermal effects which were completely absent from the current studies on the drain-current characteristic of AlGa<sub>N</sub>/Ga<sub>N</sub> HFETs is deemed as a very important future direction for this work.



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# **Appendix A: Material parameters redefinition of GaAs as GaN and AlGaAs as AlGaN**

## **A-a Material parameters redefinition of GaAs as GaN**

\$material parameters redefinition of GaAs to be GaN

Material GAAS

+ permitti=9.7

+ eg.model=1

+ affinity=3.1

+ eg300=3.47

+ egalph=7.7E-4

+ egbeta=600

+ eggamm=0

+ nc300=2.23e18

+ nc.f=1.5

+ nv300=4.6e19

+ nv.f=1.5

+ gcb=2

+ gvb=2

+ edb=0.012

+ eab=0.140

+ taun0=1e-10

+ nsrhn=1



+ an=1  
+ bn=0  
+ cn=0  
+ en=0  
+ taup0=8.7e-9  
+ nsrhp=1  
+ ap=1  
+ bp=0  
+ cp=0  
+ ep=0  
+ etrap=0  
+ m.rtun=0.25  
+ b.rtun=0  
+ s.rtun=2  
+ e.rtun=0.1  
+ c.direct=0  
+ augn=0  
+ augp=0  
+ arichn=24  
+ arichp=120  
+ n0.bgn=1e17  
+ v0.bgn=0  
+ con.bgn=0  
+ a.ehs=0  
+ b.ehs=0

+ c.ehs=0  
+ n.ioniza=5e6  
+ ecn.ii=1e7  
+ exn.ii=1.65  
+ p.ioniza=1.1e6  
+ ecp.ii=1e7  
+ exp.ii=1.32  
+ lamhn=1  
+ lamrn=1  
+ lamhp=1  
+ lamrp=1  
+ a.fn=0  
+ b.fn=0  
+ ele.cq=1  
+ ele.tauw=1e-12  
+ hol.cq=1  
+ hol.tauw=1e-12  
+ density=6.15e-3  
+ dn.lat=1  
+ dp.lat=1  
+ a.sp.he=181.5  
+ b.sp.he=0.8225  
+ c.sp.he=-0.00135  
+ d.sp.he=0  
+ f.sp.he=7.5e-7

+ g.sp.hea=0  
+ a.th.con=0.68  
+ b.th.con=5e-4  
+ c.th.con=2e-7  
+ d.th.con=0  
+ e.th.con=0  
+ op.ph.en=0.089  
+ lan300=2e-8  
+ lap300=2e-8  
+ el.emas=0.2  
+ ho.emas=1

#### Mobility GAAS

+ fldmob=2  
+ e0n=150e3  
+ mun.min=0  
+ mun.max=400  
+ nrefn=1.69e17  
+ nun=0  
+ xin=0  
+ alphan=0.75  
+ gsurfn=1  
+ ecn.mu=1e8  
+ vsatp=4.7e6  
+ vsatn=1.32e7

+ exn1.gaa=4.15  
+ exn2.gaa=4.15  
+ e0p=500e3  
+ mup.min=0  
+ mup.max=200  
+ nrefp=1e17  
+ nup=0  
+ xip=0  
+ alphap=0.75  
+ gsurfp=1  
+ ecp.mu=1e8

## **A-b Material parameters redefinition of AlGaAs as AlGaN**

\$material parameters redefinition of AlGaAs to be AlGaN

Material ALGAAS

+ affinity=3.1  
+ af.x1=-2.85  
+ eg.x1=2.73  
+ eg300=3.47  
+ permitti=9.7  
+ eg.model=4  
+ eg.x2=0  
+ af.x2=0

+ nc300=2.23e18  
+ nv300=4.6e19  
+ gcb=2  
+ gvb=2  
+ edb=0.012  
+ eab=0.140  
+ taun0=1e-10  
+ nsrhn=1  
+ an=1  
+ bn=0  
+ cn=0  
+ en=0  
+ taup0=8.7e-9  
+ nsrhp=1  
+ ap=1  
+ bp=0  
+ cp=0  
+ ep=0  
+ etrap=0  
+ m.rtun=0.25  
+ b.rtun=0  
+ s.rtun=2  
+ e.rtun=0.1  
+ c.direct=0  
+ augn=0

+ augp=0  
+ arichn=24  
+ arichp=120  
+ n0.bgn=1e17  
+ v0.bgn=0  
+ con.bgn=0  
+ a.ehs=0  
+ b.ehs=0  
+ c.ehs=0  
+ n.ioniza=5e6  
+ p.ioniza=1.1e6  
+ ecn.ii=1e7  
+ ecp.ii=1e7  
+ cn.iilam=1  
+ cp.iilam=1  
+ exn.ii=1.65  
+ exp.ii=1.32  
+ lamhn=1  
+ lamrn=1  
+ lamhp=1  
+ lamrp=1  
+ a.fn=0  
+ b.fn=0  
+ ele.cq=1  
+ ele.tauw=1e-12

+ hol.cq=1  
+ hol.tauw=1e-12  
+ density=6.15e-3  
+ dn.lat=1  
+ dp.lat=1  
+ a.sp.heav=181.5  
+ b.sp.heav=0.8225  
+ c.sp.heav=-0.00135  
+ d.sp.heav=0  
+ f.sp.heav=7.5e-7  
+ g.sp.heav=0  
+ a.th.con=0.68  
+ b.th.con=5e-4  
+ c.th.con=2e-7  
+ d.th.con=0  
+ e.th.con=0  
+ op.ph.en=0.089  
+ lan300=2e-8  
+ lap300=2e-8  
+ el.emas=0.2  
+ ho.emas=1

#### Mobility ALGAAS

+ fldmob=2  
+ e0n=150e3

+ mun.min=0  
+ mun.max=400  
+ nrefn=3.63e17  
+ nun=0  
+ xin=0  
+ alphan=0.75  
+ gsurfn=1  
+ ecn.mu=1e8  
+ vsatp=4.7e6  
+ vsatn=1.32e7  
+ exn1.gaa=4.15  
+ exn2.gaa=4.15  
+ e0p=500e3  
+ mup.min=0  
+ mup.max=200  
+ nrefp=1e17  
+ nup=0  
+ xip=0  
+ alphap=0.75  
+ gsurfp=1  
+ ecp.mu=1e8  
+ min.x1=-0.96  
+ min.x2=0  
+ man.x1=-0.97  
+ man.x2=0



+ mip.x1=-0.96

+ mip.x2=0

+ map.x1=-0.78

+ map.x2=0

+ nrefn2=1.75e18

+ nrefp2=1e30

## Appendix B: Medici input files of simulation

### B-a File: 1

TITLE AlGaIn/GaN HFET before stress.

COMMNET =====

COMMENT The following part defines device parameters.

ASSIGN name=Body.tks n.value=0.68  
ASSIGN name=InGa.tks n.value=0.002  
ASSIGN name=AGN1.tks n.value=0.015  
ASSIGN name=AGN2.tks n.value=0.0025  
ASSIGN name=GaN.tks n.value=0.025  
ASSIGN name=chan.lgt n.value=.25  
ASSIGN name=tot.lgt n.value=25  
ASSIGN name=sds.lgt n.value=3.75  
ASSIGN name=Body.dop n.value=1e5  
ASSIGN name=InGa.dop n.value=1e15  
ASSIGN name=AGN1.dop n.value=6e17  
ASSIGN name=AGN2.dop n.value=1e16  
ASSIGN name=GaN.dop n.value=1e20

COMMENT =====

COMMENT The following part generates the mesh structure of the device.

MESH nx=40 ny=60 virtual smooth.k=1

X.MESH node=1 location=0

X.MESH node=5 location=(@tot.lgt-@chan.lgt-@sds.lgt)\*0.5

X.MESH node=15 location= $(@tot.lgt-@chan.lgt)*0.5$   
X.MESH node=25 location= $(@tot.lgt-@chan.lgt)*0.5+@chan.lgt$   
X.MESH node=35 location= $(@tot.lgt+@chan.lgt+@sds.lgt)*0.5$   
X.MESH node=40 location= $@tot.lgt$

Y.MESH node=1 location=0  
Y.MESH node=9 location= $@GaN.tks$   
Y.MESH node=30 location= $@GaN.tks+@AGN1.tks$   
Y.MESH node=40 location= $@GaN.tks+@AGN1.tks+@AGN2.tks$   
Y.MESH node=50 location= $@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks$   
Y.MESH node=60 location= $@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks$   
+ $@Body.tks$

COMMENT =====

COMMENT The following part determines the material used in different

COMMENT regions of the device.

REGION name=s-ohmic ix.low=1 ix.high=5 iy.low=1  
+ iy.high=9 GAAS

REGION name=d-ohmic ix.low=35 ix.high=40 iy.low=1  
+ iy.high=9 GAAS

REGION name=barrier1 ix.low=1 ix.high=40 iy.low=9  
+ iy.high=30 ALGAAS x.mole=0.13

REGION name=barrier2 ix.low=1 ix.high=40 iy.low=30  
+ iy.high=40 ALGAAS x.mole=0.13

REGION name=channel ix.low=1 ix.high=40 iy.low=40

```

+ iy.high=50    GAAS
REGION name=substra  ix.low=1    ix.high=40    iy.low=50
+ iy.high=60    GAAS
REGION name=isol1    ix.low=5     ix.high=15    iy.low=1
+ iy.high=9     insulato
REGION name=isol2    ix.low=15    ix.high=25    iy.low=1
+ iy.high=9     insulato
REGION name=isol3    ix.low=25    ix.high=35    iy.low=1
+ iy.high=9     insulato

```

```

COMMENT =====

```

```

COMMENT The following specifies the location of contact electrodes.

```

```

ELECTRODE name=source ix.l=2 ix.h=4 iy.l=1 iy.h=1
ELECTRODE name=drain  ix.l=37 ix.h=39 iy.l=1 iy.h=1
ELECTRODE name=gate   ix.l=15 ix.h=25 iy.l=9 iy.h=9
ELECTRODE name=sub    ix.l=1  ix.h=40 iy.l=60 iy.h=60

```

```

COMMENT =====

```

```

COMMENT The following specifies the doping of each region.

```

```

PROFILE region=s-ohmic n-type x.min=0
+ x.max=(@tot.lgt-@chan.lgt-@sds.lgt)*0.5 y.min=0 y.max=@GaN.tks
+ Uniform n.peak=@GaN.dop
PROFILE region=d-ohmic n-type
+ x.min=(@tot.lgt @chan.lgt)*0.5+@chan.lgt+@sds.lgt*0.5
+ x.max=@tot.lgt y.min=0 y.max=@GaN.tks uniform n.peak=@GaN.dop

```

```

PROFILE region=barrier1 n-type x.min=0 x.max=@tot.lgt
+ y.min=@GaN.tks y.max=@GaN.tks+@AGN1.tks uniform n.peak=@AGN1.dop

PROFILE region=barrier2 n-type x.min=0 x.max=@tot.lgt
+ y.min=@GaN.tks+@AGN1.tks y.max=@GaN.tks+@AGN1.tks+@AGN2.tks uniform
+ n.peak=@AGN2.dop

PROFILE region=channel n-type x.min=0 x.max=@tot.lgt
+ y.min=@GaN.tks+@AGN1.tks+@AGN2.tks
+ y.max=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks
+ uniform n.peak=@InGa.dop

PROFILE region=substra n-type x.min=0 x.max=@tot.lgt
+ y.min=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks
+ y.max=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks uniform
+ n.peak=@Body.dop

PROFILE n.type conc=3.1E20
+ y.min=@GaN.tks+@AGN1.tks+@agn2.tks+@InGa.tks*0.5
+ char=@InGa.tks*0.02

INTERFACE region=(barrier2,channel) QF=1E13

PLOT.2D grid fill scale

COMMENT =====
COMMENT Material parameters redefinition of AlGaAs to be AlGaN.
CALL file=dataGaNupdate18809.inp
CALL file=dataAlGaNupdate18809.inp
CONTACT name=gate SCHOTTKY WORKf=5.17
SAVE MESH OUT.F=MES.MSH

```

```

MODELS  fermi auger consrh analytic fldmob hitem hjtun
COMMENT =====
COMMENT  Initial solution.
SYMB    NEWT CARR=0
SOLVE   V(sub)=0 V(source)=0 V(drain)=0.05 V(gate)=0
SYMB    NEWT CARR=2
METHOD  itlimit=60 px.toler=1e-3 cx.toler=1e-4
SOLVE
PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ DOPING LOG
+ bottom=1e2 top=1e22 left=0
+ right=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ TITLE=" Channel Doping & Electrons Device ON"
PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ Y.ST=@GaN.tks+@AGN1.tks+@AGN2.tks
+ Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks
+ ELECT LOG  COL=2
LABEL LABEL=Electrons COL=2 X=.8 Y=1e8
LABEL LABEL=Doping X=.02 Y=1e17
PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks

```

```

+ COND TOP=2.5 BOT=-5

+ NEG TITLE="HFET Band structure Device ON"

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ VAL UNCH NEG

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ QFN UNCH NEG COL=2

LABEL LABEL=Cond X=0.1 Y=1

LABEL LABEL=Qfn X=0.1 Y=0

LABEL LABEL=Val X=0.1 Y=-3

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ COND TOP=2.5 BOT=-5

+ NEG TITLE="HFET Band structure Device ON"

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ VAL UNCH NEG

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks

```

```

+ QFN UNCH NEG COL=2

LABEL LABEL=Cond X=0.1 Y=1

LABEL LABEL=Qfn X=0.1 Y=0

LABEL LABEL=Val X=0.1 Y=-3

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3

+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3

+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks

+ COND TOP=2.5 BOT=-5

+ NEG TITLE="HFET Band structure Device ON"

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3

+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3

+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks

+ VAL UNCH NEG

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3

+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3

+Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks

+ QFN UNCH NEG COL=2

LABEL LABEL=Cond X=0.1 Y=1

LABEL LABEL=Qfn X=0.1 Y=0

LABEL LABEL=Val X=0.1 Y=-3

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.25

+ X.END=(@tot.lgt-@chan.lgt)*0.25

+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks

+ COND TOP=2.5 BOT=-5

+ NEG TITLE="HFET Band structure Device ON"

```



PLOT.1D X.ST=(@tot.lgt-@chan.lgt)\*0.25  
+ X.END=(@tot.lgt-@chan.lgt)\*0.25  
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks  
+ VAL UNCH NEG

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)\*0.25  
+ X.END=(@tot.lgt-@chan.lgt)\*0.25  
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks  
+ QFN UNCH NEG COL=2

PLOT.1D X.ST=@tot.lgt-(@tot.lgt-@chan.lgt)\*0.25  
+ X.END=@tot.lgt-(@tot.lgt-@chan.lgt)\*0.25  
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks  
+ COND TOP=2.5 BOT=-5  
+ NEG TITLE="HFET Band structure Device ON"

PLOT.1D X.ST=@tot.lgt-(@tot.lgt-@chan.lgt)\*0.25  
+ X.END=@tot.lgt-(@tot.lgt-@chan.lgt)\*0.25  
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks  
+ VAL UNCH NEG

PLOT.1D X.ST=@tot.lgt-(@tot.lgt-@chan.lgt)\*0.25  
+ X.END=@tot.lgt-(@tot.lgt-@chan.lgt)\*0.25  
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks  
+ QFN UNCH NEG COL=2

PLOT.2D grid fill

COMMENT =====

COMMENT Generate plot of device structure.

PLOT.2D BOUNDARY FILL

```

+ TITLE="HFET Current Flow, Device ON"

FILL REGION=channel COLOR=5
FILL REGION=barrier1 COLOR=2
FILL REGION=barrier2 COLOR=6
FILL REGION=s-ohmic COLOR=3
FILL REGION=d-ohmic COLOR=3
FILL REGION=substra COLOR=9
FILL REGION=isol1 COLOR=11
FILL REGION=isol2 COLOR=7
FILL REGION=isol3 COLOR=11

LABEL LABEL=AlGaIn x=.5 y=.1
LABEL LABEL=GaN x=.1 y=.003
LABEL LABEL=GaN x=.9 y=.003
LABEL LABEL=PASSIVATION x=.425 y=.003
LABEL LABEL=AlGaIn x=.5 y=.04
LABEL LABEL=GaN x=.5 y=.055
LABEL LABEL=AlGaIn x=.5 y=.05

CONTOUR FLOW

SOLVE V(sub)=0 V(source)=0 V(drain)=2.5 V(gate)=-1.8

PLOT.1D x.ax=j.field y.ax=ele.vel points ^order

PLOT.1D ele.vel x.start=(@tot.lgt-@chan.lgt-@sds.lgt)*0.5
+ x.end=(@tot.lgt+@chan.lgt+@sds.lgt)*0.5
+ y.start=@GaN.tks+@AGN1.tks+@AGN2.tks+(@InGa.tks*0.5)
+ y.end=@GaN.tks+@AGN1.tks+@AGN2.tks+(@InGa.tks*0.5)

```

```

+ print out.file=velocity4.dat

plot.1d j.efield x.start=(@tot.lgt-@chan.lgt-@sds.lgt)*0.5
+ x.end=(@tot.lgt+@chan.lgt+@sds.lgt)*0.5
+ y.start=@GaN.tks+@AGN1.tks+@AGN2.tks+(@InGa.tks*0.5)
+ y.end=@GaN.tks+@AGN1.tks+@AGN2.tks+(@InGa.tks*0.5)
+ print out.file=electricfield4.dat

SOLVE V(drain)=0.05 V(gate)=-1.8
+ ELEC=drain VSTEP=.4 NSTEP=37

PLOT.1D X.AX=V(drain) Y.AX=I(drain) points ^order print out.file=bit18.dat

SOLVE V(drain)=14.85 V(gate)=-2.2
+ ELEC=drain VSTEP=-.4 NSTEP=37

PLOT.1D X.AX=V(drain) Y.AX=I(drain) points ^order unchange print
+ out.file=bit22.dat

SOLVE V(drain)=0.05 V(gate)=-2.6
+ ELEC=drain VSTEP=.4 NSTEP=37

PLOT.1D X.AX=V(drain) Y.AX=I(drain) points ^order unchange print
+ out.file=bit26.dat

SOLVE V(drain)=14.85 V(gate)=-3
+ ELEC=drain VSTEP=-.4 NSTEP=37

PLOT.1D X.AX=V(drain) Y.AX=I(drain) points ^order unchange print
+ out.file=bit3.dat

SOLVE V(drain)=0.05 V(gate)=-3.4
+ ELEC=drain VSTEP=.4 NSTEP=37

PLOT.1D X.AX=V(drain) Y.AX=I(drain) points ^order unchange print
+ out.file=bit34.dat

```

## B-b File: 2

```
TITLE      AlGaIn/GaN HFET after stress.

COMMENT    =====

COMMENT    The following part defines device parameters.

ASSIGN     name=Body.tks      n.value=0.68
ASSIGN     name=InGa.tks      n.value=0.002
ASSIGN     name=AGN1.tks      n.value=0.015
ASSIGN     name=AGN2.tks      n.value=0.0025
ASSIGN     name=GaN.tks       n.value=0.025
ASSIGN     name=trap.tks      n.value=0.011

ASSIGN     name=chan.lgt      n.value=.25
ASSIGN     name=tot.lgt       n.value=25
ASSIGN     name=sds.lgt       n.value=3.75
ASSIGN     name=trap.lgt      n.value=0.056

ASSIGN     name=Body.dop      n.value=1e5
ASSIGN     name=InGa.dop      n.value=1e15
ASSIGN     name=AGN1.dop      n.value=6e17
ASSIGN     name=AGN2.dop      n.value=1e16
ASSIGN     name=GaN.dop       n.value=1e20
```

ASSIGN name=trap.dop n.value=1e15

COMMENT =====

COMMENT The following part generates the mesh structure of the device.

MESH nx=40 ny=60 virtual smooth.k=1

X.MESH node=1 location=0

X.MESH node=5 location=(@tot.lgt-@chan.lgt-@sds.lgt)\*0.5

X.MESH node=15 location=(@tot.lgt-@chan.lgt)\*0.5

X.MESH node=25 location=(@tot.lgt-@chan.lgt)\*0.5+@chan.lgt

X.MESH node=30 location=(@tot.lgt+@chan.lgt)\*0.5+@trap.lgt

X.MESH node=35 location=(@tot.lgt+@chan.lgt+@sds.lgt)\*0.5

X.MESH node=40 location=@tot.lgt

Y.MESH node=1 location=0

Y.MESH node=5 location=@GaN.tks-@trap.tks

Y.MESH node=9 location=@GaN.tks

Y.MESH node=30 location=@GaN.tks+@AGN1.tks

Y.MESH node=40 location=@GaN.tks+@AGN1.tks+@AGN2.tks

Y.MESH node=50 location=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks

Y.MESH node=60 location=@GaN.tks+@AGN1.tks

+@AGN2.tks+@InGa.tks+@Body.tks

```

COMMENT =====
COMMENT  The following part determines the material used in different
COMMENT  regions of the device.

REGION name=s-ohmic  ix.low=1    ix.high=5  iy.low=1
+   iy.high=9    GAAS

REGION name=d-ohmic  ix.low=35   ix.high=40  iy.low=1
+   iy.high=9    GAAS

REGION name=barrier1  ix.low=1    ix.high=40  iy.low=9
+   iy.high=30   AlGAAS X.MOLE=0.15

REGION name=barrier2  ix.low=1    ix.high=40  iy.low=30
+   iy.high=40   ALGAAS X.MOLE=0.15

REGION name=channel  ix.low=1    ix.high=40  iy.low=40
+   iy.high=50   GAAS

REGION name=substra  ix.low=1    ix.high=40  iy.low=50
+   iy.high=60   GAAS

REGION name=isol1    ix.low=5    ix.high=15  iy.low=1
+   iy.high=9    insulato

REGION name=isol11   ix.low=15   ix.high=25  iy.low=1
+   iy.high=9    insulato

REGION name=isol2    ix.low=30   ix.high=35  iy.low=1
+   iy.high=9    insulato

```

REGION name=isol3 ix.low=25 ix.high=30 iy.low=1

+ iy.high=5 insulato

REGION name=trap ix.low=25 ix.high=30 iy.low=5

+ iy.high=9 insulato

COMMENT =====

COMMENT The following specifies the location of contact electrodes.

ELECTRODE name=source ix.l=2 ix.h=4 iy.l=1 iy.h=1

ELECTRODE name=drain ix.l=37 ix.h=39 iy.l=1 iy.h=1

ELECTRODE name=gate ix.l=15 ix.h=25 iy.l=9 iy.h=9

ELECTRODE name=sub ix.l=1 ix.h=40 iy.l=60 iy.h=60

COMMENT =====

COMMENT The following specifies the doping of each region.

PROFILE region=s-ohmic n-type x.min=0

+ x.max=(@tot.lgt-@chan.lgt-@sds.lgt)\*0.5

+ y.min=0 y.max=@GaN.tks uniform n.peak=@GaN.dop

PROFILE region=d-ohmic n-type

+ x.min=(@tot.lgt-@chan.lgt)\*0.5+@chan.lgt+@sds.lgt\*0.5

+ x.max=@tot.lgt y.min=0 y.max=@GaN.tks uniform n.peak=@GaN.dop

```

PROFILE region=barrier1 n-type x.min=0 x.max=@tot.lgt
+ y.min=@GaN.tks y.max=@GaN.tks+@AGN1.tks uniform n.peak=@AGN1.dop

PROFILE region=barrier2 n-type x.min=0 x.max=@tot.lgt
+ y.min=@GaN.tks+@AGN1.tks y.max=@GaN.tks+@AGN1.tks+@AGN2.tks uniform
+ n.peak=@AGN2.dop

PROFILE region=channel n-type x.min=0 x.max=@tot.lgt
+ y.min=@GaN.tks+@AGN1.tks+@AGN2.tks
+ y.max=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks
+ uniform n.peak=@InGa.dop

PROFILE region=substra n-type x.min=0 x.max=@tot.lgt
+ y.min=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks
+ y.max=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks uniform
+ n.peak=@Body.dop

PROFILE region=trap n-type x.min=(@tot.lgt+@chan.lgt)*0.5
+ x.max=(@tot.lgt+@chan.lgt)*0.5+@trap.lgt
+ y.min=@GaN.tks-@trap.tks y.max=@GaN.tks uniform
+ n.peak=@trap.dop

PROFILE N.TYPE CONC=2.98E20 Y.MIN=@GaN.tks+@AGN1.tks+@InGa.tks*0.4
+ char=@agn2.tks*0.05

INTERFACE region=(barrier2,channel) QF=1E13

INTERFACE region=(trap,barrier1) QF=-5.5e14

PLOT.2D grid fill scale

```



```

COMMENT =====
COMMENT  Material parameters redefinition of AlGaAs to be AlGaN.
CALL file=dataGaNupdate18809.inp
CALL file=dataAlGaNupdate18809.inp
CONTACT  name=gate SCHOTTKY WORKf=5.17
SAVE  MESH OUT.F=MES.MSH
MODELS  fermi auger consrh analytic fldmob hjtem hjtun

COMMENT =====
COMMENT  Initial solution.
SYMB  NEWT CARR=0
SOLVE  V(sub)=0 V(source)=0 V(drain)=0.05 V(gate)=0
SYMB  NEWT CARR=2
METHOD  itlimit=60 px.toler=1e-1 cx.toler=1e-1
SOLVE
PLOT.1D  X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ DOPING LOG
+  bottom=1e2 top=1e22 left=0
+  right=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+  TITLE=" Channel Doping & Electrons Device ON"

```

```

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ Y.ST=@GaN.tks+@AGN1.tks+@AGN2.tks
+ Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks
+ ELECT LOG COL=2

LABEL LABEL=Electrons COL=2 X=.8 Y=1e8

LABEL LABEL=Doping X=.02 Y=1e17

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ COND TOP=2.5 BOT=-5

+ NEG TITLE="HFET Band structure Device ON"

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ VAL UNCH NEG

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt/2
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ QFN UNCH NEG COL=2

LABEL LABEL=Cond X=0.1 Y=1

LABEL LABEL=Qfn X=0.1 Y=0

LABEL LABEL=Val X=0.1 Y=-3

```

```

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ COND TOP=2.5 BOT=-5
+ NEG TITLE="HFET Band structure Device ON"

```

```

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ VAL UNCH NEG

```

```

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*1/3
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ QFN UNCH NEG COL=2

```

```

LABEL LABEL=Cond X=0.1 Y=1

```

```

LABEL LABEL=Qfn X=0.1 Y=0

```

```

LABEL LABEL=Val X=0.1 Y=-3

```

```

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ COND TOP=2.5 BOT=-5
+ NEG TITLE="HFET Band structure Device ON"

```

```

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3
+X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3

```

```

+Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks

+VAL UNCH NEG

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3
+ X.END=(@tot.lgt-@chan.lgt)*0.5+@chan.lgt*2/3
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ QFN UNCH NEG COL=2

LABEL LABEL=Cond X=0.1 Y=1

LABEL LABEL=Qfn X=0.1 Y=0

LABEL LABEL=Val X=0.1 Y=-3

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.25
+ X.END=(@tot.lgt-@chan.lgt)*0.25
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ COND TOP=2.5 BOT=-5
+ NEG TITLE="HFET Band structure Device ON"

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.25
+ X.END=(@tot.lgt-@chan.lgt)*0.25
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ VAL UNCH NEG

PLOT.1D X.ST=(@tot.lgt-@chan.lgt)*0.25
+ X.END=(@tot.lgt-@chan.lgt)*0.25
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ QFN UNCH NEG COL=2

PLOT.1D X.ST=@tot.lgt-(@tot.lgt-@chan.lgt)*0.25

```

```

+ X.END=@tot.lgt-(@tot.lgt-@chan.lgt)*0.25
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ COND TOP=2.5 BOT=-5
+ NEG TITLE="HFET Band structure Device ON"
PLOT.1D X.ST=@tot.lgt-(@tot.lgt-@chan.lgt)*0.25
+ X.END=@tot.lgt-(@tot.lgt-@chan.lgt)*0.25
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ VAL UNCH NEG
PLOT.1D X.ST=@tot.lgt-(@tot.lgt-@chan.lgt)*0.25
+ X.END=@tot.lgt-(@tot.lgt-@chan.lgt)*0.25
+ Y.ST=0 Y.EN=@GaN.tks+@AGN1.tks+@AGN2.tks+@InGa.tks+@Body.tks
+ QFN UNCH NEG COL=2
PLOT.2D grid fill
COMMENT =====
COMMENT Generate plot of device structure.
PLOT.2D BOUNDARY FILL
+ TITLE="HFET Current Flow, Device ON"
FILL REGION=channel COLOR=5
FILL REGION=barrier1 COLOR=2
FILL REGION=barrier2 COLOR=6
FILL REGION=s-ohmic COLOR=3
FILL REGION=d-ohmic COLOR=3
FILL REGION=substra COLOR=9

```

FILL REGION=isol1 COLOR=11

FILL REGION=isol11 COLOR=7

FILL REGION=isol2 COLOR=11

FILL REGION=isol3 COLOR=11

FILL REGION=trap COLOR=13

LABEL LABEL=AlGaN x=.5 y=.1

LABEL LABEL=GaN x=.1 y=.003

LABEL LABEL=GaN x=.9 y=.003

LABEL LABEL=PASSIVATION x=.425 y=.003

LABEL LABEL=AlGaN x=.5 y=.04

LABEL LABEL=GaN x=.5 y=.055

LABEL LABEL=AlGaN x=.5 y=.05

CONTOUR FLOW

SOLVE V(sub)=0 V(source)=0 V(drain)=2.5 V(gate)=-1.8

PLOT.1D ele.vel x.start=(@tot.lgt-@chan.lgt-@sds.lgt)\*0.5

+ x.end=(@tot.lgt+@chan.lgt+@sds.lgt)\*0.5

+ y.start=@GaN.tks+@AGN1.tks+@AGN2.tks

+ (@InGa.tks\*0.5) y.end=@GaN.tks+@AGN1.tks+@AGN2.tks+(@InGa.tks\*0.5)

+ print out.file=velocity4.dat

PLOT.1D j.efield x.start=(@tot.lgt-@chan.lgt-@sds.lgt)\*0.5

+ x.end=(@tot.lgt+@chan.lgt+@sds.lgt)\*0.5

+ y.start=@GaN.tks+@AGN1.tks+@AGN2.tks

```

+ (@InGa.tks*0.5)  y.end=@GaN.tks+@AGN1.tks+@AGN2.tks+(@InGa.tks*0.5)

+ print out.file=electricfield4.dat

SOLVE  V(drain)=0.05  V(gate)=-1.8

+ ELEC=drain VSTEP=.4 NSTEP=37

PLOT.1D  X.AX=V(drain)  Y.AX=I(drain)  points ^order  print out.file=bit18.dat

SOLVE  V(drain)=14.85  V(gate)=-2.2

+ ELEC=drain VSTEP=-.4 NSTEP=37

PLOT.1D  X.AX=V(drain)  Y.AX=I(drain)  points ^order  unchange  print
out.file=bit22.dat

SOLVE  V(drain)=0.05  V(gate)=-2.6

+  ELEC=drain VSTEP=.4 NSTEP=37

PLOT.1D  X.AX=V(drain)  Y.AX=I(drain)  points ^order  unchange  print
out.file=bit26.dat

SOLVE  V(drain)=14.85  V(gate)=-3

+  ELEC=drain VSTEP=-.4 NSTEP=37

PLOT.1D  X.AX=V(drain)  Y.AX=I(drain)  points ^order

+ unchange print out.file=bit3.dat

SOLVE  V(drain)=0.05  V(gate)=-3.4

+  ELEC=drain VSTEP=.4 NSTEP=37

PLOT.1D  X.AX=V(drain)  Y.AX=I(drain)  points ^order

+ unchange print out.file=bit34.dat

```

