**A Study of Electroluminescence Produced by AlGaIn/GaN High
Electron Mobility Transistors**

by

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ABSTRACT

Red electroluminescence from AlGaN/GaN HEMTs from two manufacturers with completely different sources of GaN material was measured. Results for gate voltage, drain voltage, temperature and time dependency are general, and not linked to a specific growth technique. The optical spectrum of the electroluminescence showed a peak energy of 1.55eV. MEDICI device simulations along with measured data were used to build a model for photon emission that involves mid-bandgap traps possibly located in the carbon doped GaN sublayer and impact ionization for carrier supply.

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List of Abbreviations and Symbols

2DEG	2 Dimensional Electron Gas
ADC	Analog/Digital Converter
Al	Aluminum
AlGaN	Aluminum Gallium Nitride
Au	Gold
BJT	Bipolar Junction Transistor
C	Carbon
C:GaN	Carbon-doped Gallium Nitride
CCD	Charge-Coupled Device
DEI	Dynamic Electroluminescence Imaging
EL	Electroluminescence
FET	Field Effect Transistor
GaAs	Gallium Arsenide
GaN	Gallium Nitride
HBT	Hetero-Junction Bipolar Transistor
HEMT	High Electron Mobility Transistor
HP	Hewlett Packard
ID	Drain Current
IG	Gate Current
IS	Source Current
LED	Light Emitting Diode
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NRC	National Research Council
PICA	Pico-second Imaging Circuit Analysis
PLE	Photoluminescence Excitation
PMT	Photon Multiplier Tube
Pt	Platinum
RF	Radio Frequency
SMU	Source Measurement Unit
SOI	Silicon on Insulator
TCSPC	Time-correlated Single Photon Counting
TPHC	Time to Pulse Height Converter
VAR1,2	Variable mode for the HP4155A
VD	Drain Voltage
VG	Gate Voltage
VS	Source Voltage

Chapter 1 - Introduction

1.1 Motivation

With increasing demand on modern telecommunication systems by applications ranging from streaming wireless video to X-band military applications, the search for a high power, high frequency transistor to replace current technology, which is quickly reaching physical design limitations, is become more crucial. One promising candidate is the AlGaIn/GaN high electron mobility transistor (HEMT). With reported power capabilities of 3.3W/mm at 18GHz and 6.8W/mm at 10GHz[1], the AlGaIn/GaN HEMT appears to be well suited for future wireless systems.

With this promise, however, there are still challenges that must be overcome. Aside from large-scale manufacturing, reliability seems to be the limiting factor. Lattice mismatch between the substrate and the GaN layers creates increased numbers of dislocation sites where impurities may collect and create trap sites. These trap sites may result in the possible kink effect observed in some devices and may lead to increased noise during device operation. The filling and emptying of these traps may produce a photon if carrier momentum is conserved.

The study of electroluminescence has been used for failure analysis and characterization in various semiconductor technologies. To date, only limited high voltage studies [2, 3]

have been done on the electroluminescence produced from AlGaIn/GaN HEMT. The contribution to the scientific community of the work presented in this thesis is twofold.

- The electroluminescence produced by the AlGaIn/GaN HEMT, red luminescence in particular, at low to moderate drain biases will be fully characterized for gate bias, drain bias, time variation, position and energy of the electroluminescence produced.
- A theory of the origin of the electroluminescence based on empirical measurements and device simulation will be presented.

1.2 Thesis Organization

This thesis has been organized to provide the reader with theory used in the experiment, the apparatus used, the results and a discussion on the significance of the results.

Chapter 2 will provide the reader with background on the AlGaIn/GaN HEMT, including device importance, current problems and challenges, device structure and operation.

Also included is a brief discussion on electroluminescence.

Chapter 3 will provide the reader with insight into the equipment used to measure the electroluminescence. A full discussion will be included on the dynamic electroluminescence imaging (DEI) system, including operation and limitations of the measurement technique. A brief discussion on the LabRAM HR system, which was used

for spectral measurements and the Hewlett Packard 4155A, which was used to bias the device and to monitor currents, will also be included.

Chapter 4 will discuss the results of all experiments performed to characterize the electroluminescence produced by the AlGaIn/GaN HEMT. Gate and drain bias dependency, position, time variation, thermal dependency, two-terminal measurements, and spectral analysis will be presented. Analysis, where needed, will also be presented for each experiment. Chapter 5 will provide interpretation of the results. A theory of the origin of the electroluminescence will be presented along with conclusions that can be drawn from the results from chapter 4. Chapter 6 will summarize the work done and make recommendations for future work. Finally, appendix A will contain the MEDICI models used for device simulation.

Chapter 2 – The AlGa_N/Ga_N HEMT and Electroluminescence

2.1 Introduction

The purpose of the following chapter is to provide the reader with more background on the AlGa_N/Ga_N HEMT while giving more insight into the motivation behind this thesis. The first section of the chapter will discuss the importance of the AlGa_N/Ga_N HEMT, followed by a brief discussion on current issues with the AlGa_N/Ga_N HEMT. Finally, the device structure and a discussion on device operation and EL mechanisms will be presented.

2.2 Importance of the AlGa_N/Ga_N HEMT

As seen in Table 2.1 [4], the AlGa_N/Ga_N HEMT offers considerable device performance in high power microwave applications over other current technologies. To compare the various devices, Pribble et al. [4], used a Class AB amplifier. For F_t , $V_{DS,MAX}$ and I_{PEAK} , typical values for each technology were used. To calculate Z_{opt} , the optimal impedance to achieve a maximum output power for each device in the 6-18GHz band, an output capacitance of 0.2pF/mm was used. For Z_{out} , Pribble assumed a match of 15 dB to the optimum load was required for best power and power added efficiency operation. Z_{out} was then calculated and normalized to the 6 W/mm output of AlGa_N/Ga_N to compare the various technologies. This comparison shows the usefulness of AlGa_N/Ga_N technology. A large impedance transformation is required to achieve the same performance of the AlGa_N/Ga_N HEMT.

Table 2.1 – Comparison of Current Technologies

Technology	F_t (GHz)	$V_{DS, \text{Max}}$ (V)	I_{peak} (mA)	Z_{opt} (Ohms)	P_{max} (mW)	Z_{out} (Ohms)
GaAs MESFET	20	10	330	55	750	5.2
GaAs pHEMT	30	8	550	25	960	3.8
InP pHEMT	60-100	6	800	13	1000	1.7
GaN HEMT	35	35	800	75	6000	49

2.3 Current Issues with the AlGaIn/GaN HEMT

Although the AlGaIn/GaN HEMT offers many advantages over other technologies, problems with reliability must first be overcome. A good overview of current problems with AlGaIn/GaN HEMT is discussed in Mitrofanov et al. [5]. A brief summary will be included below.

During operation, a modulating gate voltage results in electron trapping in the region around the gate. It is speculated that the trapped electrons under the gate create an electric field that depletes the channel and limits the source to drain current. When this occurs it is called current collapse, also referred to as radio frequency (rf) dispersion.[5]

Another possible issue with the AlGaIn/GaN HEMT is known as the kink effect. The kink effect produces a sharp increase in drain current while in saturation. The kink effect may be seen in Figure 4.8 of chapter 4. The cause of this effect is currently unknown. A similar effect has been seen in Silicon-on-Insulator (SOI) MOSFETs and is believed to be caused by excess charge build up in the floating bulk of the device via avalanche

generation of carriers at the drain implant.[6] The AlGaN/GaN HEMT has a similar characteristic to the SOI MOSFET in that they both have a floating bulk (body). It is postulated that the kink effect in the AlGaN/GaN HEMT is the result of charge storage in the bulk however it is not known how the charge gets to the bulk (body).

2.4 HEMT Structure

The devices to be used in the experiment were fabricated by the NRC and a commercial vendor. The commercial vendor has asked not to be identified and will be referred to as Company X. Full fabrication details are available in [7][8] for the NRC devices.

Fabrication details are not available for the Company X devices due to intellectual property issues. A cross section of the NRC device is shown in figure 2.1.

Figure 2.1 – A cross section of the GaN HEMT.

Starting from the top, the first epilayer deposited by ammonia MBE at 930°C is a 20nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ barrier which donates the electrons for conduction. Next a 200nm epilayer of undoped GaN layer is deposited. The 2DEG channel is formed at the interface of the

AlGaN/GaN layer with the undoped GaN layer. A 2 μm epilayer of carbon doped GaN is added to provide isolation from other devices that may be on the substrate. The final layer is a 3nm AlN layer, deposited via sputtering, which is used to help with the lattice mismatch between the GaN and the sapphire substrate.

The gate is formed by a bilayer Pt/Au with a thin layer of Pt that is placed directly on the AlGaN to promote adhesion. The drain and source ohmic contacts are formed by a high temperature anneal of double stack of Ti/Al. Figure 2.2, shows an optical image of a NRC AlGaN/GaN dual gate stripe HEMT in microwave s-parameter pads.

Figure 2.2- Optical image of an AlGaN/GaN HEMT.

2.5 AlGaN/GaN HEMT Operation

Studies [9][10] into the formation of the 2DEG channel responsible for carrier transport suggest that the channel is a result of the spontaneous and piezoelectric polarization that occurs at the AlGaN/GaN interface. A MEDICI simulation (see appendix 1 for input files) of the conduction band edge and the electron quasi-Fermi level can be seen in figure 2.3. The channel is formed where the conduction band falls below the electron quasi-Fermi level.

Figure 2.3- Conduction band and quasi-fermi level showing the formation of the channel in the on state at $V_G=0V$.

The spontaneous polarization is the polarization at the AlGaN/GaN interface with zero strain conditions and arises from the existing net charge of the growth front.[10] The piezoelectric polarization arises from the strain at the AlGaN/GaN interface. The piezoelectric polarization is formed by two strain forces: the strain induced by the lattice mismatch of the AlGaN and the GaN layer and the thermal strain. Figure 2.4 shows the effect of spontaneous and piezoelectric polarization on the conduction band edge.

Figure 2.4- Conduction band edge showing the effects of spontaneous and piezoelectric polarizations.[9]

The net positive charge induced by spontaneous and piezoelectric polarization draws the electrons to the AlGaN/GaN interface. Further, the high electric field created at the interface causes tight confinement of the electrons to the channel region. It is the effect of the polarization that allows for high electron concentrations in the channel, even with undoped material. As reported by [9], the electron concentration in the channel can be

controlled by the fraction of Al in the AlGaIn. Figure 2.5 shows that as the fraction of Al increases, the electron concentration also increases, which corresponds to an increase of current capacity of the channel. A high fraction of Al, however, does require larger gate potentials for pinch off to occur in the channel due to an increase in the vertical electric field caused by the increase in spontaneous and piezoelectric polarization.

Figure 2.5- Electron density for various Al fractions.[9]

Applied lateral electric fields cause the channel electrons to flow horizontally. As in Si FETs, channel pinch off has been observed in GaN HEMT when high V_{DS} voltages are applied. Figure 2.6 shows this effect.

Figure 2.6- Conduction band edge and quasi-fermi level for various positions showing channel pinch off. $V_D = 10V$, $V_G = 0V$

2.6 Electroluminescence Mechanisms

Electroluminescence is the emission of light in response to an applied electric field or current.[11] In semiconductors, a photon may be released as a result of various carrier transitions listed below:

- **Inter-band transition-** In this process an electron transitions from the conduction band to the valence band or a hole transitions from the valence band to the conduction band of the material. If a photon is released, it will be at an energy equal to the band gap.

- ***Intra-band transition-*** *In this process a carrier transitions between energy states within a given energy band.*
- ***Trap state transition-*** *In this process a carrier transitions to an energy state within the band gap that is formed by an impurity or a defect in the semiconductor material.*

Studies into the origin of EL in Silicon FETs [12] suggest that the EL is the result of the above-mentioned transitions referred to as radiative transitions and only need one carrier type to occur and can only occur from intra-band and band-trap transitions. Hot carriers produced by strong lateral electric fields across the channel generally assist these radiative transitions. The other main EL mechanism in Silicon FETs is radiative recombination. Radiative recombination requires both carrier types and typically occurs at pn junctions. The result of a photon from this emission mechanism is less likely than radiative transitions in silicon FETs. Radiative recombination is the dominating EL mechanism in devices such as BJTs, HBTs and LEDs. It is believed that the dominating EL mechanism in the AlGaIn/GaN HEMT is most likely to be from a radiative transition like in the Si FET.

Chapter 3 – Experiment Apparatus

3.1 Introduction

The following chapter discusses the three main measurement systems used to characterize the EL from the AlGaIn/GaN HEMT. The first system discussed will be the Dynamic Electroluminescence Imaging (DEI) system. This system was used in the majority of the measurements and hence a large portion of the chapter will be dedicated to this. The following two instrument will be the Hewlett-Packard 4155A semiconductor parameter analyzer (HP4155A) and the Jobin And Yvon LabRam HR Micro-Raman spectrometer. These two instruments were treated more as a black box for measurement and only a short discussion will be presented.

3.2 The DEI System

3.2.1 Development of the DEI Measurement

DEI is a form of time-correlated single photon counting (TCSPC) wherein the data is spatially resolved, not just integrated for all x and y. TCSPC was first developed in 1961 at the University of Paris by Koechlin to measure molecular fluorescence decay[13]. The first application of TCSPC to semiconductor circuits came in 1987 by M^cMullen et al., who used this technique to look at relaxation processes in semiconductors. [14]

By the early 1990's IBM had developed a spatially resolved TCSPC system to analyze microprocessors. This system became commercially available under the name

Pico-second Imaging Circuit Analysis, acronym PICA. DEI was named and developed by the NRC to perform the same task of PICA. Unlike PICA, DEI is a simple system made from commercially available components. The technique was called DEI since the applications are broader than just circuit analysis.

3.2.2 Principle of a Measurement

The basic principle of DEI is to image and time correlate the EL of an operating semiconductor circuit. Figure 3.1 shows a block diagram of the DEI system. From Figure 3.1 it can be seen that light emitted from the device is imaged onto the anode of the PMT, where it is spatially resolved by the position analyzer and passed to the computer.

Concurrently, a timing pulse is created from the surge of electrons from the power supply that occurs at the arrival of a photon. This timing pulse is then compared to a reference time signal from the device under test and sent to the computer where it is stored with the corresponding X/Y data.

Figure 3.1 – Block diagram of the DEI system.

3.2.2.1 Spatial Correlation

A current pulse is created as a result of the arrival of a photon at the cathode. The current pulse propagates through the microchannel plate intensifiers, which make up the tube. The current pulse grows until the anode is reached. At the anode of the photon multiplier tube (PMT), the current pulse strikes a resistive plate. The electrons from the

current pulse spread evenly over the resistive plate. Attached to the resistive plates are four anodes that measure the relative arrival time of the current pulse.

These four signals are then passed through a discriminator that rejects false arrival pulses to effectively lower the signal-to-noise ratio of the spatial channels. From here, the valid arrival times are sent to the position analyzer, which calculates the x/y position of the arrival position of the electron pulse. The analog x/y positions are then passed to the ADCs where the position is binned into 2048 location values for both x and y. The final binned value is sent to a multi-channel analyzer where it is stored along with the time data associated with the x and y value.

3.2.2.2 Time Correlation

As shown in figure 3.1, the DEI system uses two signals for time correlation. The first signal is the start signal which is generated by the photon event created by the device under test. Upon the arrival of a photon, a current pulse is created on the high voltage power supply for the Mepsicron to supply the electrons needed for the electron pulse.

The transient current pulse is capacitively coupled to an external amplifier and then to a multilevel discriminator. It is the job of the discriminator to discriminate between a noise transient, a multi-photon event (i.e. the arrival of a photon during the propagation of the previous photon) and the desired single photon event. Once a valid photon event has been determined to have occurred, a pulse is sent to the time to pulse height converter (TPHC) to start a conversion.

Concurrently, either the device under test or a clock generator driving the device under test generates the stop signal, so long as the stop triggering signal is periodic. The stop signal is used as the reference time point for the timing correlation. The smallest time window that can be used is a 50ns time window. This corresponds to a maximum stop signal frequency of 20MHz. When measuring a device operating above 20MHz, a clock divider or a coherent reference can be used, such as the reference on the HP 8648D RF clock generator.

Once the TPHC receives both the start and stop signals, the time difference between the arrival of the start and stop is measured and output as an analog voltage. The time difference is the time that the photon arrived with respect to the reference clock edge. This value is then passed to an ADC where it is digitized into 4096 different values and sent to the multi-channel analyzer where it is stored with the corresponding x and y value.

3.2.3 System Limitations

3.2.3.1 Spatial Resolution

One limitation of DEI is the spatial resolution. In a measurement there are two main factors that limit the minimum resolution. These factors are the quantization from the analog to digital conversion at the ADC stage and the resolving power of the objectives in the optics system.

The minimum bin size and hence the minimum pixel size, after quantization by the ADC is given by Eqn. 3.1.

$$\begin{aligned} l_{pixel} &= \frac{d_{aa}}{n_h m} \\ w_{pixel} &= \frac{d_{aa}}{n_v m} \end{aligned} \quad (3.1)$$

where d_{aa} is the diameter of the active area of the imaging anode (23mm), n_h is the number of horizontal pixels(1530 pixels), n_v is the number of vertical pixels(1536 pixels), and m is the magnification. Table 3.1 shows the minimum pixel size for various magnifications.

Table 3.1- Pixel size for various magnifications

Magnification	Pixel Size (μm)	
	Horizontal	Vertical
1X	15	14
5X	3	3
10X	1.5	1.49
20X	0.75	0.748
50X	0.30	0.299
100X	0.15	0.149

The resolving power of the objectives in the optical system is defined as the ability of the objective to produce separable images of different points on an object.[15] The resolving power for various magnifications is given in table 3.2.

Table 3.2- Mitutoyo LWD APO Objectives Resolving power [16]

Magnification	Resolving Power (μm)
5X	2
10X	1
20X	0.7
50X	0.5
100X	0.4

Comparing the values in Table 3.1 and 3.2, it can be seen that for magnifications including and below 20X, the spatial resolution is limited by the quantization of the data by the ADC. Above 20X however, the spatial resolution is limited by the resolving power of the objective lenses in the optical system. Experimentally it has been found that the spatial resolution is better than $1\mu\text{m}$. Figure 3.2 shows the measured time integrated EL from a GaAs HBT with $1\mu\text{m}$ emitter metal width spatially resolved.

Figure 3.2 – GaAs HBT with $1\mu\text{m}$ width spatially resolved.[17]

3.2.3.2 Photon Multiplier tube and Detector Sensitivity

An important limitation to any DEI measurement is the physical limitations of the photon multiplier tube (PMT) and the detector sensitivity. The biggest limitation on a measurement from the PMT is the spectral response of the detector as seen in figure 3.3. From figure 3.3 the Mepsicron II detector shows a flat response from approximately 550nm to 825nm. Other important specifications for the Mepsicron II detector are listed in table 3.3.

Figure 3.3 –Typical detector spectral response for the Mepsicron II detector. [18]

Table 3.3- Mepsicron Sensitivity Specifications [18]

Specification	Value
Radiant Quantum Efficiency	6.7% @500nm 5.4% @800nm 0.7% @900nm
Background Dark Rate Count	316

3.3 The Jobin Yvon LAB Ram HR

When light is shone on a molecule, the scattered light is generally at the same energy. A small percentage of the light scattered however has a different energy than the incident light. Raman spectroscopy measures the photons with different energies and can be used to determine chemical composition. A Raman spectroscopy system can be used for spectral measurements in general by removing the light source and simply looking at the light produced by the device under test. For all spectral measurements the Jobin Yvon LabRAM HR instrument was employed. The LabRAM HR is an 800 mm focal length spectrograph with microscope optics for luminescence input. To measure the luminescence a 1024 channel cooled CCD detector is employed with a 600 groove/mm grating giving the detector a spectral coverage of approximately 40 nm. Since only a 40 nm region of the spectrum could be recorded at one time, many disjoint spectral regions are recorded and the full spectrum is knitted together with software.

3.3.1 Specifications

For full specifications, please refer to [19]. Below table 3.4 shows highlights of the LabRAM HR specifications.

Table 3.4- LabRAM HR Specifications [19]

Specification	Value
Quantum efficiency	20%@300nm 50%@750nm 0%@1100nm
Spectral coverage per measurement	40nm
Focal Length	800mm

3.4 Hewlett Packard 4155A

The HP 4155A is a semiconductor parameter analyzer that was used to bias the AlGaIn/GaN HEMT in all performed measurements. The HP4155A employs 4 medium powered source measurement units (SMU) to both supply a voltage or current and measure the current or voltage depending on what it is supplying. The SMU can be set in four different configurations which are listed below:

- **CONST** – *supply a constant voltage for the duration of the measurement while measuring current.*
- **VAR1** – *is the primary sweep variable. Provides a variable voltage while measuring current.*
- **VAR2** – *is the secondary sweep variable. Provides a variable voltage while measuring current.*
- **GROUND** – *connects the SMU to the ground of the HP4155A while measuring current.*[20]

In the case where both **VAR1** and **VAR2** are employed the HP4155A will first perform the sweep specified by **VAR1** then step **VAR2**. This is analogous to a nested loop in programming where **VAR2** is the outer loop and **VAR1** is the inner loop.

3.4.1 Specifications

For full specifications, please refer to the medium powered SMU specification table listed in [20]. Table 3.5 below shows highlights of the HP4155A specifications.

Table 3.5- Hewlett Packard 4155A Specifications [20]

Specification	Value
Max Supply Voltage	100V
Min Supply Voltage	100 μ V
Voltage Measure Resolution	2 μ V @ 2V range, 20 μ V@20V range 100 μ V@ 100V range
Max Current	100mA @ 2V range 20mA@100V range
Current Measure Resolution	10fA @ 1nA range 10nA@10mA range 100nA@100mA range

Chapter 4 – Results

4.1 Introduction

Various experiments were designed and performed on AlGa_N/Ga_N HEMTs from two suppliers. The devices under test were supplied from the National Research Council (NRC) and a commercial vendor who-wished not to be named and will be hereafter referred to as Company X. This chapter will present the results of tests performed. Each subsection will begin with an outline of the test described, including setup. All interpretation of the results will be done in chapter 5.

4.2 Devices

The EL of several devices from two sources, the NRC and COMPANY X, was examined. Below table 4.1 shows the properties of the tested devices. All devices were packaged in an open top gold-ceramic package for measurement stability. Also, all results presented were measured from the same company X device or NRC device to ensure that the data is comparable.

Table 4.1 – Measured Device Properties

Property	Supplier	
	NRC	Company X
Gate Length	2 μm	0.75 μm
Gate Width	20 μm	50 μm
Gate Fingers	2	2
Total Gate Width	40 μm	100 μm
Substrate type	Sapphire	Si
x, Al _x GaN _{1-x} /Ga _N	38	Unavailable
Surface	Unpassivated	Passivated

Load pull tests performed at 3.5GHz with an input power of 25dBm into a 50 Ω system on the company X devices showed no evidence of current collapse [21]. Insufficient tests by the supplier of the NRC devices were performed to determine the presence of current collapse in the NRC devices [22].

4.3 Position of EL Emission

One of the first tests done on both the NRC and Company X devices was to determine the position of the EL. Exact location is not possible due to the limits of spatial resolution as discussed in Chapter 3.4.1.

To find the position of the EL, the device was biased at a low drain voltage of 8V and a gate voltage of -3.5V. This was done to limit the EL coming from the device. High metal stacks on each side of the channel region cause light to reflect over the entire channel region at increased levels of EL. Once the device was powered, it was illuminated with the strongly attenuated lamp of the Karl Suss probe station so that the metal structure of the device can be imaged by the PMT.

Figure 4.1 and 4.2 shows the EL position from the COMPANY X and NRC devices respectively. Both devices show the EL on the drain side of the gate in the channel region. In particular, the lower gate finger in Figure 4.1 shows the EL to be at the edge of the gate on the drain side.

Figure 4.1 – Time integrated EL of the Company X GaN HEMT showing the position of the EL at the edge of the gate on the drain side of the channel.

Figure 4.2 – Time integrated EL of the NRC GaN HEMT showing the position of the EL on the drain side of the channel.

4.3.1 Anomalous EL Emission Position

During various tests, EL on the Source side of the channel was observed on several of the NRC devices. One such test was a slow pulse test where the gate voltage was held at -5V for 100 seconds and then the gate voltage was switched to 0V. Upon analysis, two EL spots were found on the source side of the channel as seen in Figure 4.3, the time integrated EL image.

Figure 4.3 – Time integrated EL of an NRC GaN HEMT showing the anomalous EL position on the source side of the channel.

Examining the source and gate current, a leakage path between the gate and the source where the anomalous EL emission was occurring was identified. A plot of the current is

shown in Figure 4.4. It should be noted that this EL anomaly was observed in static tests with sufficiently negative gate biases.

Figure 4.4 –Plot of Device current showing gate to source leakage.

The measured EL on the source side of the channel highlights a failure mechanism for increased gate leakage. Since this effect was anomalous, it was not further investigated. It does, however, highlight the potential usefulness of the DEI system to diagnose device failure in a circuit where individual terminal currents cannot be measured.

4.4 Voltage Dependency of the EL Emission

Measuring dependency with respect to drain and gate voltage was the next step in characterizing the EL of the AlGaIn/GaN HEMT. To perform these tests a Hewlett-Packard 4155A (HP4155A) semiconductor parameter analyzer was used to supply the

node biases. The DEI system was used to measure the EL intensity versus time. The time was then converted to the corresponding drain or gate voltage. Figure 4.5 shows a typical test setup.

Figure 4.5 –Schematic of a typical test setup

In test 1, the drain voltage was swept from 0 to 11V in 20mV steps using the HP4155A VAR1. The gate voltage was then stepped in either 1V steps from -5V to 1V for the NRC devices or in 0.5V steps from -3V to 1V for the COMPANY X devices using VAR2. The two step ranges were done since the COMPANY X devices showed no EL below a gate voltage of -3V and the HP4155A has a limited buffer size for storing the results of a measurement. The sources were biased to 0V.

In test 2, the gate voltage was swept from -5.5V to 1V in 15mV steps using the HP4155A VAR1. The drain voltage was then stepped in 1V steps from 4V to 11V using VAR2. The results of both test 1 and 2 will be discussed further in subsection 4.4.1 and 4.4.2

respectively. A 3D plot of the EL results was made from the results obtained from test 1 and 2. Figure 4.6 shows the V_G and V_D dependency for the AlGaIn/GaN HEMT. The sources were biased to 0V.

Figure 4.6 – V_G and V_D EL dependency for the NRC device.

For both tests a separate source-measurement unit (SMU) was used for each of the drain, gate, source1 and source2 biasing so that the current on each node could be monitored and recorded.

The timing of the measurement performed was of great concern since the time of the DEI measurement was converted to voltage. To ensure an accurate measurement, the HP4155A was set to a fixed measurement time for each bias step so that the bias steps would be evenly spaced in time, and thus the time/voltage value conversion could be performed. If the measurement time is set to automatic, the HP4155A will change the integration time of the measurement based on the current range of the measurement. Since the lower current range requires a longer integration, this could skew the data.

4.4.1 EL Drain Voltage Dependency

4.4.1.1 Company X Devices

Figure 4.7 shows the measured EL for the COMPANY X devices. Along with measuring the EL the current was also measured to check for possible correlations. The drain current is plotted in Figure 4.8 and the gate current is plotted in Figure 4.9.

Figure 4.7 – Company X device drain voltage EL dependency for various gate biases.

Examination of Figure 4.7 reveals that there appears to be two curve shapes for the EL drain bias relation dependent on the gate voltage. At low gate biases, when V_G is more negative than -2V, the EL curve appears to have a more gentle increase than when the gate voltages are more positive than -2V. Further, it appears as if there are a minimum of two mechanisms that produce the EL. It is unclear, however, whether the mechanisms are superimposed at more positive gate biases, or whether there are distinct and separate EL processes for the two gate bias regions.

Fitting the EL curves in Figure 4.7 revealed that the curves are not exponential or double exponential or the tail of a Gaussian distribution.

Figure 4.8 – Company X device I-V characteristics for V_D vs. I_D for various gate biases.

Figure 4.9 – Company X device I-V characteristics for V_D vs. I_G for various gate biases.

While comparing the drain current in Figure 4.8 with the drain bias EL dependency curves, a correlation was found between the beginning of the EL and the bump in the drain current, particularly apparent on the $V_G = -2V$ to $V_G = -1V$ curves. As the gate bias is increased (i.e. becoming more positive), the bump in the current occurs at a higher drain bias. Likewise, the onset of EL also increases exactly in drain bias as the gate potential becomes more positive. The EL, however, appears to have no dependency on the amount of current present in the channel with respect to drain bias. In particular, when the gate bias is $-3V$ the channel current reaches saturation at a drain bias of approximately $0.75V$. The EL on the other hand does not begin until a drain bias of approximately $3.1V$. As mentioned above, interpretation of the results will be in chapter 5. No direct correlation was found between the gate current and the EL dependency on the drain bias.

4.4.1.2 National Research Council Devices

Figure 4.10 show the measured EL for the NRC devices. Along with measuring the EL, the current was also measured to check for possible correlations. The drain current is plotted in Figure 4.11 and the gate current is plotted in Figure 4.12.

Figure 4.10 – NRC device drain voltage EL dependency for various gate biases.

Like the COMPANY X device, the NRC devices show similar EL drain bias dependencies. Examination of Figure 4.10 shows two curve shapes for the EL drain bias dependency which depends on the gate voltage. At more negative gate biases, i.e. more negative than $-2V$, the EL curve increases more gently as the drain bias increases than when the more positive gate biases. Once again, fitting the EL curves in Figure 4.11, like when fitting to curves in Figure 4.7, revealed that the curves are not exponential or double exponential in nature. Also the curves are not the tail of a Gaussian distribution.

Figure 4.11 – NRC device I - V characteristics for V_D vs. I_D for various gate biases.

Figure 4.12 – NRC device I - V characteristics for V_D vs. I_G for various gate biases.

Similar to the COMPANY X devices, the NRC devices show comparable correlations when comparing the drain currents in Figure 4.11 and the EL drain voltage dependency in Figure 4.9. A bump in the drain current, particularly apparent on the $V_G = -2V$ and $V_G = -1V$ curves. Trends are the same for the NRC devices as for the COMPANY X devices because as the gate bias becomes more positive, the bump in the current also increases to a more positive drain potential. The onset of EL also increases exactly in drain bias as the gate potential becomes more positive.

Similar to the COMPANY X devices, the NRC devices show no real correlation between the amount of current in the channel and the amount of EL. No direct correlation was found between the gate current and the EL dependency on the drain bias.

4.4.2 EL Gate Voltage Dependency

4.4.2.1 Company X Devices

Figure 4.13 shows the measured EL against gate potentials for various drain potentials. Along with measuring the EL the current was also measured and plotted to check for possible correlations. The drain current is plotted in Figure 4.17 and the gate current is plotted in Figure 4.18.

Figure 4.13 – *COMPANY X* device gate voltage EL dependency for various drain biases.

Examining Figure 4.13 the EL curves have an interesting shape. Examining the peak of the EL as the drain biased is increased, the peak of the EL shifts to a more positive gate potential. To quantify this, the curve was fit with a three-Gaussian function in Matlab, as shown in figure 4.14. From the fitted function the maximum EL value was found. Table 4.2 shows the value of V_G for which the maximum EL value occurred.

Figure 4.14 – Matlab fitted function (red) used for analysis.

Table 4.2 – V_G value for peak EL value

V_D (V)	V_G , peak (V)
11	-1.24
10	-1.39
9	-1.58
8	-1.79
7	-1.92
6	-2.14
5	-2.33

The values in Table 4.2 were plotted to determine the drain voltage dependency of the peak. Plotted in Figure 4.15, the peak gate bias value was easily fitted to a line. The approximate change of the peak voltage with respect to a change in drain bias is 0.182V/1V.

Figure 4.15 – $V_{G, peak}$ EL value verses V_D .

Further examination of Figure 4.13 revealed that the EL curve has different characteristics, depending on which side of the peak the EL occurs. On the side heading more negative, the rise of the EL is steep. Contrary, on the side going more positive, the fall of the EL is much more gradual. To quantify the “skewness” of the EL gate dependency, the left/ right (where left is heading more negative and right is heading more positive) half maximum value has determined for each drain voltage. Plotted in Figure 4.16, it is confirmed that the right side of the peak rises much more quickly at approximately 5.37 times faster than the left side of the peak returns to zero.

Figure 4.16 – V_G half maximum EL verses V_D .

Figure 4.17 – Plot of Full width at half maximum for various V_D values.

Also from Figure 4.16, it can be seen that both the right and left values are linear with respect to the drain bias. From the left and right value the full width at half maximum (FWHM) was calculated by subtracting the left/right gate voltages at which the half maximum EL values occurred. The FWHM is a way to express the width of a function. Plotted for various drain biases in Figure 4.17, it was concluded that as the drain bias increases the width of the EL gate dependency increases linearly at a rate of 264mV for every 1V increase in drain bias.

Figure 4.18 – Company X device I - V characteristics for V_G vs. I_D for various drain biases.

In comparing the drain current in Figure 4.18 with the gate bias EL dependency curves, a correlation was found between the beginning of the EL and turn on of channel current. As with the case of the EL drain bias dependency, there is no apparent correlation between the amount of current in the channel and the amount of EL emission at more positive gate

biases. In particular, when $V_D = 11\text{V}$, the peak EL, occurs at a gate bias of -1.23V , which corresponds to a drain current of approximately 21mA , at $V_G = 0\text{V}$, the EL emission is approximately 53% of the peak EL value despite a channel current of approximately 34mA .

Figure 4.19 – Company X device I-V characteristics for V_G vs. I_G for various drain biases.

Analysis of the gate current in Figure 4.19 with the EL emission curves in Figure 4.13 showed a strong correlation between the kink in gate current around $V_G = -2.8\text{V}$ and the beginning of the EL emission. Qualitatively, the more amount of EL appears to be proportional to the amount of gate current in that the higher the gate current, the higher the EL emission.

4.4.2.2 National Research Council Devices

Figure 4.20 shows the measured EL against gate potentials for various drain potentials. Like the COMPANY X devices, the NRC devices show similar gate bias dependency. One difference however is the off state (V_G less than -4V) EL emission. The NRC devices have a small EL emission that increases as the gate voltage becomes more negative. This is believed to be caused by the higher gate leakage in the device.

Figure 4.20 – NRC device gate voltage EL dependency for various drain biases.

4.5 Temperature Dependence of EL Emission

In performing voltage dependency experiments, it was noticed that the AlGaIn/GaN HEMT suffered from thermal self heating. Apparent by the negative slope in the device transconductance curve (Figure 4.21), it was questioned as to how a thermal change

would affect the EL emission. The gate voltage dependency test was therefore preformed at increased temperature. Using a thermal chuck and a thermocouple to monitor the temperature at the top of the ceramic package, the device was mounted in the temperature was raised from 21°C to 55°C and allowed to soak for twenty minutes to ensure the baseline temperature of the device was in fact 55°C. The test was then run at temperature. The device was then allowed to cool back to room temperature (21°C) and the test was run with exactly the same setup. The results are shown in Figure 4.22.

Figure 4.21 – Transconductance vs. V_G for a COMPANY X device. The negative slope in the transconductance indicates thermal self heating in the device.

Figure 4.22 – Gate voltage dependency for 21°C and 55°C performed on a COMPANY X device.

Examination of Figure 4.22 revealed that a 34 Celsius degrees in the device baseline temperature does not affect the EL emission of the device.

4.6 Two Terminal EL Emission

To gain a better understanding of how injected carriers from the source, gate and drain contribute to the overall EL emission, a series of two terminal tests were performed. The first test performed was to float the gate and sweep the drain voltage while holding the

source at ground. By floating a node, the node can no longer inject carriers to the EL emission processes.

Performing this test was not as trivial as initially thought. In an ideal device, if the gate is floated, the channel should behave like a low resistance resistor and in fact this happened with the COMPANY X devices as well as with gateless (no gate metal patterned) NRC devices. The problem found was that the current reached the compliance of the HP4155A, 100mA, rather quickly. In the COMPANY X device, the current reached 100mA at approximately 1.3V. From previous measurements, such as the drain and gate voltage dependency, it is believed that the amount of carriers in the channel is not relevant to EL emission, but rather the energy of the carriers of that results in EL emission. In this measurement, no EL emission was seen. This result is determined to be inconclusive since the drain voltage was not brought above 1.3V. Unfortunately, the risk of permanently damaging a device was too great to raise the drain bias due to the very limited supply of devices from COMPANY X.

While performing this measurement, the gate could not truly be floated in devices with high levels of gate current (in the order of 10 μ A). Figure 4.23 shows the result of one such measurement on an NRC device.

Figure 4.23 – Drain voltage dependency with floated gate performed on an NRC device with gate leakage on the order of $10\mu\text{A}$.

It is believed that in instances of increased gate leakage, charge from the biased drain can leak to the gate. This leaked charge can then bias the gate and supply enough carriers to cause control of the channel, which should not be possible with a truly isolated gate.

The next test performed was to float the source terminals and sweep the gate voltage for various drain biases, much like the gate voltage dependency test. This test effectively removes channel carriers. Performed on the COMPANY X devices, no EL emission was found.

The final two terminal test performed was to float the drain and sweep the gate voltage for various drain biases. Like the previous two terminal test, channel carriers are removed

from participating in the EL emission processes. Once again this test was performed on the COMPANY X devices and no EL emission was found. Table 4.3 summaries the results for all three two-terminal tests.

Table 4.3 – Two terminal Measurement Result Matrix as Performed on the COMPANY X Devices

	V_G/V_D biased	V_G/V_S biased	V_D/V_S biased
V_G floating	NA	NA	current too high
V_S floating	no EL	NA	NA
V_D floating	NA	no EL	NA

4.7 EL Emission Time Variation

Before performing spectral measurements on the AlGaIn/GaN HEMT, the time variation of the EL emission needed to be determined. To perform this test a static bias was provided to the device, and then the EL emission was measured over time. Figure 4.24 shows the EL emission rate verses chronological time.

Figure 4.24 – Time variation EL emission result

Examination of Figure 4.24 shows that the EL emission rate is fairly constant over time. A fitted line reveals that the EL emission rate falls slightly over time. This however is believed to be an issue with the focus rather than a change in EL emission rate. The DEI system can be prone to a wandering focus, especially at higher focuses. In general, the more something goes out of focus, the less light is collected. A slight focus problem can be seen in Figure 4.25, the time integrated EL of the measurement.

Figure 4.25 – Time integrated image for the time variation measurement, showing slight un-focus.

4.8 EL Emission Spectral Analysis

For spectral analysis a Jobin and Yvon Micro-Ramin system was used. Although the system is not ideal due to the high resolution spectrograph, the system could detect the low light levels produced by the AlGaIn/GaN HEMT. Early attempts to measure the spectra of the EL emission on a better-suited low-resolution spectrograph failed due to the low light levels.

To measure the spectrum of the EL the device was biased at peak EL emission, so to maximize the light. Like in the time variation measurement, the device was kept in a static state for the duration of the measurement. Figure 4.26 shows a typical measurement result.

Figure 4.26– Raw (dark blue), cleaned (medium blue), and fitted (light blue) spectral result.

The raw data from Figure 4.26 is quite messy. First, the detector response of the spectrometer (the wave on top of the raw data) had to be removed. To remove the detector response the Fourier transform of the data was taken. From the transform the frequency components associated with the detector response were removed and the inverse Fourier transform was taken to give the cleaned data. Next, a line was fitted to remove the background noise. Finally, the cleaned data was fitted with two Gaussian functions. Figure 4.27 shows a range of spectral measurements for the COMPANY X devices. Figure 4.28 shows the spectral results of the NRC devices.

Figure 4.27– COMPANY X spectral results for various gate and drain biases.

Analysis of Figure 4.27 showed that the median of the envelope of spectral distribution of the EL emission is 797nm or 1.55eV which is near the midgap of GaN. The peak of the two Gaussian functions that make the envelope are centered at 734nm (1.69eV) and 860nm(1.44eV) with a full width at half maximum of 165nm and 193nm, respectively.

Figure 4.28– NRC spectral results for $V_G=0V$ and $V_D=12V$.

The spectral distribution of the EL emission of the NRC device matched the COMPANY X results. The NRC device, however, shows a ripple on the residual of the fitted function. This ripple is believed to be created by reflections. Since light is emitted in all directions, it is believed that light reflects off the AlN layer back up to the detector. Based on the wavelength, the reflection would either add constructively or destructively. Using the refractive index of GaN, 2.4, the carbon doped GaN layer thickness was calculated to be 2.052mm. This confirmed that the ripple on the residual of the fitted function is indeed caused by reflections, since the thickness of the carbon doped GaN layer is supposed to be 2mm thick. Table 4.4 summaries the results of the spectral measurements.

Table 4.4 – Spectral Measurements Result Summary

	Value
Mean of distribution envelope	1.55eV or 797nm
Peak of gaussian fit 1	1.69eV or 734nm
Peak of gaussian fit 2	1.44eV or 860nm

Chapter 5 - Discussion

5.1 Introduction

Close examination of the results presented in Chapter 4 allows for hypotheses to be made regarding the origin of the EL in the AlGaIn/GaN HEMT. Since the AlGaIn/GaN HEMT is a relatively new device and growth of epitaxial AlGaIn/GaN films is not a standardized process some of the hypotheses are speculative. The hypotheses presented are, however, consistent with all the experimental results, and the author believes they have a high probability of being correct.

5.2 Energy Levels Responsible for EL

The first hypothesis regarding the EL emission is that it originates from mid and near mid gap energy levels. Evidence for this originates from the spectral measurements presented in Chapter 4, section 4.8. From the photon energy of the EL, which is close to half the bandgap energy of GaN, it is apparent that the EL is not the result of conduction band to valence band transitions. Further since the spectrum has a peak, the EL is not the result of intra-band transitions, which would result in a continuum spectral distribution. There is also no mechanism in these devices to generate the large number of extremely hot carriers that would be required to produce a strong intra-band transition spectrum. The spectral data then suggests that the EL is a result of transitions through mid gap or near mid gap energy levels.

5.3 Importance of C:GaN Sublayer

The following subsection is a speculation as to where the traps responsible EL exist in the device. Speculation is required since the exact device composition of the Company X device is not known, however, the composition of the NRC devices is well known.

Comparing the spectral results with photoluminescence (PL) experiments performed by Reuter *et al.* [23] it is apparent that the EL may originate from carrier injection into the carbon doped semi-insulating layer that lies beneath the undoped GaN layer where the channel is formed. Reuter *et al.* performed PL with a source below the band gap on a bare carbon doped GaN layer. Mid level trap states with peaks near 1.5eV and 1.64eV were found. This is close to the envelope mean of 1.55eV and the 1.44eV and 1.69eV fitted peaks. This suggests that the EL originates from the carbon doped GaN layer.

Internal current flow simulation in the AlGaIn/GaN HEMT was done using MEDICI to find from where the carriers that fill the traps in the carbon doped GaN layer are supplied. Figure 5.1 shows a 2D current flow plot for a drain bias of 10V and a gate bias of 0V. The bottom contour line on the plot represents 1.62 μ A of current. From these simulations it was found that the channel current reaches the C:GaN sublayer. Further the simulation is consistent with the EL position measurement as shown in Figures 4.1 and 4.2.

Figure 5.1- Current flow simulation for $VD=10V$ and $VG=0V$.

5.4 Carrier Supply to the EL Mechanism

The next hypothesis that can be drawn from the EL data is that the EL emission process can reach a steady state emission rate. Evidence for this arises from the time variation measurement presented in Chapter 4, section 4.7. This hypothesis is important because it implies that if a steady state can be reached by the emission process, then constant emptying and filling so there must be a form of carrier supply to the EL mechanism.

It is believed that the carrier supply mechanism is impact ionization. Previous studies into impact ionization in AlGaIn/GaN HEMT[24] have shown that the high-field drift region that exists between the gate and drain can create hot electrons with energies equal to the bandgap of the GaN channel. The hot electrons can undergo impact ionization resulting in two conduction band electrons and a hole in the valence band. Brar *et al.* speculated that the electrons are simply collected by the drain but the source, gate or traps in interlayer barriers can either collect the generated holes. Medici simulations of the

impact ionization have shown generation rates in the order of 10^{24} to 10^{27} (pairs/cm³)/s dependant on gate bias.

Examination of the EL versus gate bias as presented in Chapter 4, section 4.4.2 showed that for sufficiently negative gate biases, i.e. $V_G < -2.5\text{V}$ at $V_D = 11\text{V}$, the channel current can be directly correlated to the EL emission. In Figure 5.2, the drain current and EL emission were plotted on separate axis against gate bias. The vertical axes were scaled so that the drain current and EL emission could be compared. This suggests that the impact ionization in this gate bias region is dominated by the amount of channel electrons.

Figure 5.2 – At sufficiently negative gate biases, the drain current correlates directly to EL emission.

As the gate bias becomes more positive, i.e. closer to 0V, the impact ionization rate becomes dominated by the strength of the electric field in high drift region between gate

and the drain and not the amount of channel electrons. As V_G approaches 0V and V_D remains relatively high, i.e. $V_D=11V$, pinch-off effects at the edge of the gate on the drain side disappears and the electric field decreases and impact ionization becomes less favorable. The reduction of impact ionization rates, EL rates fall accordingly.

The impact ionization and electroluminescence in the AlGaIn/GaN HEMT is analogous to impact ionization and substrate current in Si MOSFETs. The effect of impact ionization in Si MOSFETs is a well studied and well understood phenomenon [25,26]. In an nMOS device, hot carriers produced by high electric fields in the channel may undergo impact ionization and generate an electron hole pair. The generated holes then follow to the substrate. Figure 5.3 shows a plot of substrate current versus gate bias for various drain biases for a Si MOSFET. Figure 5.4 shows a plot of $\log(EL)$ versus gate bias for various drain biases for a AlGaIn/GaN HEMT.

Figure 5.3 – Substrate current vs. V_G vs. V_D produced by hot carriers and impact ionization for a Si MOSFET.[25]

Figure 5.4 – $\log(EL)$ vs. V_G vs. V_D produced for a AlGaIn/GaN.

Comparing the plots in figures 5.3 and 5.4 it can be seen that the substrate current in a Si MOSFET and the EL produced in an AlGaIn/GaN HEMT have similar shapes and characteristics.

Further evidence to support the impact ionization model arises from the position of the EL, drain bias dependency and the floating terminal measurements. From the floating terminal measurements presented in section 4.6, it is apparent that for EL to take place channel carriers must be present. The carriers that undergo impact ionization in the AlGaIn/GaN HEMT are the channel carriers. Position measurements for the EL revealed that the EL takes place in the high drift region between the gate and the drain where the impact ionization also occurs. Finally, the EL shows a lateral electric field dependency from the drain bias dependency tests. Results show that as drain bias increases (thus electric field increases) the EL rate increases as well. This is consistent with impact ionization that as the applied electric field increases; the impact ionization rate increases as well.

Chapter 6 - Summary

6.1 Summary

The goal of the research, to characterize and find the physical mechanism for electroluminescence emission in the AlGaIn/GaN HEMT, was achieved through a series of measurements using the Dynamic Electroluminescence Imaging system and the Jobin-Yvon LabRAM HR system and device simulations using MEDICI.

The characterization of the electroluminescence was performed on various devices from two manufacturers. The fact that two completely different sources of GaN material were used suggests that the results are general, and not linked to a specific growth technique.

Listed below are the parameters for which the AlGaIn/GaN HEMT devices were characterized:

- Gate bias dependency for a range of -5.5V to 1V.
- Drain bias dependency for a range of 0V to 11V.
- Position of the EL.
- Spectral composition of the EL.
- Time variation.
- Thermal dependency.
- Floating terminal behavior

From the above measurements and device simulations it was concluded that the electroluminescence originates from mid-bandgap traps possibly located in the semiinsulating carbon doped GaN (C:GaN) layer that lies beneath the undoped GaN layer where the 2DEG channel is formed. The carriers responsible for the photon release by radiative transitions are created by impact ionization of channel electrons. Evidence for this was presented in Chapter 5.

6.2 Thesis Contributions

The primary contributions of this thesis to the scientific and engineering community can be summarized as follows.

- The electroluminescence produced, by the AlGaIn/GaN HEMT, in particular red luminescence, at low to moderate drain biases was fully characterized for gate bias, drain bias, time variation, position and spectral composition.
- A theory of the origin of the electroluminescence in AlGaIn/GaN HEMTs consistent with these measurements and device simulation was presented.

6.3 Publications

As a result of the research on the Dynamic Electroluminescence Imaging System, some of which this thesis includes, the following papers were presented at international conferences on devices and semiconductor failure analysis. The papers appear in the conference proceedings.

- **“Time resolved electroluminescence measurements on GaAs and GaN devices”**- Journal of Vacuum Science and Technology A: Vacuum, Surfaces and Films, Vol. 24,n3, Pg 686-9.
- **“Dynamic electroluminescence imaging as an optical oscilloscope probe”** - ISTFA 2005. Proceedings of the 31st International Symposium for Testing and Failure Analysis. Pg 245-8.
- **“Watching semiconductor circuitry work”**- Progress in Biomedical Optics and Imaging - Proceedings of SPIE, Vol 5969 Pg 59692U-1 – 59692U-8.

6.4 Recommendations and Future Work

Despite the success of this project in characterizing and explaining the electroluminescence produced by the AlGaIn/GaN HEMT, equipment and software constraints have left room for future work and improvement.

Although it is known the EL is the result of carrier interaction with mid-gap energy states, it is uncertain how the trap states are emptied. Two mechanisms appear possible. The traps could be emptied via voltage assisted tunneling with the electron returning back into the channel. Alternatively, the trap could be emptied by recombination. Since the device has an isolated body, substrate current measurements cannot be made. Device simulations with newer versions on MEDICI that include GaN and AlGaIn models may give more accurate simulations and better insight to this problem. Also, Current-Deep Level Transient Spectroscopy at negative gate biases and EL studies at extreme temperatures may reveal more about the trap activation energies.

Another idea for a future experiment would be to correlate the possible kink effect seen in the drain current with the onset of hot carrier effects. Results presented in this thesis suggest a correlation, however the present data are not conclusive cannot be determined.

Finally, yet another idea for a future experiment would be to study the effect of hot carrier trapping in the C:GaN on the overall noise of the device. If the noise contribution

is high the DEI system may be a very effective tool to quickly characterize the noise performance of the AlGaIn/GaN HEMT for RF design purposes. .

Appendix A – MEDICI Simulation Code

To simulate the behavior of the AlGaIn/GaN HEMT the Synopsys TCAD program MEDICI was used. In total, three files were needed to model the AlGaIn/GaN HEMT. The first file was HFET.DEFINE. Shown below in Figure A.1 this file was used to define all layer thickness, dopings and other properties. All values used reflect the NRC devices properties.

```

TITLE      DEFINITION FILE FOR GaN HFET or RES STRUCTURE GEOMETRY
$
$      Original version:      Tom MacElwee   Apr  1 1996
$      Revision 1:           Keith Sarault   May 2006
$
$.....
$
$      DEVICE DIMENSIONS
$.....

ASSIGN NAME=DEVICE      C.VALUE=HFET
ASSIGN NAME=Alx          N.VALUE=0.38
ASSIGN NAME=L            N.VALUE=2
ASSIGN NAME=lgs          N.VALUE=1
ASSIGN NAME=lgd          N.VALUE=1.5
ASSIGN NAME=W            N.VALUE=20
ASSIGN NAME=scale        N.VALUE=2
ASSIGN NAME=tcap          N.VALUE=0.0060
ASSIGN NAME=tbar         N.VALUE=0.0060
ASSIGN NAME=tspace       N.VALUE=0.0060
ASSIGN NAME=tch          N.VALUE=0.2000
ASSIGN NAME=tbuf         N.VALUE=2.000
ASSIGN NAME=tsub         N.VALUE=100.0
ASSIGN NAME=Ndcap        N.VALUE=5E19
ASSIGN NAME=Ndbar        N.VALUE=5E19
ASSIGN NAME=Ndspace      N.VALUE=5E19
ASSIGN NAME=Ndch         N.VALUE=1
ASSIGN NAME=Ndbuf        N.VALUE=1E2
ASSIGN NAME=Ndsd         N.VALUE=1.0E14
ASSIGN NAME=Ndsb         N.VALUE=1E1
ASSIGN NAME=HL           N.VALUE=@L/2
ASSIGN NAME=SD           N.VALUE=15.0
ASSIGN NAME=TEMP         N.VALUE=50
ASSIGN NAME=Schottky      N.VALUE=5.20
ASSIGN NAME=Phimc        N.VALUE=0.0
$.....
$
$      AC Parasitic Device Elements
$      Gate Resistances in ohms/sq
$      Contact Resistances ohm-mm
$      Inductances in H/um width
$      Capacitance in F/um^2
$.....
$

```

```

$      Gate inductance approximated by treating the gate as a
$      microstrip line. Lg is given by  $\mu * d * Z / (m * 2 * L)$ 
$      where
$      mu is the permeability
$      d is the depletion depth under the gate
$      Z is the total transistor width in microns
$      m is the number of fingers
$      L is the gate length in microns
$
ASSIGN NAME=GateR          N.VALUE=4e-2
ASSIGN NAME=SourceR        N.VALUE=9.37e-1
ASSIGN NAME=SourceL        N.VALUE=0
ASSIGN NAME=DrainR          N.VALUE=9.37e-1
ASSIGN NAME=DrainL          N.VALUE=0
ASSIGN NAME=Cdpar           N.VALUE=4.5e-19
ASSIGN NAME=Cgpar           N.VALUE=4.5e-19

$.....
$
$      STRUCTURE FORMATION RELATED INFORMATION
$.....

ASSIGN NAME=q              N.VALUE=1.602E-19
ASSIGN NAME=Eperm          N.VALUE=9-(0.5*@Alx) PRINT
ASSIGN NAME=es             N.VALUE=8.854E-14*@Eperm PRINT
ASSIGN NAME=Vs             N.VALUE=1.42
ASSIGN NAME=dEc            N.VALUE=(1E-3+1.34*@Alx) PRINT
ASSIGN NAME=d              N.VALUE=@tcap+@tbar+@tspace
ASSIGN NAME=dcr            N.VALUE=3.5e-7
ASSIGN NAME=Qpol           N.VALUE=@es*(@Vs-@dEc)/@dcr/@q PRINT
ASSIGN NAME=CCL            N.VALUE=(@SD+@lgs+@L/2)
ASSIGN NAME=XSTART         N.VALUE=0
ASSIGN NAME=XSTOP          N.VALUE=(@SD+@lgs+@L+@lgd+@SD/2)
ASSIGN NAME=YSTART         N.VALUE=-2
ASSIGN NAME=YSTOP          N.VALUE=(@tcap+@tbar+@tspace+@tch+@tbuf+@tsub)
ASSIGN NAME=tAlGaN         N.VALUE=(@tcap+@tbar+@tspace)
ASSIGN NAME=QHI            N.VALUE=3.58E13*@Alx PRINT
ASSIGN NAME=QSI            N.VALUE=4*@QHI/4
ASSIGN NAME=TOX            N.VALUE=0.3
ASSIGN NAME=VMAX           N.VALUE=-10.0
ASSIGN NAME=IMAX           N.VALUE=0.1
ASSIGN NAME=FTMAX          N.VALUE=35

```

Figure A.1 – The HFET.DEFINE code.

The second file needed was COEFFICIENTS. Since the MEDICI simulator did not support GaN, AlGaN or AlN, similar type materials were used and the adjustable material properties were shifted to reflect those of GaN, AlGaN, and AlN. The COEFFICIENTS file is shown in figure A.2.

```

$      MATERIAL COEFFICIENTS FOR ALGAN/GAN MEDICI SIMULATIONS

$      Tom MacElwee & Iain Calder          Jun 17 1992
$      Revision #1                          Dec 1 1992
$      Revision #2                          May 18 1993
$      Revision #3                          July 3 1994
$      Revision #4 Tom MacElwee 6H-SiC      Apr 2 1996
$      Revision #5 Tom MacElwee 6H-SiC      Apr 26 1996
$      Revision #6 Tom MacElwee 4H-SiC      Aug 11 1996
$      Revision #7 Tom MacElwee REGION=ZnSe/REGION=ZnTe Aug 18 1997

```

```

$*****
$
$      NOTE ZnSe = GaN and ZnTe = AlN
$
$*****
$***** Auger recombination coefficients (#2.2.2)
$      ZnSe= GaN  ZnTe = AlN  InAs = AlGaIn 15%
$*****

$MATERIAL  ZnSe          AUGN=2.8E-31  AUGP=9.9E-32
$MATERIAL  ZnTe          AUGN=2.8E-31  AUGP=9.9E-32
$MATERIAL  InAs          AUGN=2.8E-31  AUGP=9.9E-32
MATERIAL  SiC            AUGN=2.8E-31  AUGP=9.9E-32
MATERIAL  SILICON        AUGN=5E-32    AUGP=9.9E-32
MATERIAL  POLYSILICON    AUGN=5E-30    AUGP=9.9E-30

$*****
$      Concentration dependent lifetimes (#2.2.4)
$*****

MATERIAL  SiC            TAUN0=5.0E-7  NSRHN=5.0E16
+          AN=1.00        BN=0.0        CN=1.0
+          EN=0.30        TAUP0=5.0E-8  NSRHP=5.0E16
+          AP=1.00        BP=0.0        CP=1.0
+          EP=0.30
MATERIAL  SILICON        TAUN0=8.0E-6  NSRHN=1.0E18
+          AN=2.03        BN=254.8      CN=13.1
+          EN=1.72        TAUP0=5.0E-6  NSRHP=6.68E18
+          AP=4.22E-3     BP=38.3      CP=58.6 EP=2.0
MATERIAL  POLYSILICON    TAUN0=9.0E-6  NSRHN=2.5E15
+          AN=1.0         BN=0.0        CN=1.0
+          EN=0.5         TAUP0=3.0E-6  NSRHP=2.5E15
+          AP=1.0         BP=0.0        CP=1.0
+          EP=0.5
$*****
$      Bandgap and density of states coefficients (#2.2.6)
$*****
$
$      NOTE ZnSe = GaN and ZnTe = AlN      InAs = AlGaIn
$
$      need to assign AlGaIn permitivity, effective mass etc.
$
$
$      ASSIGN  NAME=EPMR  N.VALUE=9-(0.5*@Alx)
$      ASSIGN  NAME=ELMAS N.VALUE=0.12+(0.194*@Alx)
$      ASSIGN  NAME=EHRM  N.VALUE=0.259+(0.212*@Alx)
$      ASSIGN  NAME=TCN   N.VALUE=0.77-0.5*@Alx
$
$
MATERIAL  InAs          EG300=3.42    NC300=6.83E18  NV300=1.794E19
+          EGALPH=3.3E-4  EGBETA=5.8E-4
+          PERMITTI=@EPMR
+          EL.EMAS=@ELMAS  HO.EMAS=1      ARICHN=110
+          EM.MODEL=0      EG.MODEL=0
+          AFFINITY=4.07  AF.X0=-1e-3
+          AF.X1=-1.34    AF.X2=0.0
+          EG.X1=2.78     EG.X2=0.0
+          A.TH.CON=@TCN
$+          V0.BGN=9.6E-3  N0.BGN=1.0E19  CON.BGN=0.0

MATERIAL  ZnSe          EG300=3.42    NC300=1.04E18  NV300=1.794E19
+          EGALPH=3.3E-4  EGBETA=5.8E-4
+          PERMITTI=9.0
+          EL.EMAS=0.12   HO.EMAS=1      ARICHN=110
+          EM.MODEL=0     EG.MODEL=0

```

```

+          AFFINITY=4.07  AF.X0=0.0
+          AF.X1=0         AF.X2=0.0
+          EG.X1=0.0       EG.X2=0.0
+          A.TH.CON=0.77
$+         V0.BGN=9.6E-3   NO.BGN=1.0E19  CON.BGN=0.0
$+         AFFINITY=3.77  AF.X0=0.0

MATERIAL  ZnTe          EG300=6.20      NC300=8.346E18      NV300=8.112E18
+          EGALPH=3.3E-4  EGBETA=5.8E-4
+          PERMITTI=8.50
+          EL.EMAS=0.48   HO.EMAS=0.471  ARICHN=110
+          EM.MODEL=0     EG.MODEL=0
+          AFFINITY=2.624 AF.X0=0.0
+          AF.X1=0         AF.X2=0.0
+          EG.X1=0.0       EG.X2=0.0
+          A.TH.CON=0.5
$+         V0.BGN=9.6E-3   NO.BGN=1.0E19  CON.BGN=0.0

MATERIAL  SiC           EG300=3.30      NC300=3.53E19 NV300=1.794E19
+          PERMITTI=9.66  AFFINITY=3.313
+          V0.BGN=9.6E-3  NO.BGN=1.0E19  CON.BGN=0.0
+          EL.EMAS=1     HO.EMAS=1     ARICHN=110
+          A.TH.CON=0.3333
MATERIAL  SILICON       EG300=1.124   NC300=3.22E19  NV300=1.83E19
+          V0.BGN=9.6E-3  NO.BGN=7.7E17  CON.BGN=0.122

MATERIAL  POLYSILICON   EG300=1.124   NC300=3.22E19  NV300=1.83E19
+          V0.BGN=3.5E-3  NO.BGN=5.91E17 CON.BGN=0.0

MATERIAL  OXIDE         PERMITTI=1.0

MATERIAL  SAPPHIRE      PERMITTI=9.39  A.TH.CON=2

$*****
$      Impact ionization coefficients      (#2.9)
$*****

MATERIAL  SiC           N.IONIZA=4.57E6      ECN.II=3.407E7  EXN.II=1.0
+          P.IONIZA=5.18E6      ECP.II=1.00E7  EXP.II=1.0

$MATERIAL  ZnSe         N.IONIZA=4.57E5      ECN.II=3.407E8  EXN.II=1.0
+          P.IONIZA=5.18E5      ECP.II=1.00E8  EXP.II=1.0

MATERIAL  SILICON       N.IONIZA=3.0E5  ECN.II=1.231E6
+          P.IONIZA=2.71E5      ECP.II=1.69E6

MATERIAL  POLYSILICON   N.IONIZA=3.0E5  ECN.II=1.231E6
+          P.IONIZA=2.71E5      ECP.II=1.69E6

$*****
$      Dopant Ionization Energy
$      ZnSe= GaN  ZnTe = AlN  InAs = AlGaN 15%
$*****

$MATERIAL  SiC          EDB=0.100      EAB=0.200
$+          GCB=2.0      GVB=4.0
$MATERIAL  SILICON      ETRAP=-0.1
$MATERIAL  InAs         EDB=0.056      EAB=0.230
+          GCB=2.0      GVB=4.0
$+          ETRAP=1.5
$MATERIAL  ZnTe         EDB=0.024      EAB=0.240
+          GCB=2.0      GVB=4.0
$MATERIAL  ZnSe         EDB=0.090      EAB=0.160
+          GCB=2.0      GVB=4.0

$*****
$      Thermal Conductivity
$*****

```

```

MATERIAL   SiC          A.TH.CON=0.303 B.TH.CON=0
+          C.TH.CON=0.0  D.TH.CON=0.0
+          E.TH.CON=0.0

$*****
$   Low Field Mobility Numbers based on measured data
$*****
$*****
$
$   ZnSe= GaN  ZnTe = AlN  InAs = AlGaIn
$
$*****

MOBILITY   SiC          MUN0=272      FLDMOB=1      BETAN=0.8549
+          VSATN=1.37E7

MOBILITY   ZnSe          MUN0=1100     FLDMOB=2      E0N=1.2E5
+          VSATN=9E6

$MOBILITY  ZnSe          MUN0=960      FLDMOB=1      BETAN=1.8
+          VSATN=9.4E6

$MOBILITY  ZnSe          MUN0=1100     FLDMOB=1      BETAN=0.85
+          VSATN=2.E6

$MOBILITY  ZnSe          MUN0=450      FLDMOB=1      BETAN=1.335
+          VSATN=2.67E7

MOBILITY   InAs          MUN0=200      FLDMOB=0      BETAN=1.335
+          VSATN=2.67E5

MOBILITY   ZnTe          MUN0=35 FLDMOB=0      BETAN=0.8549
+          VSATN=1.37E7

```

Figure A.2 – The COEFFICIENTS file code

The final file is the simulation file HFET_STRUCTURE. This file is used to set the mesh grid for simulation, the models to be used and what plots to be output. Figure A.3 shows the code for the HFET_STRUCTURE file.

```

TITLE      MEDICI SIMULATION OF A ZnSe HFET TRANSISTOR STRUCTURE
$
$   GaN MESFET simulation: Tom MacElwee Nov. 6 1997
$   Revised: Keith Sarault June 2006
$
$   Set the directory that the impurity profiles will be
$   sourced from and the plotting device.

$CALL      FILE=SOURCES ^PRINT
$CALL      FILE=STYPE
CALL       FILE=HFET.DEFINE

$.....
$
$   Specify a rectangular mesh
$.....
MESH      RECTANGULAR  SMOOTH=1
+         ^DIAG.FLI
+         VIRTUAL

```



```

+          OUTFILE=@L"_@DEVICE".GRID"

X.MESH  LOCATION=@XSTART
X.MESH  LOCATION=@SD-1.0          N.SPACES=3
X.MESH  LOCATION=@SD              N.SPACES=4
X.MESH  LOCATION=@SD+@lgs         H1=0.25 H2=@HL/5
X.MESH  LOCATION=@CCL              N.SPACES=5
X.MESH  LOCATION=@CCL+@HL         N.SPACES=5
$X.MESH LOCATION=@CCL+@HL+@lgd     N.SPACES=10
X.MESH  LOCATION=@CCL+@HL+@lgd     H1=@HL/5 H2=@lgd/10
X.MESH  LOCATION=@CCL+@HL+@lgd+1.0 N.SPACES=4
X.MESH  LOCATION=@XSTOP-1.0        N.SPACES=3

Y.MESH  NODE=1                    LOCATION=@YSTART
Y.MESH  NODE=3                    LOCATION=-0.3
Y.MESH  NODE=5                    LOCATION=0.0
Y.MESH  DEPTH=@tcap               N.SPACES=4
Y.MESH  DEPTH=@tbar               N.SPACES=5
Y.MESH  DEPTH=@tspace              N.SPACES=3

Y.MESH  DEPTH=@tch                 H1=0.001      H2=@tbuf/50

Y.MESH  DEPTH=@tbuf                N.SPACES=5

Y.MESH  DEPTH=@YSTOP-(@tcap+@tbar+@tspace+@tch+@tbuf)  N.SPACES=10
$.....
$
$      ELIMINATE UNWANTED NODES
$
$.....
$ELIMINATE ROWS X.MIN=@XSTART X.MAX=@SD-1
+      Y.MIN=0.0 Y.MAX=@YSTOP-(@tcap+@tbar+@tspace+@tch+@tbuf)
$ELIMINATE ROWS X.MIN=@CCL+@HL+@lgd+1.0 X.MAX=@XSTOP
+      Y.MIN=0.0 Y.MAX=@YSTOP-(@tcap+@tbar+@tspace+@tch+@tbuf)
$ELIMINATE ROWS X.MIN=@SD X.MAX=(@CCL+@L/2+@lgd)
+      Y.MIN=(@tcap+@tbar+@tspace+@tch)
+      Y.MAX=@YSTOP-(@tcap+@tbar+@tspace+@tch+@tbuf)
$.....
$
$      Specify oxide and GaN/AlGaIn regions
$      ZnSe= GaN ZnTe = AlN InAs = AlGaIn
$.....

REGION  NAME=Oxide  OXIDE
+      X.MIN=@XSTART
+      X.MAX=@XSTOP
+      Y.MIN=@YSTART
+      Y.MAX=0.0

REGION  NAME=IGS    OXIDE
+      X.MIN=@CCL-@L/2-7*@lgs/10
+      X.MAX=@SD+@lgs
+      Y.MIN=@YSTART
+      Y.MAX=0.0
$+      X.MIN=@SD

REGION  NAME=IGD    OXIDE
+      X.MIN=@CCL+@L/2
+      X.MAX=@CCL+@L/2+7*@lgd/10
+      Y.MIN=@YSTART
+      Y.MAX=0.0

REGION  NAME=Cap     InAs  X.MOLE=@Alx
+      X.MIN=@XSTART
+      X.MAX=@XSTOP
+      Y.MIN=0.0

```

```

+                                Y.MAX=(@tcap)

REGION  NAME=Barrier InAs      X.MOLE=@Alx
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=@tcap
+                                Y.MAX=(@tcap+@tbar)

REGION  NAME=Spacer  InAs      X.MOLE=@Alx
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=(@tcap+@tbar)
+                                Y.MAX=(@tcap+@tbar+@tspace)

REGION  NAME=Channel ZnSe      X.MOLE=0
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=(@tcap+@tbar+@tspace)
+                                Y.MAX=(@tcap+@tbar+@tspace+@tch)

REGION  NAME=Buffer1 ZnSe      X.MOLE=0
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=(@tcap+@tbar+@tspace+@tch)
+                                Y.MAX=(@tcap+@tbar+@tspace+@tch+@tbuf/5)

REGION  NAME=Buffer2 ZnSe      X.MOLE=0
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=(@tcap+@tbar+@tspace+@tch+@tbuf/5)
+                                Y.MAX=(@tcap+@tbar+@tspace+@tch+2*@tbuf/5)

REGION  NAME=Buffer3 ZnSe      X.MOLE=0
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=(@tcap+@tbar+@tspace+@tch+2*@tbuf/5)
+                                Y.MAX=(@tcap+@tbar+@tspace+@tch+3*@tbuf/5)

REGION  NAME=Buffer4 ZnSe      X.MOLE=0
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=(@tcap+@tbar+@tspace+@tch+3*@tbuf/5)
+                                Y.MAX=(@tcap+@tbar+@tspace+@tch+4*@tbuf/5)

REGION  NAME=Buffer5 ZnSe      X.MOLE=0
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=(@tcap+@tbar+@tspace+@tch+4*@tbuf/5)
+                                Y.MAX=(@tcap+@tbar+@tspace+@tch+@tbuf)

REGION  NAME=Sub      Sapphire
+                                X.MIN=@XSTART
+                                X.MAX=@XSTOP
+                                Y.MIN=(@tcap+@tbar+@tspace+@tch+@tbuf)
+                                Y.MAX=@YSTOP

$ .....
$
$      Electrode definition:
$
$      GATE=1      SOURCE=2      DRAIN=3      SUBSTRATE=4
$ .....
IF      COND=(@DEVICE="RES")
ELSE
  ELECTRODE NAME=Gate  X.MIN=(@SD+@lgs)
+                      X.MAX=(@SD+@lgs+@L)
+                      Y.MIN=-0.3
+                      Y.MAX=0.0

```

```

IF.END
ELECTRODE NAME=Source X.MIN=@XSTART
+ X.MAX=@SD
+ Y.MIN=-0.3
+ Y.MAX=0.0
ELECTRODE NAME=Drain X.MIN=(@SD+@lgs+@L+@lgd)
+ X.MAX=@XSTOP
+ Y.MIN=-0.3
+ Y.MAX=0.0

ELECTRODE NAME=Substrate BOTTOM THERMAL
$.....
$
$ NOW DOPE AND FORM THE Buffer and CHANNEL LAYERS
$.....
$

PROFILE REGION=Cap N-TYPE N.PEAK=@Ndcap
+ X.PEAK=@XSTART WIDTH=@XSTOP
+ Y.MIN=0.0
+ Y.MAX=@tbar
+ UNIFORM

PROFILE REGION=Barrier N-TYPE N.PEAK=@Ndbar
+ X.PEAK=@XSTART WIDTH=@XSTOP
+ Y.MIN=@tcap
+ Y.MAX=@tcap+@tbar
+ UNIFORM

PROFILE REGION=Spacer N-TYPE N.PEAK=@Ndspace
+ X.PEAK=@XSTART WIDTH=@XSTOP
+ Y.MIN=@tcap+@tbar
+ Y.MAX=@tcap+@tbar+@tspace
+ UNIFORM

PROFILE REGION=Channel N-TYPE N.PEAK=@Ndch
+ X.PEAK=@XSTART WIDTH=@XSTOP
+ Y.MIN=@tcap+@tbar+@tspace
+ Y.MAX=@tcap+@tbar+@tspace+@tch
+ UNIFORM

PROFILE REGION=(Buffer1,Buffer2,Buffer3,Buffer4,Buffer5)
+ N-TYPE N.PEAK=@Ndbuf
+ X.PEAK=@XSTART WIDTH=@XSTOP
+ Y.MIN=(@tcap+@tbar+@tspace+@tch)
+ Y.MAX=@tcap+@tbar+@tspace+@tch+@tbuf
+ UNIFORM

$.....
$
$ NOW DOPE THE SOURCE/DRAIN JUNCTIONS
$.....
$
PROFILE REGION=Cap N-TYPE N.PEAK=@Ndscd
+ X.PEAK=@XSTART WIDTH=@SD
+ Y.MIN=0.0 Y.MAX=@tcap
+ UNIFORM

PROFILE REGION=Cap N-TYPE N.PEAK=@Ndscd
+ X.PEAK=@XSTOP-@SD/2 WIDTH=@SD/2
+ Y.MIN=0.0 Y.MAX=@tcap
+ UNIFORM

$.....
$
$ NOW DOPE THE SiC Substrate
$.....

```

```

$
$PROFILE    REGION=Sub N-TYPE N.PEAK=@Ndsub
+          X.PEAK=@XSTART WIDTH=@XSTOP-@XSTART
+          Y.MIN=@tcap+@tbar+@tspace+@tch+@tbuf
+          Y.MAX=@YSTOP
+          UNIFORM

$.....
$
$          Specify contacts
$
$.....
IF          COND= (@DEVICE="RES")
$CONTACT   NAME=Source          WORKFUNCTION=@Phimc
$CONTACT   NAME=Drain           WORKFUNCTION=@Phimc
CONTACT    NAME=Source          NEUTRAL
CONTACT    NAME=Drain           NEUTRAL
ELSE
CONTACT    NAME=Gate            WORKFUNCTION=@Schottky
$+         VSURFN=100.0 VSURFP=100.0
CONTACT    NAME=Source          NEUTRAL
CONTACT    NAME=Drain           NEUTRAL
CONTACT    NAME=Substrate       NEUTRAL
IF.END

$.....
$
$          hetrojunction interface piezo-electric charge density
$.....
$INTERFACE REGION=(Cap,Oxide)      QF=-@QHI
INTERFACE REGION=(Spacer,Channel)  QF=@QHI
INTERFACE REGION=(IGD,Cap)         QF=-@QSI
INTERFACE REGION=(IGS,Cap)         QF=-@QSI

INTERFACE REGION=(Channel,Buffer1) N.ACCEPT=2E10
INTERFACE REGION=(Buffer1,Buffer2) N.ACCEPT=2E10
INTERFACE REGION=(Buffer2,Buffer3) N.ACCEPT=2E10
INTERFACE REGION=(Buffer3,Buffer4) N.ACCEPT=2E10
INTERFACE REGION=(Buffer4,Buffer5) N.ACCEPT=2E10
$.....
$
$          Save starting solution
$.....
SYMBOLIC    NEWTON          CARRIERS=0
METHOD      ITLIMIT=20      ICCG
SOLVE       INIT

SYMBOLIC    NEWTON          CARRIERS=1
METHOD      ITLIMIT=20      ICCG
SOLVE       PREVIOUS

$REGRID     ELECTRON        RATIO=1.1
$+          OUTFILE=@L"_"@DEVICE".GRID"
$+          X.MIN=@XSTART X.MAX=@XSTOP
$+          Y.MIN= (@tcap+@tbar) Y.MAX= (@tcap+@tbar+@tspace+@tch)

SYMBOLIC    NEWTON          CARRIERS=1 VIRTUAL
METHOD      ITLIMIT=20      ICCG
SOLVE       PREVIOUS
$+          OUTFILE=@L"_"@DEVICE"_0_0_0.SOLUTION"      SAVE.BIA

$.....
$
$          Specify models, materials
$.....
CALL        FILE=COEFFICIENTS      PRINT

```

```

MATERIALS PRINT
MOBILITY          PRINT
MODELS    TEMPERAT=(273+@TEMP)    ^BGN    ^AUGER ^SRH    ^PRINT
MODELS    ^ET.MODEL PREMOB FLDMOB ^BTBT ^INCOMPLETE FERMIDIR ND.MOB
+         HJTEM HJTUN ^HJSC1 ^HJSC2 PRINT
$MODELS    QM.PHILI QM.NORP=0 QM.EFIEL=0 QM.METHO=1

SYMBOLIC  NEWTON          CARRIERS=1
METHOD    ITLIMIT=60      ETX.TOLE=1E-1 LTX.TOLE=1E-2
+         ETR.TOLE=1E-10 LTR.TOLE=1e-8
SOLVE     PREVIOUS
+         OUTFILE=@L"_"@DEVICE"_0_0_0.SOLUTION"          SAVE.BIA

$$SYMBOLIC NEWTON          CARRIERS=1 LAT.TEMP COUP.LAT
$METHOD    ITLIMIT=40      ETX.TOLE=1E-1 LTX.TOLE=1E-2
$+         ETR.TOLE=1E-10 LTR.TOLE=1e-8
$$SOLVE    PREVIOUS
$+         OUTFILE=@L"_"@DEVICE"_0_0_0.SOLUTION"          SAVE.BIA

EXTRACT
+         ELECTRON
+         X.MIN=(@SD+@lgs)+@L/2
+         X.MAX=@SD+@lgs+@L/2
+         Y.MIN=0.0
+         Y.MAX=@tcap+@tbar+@tspace          PRINT
EXTRACT
+         ELECTRON
+         X.MIN=@SD+@lgs+@L/2
+         X.MAX=@SD+@lgs+@L/2
+         Y.MIN=@tcap+@tbar+@tspace
+         Y.MAX=@tcap+@tbar+@tspace+@tch          PRINT
EXTRACT SHEET.RE
+         X.POINT=@SD+@lgs/2
+         Y.MIN=@tcap+@tbar+@tspace
+         Y.MAX=@tcap+@tbar+@tspace+@tch          PRINT
EXTRACT
+         ELECTRON
+         X.MIN=@SD+@lgs/2
+         X.MAX=@SD+@lgs/2
+         Y.MIN=@tcap+@tbar+@tspace
+         Y.MAX=@tcap+@tbar+@tspace+@tch          PRINT
EXTRACT SHEET.RE
+         X.POINT=(@SD+@lgs)/2
+         Y.MIN=@tcap+@tbar+@tspace
+         Y.MAX=@tcap+@tbar+@tspace+@tch          PRINT
EXTRACT SHEET.RE
+         X.POINT=@SD+@lgs+@L+@lgd/2
+         Y.MIN=@tcap+@tbar+@tspace
+         Y.MAX=@tcap+@tbar+@tspace+@tch          PRINT

$*****
$
$           Define Output plots
$
$*****

$Set solution
SOLVE V(GATE)=0 V(DRAIN)=10 V(SOURCE)=0.0
IMPACT.I GATE.CUR

$OUTPUT CURRENT FLOW
PLOT.2D DEVICE="CL/POSTSCRIPT" BOUNDARY FILL SCALE X.MIN=14 X.MAX=20 Y.MIN=-0.3 Y.MAX=1
TITLE="Current flow VG=0V VD=10V"
PLOT.OUT=CF10_0.ps
CONTOUR flow NCONTOUR=10

```

```
$OUTPUT ELECTRON CONCENTRATION
$PLOT.1D X.ST=17 X.EN=17 Y.ST=0 Y.EN=(@tcap+@tbar+@tspace+@tch) ELECT
OUTFILE="elec17g0vd7.txt"

$OUTPUT ELECTRIC FIELD LINES
$PLOT.1D X.ST=17 X.EN=17 Y.ST=0 Y.EN=(@tcap+@tbar+@tspace+@tch) E.FIELD
OUTFILE="efield17g0d7.txt"

$OUTPUT ENERGYBANDS

PLOT.1D DEVICE="CL/POSTSCRIPT" X.ST=17 X.EN=17 Y.ST=0 Y.EN=(@tcap+@tbar+@tspace+@tch+0.2)
COND TOP=8 BOT=-20
+ NEG TITLE="BAND STRUCTURE VG=0, VD=10V X=17" PLOT.OUT=17ext.ps OUTFILE="band17c.txt"
PLOT.1D X.ST=17 X.EN=17 Y.ST=0 Y.EN=(@tcap+@tbar+@tspace+@tch+0.2) VAL UNCH NEG COL=3
OUTFILE="band17v.txt"
PLOT.1D X.ST=17 X.EN=17 Y.ST=0 Y.EN=(@tcap+@tbar+@tspace+@tch+0.2) QFN UNCH NEG COL=2
OUTFILE="band17q.txt"

$OUTPUT Contour plot

$PLOT.2D DEVICE="CL/POSTSCRIPT" BOUNDARY FILL SCALE Y.MIN=-1 Y.MAX=50 TITLE="Potential
VG=0V VD=10V" PLOT.OUT=Potential_VG0V.ps
$CONTOUR POTENTIAL
```

Figure A.3 – The HFET_STRUCTURE file code

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