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13. ABSTRACT (Maximum 200 words) AlGaN/GaN HFET's demonstrate considerable promise for advanced RF power sources for communications and radar systems. Experimental HFET devices have produced RF output power on the order of 10-12 W/mm of gate periphery at frequencies up to X-band. However, as frequency is increased to the mm-wave region RF performance significantly degrades. There are a variety of physical effects that currently limit the high frequency performance of these devices. In particular, it is proposed that charge non-confinement in the conducting channel of these devices can produce space charge and related effects that limit the performance of the HFET's. This project investigates charge non-confinement phenomena and develops an analytic channel charge model that can be used in a comprehensive HFET model for use in large-signal RF circuit simulators.			
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mm-Wave AlGaIn/GaN HFET's

A Final Report on Grant No. DAAD19-01-1-0753

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mm-Wave AlGaN/GaN HFET's

1 Introduction

AlGaN/GaN HFET's demonstrate considerable promise for advanced RF power sources for communications and radar systems. Experimental HFET devices have produced RF output power on the order of 10-12 W/mm of gate periphery at frequencies up to X-band. However, as frequency is increased to the mm-wave region RF performance significantly degrades. There are a variety of physical effects that currently limit the high frequency performance of these devices. In particular, it is proposed that charge non-confinement in the conducting channel of these devices can produce space charge and related effects that limit the performance of the HFET's. This project investigates charge non-confinement phenomena and develops an analytic channel charge model that can be used in a comprehensive HFET model for use in large-signal RF circuit simulators.

2 Drift-Diffusion Model

The properties of the AlGaN/GaN device have been derived first from a one-dimensional model.

2.1 Model

Assuming the AlGaN layer has a fixed charge layer, a fixed surface charge number density n_{ss0} (induced polarization charge) was assigned to the interface between the AlGaN and the GaN and has been experimentally determined: $n_{ss0} = 4 \times 10^{12} (cm^{-2})$. We start with the differential equation for the charge balance at equilibrium in one dimension (1-D). Here the diffusion and the drift currents are set equal in order to maintain equilibrium.

$$J_{total} = 0 = q \mu_n n(x) E(x) + q D_n \frac{dn(x)}{dx} \quad (1)$$

where we have assumed a fixed charge mobility, μ_n and a fixed charge, q . The electric field $E(x)$ and the charge density $n(x)$ are both functions of the distance into the medium. In addition, we use Gauss' Law for electrostatics,

$$\frac{dE(x)}{dx} = -\frac{q}{\epsilon} n(x) \quad (2)$$

and assuming the charge density is differentiable and the electric field is twice differentiable, Gauss' Law can be written as

$$\frac{d^2 E(x)}{dx^2} = -\frac{q}{\epsilon} \frac{dn(x)}{dx}$$

(3)

Substituting equation (3) into equation (1) results in a Riccati equation and the boundary conditions

$$\frac{dE(x)}{dx} + \frac{q}{2kT} E^2(x) = 0 \quad (4)$$

The constants are found through a substitution of the boundary conditions. At the interface, $x=0$, the

$$E(0) = E_{\max} \quad \text{and} \quad n(0) = n_{ss}$$

where the maximum charge on the GaN side of the interface between the AlGaIn/GaN is given by n_{ss} . The maximum electric field, E_{\max} at the interface can be found from Gauss' law under the assumption that the polarization charge at the interface is the sheet charge density introduced earlier, $n_{ss0} = 4 \times 10^{12} \text{ (cm}^{-2}\text{)}$. Hence, from the solution for the electric field due to a static sheet charge density, we find the maximum electric field at the interface, $E_{\max} = -qn_{ss0} / \epsilon_2$ where ϵ_2 is the permittivity of the GaN material.

Using the appropriate substitutions, this equation may be solved exactly. Consequently, the electric field distribution, $E(x)$, inside the GaN material is then found to be

$$E(x) = \sqrt{\frac{2kTC}{q}} \left[\frac{A_1 \exp\left\{\sqrt{\frac{qC}{2kT}} x\right\} - A_2 \exp\left\{-\sqrt{\frac{qC}{2kT}} x\right\}}{A_1 \exp\left\{\sqrt{\frac{qC}{2kT}} x\right\} + A_2 \exp\left\{-\sqrt{\frac{qC}{2kT}} x\right\}} \right] \quad (5)$$

The constants A_1 and A_2 are determined from the solution of the Riccati equation

$$A_1 = 1 + \sqrt{\frac{q}{2kTC}} E_{\max} ; \quad A_2 = 1 - \sqrt{\frac{q}{2kTC}} E_{\max}$$

Apply to solution to get two equations in two unknowns:

$$4C \frac{A_1 A_2}{(A_1 + A_2)^2} = -\frac{q}{\epsilon} n_{ss} \quad (6)$$

Once we get the electric field as a function of distance, $E(x)$, one can find the charge distribution, $n(x)$, from Gauss' law

$$n(x) = -\frac{\epsilon}{q} \frac{dE(x)}{dx}$$

where the peak charge distribution at the GaN side of the interface is given by $n(0) = n_{ss}$. Consequently, a simple derivative of the field yields the charge density as a function of

depth into the material. Using these boundary conditions, the constant, C is given as function of the maximum electric field and the charge at the interface,

$$C = E_{\max}^2 \frac{q}{2kT} - \frac{q}{\epsilon} n_{ss} \quad (7)$$

n_{ss} is the injection level and as injection increases, C gets smaller. The constants A_1 and A_2 are also a function of n_{ss} , so the high injection effect should be interesting.

2.2 Sample Results

The parameters for the simulation of the one dimensional model were drawn from published literature. In the following example, the electric field, the charge number density and the total charge enclosed are given for a variety of enclosed total charge values. The first and largest total charge enclosed is given by the precise distribution which balances the polarization-induced sheet charge density (red/solid line). The second trace is roughly 0.5*maximum charge density at the interface for the given (fixed) polarization charge (blue/small dash). The third trace is roughly the 0.25*charge density of the operating point at the interface for the given (fixed) polarization charge (black, large dash).

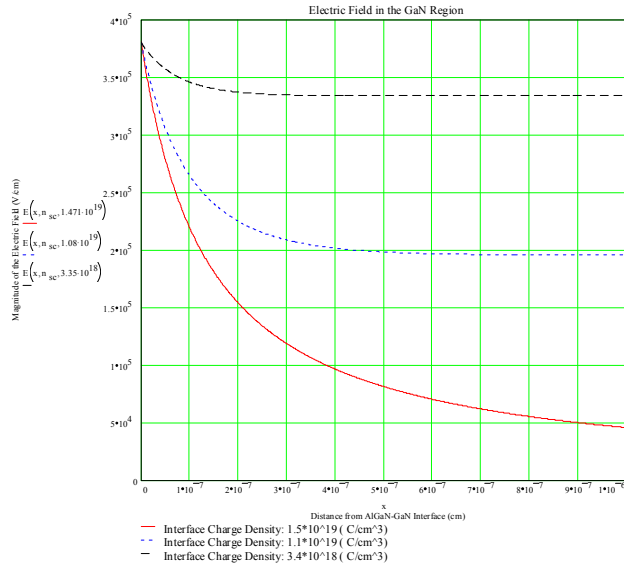
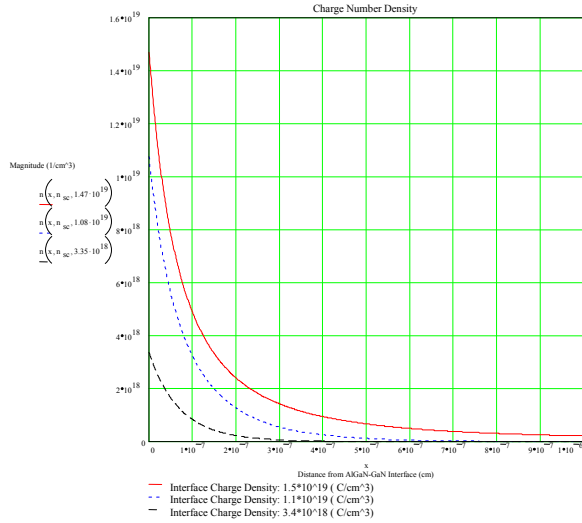
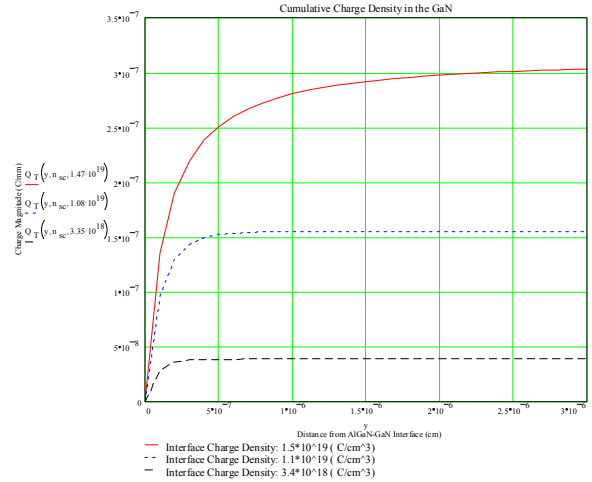


Figure 1: The Electric Field Intensity for (1) constant polarization induced sheet charge ($n_{ss0} = 4 \times 10^{12} (cm^{-2})$) and (2) a varying total charge in the 1-D cross-section



(a) Charge Number Density



(b) Total Charge

Figure 2: The Charge Characteristics for a constant polarization induced charge, but varying maximum charge density at the interface

3 Numerical Solution of the Two-Dimensional Problem

The solution of the one-dimensional problem was adequate as a first cut for the problem solution and we found that its results matched well with the measured results in the literature. However, the device represents a three-dimensional problem; however, for speed and convenience, a two-dimensional solution was sought at this point. This model should lend greater insight into the operation of the device.

3.1 Model

The numerical solution was created first using a finite element model for Poisson's equation. Although this will be the preferred route, the finite element method required absorbing boundary conditions at the free edges of the device. At this point, the finite element model was not cooperating and was "shelved" in order to construct a simpler model using a finite difference approach. Figure 3 displays the geometry and the electrical parameters of interest in this problem. Note there are three layers: the AlGaIn layer, the GaN layer, and the substrate. Actual devices may be constructed with a larger number of similar layers and the simulation code can accommodate these problems as well. For transparent results, however, this simple model was chosen. The contacts for the drain, the source and the gate are shown with heavy lines and an associated voltage. The gate voltage, V_G , is not assigned since it will remain a variable in the following simulations. In each simulation event, two plots are show for the two dimensional device: a contour plot and a surface plot.

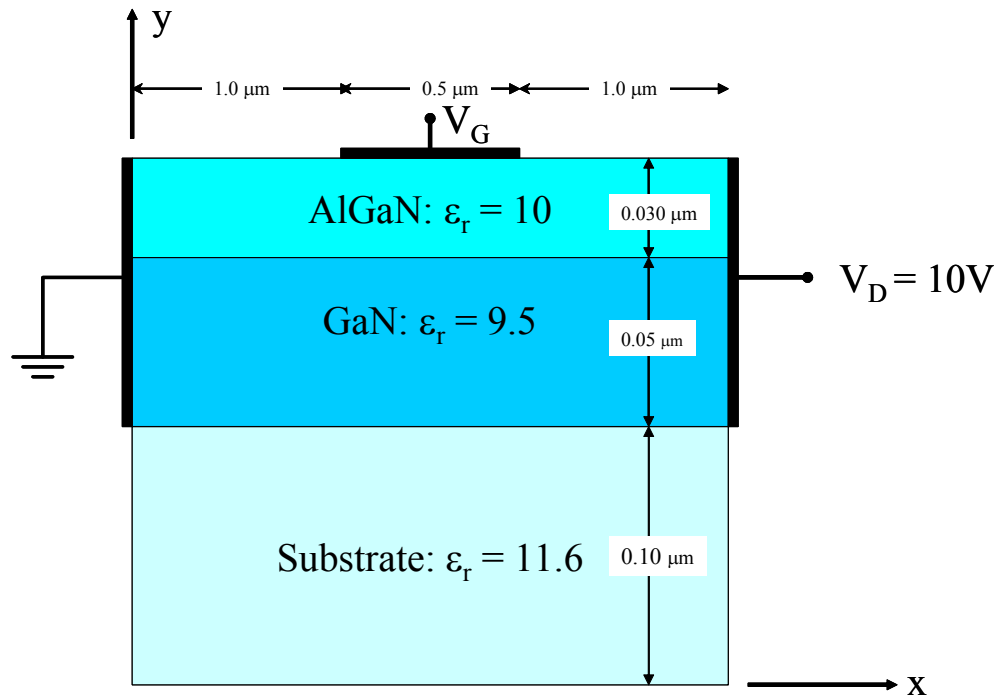


Figure 3: The AlGaN Device Geometry for Two-Dimensional Simulations

In each of the following cases, the potential due to the induced, fixed surface charge at the interface is held to the previously reported value: $1.6 \times 10^{14} \text{ (C/m}^2\text{)}$, the drain voltage was held to 10 volts and the source was held to common. The dimensions of the device are given in Figure 3. The materials include the AlGaN layer, the GaN layer and a layer of substrate, assumed to be sapphire (the relative permittivity of sapphire was set to 11.6). At the open regions of the AlGaN, the free space region was terminated after two levels of spatial discretization with a radiation-like boundary condition. Hence, the field was permitted to progress without reflection. This of course could only be approximated.

3.2 Sample Results

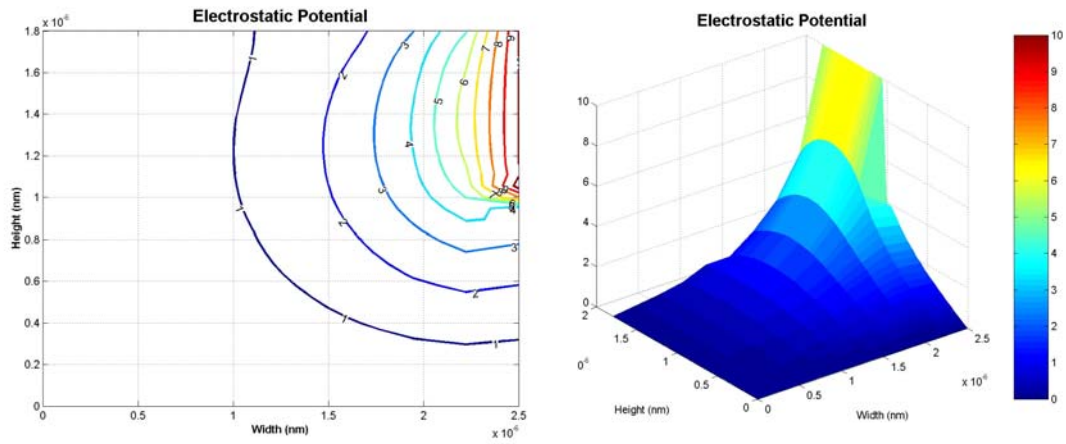


Figure 4: Forward Biased: Gate Voltage held to 1 Volt

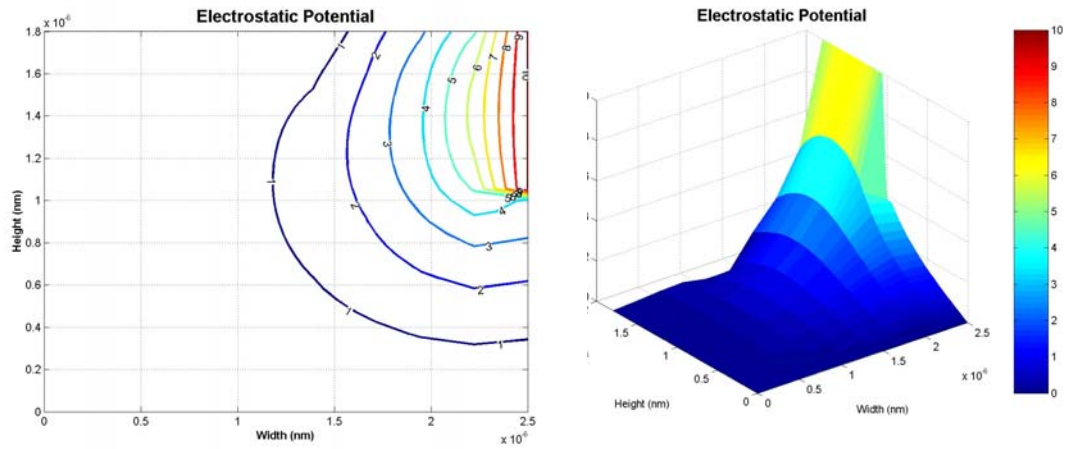


Figure 5: Forward Biased: Gate Voltage held to 0 Volts

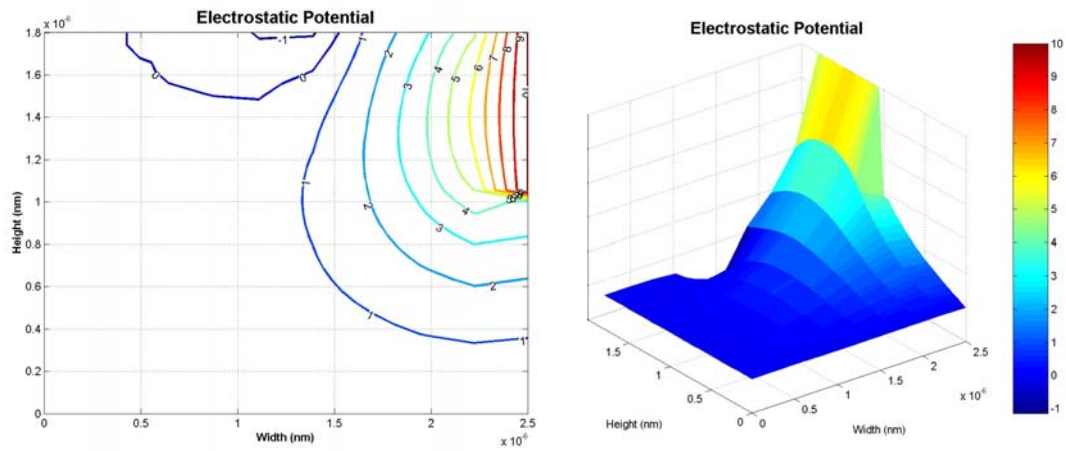


Figure 6: Forward Biased: Gate Voltage held to -1.15 Volt

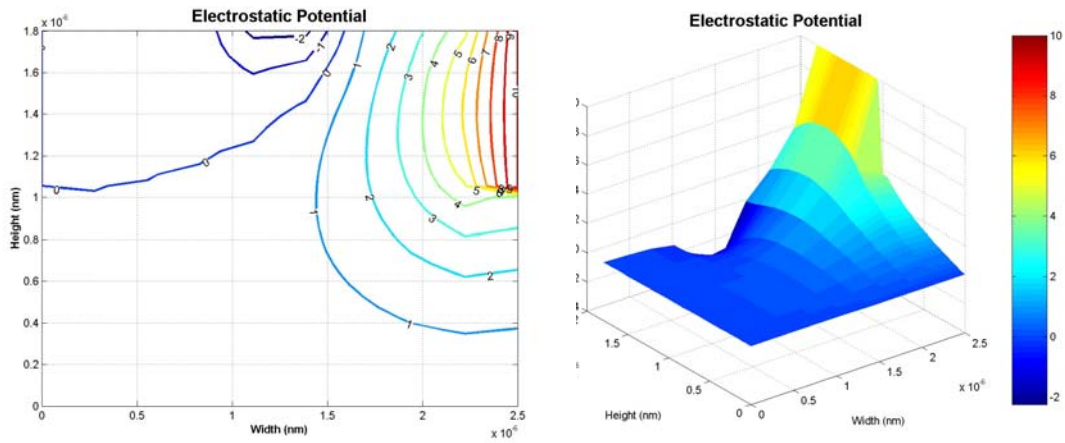


Figure 7: Forward Biased: Gate Voltage held to -2.25 Volts

This final case was chosen such that the channel has closed. One side of the device maintains a positive potential while the other side is negative. Simulations reaching beyond this bias yield an even stronger division.

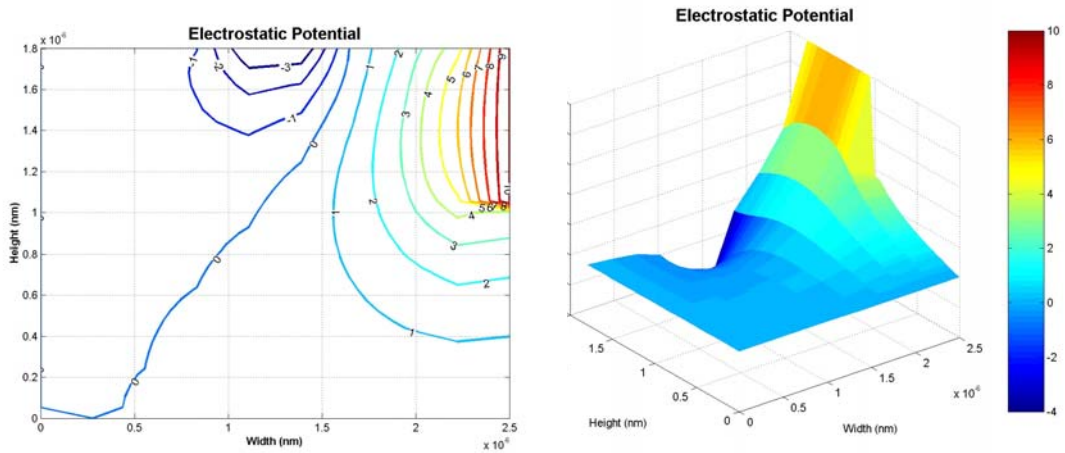


Figure 8: Forward Biased: Gate Voltage held to -4 Volts

4 Particle in Cell

The next step in this process is to allow the free charges to redistribute in the two-dimensional model. This process will be simulated with the particle in cell method, as outlined in Figure 9.

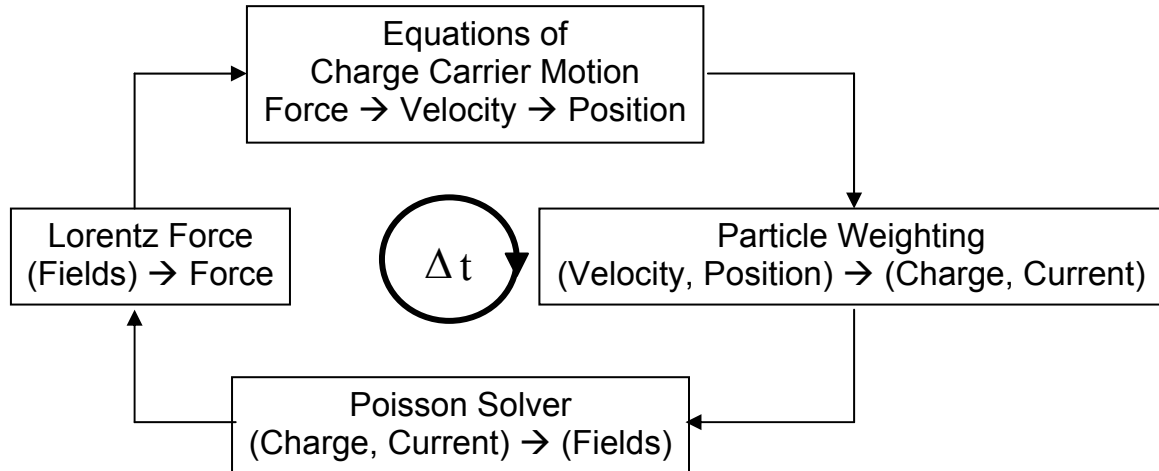


Figure 9: Calculation Cycle for Particle in Cell [Birdsall, 1991]

5 References

1. Birdsall and Langden, *Plasma Physics Via Computer Simulation*, Adam Hilger; June 1991.
2. E.T. Yu, et. al. "Measurement of piezoelectrically induced charge in GaN/AlGaIn heterostructure field-effect transistors," *Applied Physics Letters*, **71** (19), November, 1997.