

# DESIGN AND SIMULATION OF DRIFT-DIFFUSION AND HYDRODYNAMIC MODELS FOR AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs

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## Abstract

Gallium Nitride based HEMTs because of their peculiar material properties are widely used to realize high power, high frequency communication device and very much suitable for bio-sensing application. But to realize AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs for these application many issues are remain to investigate for further improvement in the device technology like design optimization and other performance limiting factor. In this work we proposed two electron transportation models these are drift-diffusion and hydrodynamic models both having their own feasibility to be used in particular application. Now a day's hydrodynamic model is becoming more popular as this model is suitable for deep submicron technology where conventional drift-diffusion model fails to deliver accurate results in case of deep submicron technology the reason is that drift diffusion model neglects some phenomenal effects like velocity overshoot and diffusion associated with the carrier. As drift-diffusion model require little parameterization so this model require less time to simulate the device on the other hand Hydrodynamic model require more parameterization so the time require for its simulation is more. These transportation models are design and simulated using commercially available software silvaco-ATLAS and the results obtained after the simulation of drift-diffusion and hydrodynamic models are compared and analyzed to better understand the device characteristic for further improvement in device technology.

## Keywords:

Drift-Diffusion, Hydrodynamic, 2DEG, HEMTs, Gallium Nitride

## 1. INTRODUCTION

The band gap energy, peak carrier velocity, breakdown voltage and thermal conductivity are the most important factors to determine the device characteristics of high electron mobility transistors (HEMTs). Of these large band gap, high breakdown voltage and high saturation or peak carrier velocity are responsible for high power and high efficiency performance. Gallium Nitride (Ga<sub>N</sub>) belongs to III-V group materials in periodic table and has a very large band gap of 3.4eV as compared to other semiconductor material silicon (Si) 1.12eV and Gallium Arsenide (GaAs) 1.42eV. The Table.1 shows a comparison of material properties of Ga<sub>N</sub>, Si, GaAs from the comparison it is concluded that Ga<sub>N</sub> has many superior properties such as high break down voltage, good thermal conductivity, able to operate at high temperature also Johnson figure of merit is 760 compare to 11 in case of GaAs. All these factors combined to make Ga<sub>N</sub> a suitable material for high electron mobility transistor (HEMTs) [1]. And Ga<sub>N</sub> based HEMTs are used in application such as satellite communication, mobile base station, radars, missiles, biosensors and communication network [3].

Table.1. Material Properties comparison between Ga<sub>N</sub>, GaAs, Si

Property/Units	GaN	GaAs	Si
Band gap, $E_g$ (eV)	3.4	1.4	1.1
Electron Mobility(Cm <sup>2</sup> /Vs)	800	8500	1500
Saturation Velocity 10 <sup>7</sup> cm/s	2.7	2	1
Breakdown Field (MV/cm)	3.3	0.4	0.3
Thermal Conductivity (W/cm-K)	1.3	0.5	1.5
Melting point °C	2773	1510	1690
Operating Temperature °C	750	500	300
Johnson figure of merit $\alpha V_{br}^2 \times V_{sat}^2$	760	11	1

In the device structure layers are created using different material having different energy gap  $E_g$ , permittivity's  $\epsilon$  and work functions  $\phi_s$  due to these a hetero-junction or hetero-structure is formed. If a wide band gap semiconductor comes into a contact with the narrow band gap semiconductor, a discontinuity exists in the conduction and valance band. This discontinuity in the conduction band creates a triangular quantum well, and near to the boundary at the bottom side, the two dimensional electron gas is formed (2DEG) [5], [7]. The 2DEG in AlGa<sub>N</sub>/Ga<sub>N</sub> occurs naturally by the effect of polarization as Ga<sub>N</sub> materials are strongly polar in nature due to this they possess spontaneous polarization that leads to sheet charge accumulation on the end faces of the crystal and these sheet charges are equal in magnitude and opposite in sign to maintain charge neutrality and AlGa<sub>N</sub> also possesses spontaneous polarization of different magnitude compare to Ga<sub>N</sub>. Due to having different spontaneous polarization between AlGa<sub>N</sub> and Ga<sub>N</sub> there is a discontinuity at hetero-junction, also the strain originate due to lattice mismatched AlGa<sub>N</sub> on Ga<sub>N</sub> induces piezoelectric polarization, which supplies additional electrons to the HEMT channel so due to the combined effect of spontaneous and piezoelectric polarization in AlGa<sub>N</sub>/Ga<sub>N</sub> a two dimensional electron gas is formed which is responsible for high electron mobility in the channel due to the formation of 2DEG so for these device is known as high electron mobility transistors(HEMTs) [5].

## 2. BASIC DEVICE STRUCTURE FOR SIMULATION

The basic device structure for AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs are shown in Fig.1. It consists of a barrier layer, a supply layer, a spacer layer and a buffer layer grown on a semi insulating substrate. Starting from a sapphire substrate, an AlN nucleation layer, 2.7 $\mu$ m thick Ga<sub>N</sub> bulk layer was grown, followed by AlGa<sub>N</sub> layer of 25nm thick. The device has a gate length of  $L_g = 1\mu$ m and gate width of

$W = 100\mu\text{m}$  and the gate work function chosen to be  $5.6\text{eV}$ . Considering these parameter and structure, device is simulated using silvaco-ATLAS and the structure obtained after simulation is shown in Fig.2.

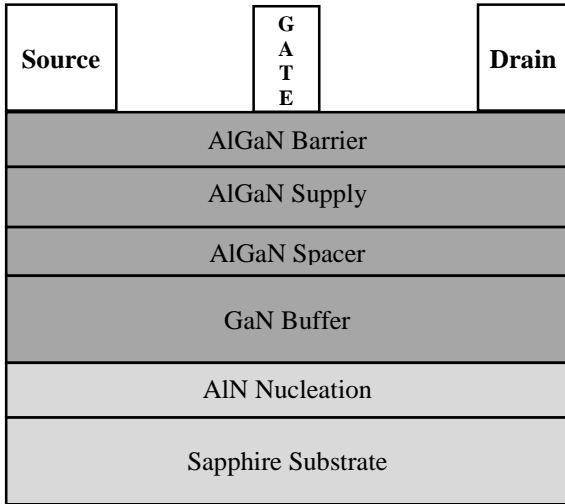


Fig.1. Basic device structure of AlGaIn/GaN HEMTs

Different substrate for AlGaIn/GaN epitaxy can be used. In this work sapphire substrate is used as it offer large area availability (6 inches), good insulating and good mechanical properties at low costs. AlN nucleation layer is used to reduce the misfit between GaN and sapphire substrate above nucleation layer there is GaN buffer layer it is used for the electron transport in the upper part of this layer near to boundary 2DEG is localized. Above this AlGaIn spacer layer is used this layer serve to space separation of carriers supplying from carrier supply layer to 2DEG. Barrier layer covers the supply layer this layer is used to increase the barrier height of schottky contact placed in this layer and supply layer consists of intentionally doped or un-doped AlGaIn layer the doping of this layer is not necessary because of the effect of polarization.

### 3. DRIFT-DIFFUSION AND HYDRODYNAMIC MODEL SIMULATIONS

#### 3.1 SIMULATION AND RESULTS FOR DRIFT-DIFFUSION MODEL

The most prevalent semiconductor device simulation tool is based on the coupled solution of the carrier drift-diffusion equations and Poisson equation. The drift-diffusion equations are obtained by taking the first two moments of the Boltzmann equation [4]. The advantage of drift diffusion model is that it is computationally fast and requires little parameterization or it includes less physical phenomenon. For these reasons it is extensively used in semiconductor device simulation. Output characteristic obtained by simulation and plotted by extracting parameter obtained by simulation are shown in Fig.3 and Fig.4 respectively. The drain current ( $I_{ds}$ ) versus drain source voltage ( $V_{ds}$ ) for several gate biases (-1V, 0V, 1V, 2V) and the gate voltage is varied from -1V to +2V in steps of +1V. The drain bias is ramped from 0V to 10V for each of the gate biases for the simulated AlGaIn/GaN HEMT with gate length of  $1\mu\text{m}$  is shown in Fig.4. The maximum channel current ( $I_{ds}$ ) of  $0.61\text{A}/\text{mm}$  at  $V_{gs} = +2\text{V}$  is obtained for this structure and at  $V_{gs} = -1\text{V}$  output current

becomes zero and device is pinching at this voltage.

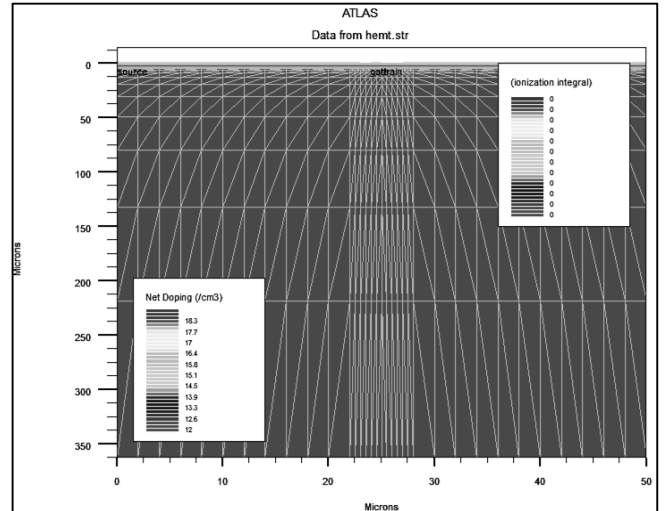


Fig.2. Device structure of AlGaIn/GaN HEMT after simulation

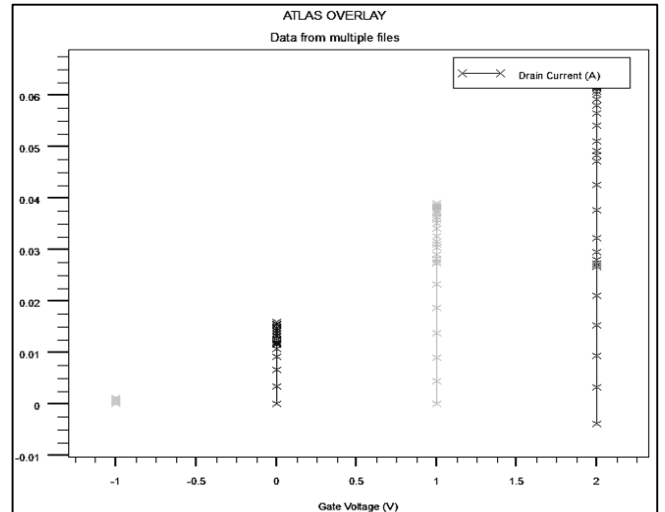


Fig.3. Drain current ( $I_d$ ) at different gate voltage ( $V_g$ ) obtained by simulation for drift-diffusion model

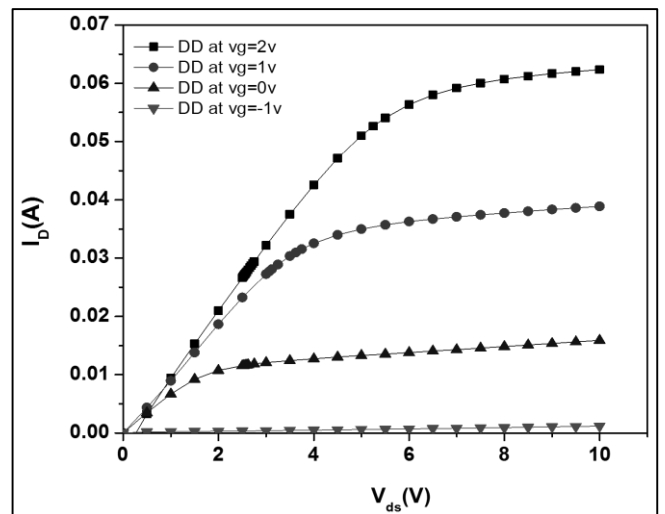


Fig.4. Drain current ( $I_d$ ) at different gate voltage ( $V_g$ ) obtained by simulation for drift-diffusion model

### 3.2 SIMULATION AND RESULTS FOR HYDRODYNAMIC MODEL

The hydrodynamic simulation is obtained by taking the next two higher moments of the Boltzmann equation over that for the drift-diffusion simulation [4]. The hydrodynamic simulation consists of more physical phenomenon than the drift-diffusion model thereby extending its range of validity and accuracy [7]. Output characteristic obtained by simulation and plotted by extracting parameter are shown in Fig.5 and Fig.6 respectively. The drain current ( $I_{ds}$ ) versus drain source voltage ( $V_{ds}$ ) for several gate biases (-1V, 0V, 1V, 2V) the gate voltage is varied from -1V to +2V in steps of +1V and the drain biased is ramped from 0V to 10V for each of the gate biases for the simulated AlGaIn/GaN HEMT with gate length of 1 $\mu$ m is shown in Fig.6.

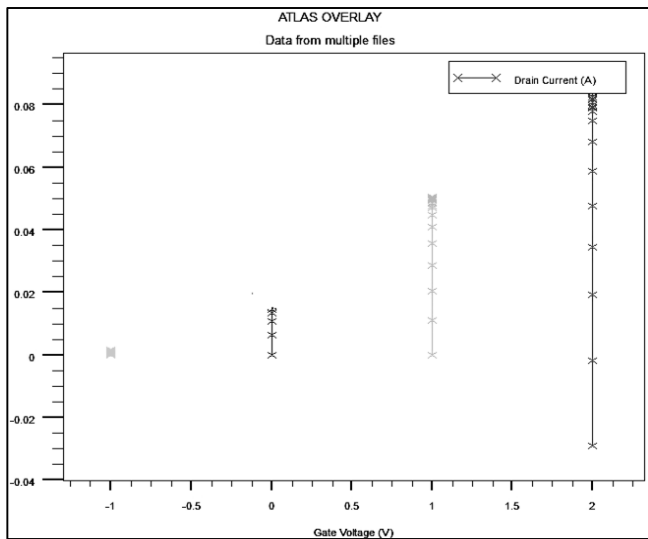


Fig.5. Drain current ( $I_d$ ) at different gate voltage ( $V_g$ ) obtained by simulation for hydrodynamic model

### 4. RESULTS AND DISCUSSION

In this work we simulated two models drift-diffusion and hydrodynamic and we get the simulated result using silvaco-ATLAS and the result those obtained signifies the importance of hydrodynamic models as compare to drift diffusion models. It is because hydrodynamic model captures all the physical phenomenon which drift diffusion model cannot capture like non-stationary transport effects. Drift-diffusion model is advantageous as it require less computational time to simulate because of the inclusion of less physical phenomena. To better understand these two models a comparison is required to differentiate these models. The Fig.7, Fig.8, Fig.9 shows the comparison between these models. The Fig.7 shows output characteristic curve it shows the increased drain current ( $I_d$ ) of 0.85A/mm is obtained for hydrodynamic model and drain current ( $I_d$ ) of 0.61A/mm is obtained for drift-diffusion model. Increased drain current is observed in case of hydrodynamic model.

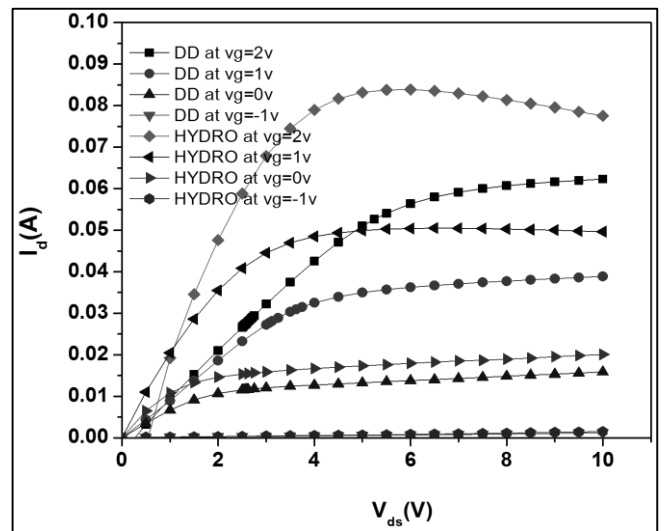


Fig.7. Comparative output characteristic curve for drift-diffusion and hydrodynamic model

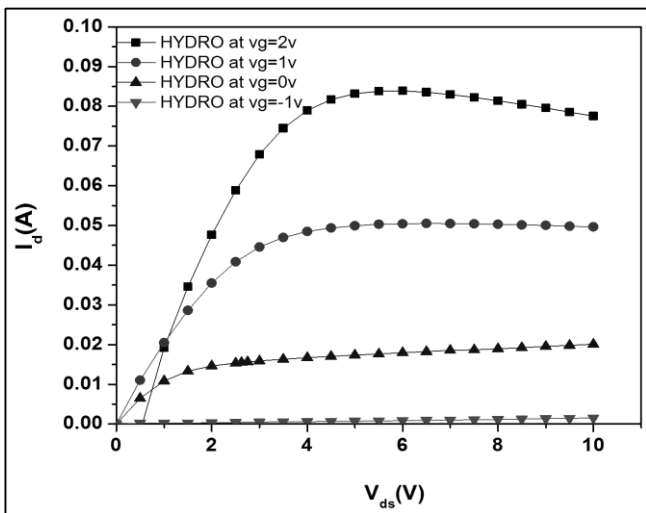


Fig.6. Drain current ( $I_d$ ) at different gate voltage ( $V_g$ ) obtained by simulation for hydrodynamic model

The maximum channel current ( $I_{ds}$ ) of 0.85 A/mm at  $V_{gs} = +2V$ ,  $V_{ds} = 10V$  is obtained for this structure and at  $V_{gs} = -1V$  output current becomes zero and device is pinching at this voltage.

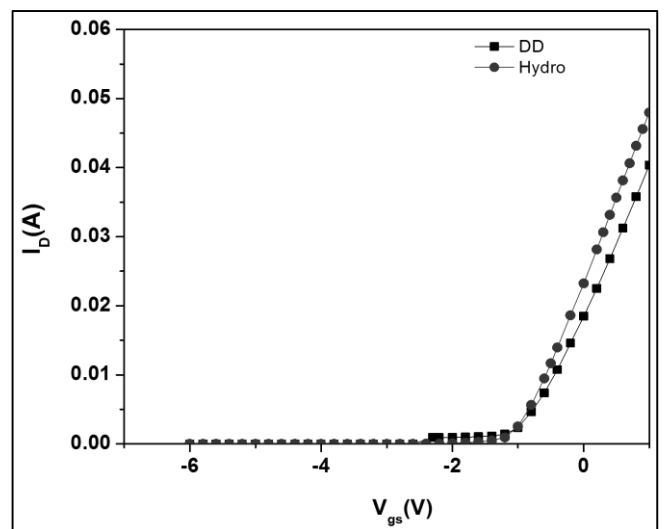


Fig.8. Comparative Transfer characteristic curve for drift-diffusion and hydrodynamic model

The Fig.8 shows the comparative transfer characteristic curve for drift-diffusion and hydrodynamic model obtained by extracting the parameter after simulation this curve also shows better results for drain current  $I_d$  at various gate voltage  $V_g$  keeping drain voltage constant ( $V_d$ ) = 10V for hydrodynamic model as compare to drift diffusion model.

For bio-sensing and power application transconductance should be high as transconductance signifies the sensitivity of device and this parameter also signifies the importance of hydrodynamic model, Fig.9 shows the greater transconductance for hydrodynamic model as compare to drift diffusion model obtained by simulation.

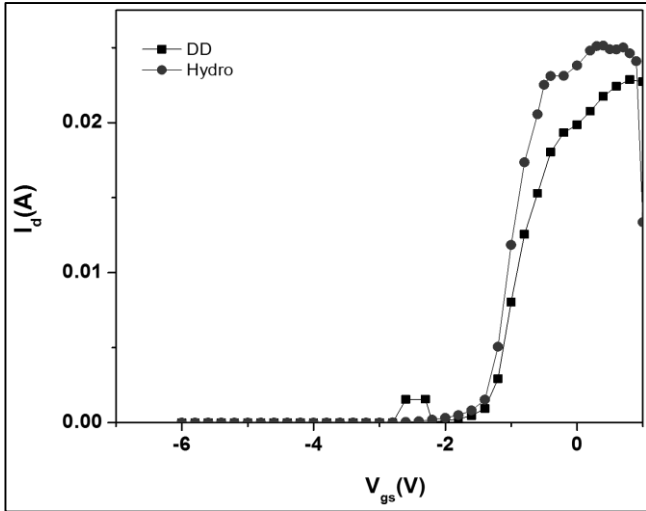


Fig.9. Comparative transconductance curve of drift-diffusion and hydrodynamic model

All these results those obtained after simulation signifies the importance of hydrodynamic model which is suitable for deep sub-micron technology.

## 5. CONCLUSION

In this work we simulate and investigate the transfer and output I-V characteristic for drift-diffusion and hydrodynamic models for AlGaIn/GaN HEMTs and it is concluded that hydrodynamic model gives the best result with increased transconductance ( $g_m$ ), increased drain current ( $I_d$ ), good transfer characteristic (curve between  $I_d$  and  $V_g$ ) and good output characteristic (curve between  $I_d$  and  $V_d$ ) because it includes more

physical phenomenon as compare to drift-diffusion model. Also drift-diffusion model neglects some phenomenal effects such as non-local transport effects such as velocity overshoot, diffusion associated with the carrier and the dependence of impact ionization rates on carrier energy distributions. So for these reason drift-diffusion models in not suitable for deep submicron technology on the other hand hydrodynamic models are very much suitable for deep sub-micron technology. The only advantage of drift-diffusion model is that it requires less computational time for simulation because of the inclusion of less physical phenomenon and hydrodynamic simulation requires more computational time because of the inclusion of more physical phenomena. For these particular reasons hydrodynamic simulation is mostly used for the simulation of AlGaIn/GaN HEMTs.

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