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# PHYSICS BASED CHARGE AND DRAIN CURRENT MODEL FOR AlGaN/GaN HEMT DEVICES

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## ABSTRACT

A simple Physics based drain current model of AlGaN/GaN High Electron Mobility Transistor model (HEMT) is developed. The Proposed is useful for fast and accurate circuit simulation and analysis of Microwave and DC Characteristics. This model includes Channel length modulation and Velocity Saturation effect. Derived model results are compared with 1µm gate $Al_{0.50}Ga_{0.50}N$/GaN HEMT structure and 0.12 µm gate $Al_{0.25}Ga_{0.75}N$/GaN HEMT structure experimental data. The predicted Drain current are 1.23A/mm for 0.12µm gate and 5.23A/mm for 1µm gate length, which are in good agreement with experimental data.

**Keywords:** AlGaN/GaN HEMT, compact models, sheet charge density, 2-D electron gas (2DEG)

## I. INTRODUCTION

GaN is the excellent candidate for high power, high temperature and high frequency applications [1-2]. The capacitance and dc characteristics model is thus very important for accurate simulation of high-speed digital and analog circuits in AlGaN/GaN HEMT. Among various numerical models only limited models are available in physics based [3].The variation of 2-D electron gas (2DEG) channel density $n_s$ with gate voltage and the physical effects should be modeled for accurate simulation. The asymmetric triangular well confined 2DEG channel region is solved using Schrodinger equation. In this model lowest conduction band energy level is considered because E1≈3E0 [4]. So low band parameter from [5] $\gamma_0$ is considered in this model. The physics based model presented here has minimal set of parameters. Channel length modulation (CLM) and velocity saturation effects are considered in this model and explained with reference.

The paper is arranged as follows. Model structure in accordance to experimental dimensions is given in Section II. Section III gives detailed expression for drain current model for AlGaN/GaN with physical effect of velocity saturation and channel length modulation. Model experimental comparison (MEC) is explained for long and short gate length device is given in Section IV.

## II. MODEL DESCRIPTION

The cross-sectional view of AlGaN/GaN HEMT for two different experimentally determined gate length device structures are shown in Fig. 1. The layer sequence, from bottom to top, is GaN-undoped/UID-AlGaN/n-AlGaN/metal, with 2DEG channel formed at the interface between GaN-undoped/UID-AlGaN. The difference between these two experimental structures is 0.12 µm gate length with Al mole fraction of $Al_{.25}Ga_{.75}N$, width 100µm [6] and 1µm gate length device with 75µm width, Al mole fraction of $Al_{.50}Ga_{.50}N$ [7-8].

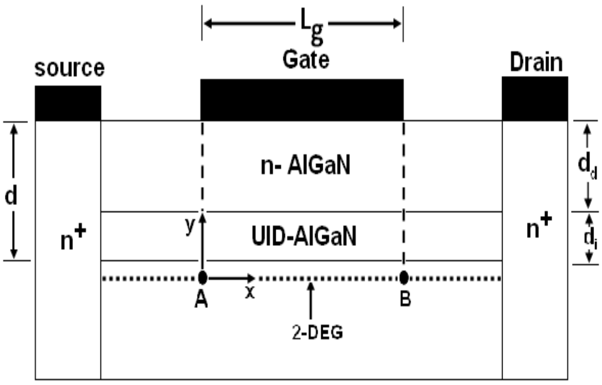


**Fig 1:** Cross-sectional view of AlGaN/GaN HEMTs with Gate length $L_g$. $d_i$ spacer layer thickness and $d_d$ n-AlGaN layer thickness.

**Table 1:** List of symbols

| Symbol | Physical meaning |
|---|---|
| $q$ | Electron charge |
| $\varepsilon$ | Permittivity of AlGaN |
| D | Density of states |
| $V_{th}$ | Thermal voltage |
| $V_g$ | Gate to source voltage |
| $n_s$ | Charge density of 2DEG |
| $d_d$ | Thickness of n-AlGaN layer |
| $d_i$ | Thickness of UID AlGaN |
| $d= d_d+ d_i$ | Total thickness of AlGaN |
| $C_g=\varepsilon /d$ | Gate capacitance per unit area |

## III. MATHEMATICAL MODEL FOR DRAIN CURRENT

### III. 1 Charge Density Model

The unified $n_s$ model is given as [9]

$$n_s = \frac{C_g V_{g0}}{q} \frac{V_{g0} + V_{th}[1-\ln(\beta V_{gon})] - \frac{\gamma_0}{3}\left(\frac{C_g V_{g0}}{q}\right)^{\frac{2}{3}}}{V_{g0}\left(1+\frac{V_{th}}{V_{god}}\right) + \frac{2\gamma_0}{3}\left(\frac{C_g V_{g0}}{q}\right)^{\frac{2}{3}}} \quad .. (1)$$

The thermal voltage $V_{th}$ in this equation has less impact on $n_s$ (Charge Density), thus we propose to neglect $V_{th}$ from the above ns equation. In Fig 2, region 1 is having $E_0$ greater than $E_f$, corresponding to $V_{g0}$ < 0.9 V, and Region II is having $E_0$ less than $E_f$ corresponding to $V_{g0} \geq 0.9$ V [9]. Fig-2 gives the comparison between the models of region-1 and region-2, ns model with $V_{th}$, and $n_s$ model without $V_{th}$. So new charge density model neglecting $V_{th}$ can be written as eq (2)

$$n_s = \frac{C_g V_{go}}{q} \frac{V_{go} - \frac{\gamma_o}{3}\left(\frac{C_g V_{go}}{q}\right)^{2/3}}{V_{go} + \frac{2\gamma_o}{3}\left(\frac{C_g V_{go}}{q}\right)^{2/3}} \quad ..(2)$$

where $V_{go} = V_{gs} - V_{off} - V_x$, $V_{gs}$ is the gate to source voltage, $V_{off}$ the cut off voltage, $V_x$ the channel potential along x-direction, $C_g$ the gate capacitance, $q$ the electronic charge and $\gamma_o$ is an experimental data for $E_0$ [5].

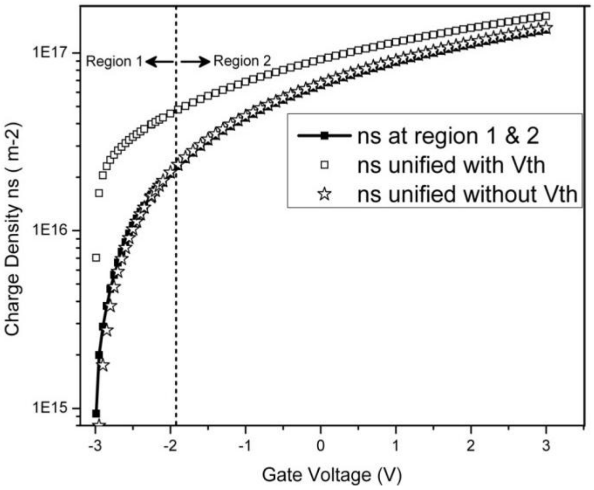


**Fig-2.:** Comparison between the models of region-1 and region-2, $n_s$ model with $V_{th}$, and $n_s$ model without $V_{th}$. Region-1 (Vgo<0.9) and region-2 (Vgo>=0.9), where $V_{go}=V_{gs}-V_{off}$ (where $V_{off}$ =-3V).

### III. 2 Current Model

The drain current ($I_d$) for this device can be written as

$$I_d = -q w_g n_s(V_g, V_x) v(E_x) \qquad ..(3)$$

where $w_g$ =width of the device, $v(E_x)$ =electron drift velocity. In the low-field region, the longitudinal electric field along the channel $E_x$ is less than the critical field $E_T$, thus the electron drift velocity can be given as

$$v(E_x) = \frac{\mu_{LF} E_x}{1 + u_a\left(\frac{E_x}{E_T}\right)} \qquad ..(4)$$

where $u_a$ is constant extracted from experimental data, $\mu_{LF}$ is low longitudinal field mobility depends on the vertical electric field in 2DEG of GaN. Longitudinal field mobility is given as

$$\mu_{LF} = \frac{\mu_0}{1 + p_1 E_{y,eff} + p_2 E_{y,eff}^2} \qquad .(5)$$

where $\mu_0$ is the low field mobility, $p_1$ and $p_2$ are the experimental determined parameters, $E_{y,eff}$ is the vertical electric field of 2DEG. $E_{y,eff}$ can be calculated from average of $Q_{2DEG}(x) = w_g q n_s(V_g, V_x)$ along the lateral direction i.e

$$E_y(x) = \frac{Q_{2DEG}(x)}{\varepsilon} \qquad ..(6)$$

We define $E_x = -\frac{dV_x}{dx}$ and substitute (2), (4) and (5) in equation (3). After substituting, integration of equation (3) is done from source to drain, giving the drain current as

$$I_d \int_0^{L_g} \left\{1 + u_a\left(\frac{-\frac{dV_x}{dx}}{E_T}\right)\right\} dx = \frac{-q\mu_0 w_g c_g}{R} \int_{V_s}^{V_d} V_{go}\left(\frac{V_{go} - \beta(V_{go})^{2/3}}{V_{go} + 2\beta(V_{go})^{2/3}}\right)(-dV_x) \qquad ...(7)$$

Where $L_g$ is the channel length, $V_s$ and $V_d$ are source and drain potential, $\beta = \frac{\gamma_o}{3}\left(\frac{c_g}{q}\right)^{2/3}$ and $\Re = 1 + p_1 E_{y,eff} + p_2 E_{y,eff}^2$. After integrating (7) the drain current is obtained as

$$I_d = -\alpha \left[\begin{array}{l} 288\beta^6 \mathrm{Log}_e(t) - 816\beta^5 t \\ +480\beta^4 t^2 - 200\beta^3 t^3 \\ +52.5\beta^2 t^4 - 7.8\beta t^5 + 0.5 t^6 \end{array}\right]_{t_{lower\,limit} = (V_g - V_{off} - V_s)^{1/3} + 2\beta}^{t_{upper\,limit} = (V_g - V_{off} - V_d)^{1/3} + 2\beta} \qquad ..(8)$$

where $\alpha = \frac{q\mu_0 w_g c_g}{L_g \Re \delta}$ and $\delta = 1 - ua\left(\frac{V_d - V_s}{E_T L_g}\right)$

### III. 3 Velocity Saturation

The obtained drain current model is best fitted for linear region. For saturation region $I_d$ is differentiate with respect to $V_{ds.}$ The differentiation gives zero, since the current is remain constant in saturation region. To calculation of $V_{d,sat}$ from (8) is too difficult. Thus a smoothing function $V_{d,eff}$ is used in place of $V_d$, while calculating $I_d$.

$$V_{d,eff} = \frac{V_d V_{d,sat}}{\sqrt{V_d^2 + V_{d,sat}^2}} \qquad ..(9)$$

where $V_{d,sat} = \frac{V_{gs} - V_{off}}{m}$, $V_{gs}$ is the gate potential applied, $V_{off}$ the cut off voltage and m the body co-efficient.

**Table II** Parameters used in the Calculation for different Devices

| Parameter | Quantity | Fig 3a Fig 3b | Fig 4a Fig 4b |
|---|---|---|---|
| $V_{off}$ (V) | Offset Vol. | -2.9 | -6.5 |
| R*s*(Ω) | Par Source R | 0.13 | 0.6 |
| R*d*(Ω) | Par Drain R | 0.43 | 0.9 |
| W(μm) | Gate Width | 75 | 100 |
| $L_g$(μm) | Gate Length | 1 | 0.12 |
| $E_T$ | Crit electric field | 178 | 190 |
| $u_a$ | Parameter | 1.14 | 0.93 |
| $u_0$ | Parameter | 0.033 | 0.001 |
| $p_1$ | Low field μ Parameter | 1.13e-9 | -1.1e-12 |
| $p_2$ | Low field μ Parameter | 125e-18 | 14e-10 |
| $\lambda(V^{-1})$ | CLM Para. | 1e-6 | 1e-6 |
| m | Body Coefficient | 3.8 | 2 |
| $\gamma_0$(1e-12) | Exp. Parameter[5] | 2.12 | 2.19 |

### III. 4 Channel length modulation

Increase in gate bias leads to increase the output conductance in saturation region when CLM effect occurs. The simple observation of $I_d$ with CLM effect in first order equation is [10]

$$I_{d,CLM} = I_d(1 + \lambda V_{d,eff}) \qquad ..(10)$$

where $\lambda$ is the CLM extracted parameter from the saturation region. For short channel devices the $n_s$ model should be solved using 2D Poisson's equation The final drain current model with CLM is given in (10).

### IV. RESULT AND DISCUSSION

The model and experimental data compared in this section. The MECs (model-experimental comparison) are done for 1μm×75μm gate and 0.12μm×100μm gate lengths from the experimental data in paper [6-8]. Table II gives the parameters used in these devices.

The experimental results and proposed model results show excellent concurrence in the $I_d$-$V_d$ and $I_d$-$V_g$ characteristics after incorporation of velocity saturation and CLM effects.

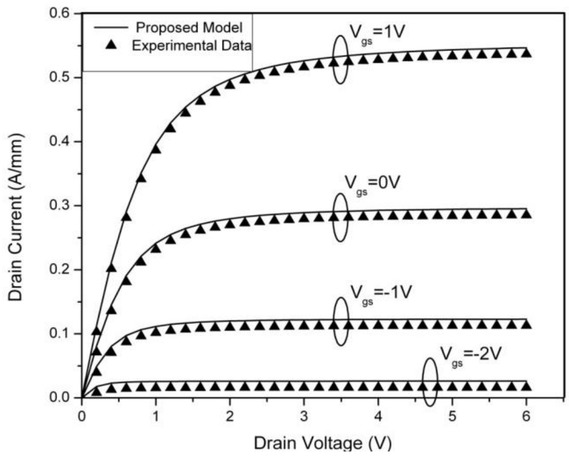


**Fig. 3a:** Comparison of model $I_d$-$V_d$ characteristics with experimental data for $Al_{.50}Ga_{.50}N$/GaN for $L_g$=1μm device. Experimental data taken from [7-8].

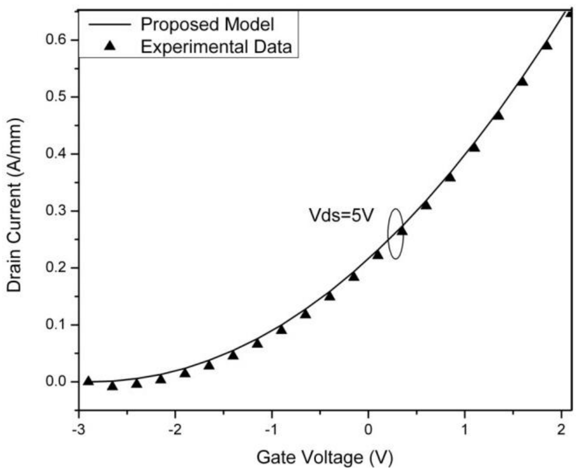


**Fig. 3b:** Comparison of model $I_d$-$V_g$ characteristics with experimental data from [7-8] measured at $V_d$=5V for $Al_{.50}Ga_{.50}N$/GaN $L_g$=1μm device.

Fig 3a shows the $I_d$-$V_d$ characteristics compared with MEC for $Al_{.5}Ga_{.5}N$/GaN $L_g$=1µm. Results are good agreement with experimental data [7-8]. Fig. 3b shows $I_d$-$V_g$ characteristics with $V_d$=5V [8], exhibiting excellent matching

For further investigation of SCE (Short Channel Effects) and CLM in this model, comparison of the model against experimental data for the $L_g$=0.12µm is done. Fig. 4a shows the comparison of $I_d$-$V_d$ characteristics of the model, compared with experimental data [6] for $Al_{.25}Ga_{.75}N$/GaN with $L_g$=0.12µm, indicating a good agreement. Fig. 4b shows $I_d$-$V_g$ characteristics with $V_d$=8V and experimental data in paper[6], indicating good agreement.

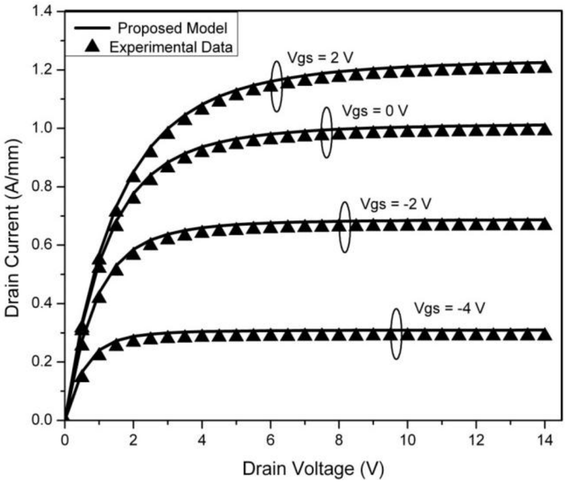


**Fig. 4a:** Comparison of model $I_d$-$V_d$ characteristics with experimental data of $Al_{.25}Ga_{.25}N$/GaN HEMT with $L_g$=0.12µm. Experimental data taken from [6].

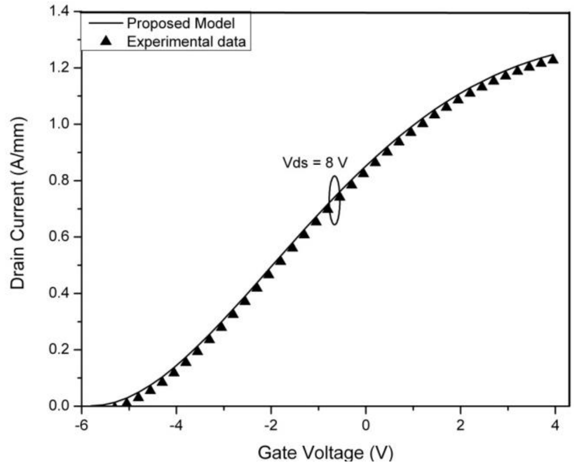


**Fig. 4b:** Comparison of model $I_d$-$V_d$ characteristics with experimental data for $Al_{.25}Ga_{.25}N$/GaN HEMT having $L_g$=0.12µm. Experimental data taken from [6].

## V. CONCLUSIONS

Fully physics based analytical model for drain current in GaN HEMT device is presented. The model exhibits excellent agreement with experimental results for both long and short gate length AlGaN/GaN HEMTs. Velocity saturation and channel length modulation effects are also included in the model. Extraction of physical parameters from the proposed model is convenient. This model can be used to develop GaN HEMT compact model.

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