



## MODELING OF SHEET CARRIER DENSITY AND DC CHARACTERISTICS BASED HEMT DEVICES

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### ABSTRACT

In this paper, 2-D physics based model for electron gas (2DEG) Sheet Carrier density and DC characteristic of the proposed spacer layer based InAlN/InAlN/GaN High Electron Mobility Transistors (HEMTs) is modeled by considering the triangular quantum well. To obtain Charge density  $n_s$ , the variation of Fermi level with supply voltage and the formation of Energy Sub-bands E0, E1 is considered. The obtained results are simple and easy to analyze HEMT power devices. Due to large 2DEG Sheet carrier density and high velocity, the maximal drain current density achieved is very high. All results are calibrated and verified with experimental data. The frequency using the transconductance value or by reducing the capacitance value is determined.

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**Index terms-** InAlN/InAlN/GaN, 2DEG Sheet charge density, triangular quantum well, DC characteristics model, Piezoelectric and Spontaneous polarization, alloy scattering.

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### I.INTRODUCTION

AlGaIn/GaN high-electron mobility transistors (HEMTs) have been pursued as a solution for high-power electronics for wide-band, X-band, and Ka-band electronics. To date, these III-Nitride systems have achieved impressive performance metrics such as very high current densities and high breakdown voltages. Compound Semiconductors from group III-V achieved significant progress in Optoelectronic devices. GaN-based material has unique properties and becomes an attractive candidate for future microwave and nanoscale power devices and these devices work well in the microwave frequency range between 1 to 40 GHz. In<sub>x</sub>Al<sub>1-x</sub>N/InAlN/GaN HEMTs with spacer layer have some unique features that make it outperform upon other In<sub>x</sub>Al<sub>1-x</sub>N/GaN heterostructures such as high two-dimensional electron gas (2DEG) Sheet Carrier density, Carrier mobility and also due to their excellent DC and RF performance. Existence of alloy disorder scattering, limits the mobility of two-dimensional electron gas (2DEG) in Conventional In<sub>x</sub>Al<sub>1-x</sub>N/GaN HEMT. An InAlN spacer layer is provided in between the InAlN and GaN layers. Due to the Wideband gap of binary InAlN Spacer layer, it

reduces the two-dimensional electron gas (2DEG) electron-wave penetration into the InAlN barrier layer can significantly increase the Sheet Carrier density ( $n_s$ ) and mobility. The GaN wurtzite *hexagonal close packed* (HCP) structure with non-Centro-symmetric property is the main source for the formation of two-dimensional electron gas (2DEG) at the In<sub>x</sub>Al<sub>1-x</sub>N/InAlN/GaN interface mainly due to Piezoelectric and Spontaneous polarization as it does not require any external force like electric field or deformation, resulting in a high Sheet carrier density of the order of  $10^{13} \text{ cm}^{-2}$ . On the other hand, the high GaN channel electron mobility of up to  $2000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  and high 2DEG sheet carrier densities of  $1.4 \times 10^{13} \text{ cm}^{-2}$  has previously been reported and shows advantageous in high speed and high power applications. The thermal conductivity in GaN devices is more than three times higher than in GaAs. Good transport properties, lattice-matched.

The principle objective of this paper is to improve the Sheet carrier density by the insertion of spacer (InAlN) and to analysis of physical processes in the HEMT transistors. Total-induced Polarization charge and energy bandgap calculations for InAlN /InAlN/GaN HEMT device. The Calculating the

threshold voltage of the transistor. Later Calculating and modeling the equation for the concentration of electrons  $N_s$  (sheet carrier density) in the channel HEMT. And analyzing and deriving the DC and

2DEG	Two-dimensional electron gas
UID	Unintentionally doped
$\Phi_{\text{eff}}$	Schottky barrier height
$\epsilon_{\text{InAlN}}$	Permittivity or dielectric constant of InAlN
$\epsilon_{\text{InAlN}}$	Permittivity or dielectric constant of InAlN Spacer
$d_d$	Thickness of InAlN barrier layer
$d_i$	Thickness of InAlN barrier layer
$d = d_d + d_i$	Total thickness of InAlN barrier and InAlN Spacer layer
$\Delta E_{c,\text{eff}}$	Conduction band offset
$N_d$	Doping concentration in InAlN
$\sigma_{\text{int}}$	Total induced polarization charge density
$\mu_0$	Low- filed mobility
$n_s$	Sheet Carrier density
$V_{\text{th}}$	Thermal voltage
$C_g$	Gate capacitance
$\Lambda$	Channel length modulation parameter
$D$	Density of states
$Q$	Electron charge
$K$	Boltzmann's constant
$E_0, E_1$	Formation of first and second Energy sub-bands
$\gamma_0, \gamma_1$	Experimentally determined parameters using InAlN effective mass

Small-signal and Frequency analysis of transistors HEMT. Finally the model is numerically simulated using MATLAB and the results are simulated TCAD.

**Nomenclature**

**II.DEVICE STRUCUTRE AND DESCRIPTION**

Fig.1 shows the Cross-section view of proposed enhanced Spacer based  $\text{In}_x\text{Al}_{1-x}\text{N}/\text{InAlN}/\text{GaN}$  HEMT. The layer sequence from top to bottom is Metal/InAlN/UID InAlN/GaN, with a two-dimensional electron gas (2DEG) channel formed at the interface between the un-intentionally doped (UID) InAlN and GaN. The band diagram of Spacer layer based  $\text{In}_x\text{Al}_{1-x}\text{N}/\text{InAlN}/\text{GaN}$  HEMT shows that the insertion of the thin InAlN Spacer layer produces a large effective band offset  $\Delta E_{c,\text{eff}}$ , defined as a conduction band offset between InAlN and GaN at

both sides of InAlN shown in Fig.2. This is due to both the wide band gap of InAlN Spacer layer and the very strong polarization effect in InAlN. The Large effective band offset  $\Delta E_{c,\text{eff}}$  is good for both Carrier concentration and mobility at the interface between InAlN and GaN.

In this model, we have discussed InAlN/InAlN/GaN HEMT devices with three different gate lengths and widths and the corresponding results are calibrated with experimental data to validate our model. Comparative experimental results from InAlN/InAlN/GaN HEMT devices of two different Al mole fractions are chosen. The model and experimental comparisons are done for Spacer layer based  $\text{In}_{0.3}\text{Al}_{0.7}\text{N}/\text{InAlN}/\text{GaN}$ ,  $\text{In}_{0.50}\text{Al}_{0.50}\text{N}/\text{InAlN}/\text{GaN}$  HEMT devices and the corresponding gate lengths and widths are  $0.7\mu\text{m} \times 150\mu\text{m}$ ,  $0.6\mu\text{m} \times 100\mu\text{m}$  and  $1\mu\text{m} \times 200\mu\text{m}$ .

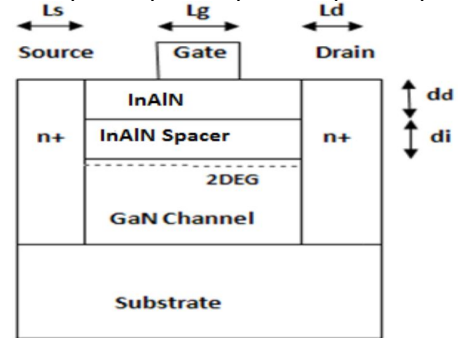
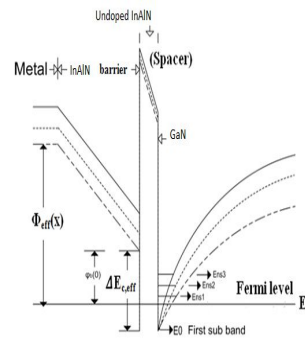


Figure.1



Energy Bandgap Diagram

Figure.2

The Conduction energy band diagram of  $\text{In}_x\text{Al}_{1-x}\text{N}/\text{InAlN}/\text{GaN}$  HEMTs as shown in Fig.2. The wider bandgap InAlN barrier and InAlN spacer layer thickness give the effective Conduction band offset  $\Delta E_{c,\text{eff}}$ . Mobility of the electrons increases because of their separation from a parent ionized donor. Mobility is increased further by using a spacer

layer InAlN which separates the two-dimensional electron gas (2DEG) from ionized donors near heterointerface.

### III. DEVICE CALCULATION

A. Polarization and Energy band gap calculations for spacer based Al<sub>x</sub>Ga<sub>1-x</sub>N/InAlN/GaN HEMTs:

InAlN/InAlN/GaN heterojunction possesses high electron concentration due to its strong polarization effect and high breakdown due to the larger band gap. A high sheet carrier density is induced in the channel even if the barrier layer is un-doped due to two types of polarization i.e., Piezoelectric and Spontaneous. Piezoelectric polarization due to the crystal lattice mismatch between the layers can be calculated by Vegard's interpolation formula and is given by:

$$P_{pz}^{InAlN} = -1.808\eta_b + 5.624\eta_b^2 \text{ for } \eta_b < 0$$

$$P_{pz}^{InAlN} = -1.808\eta_b - 7.888\eta_b^2 \text{ for } \eta_b > 0$$

$$P_{pz}^{GaN} = -0.918\eta_b - 9.541\eta_b^2$$

and an equilibrium lattice constant a(x), the basal strain field  $\eta_1(x)$  for the alloy matched to a GaN substrate defined as

$$\eta_1(x) = (a^{GaN} - a(x)) / a(x)$$

Spontaneous polarization due to lack of inversion symmetry and high electro-negativity of Nitrogen atom and is given in terms of Al-mole fraction(x) as

$$P_p(InAlN) = [-0.090x - 0.034(1-x) + 0.019x(1-x)] \text{Cm}^{-2}$$

And the total polarization  $\sigma_{int}$  induced at the heterostructure is the sum of Ppz and Psp of the two layers forming the heterostructure and is given by the expression

$$P_{int}(InAlN) = P_{pz}(InAlN) + P_p(InAlN)$$

$$\sigma_{int} = P_{GaN} - P_{InAlN} - P_{InAlN}$$

B. Band Gap Calculation:

The band-gap of InAlN for different mole concentration is measured to be

$$E_g(x) = 6.13x + 3.42(1-x) - x(1-x) \text{ eV}$$

and the linear interpolation of dielectric constant is given by

$$\epsilon(x) = 10.4 - 0.3x$$

The threshold voltage of the HEMT is given by

$$V_{off} = \phi_{eff}(x) - \Delta E_{c,eff}(x) - \frac{qN_d d_d^2}{2\epsilon(x)} - \frac{\sigma_{total}}{\epsilon(x)}(d_d + d_i)$$

Where,  $\phi_{eff}(x)$  is the effective height of the Schottky barrier,  $\Delta E_{c,eff}$  is the Conduction band offset between InAlN spacer and GaN.  $N_d$  is the doping concentration in the InAlN barrier,  $\sigma_{int}$  is the total induced polarization charge at the interface.

The 2DEG density in the InAlN/InAlN/GaN structure can be obtained by:

$$n_s = \frac{\sigma_{InAlN} \cdot t_{InAlN} + \sigma_{InAlN} \cdot t_{InAlN} - \frac{\epsilon\epsilon_0}{q}(\phi_B - \frac{\Delta E_{c,InAlN}}{q})}{t_{InAlN} + t_{InAlN} + d_n}$$

$$= \frac{\sigma_{InAlN} t_{InAlN} - \frac{\epsilon\epsilon_0}{q}\phi_B + \frac{\epsilon\epsilon_0}{q^2}\Delta E'_{c,eff}}{t_{InAlN} + t_{InAlN} + d_0}$$

$$\text{Where } \Delta E'_{c,eff} = \Delta E_{c,InAlN} + \frac{q^2}{\epsilon\epsilon_0} \sigma_{InAlN} t_{InAlN}$$

C. Sheet Charge density model:

A two-dimensional electron gas (2DEG) is formed at the interface due to the difference in the electron affinity of these layers. The Variation of Fermi-level  $E_f$  with  $n_s$  in the quasi-triangular quantum well is given by

$$n_s = DV_{th} \left\{ \ln \left[ \exp \left( \frac{E_f - E_o}{V_{th}} \right) + 1 \right] + \ln \left[ \exp \left( \frac{E_f - E_1}{V_{th}} \right) + 1 \right] \right\}$$

The unified sheet carrier density model for  $E_f$  and  $n_s$  applicable for a full range of voltages is given by

$$n_s = \frac{c_g V_{go}}{q} \frac{V_{go} V_{th} [1 - \ln(\beta V_{go})] - \frac{\gamma_0}{3} \left( \frac{C_g V_{go}}{q} \right)^{2/3}}{V_{go} \left( 1 + \frac{V_{th}}{V_{go}} \right) + \frac{2\gamma_0}{3} \left( \frac{C_g V_{go}}{q} \right)^{2/3}}$$

After solving the new Sheet carrier density equation becomes

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

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

Where,  $\theta = \frac{\gamma_o}{3} \left( \frac{C_g}{q} \right)^{2/3}$ .  $C_g$  is the gate capacitance

formed between the layers.

#### D. Mobility model

The Spacer layer based InAlN/InAlN/GaN device's exhibit improvement in electrical properties over InAlN/GaN devices. Achieved enhanced mobility by the addition of Spacer layer InAlN and it does not degrade the radiation tolerance. We determine an analytic form for the low-field mobility as functions of temperature, ionized donor concentration, and compensation ratio. The Conwell-Weisskopf (CW) model was chosen for the parameterized expression because it covers a greater portion of the range of ionized impurity concentrations and compensation ratios than the Brooks-Herring (BH) model. The different mobilities are combined through Matthiessen's rule. Parameters (a,b,c) are obtained and calibrated from fitting to the Monte Carlo calculation results. The overall mobility results are in satisfactory agreement with GaN mobilities calculated with a variational scheme and should be approached with experimental data as crystal quality improves. The parameterized mobility versus ambient temperature for ionized donor concentration for different doping  $N_D$  using an expression of the form

$$\frac{1}{\mu} = a \left( \frac{N_i}{10^{17} \text{ cm}^{-3}} \right) \ln(1 + \beta_{cw}) \left( \frac{T}{300k} \right)^{-1.5} + b \left( \frac{T}{300k} \right)^{1.5} + \frac{c}{\exp\left(\frac{\theta}{T}\right) - 1}$$

Where,  $\beta_{cw}^2 = 3 \left( \frac{T}{300k} \right)^2 + \left( \frac{N_i}{10^{17} \text{ cm}^{-3}} \right)^{-2/3}$

$$\theta = \frac{h\omega_{Lo}}{k_B} = 1065k, N_i = (1 + K_c) N_D$$

Here,  $N_D$  is the ionized donor concentration in  $\text{cm}^{-3}$ ,  $T$  is the ambient temperature in Kelvin,  $h$  is the plank's constant and  $K_c = N_A/N_D$  is the compensation ratio. This expression approximates our Monte Carlo results with a maximum deviation of 6% within the ranges  $300 \text{ K} < T < 600 \text{ K}$ ,  $10^{16} \text{ cm}^{-3} < N_D < 10^{18} \text{ cm}^{-3}$ , and  $0 < K_c < 1$ . The parameters used in the calculation of mobility model are  $a = 2.61 \times 10^{-4} \text{ V s cm}^{-2}$ ,  $b = 2.90 \times 10^{-4} \text{ V s cm}^{-2}$  and  $c = 1.70 \times 10^{-2} \text{ V s cm}^{-2}$ . On the other hand, the high GaN electron mobility of up to  $2000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  and shows advantageous in high speed and high- power applications.

#### E. Current-Voltage characteristics

The drain current in the quasi-triangular quantum well is calculated by using the relation

$$I_d = qwn_s(x)V_s$$

Where  $W$  = width of the device,  $V_s$  = electron drift velocity. In the low-field region, where the longitudinal electric field along the channel,  $E$  is less than the critical field  $E_T$  ( $E \leq E_T$ ) with

$$E = \frac{-dV_c(x)}{dx}$$

the electron drift velocity is given by

$$V_s = \frac{\mu_0 E}{1 + \frac{E}{E_T}} \quad \text{if } E \leq E_T$$

With  $E_T = \frac{E_c V_{sat}}{(\mu_0 E_c - V_{sat})}$  where  $E_c$  is the

saturation electric field and  $V_{sat}$  is the Saturation drift velocity. Substituting in above equations and  $E_T$  in equation we get,

$$I_d \left( 1 - \frac{1}{E_T} \frac{dV_c(x)}{dx} \right) = -w\mu_0 qn_s \frac{dV_c(x)}{dx}$$

$$I_d \left( 1 - \frac{1}{E_T} \frac{dV_c(x)}{dx} \right) dx = -qw\mu_0 \frac{C_g}{q} \left( \frac{V_{go} - \theta (V_{go})^{2/3}}{V_{go} + 2\theta (V_{go})^{2/3}} \right) dV_c(x)$$

$$I_d \left( 1 - \frac{1}{E_T} \frac{dV_c(x)}{dx} \right) dx = -w\mu_0 C_g \left( \frac{(V_{go})^{1/3} - \theta + 2\theta}{(V_{go})^{1/3} + 2\theta} \right) dV_c(x)$$

The drain current is obtained by integrating the left side along the channel Length  $L_{channel}$  from 0 to  $L_g$  and right side along from Source voltage  $V_s$  to drain voltage  $V_d$ .

$$I_d \int_0^{L_g} \left( 1 - \frac{1}{E_T} \frac{dV_c(x)}{dx} \right) dx = -w \mu_0 C_g \int_{V_s}^{V_d} \left( V_{gp} \frac{(V_{gp})^{\frac{1}{3}} - \theta + \theta}{(V_{gp})^{\frac{1}{3}} + \theta} \right) dV_c(x)$$

With a limit  $V_c(x=0) = V_s$  and  $V_c(x=L_g) = V_d$  and by substitution method the above equations become,

$$I_d = \zeta \left\{ \begin{array}{l} 2880^6 \log_e(t_{drain} + t_{source}) - 8160^5 (t_{drain} - t_{source}) \\ + 4800^4 (t_{drain}^2 - t_{source}^2) - 2000^3 (t_{drain}^3 - t_{source}^3) \\ + 52.50^2 (t_{drain}^3 - t_{source}^3) - 7.80 (t_{drain}^5 - t_{source}^5) \\ + 0.5 (t_{drain}^6 - t_{source}^6) \end{array} \right\}$$

Where,  $t_{source} = (V_{gs} - V_{off} - (V_s))^{\frac{1}{3}} + \theta$ ,

$$\zeta = \frac{w \mu_0 C_g}{L_g \Delta}$$

$t_{drain} = (V_{gs} - V_{off} - (V_d))^{\frac{1}{3}} + \theta$ ,

$$\Delta = 1 - \left( \frac{V_d - V_s}{E_T L_g} \right) \text{ and } \theta = \frac{\gamma_0}{3} \left( \frac{C_g}{q} \right)^{\frac{2}{3}}$$

F. Channel length modulation

In the saturation region, the channel current tends to saturate with an increase in drain source voltage across the drain end with  $x=L_g$

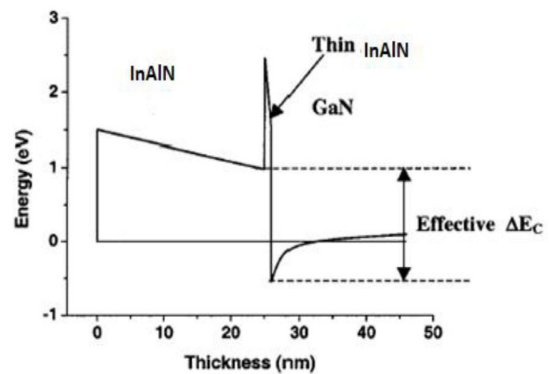
$$I_{d, sat} = I_d (1 + \lambda V_{d, eff})$$

Where,  $\lambda$  is the Channel length modulation parameter [14] and is given in Table1. So the drain currents with channel length modulation effects are considered.

IV RESULTS AND DISCUSSIONS

The growth of wider band gap material over narrow band gap material creates 2DEG at the heterostructure, so that confinement of electron is possible, which leads to high mobility and resulting into a high speed device. This is due to both of the wide band gap of the InAlN and the very strong polarization effect in InAlN. If the conduction band offset between InAlN and GaN at the both sides of InAlN is defined as the effective  $\Delta E_c(\Delta E_c, eff)$ , this value is larger than the  $\Delta E_c$  in the standard InAlN/GaN HEMT.

Figure a. Energy band dia



gram of InAlN/InAlN/GaN HEMT's. InAlN barrier and InAlN Spacer layer thickness give effective conduction band offset  $\Delta E_c, eff$ . The Higher the Al mole fraction, the smaller is the penetration.

In Figure we discussed about the introduction of thin InAlN spacer interlayer improves transport properties of the 2DEG, and the mobility linearly increases due to suppression of the alloy scattering. The conduction band diagram with InAlN spacer shown in Figure.

The plot for Figure shows the variation of ns with barrier thickness using equation. From this plot, we can say that, the decrease in ns is either based on the reduced barrier thickness dd, the reduced interface polarization charge  $\sigma_{int}$ . Higher the Al mole fraction will lead to higher sheet carrier density. The variation of the gate to source voltage with respect to sheet carrier density shows excellent agreement with the experimental data.

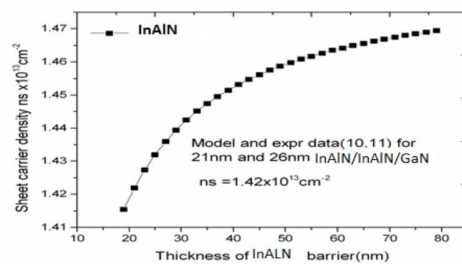


Figure b. Variation of Sheet carrier density with respect to Al mole fraction and thickness of barrier.

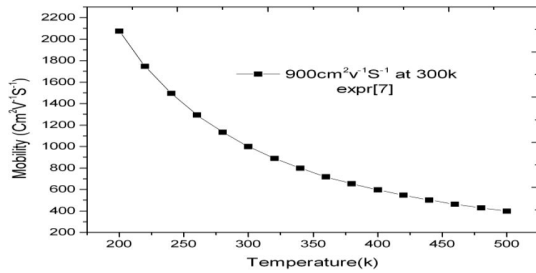


Figure c. Comparison of electron mobility in the GaN channel along different values of temperature.

## V CONCLUSION

A two dimensional physics based model has been calculated for AlGa<sub>N</sub>/AlN/GaN HEMT. At the initial step, the effect of alloy scattering, Piezoelectric and Spontaneous and the polarization dependent threshold voltage are discussed. In the second step, the Sheet Charge density for HEMTs is modeled. The model shows a good agreement with Sheet carrier density with long and short gate experimental InAlN/InAlN/GaN HEMT devices. So this model is easy to use and is compatible for any GaN based channel HEMT devices for performance evaluation. The device shows very good candidate for future microwave and nanoscale power devices and these devices works well in the microwave frequency range between 1 to 40 GHz ranges. Decrease in ns is either based on the reduced barrier thickness d, the reduced interface polarization charge  $\sigma_{int}$ . Higher the Al mole fraction will lead to higher sheet carrier density. The variation of the gate to source voltage with respect to sheet carrier density shows excellent agreement. Also rise in temperature will leads to decrease in mobility in the channel. In future due to the InAlN spacer layer, the system shows the excellent performance for DC characteristics and the reduced scattering. As well as the DC model small signal parameters and microwave frequency performance for HEMT will be modeled later using the MATLAB software. So that the device shows the very good candidate for future microwave and nanoscale power devices. Later , the Sheet Charge density, DC model, Small-signal parameters and microwave frequency performance for HEMTs will be simulate using Technology CAD software. Thus it can be broadly used in wide application and nano scale applications. Finally, we are going to determine the frequency using the transconductance value gm or by reducing the capacitance value.

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