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Modeling and analysis of barrier/interface charge and electrical characteristics of AlGaN/AlN/GaN HEMT for high power Application

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Abstract--**In this paper present, a physics based compact model for the 2-dimensional electron gas (2-DEG) sheet charge density (n_s) in AlGaN/GaN High Electron Mobility Transistor is developed by considering AlGaN barrier layer. To obtain the various electrical characteristics such as transconductance, cut-off frequency (fc), of the proposed spacer layer based AlGaN/AlN/GaN High Electron Mobility Transistor (HEMTs) is modelled by considering the quasi-triangular quantum well. This model valid for entire range of operation. The spacer layer based AlGaN/AlN/GaN heterostructure HEMTs shows excellent promise as one of the candidates to substitute present AlGaN/GaN HEMTs for future high speed and high power applications. To compare the result with HEMT structure.**

Keywords: AlGaN/AlN/GaN 2-DEG sheet charge density triangular quatum well, High electron mobility transistor, Electrical characteristics model.

1. INTRODUCTION

The High Electron Mobility Transistor (HEMT) is an important device for high speed, high frequency, digital circuits and microwave circuits with low noise applications. These applications include telecommunications, computing and instrumentation. HEMT is a field effect transistor incorporating a junction between two materials with different band gap as the channel. The basic structure for a High Electron Mobility Transistor (HEMT) consist of two layers in which the material with the wider band gap energy (in this case AlGaN) is doped and that with the narrow band gap energy (in this case GaN) is undoped [14]. It is referred to as heterojunction field-effect transistor (FET). It is two main features are low noise and high frequency capability. HEMT transistor are operate in high frequencies and are used in high frequencies product such as cell phones, satellite television receiver. Radar equipment and voltage converters. An AlN spacer layer is provided between the AlGaN/GaN layers. Due to the wideband gap of AlN spacer layer, its reduces the two dimensional electron gas electron wave penetration into the AlGaN barrier layer can significantly increase the sheet charge density (n_s) drain current and mobility. A novel heterojunction AlGaN/AlN/GaN was used to to make a HEMT. The insertion of the AlN interfacial layer generates a dipole to increase the effective E_C, by small increase in 2-DEG density. The structure also decrease the alloy disorder scattering, thus

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improving the electron mobility [9]. GaN based HEMTs is the one of the best device for high power, high temperature and high frequency applications. GaN based device has better power handling capability. GaN has widely used in optoelectronics and microwave applications in the form of nitride based light emitting diodes (LEDs) especially in mobile phones. The formation of two dimensional electron gas (2-DEG) in the quantum well is the main principle of the HEMT device operation. To achieve proper operation of the device, the barrier layer AlGaN must be at a higher energy level than the conduction band of the GaN channel layer. This conduction band offset transfers electrons from the barrier layer to the channel layer. The electrons that are transferred are confined to a small region in the channel layer near the hetero-interface. This layer is called the 2-DEG.

2. DEVICE STRUCTURE AND DESCRIPTION

The schematic diagram of the proposed Spacer layer based AlGaN/AlN/GaN HEMT is shown in Fig.1. The equations derived in this work of the channel region under the gate contact. The layer sequence from top to bottom is Metal/AlGaN/UID AlN/GaN, with a two-dimensional electron gas (2DEG) channel formed at the interface between the UID AlN and GaN. The primary advantage of the AlN layer is the decrease in alloy disorder scattering leading to an increase in mobility. This is because the electron penetration into the AlGaN is reduced due to the higher and also the binary AlN at the interface has no alloy disorder scattering.

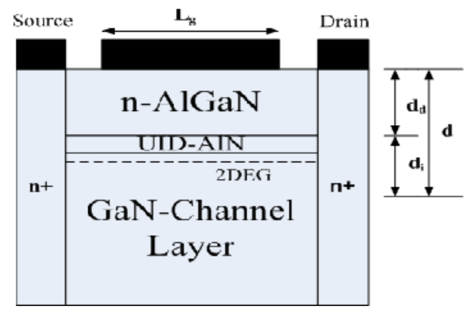

Fig: 1. Schematic diagram of a Spacer layer based AlGaN/AlN/GaN HEMTs with gate length Lg, d_d AlGaN barrier and di AlN Spacer layer thickness.

3.DEVICE CALCULATION

For the purpose of developing a compact drain current model, a continuous unified expression for n_s valid in all regimes of device operation is desirable. The expression for n_s valid in the moderate and strong regime 2-DEG can be written as [6]

$$n_{s,aboveVoff} = \frac{C_g V_{go}}{q} H(V_{go})$$

Where,

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

The unified charge density model shows the Sheet carrier concentration (n_s) both above and below threshold. The term H (V_{go}) in the denominator

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simulates the non-linear behavior in the above threshold region [15] given as

$$n_{s,unified} = \frac{2V_{th}(C_g/q)\ln\{1+\exp(V_{go}/2V_{th})\}}{1/H(V_{go})+(C_g/qD)\exp(-V_{go}/2V_{th})}$$

Where, $V_{go} = V_{gs} - V_{off} - V_x$,

$$\beta = C_g/(qDV_{th}), c_g = \left(\frac{\varepsilon_0\varepsilon_{InAlN}}{d_d} + \frac{\varepsilon_0\varepsilon_{AlN}}{d_i}\right)$$

denotes the total capacitance formed on the InAlN barrier and AlN Spacer gives effective gate capacitance due to the addition of spacer layer, V_{gs} = gate to source voltage, V_{off} = threshold voltage of the device, $d = d_d + d_i$ denotes the total thickness of AlGaN barrier and AlN Spacer layer, V_x = channel potential along x-direction from Source to drain end, D is the density of states, q=electronic charge and γ_0 = experimental data calculated using an AlGaN effective mass of the barrier [6]. The thermal voltage shows less effect on n_s in this model and is negligible.

After solving the new Sheet carrier density equation [27] becomes

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

Where, $\theta = \frac{\gamma_0}{3}\left(\frac{C_g}{q}\right)^{\frac{2}{3}}$. C_g is the gate capacitance formed between the layers and γ_0 is the experimental parameter extracted from data mentioned in Table 1. Under such assumptions, we get the simplified expression for sheet carrier density can be written as,

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

3.1 DRAIN CURRENT MODEL

The drain current in the quasi-triangular quantum well is calculated by using the relation [17]. The model can be formulated using the definition of drain current along the channel. To obtain the drain current model, we started from the following physical equation:

$$I_d = qwn_s(x)V_s$$

Where *W* and L_g are the gate width and length, V_s = electron drift velocity and μ_0 is the low field mobility. In the low-field region, where the longitudinal electric field along the channel, E is less than the critical field E_T ($E \le E_T$) with $E = \frac{-dV_c(x)}{dx}$,

The electron drift velocity can be calculated as

$$V_s = \begin{cases} \dfrac{\mu_0 E}{1+\delta\left(\dfrac{E}{E_T}\right)} & \text{if} \quad E \le E_T \\ \mu_0 E_T & \text{if} \quad E \ge E_T \end{cases}$$

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With $E_T = \frac{E_c V_{sat}}{(\mu_0 E_c - V_{sat})}$ where, E_c is the saturation electric field, $V_c(x)$ is the potential at any point x along the channel and V_{sat} is the Saturation drift velocity of electrons. Substituting the above equations we get simplified form,

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

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

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

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.e., From the source end to the drain end of the channel under the gate will give a simple model of the drain current which can be written as,

$$I_d\int_0^{L_g}\left(1-\frac{1}{E_T}\frac{dV_c(x)}{dx}\right)dx = -w\mu_0 C_g \times \int_{V_s}^{V_d}\left(V_{g0}\frac{(V_{g0})^{\frac{1}{3}}-3\theta+2\theta}{(V_{g0})^{\frac{1}{3}}+2\theta}\right)dV_c(x)$$

Where V_s and V_d are the potentials at the source and drain end of the channel. With a limit $V_c(x=0) = V_s$ and $V_c(x=L_g) = V_d$ and by substitution method which helps us to develop the following expression for drain current I_d is expressed as,

$$I_d = \zeta\left\{\begin{array}{l} 288\theta^6\log_e(t_{drain}+t_{source}) - 816\theta^5(t_{drain}-t_{source}) \\ +480\theta^4(t_{drain}^2-t_{source}^2) - 200\theta^3(t_{drain}^3-t_{source}^3) \\ +52.5\theta^2(t_{drain}^3-t_{source}^3) - 7.8\theta(t_{drain}^5-t_{source}^5) \\ +0.5(t_{drain}^6-t_{source}^6) \end{array}\right\}$$

As the operating power of GaN HEMT device increases, it has also become important to include effects like velocity Saturation and channel length modulation (CLM) into this core drain current model are explained and shown below. Where, δ is a fitting parameter with

$$t_{source} = (V_{gs}-V_{off}-(V_s))^{\frac{1}{3}}+2\theta,$$

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

$$t_{drain} = (V_{gs}-V_{off}-(V_d))^{\frac{1}{3}}+2\theta,$$

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

4. SIMULATION RESULT

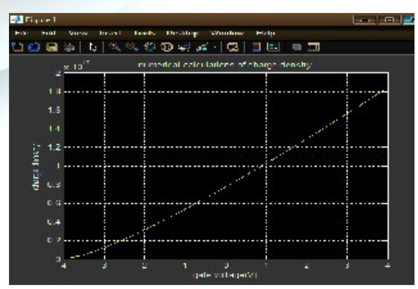

Fig:2 Numerical calculation of charge density with applied gate voltage

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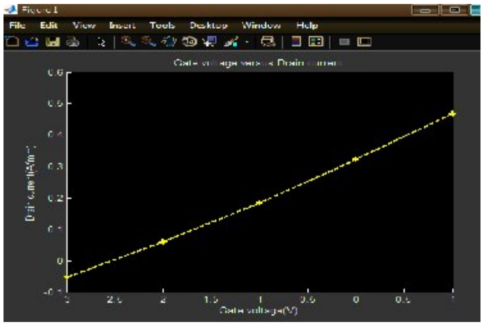

Fig:3 The gate voltage versus drain voltage

5. CONCLUSION

The concluded that to analyze the various characteristics of HEMT (High Electron Mobility Transistor) with spacer layer using Device modelling. To demonstrate the fluctuation in Charge density, Mobility, Drain current, Electron drift velocity, Transconductance, Capacitance and Cut-off frequency. To compare the resuls with HEMT structure.

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