Analytical Model Development for Unified 2D Electron Gas Sheet Charge Density of AlInN/GaN MOSHEMT

Gaini Amarnath, Trupti Ranjan Lenka

Abstract—We have developed a unified analytical model for computation of 2D electron gas sheet charge density in AlInN/GaN metal-oxide-semiconductor high electron mobility transistor device structure. This model has been developed by incorporating the variation in lowest three energy sub-bands and Fermi level energy in the quantum-well with respect to gate voltage. We noticed that the dependency of lowest sub-band energy with Fermi energy having two fields, which are the lowest sub-band energy is greater and lesser than the Fermi level energy. According to these two fields, we have developed the fermi energy and sheet charge density expressions in each field. By combining each field of the models, developed a unified 2D electron gas sheet charge density model. The Fermi level and sheet charge density are interdependent in the model development. The developed model results are compared with TCAD simulation results and obtain a good consistency between them. This model is fitted to other metal-oxide-semiconductor high electron mobility transistor devices also with modifications in related physical values.

Keywords—2DEG, AlInN/GaN, MOSHEMT, TCAD

I. INTRODUCTION

From the past few years, AlInN/GaN high electron mobility transistors (HEMTs) are representing an attractive performance in high frequency, low noise, high switching voltage and high power areas [1-3]. These devices have been studied systematically as a replacement to AlGaN/GaN HEMTs. The primary benefit of AlInN/GaN HEMTs device is that use of thin AlInN barrier and it is nearly lattice matched to GaN. It provides a high 2D electron gas (2DEG) sheet charge density (n_s) in the channel due to large spontaneous polarization charges present and also minimized short channel effects. However, these devices are affected by gate leakage current due to thin barrier material and restricted Schottky barrier thickness resulting in low off-state behavior and poor forward gate swing. In this situation, metal-oxide-semiconductor HEMTs (MOSHEMTs) are introduced to overcome the mentioned problems [3]. The GaN-based MOSHEMT devices are using the gate dielectric/oxide material as SiN [4], SiO_2 [5], Al_2O_3 [6], HfO_2 [7], La_2O_3 [8], AlN [9], LaLuO_3 [10], MgCaO [3]. Among these oxides, HfO_2 is considered in this work.

The 2D electron gas sheet charge density is formed in the quantum well of hetero-interface and it is the key principle to the further heterostructures device study. The 2DEG sheet charge density modeling is a primary requirement in the efficient DC model development for these devices. So, the authors have shown interest in developing physics related unified analytical model for n_s. The development of n_s has to be calculated from the prominent charge control expression [11] as a self-consistent Schrodinger’s and Poisson’s equations in the triangular potential well.

In this work, we develop the fermi energy and 2D electron sheet charge density expressions in two different fields and combining to develop a unified 2D electron gas sheet charge density model. In model development, the Fermi-Dirac distribution function is multiply with a density-of-states function associated with the quantum-well electric field. Also, investigate the effects on sub-band energy levels and n_s with respect to varying the oxide thickness which is distinctive feature of this work.

II. 2D ELECTRON GAS SHEET CHARGE DENSITY MODEL

To develop the model, we have considered HfO_2/AlInN/GaN MOSHEMT device structure as shown in figure 1. The symbols of the definition and parameters used in this work are listed in table 1. In hetero interface structure, such as HfO_2/AlInN/GaN MOSHEMT the sheet charge density is created at the interface and accumulated in the quantum potential well. This charge density is the 2DEG sheet charge density (n_s). This is one of the main key factors determining the operation and performance of device structure. This can be derived from solving self-consistent Schrodinger’s and Poisson’s equations in the triangular potential well.

In model development, considered three quantum-well energy sub-bands say E_0, E_1, and E_2 to develop n_s model.
using density-of-states function (DOS) related to Fermi-Dirac distribution function \( f(E) \) and sub-bands and is represented as,

\[
\begin{align*}
n_s &= 1. \text{DOS} \int_{E_0}^{E_f} \frac{1}{\text{exp} \left( \frac{E - E_f}{kT} \right) + 1} dE + 2. \text{DOS} \int_{E_1}^{E_2} \frac{1}{\text{exp} \left( \frac{E - E_f}{kT} \right) + 1} dE + 3. \text{DOS} \int_{E_2}^{E_{\infty}} \frac{1}{\text{exp} \left( \frac{E - E_f}{kT} \right) + 1} dE
\end{align*}
\]  

Where \( \text{DOS} = \frac{q m^*}{\pi \hbar^2} \) and \( f(E) = \frac{1}{\text{exp} \left( \frac{E - E_f}{kT} \right)} \)  

(1)

From the equation (2) and (3), the \( n_s \) variation with \( V_g \) is a complicated superlative function. So, we propose an analytical model for \( n_s \) with respect to \( V_g \) by making simple assumptions. The \( E_f \) and sub-band positions \( E_0, E_1 \) and \( E_2 \) are carried out for different \( V_g \) and plotted \( E_f - E_0, E_f - E_1 \) and \( E_f - E_2 \) as shown in figure 2. It is potent to state that the quantum-well sub-band level relative positions are in a contrast with \( E_f \) and plotted.

Table I:  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definitions</th>
</tr>
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<tbody>
<tr>
<td>( n_s )</td>
<td>2DEG charge density (cm(^{-2}))</td>
</tr>
<tr>
<td>( E_f )</td>
<td>Fermi energy level</td>
</tr>
<tr>
<td>( E_k )</td>
<td>( k ) th position of sub-band energy</td>
</tr>
<tr>
<td>( V_T )</td>
<td>Thermal voltage, ( V_T = kT/q )</td>
</tr>
<tr>
<td>( V_p )</td>
<td>Potential in the channel at any point ( p )</td>
</tr>
<tr>
<td>( W )</td>
<td>Gate width, 100 ( \mu )m</td>
</tr>
<tr>
<td>( DOS )</td>
<td>Conduction band density of states, 3.24e17 m(^{-2})V(^{-1}) [12]</td>
</tr>
<tr>
<td>( \varepsilon_{\text{oxide}} )</td>
<td>Permittivity of HfO(_2), 22.3 ( \varepsilon_0 ) F/m [7]</td>
</tr>
<tr>
<td>( \varepsilon_{\text{AlInN}} )</td>
<td>Permittivity of AlInN, 8.5 ( \varepsilon_0 ) F/m [8]</td>
</tr>
<tr>
<td>( t_{\text{AlInN}} )</td>
<td>Thickness of AlInN, 15nm</td>
</tr>
<tr>
<td>( V_{FB} )</td>
<td>Flat-band voltage, -3.65V [3]</td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>Low-field mobility, 900 cm(^2) V(^{-1}) s(^{-1})</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>Experimentally determined parameter, 2.12e - 12 V.m(^{4/3}) [13]</td>
</tr>
</tbody>
</table>

Fig. 2. \( E_f \) and sub-band positions \( E_0, E_1, \) and \( E_2 \) with respect to different gate voltage.

Fig. 1. Schematic view of AlInN/GaN MOSHEMT device structure.

In equation (1), neglecting the higher terms, means above \( E_2 \) state, and applying the limits, we get,

\[
n_s = \text{DOS}V_T \left\{ \ln \left[ \text{exp} \left( \frac{E_f - E_0}{kT} \right) + 1 \right] + \ln \left[ \text{exp} \left( \frac{E_f - E_1}{kT} \right) + 1 \right] + \ln \left[ \text{exp} \left( \frac{E_f - E_2}{kT} \right) + 1 \right] \right\}
\]  

(2)

Where \( E_0 = u_0, n_s^{2/3}, E_1 = u_1, n_s^{2/3} \) and \( E_2 = u_2, n_s^{2/3} \) are three lowest level energy sub-bands in the quantum-well, \( E_f \) is fermi energy level and \( V_T = kT/q \) thermal voltage. Assuming the AlInN layer is ionized completely, and we can express as

\[
n_s = \frac{e}{q \cdot t} (V_{g0} - E_f)
\]  

(3)

Where \( e = \varepsilon_{\text{oxide}} + \varepsilon_{\text{AlInN}}, t = t_{\text{oxide}} + t_{\text{AlInN}}, V_{g0} = V_g - V_{FB} \) and \( V_{FB} \) is the flat-band voltage and assuming typical voltage of -3.65V \[3\].
From figures 2 and 3, we have observed two kinds. First, the upper levels $E_2$ and $E_1$ are higher than $E_f$ and also with $E_0$ throughout the applied gate voltage. So, the contribution of higher order sub-band energy levels $E_2$ and $E_1$ are safely neglected in 2DEG charge density derivation. Second, the lowest sub-band energy level $E_0$ having two noticeable fields which are (i) $E_f < E_0$ and (ii) $E_f > E_0$. According to the above observations, we have developed 2DEG charge density model separately in field 1 ($E_f < E_0$) and field 2 ($E_f > E_0$). Then these two fields of the models are combined to develop a unified 2DEG charge density analytical model.

(i). Field-1 ($E_f < E_0$) of 2DEG Charge Density Model

From the above-mentioned observations, the contribution of higher order sub-band energy levels $E_2$ and $E_1$ are neglected. Then by considering only the lowest sub band energy level term the equation (2) becomes,

$$n_s = DOS \cdot V_T \cdot \ln \left[ \exp \left( \frac{E_f - E_0}{V_T} \right) + 1 \right]$$

The equation (4), we can write also as

$$\exp \left( \frac{n_s}{DOS \cdot V_T} \right) = \exp \left( \frac{E_f - E_0}{V_T} \right) + 1$$

The aim of this 2DEG charge density modelling is to develop an explicit $E_f$ with respect to $V_g$ expression as related to the precise solution as feasible, which is appropriate for drain current and other model development. Now, the Taylor’s theorem approximation $\ln(1 + x) \approx x$ for $x << 1$ is used in equation (4) and $E_f$ can be approximated as

$$E_f \approx u_0 \cdot n_s^{2/3} + V_T \cdot \ln \left( \frac{n_s}{DOS \cdot V_T} \right)$$

Next, the equation (3) is substituted in equation (6) to eliminate $n_s$ term.

$$E_f = u_0 \left( \frac{\varepsilon \cdot V_{g0} - E_f}{q \cdot t} \right)^{2/3} + V_T \cdot \ln \left( \frac{\varepsilon \cdot V_{g0} - E_f}{q \cdot t \cdot DOS \cdot V_T} \right)$$

Now expanding the right-hand side of the two terms to first order in the form of $E_f/V_{g0}$. Then we can get,

$$E_f = u_0 \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t} \right)^{2/3} - \frac{2}{3} u_0 \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t} \right)^{2/3} E_f \cdot V_{g0} + V_T \cdot \ln \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t \cdot DOS \cdot V_T} \right) - \frac{V_T}{V_{g0}} \cdot \frac{E_f}{V_{g0}}$$

(8)

With further simplifications of equation (8), the $E_f$ can be written as

$$E_f = V_{g0} \cdot V_T \ln \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t \cdot DOS \cdot V_T} \right) + u_0 \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t} \right)^{2/3} + V_T$$

(9)

To derive the $n_s$ expression with respect to $V_g$, the equation (9) is substitute in (3) and we get,

$$n_s = \frac{\varepsilon \cdot V_{g0} \cdot V_T + V_T \ln \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t \cdot DOS \cdot V_T} \right) - \frac{u_0 \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t} \right)^{2/3}}{V_{g0} + \frac{2}{3} u_0 \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t} \right)^{2/3} + V_T}}{V_{g0} + \frac{2}{3} u_0 \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t} \right)^{2/3} + V_T}$$

(10)

(ii). Field-2 ($E_f > E_0$) of 2DEG Charge Density Model

In field-2, it is noticed that the $E_f$ is greater than $E_0$. By applying the first and second observations to the equation (2), the $n_s$ expression approximated as

$$n_s \approx DOS \left( E_f - E_0 \right)$$

(11)

To derive the $E_f$ and $n_s$ expression with respect to $V_g$ use the equation (11) and (3)

$$\frac{\varepsilon}{q \cdot t} \left( V_{g0} - E_f \right) = DOS \left( E_f - u_0 \cdot n_s^{2/3} \right)$$

(12)
The \( E_f \) expression with respect to \( V_g \) in field-2 is derived from equation (12) and the same approach is used as in field-1, and written as

\[
E_f = V_{g0} \frac{\varepsilon \cdot V_{g0} \cdot u_0 \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t} \right)^{2/3}}{q \cdot t \cdot DOS + 1} + \frac{2}{3} \left( \frac{\varepsilon \cdot V_{g0}}{q \cdot t} \right)^{2/3}.
\]

Then, the equation (13) is substitute in (3) to get field-2 of \( n_s \) model with respect to \( V_g \) as,

\[
n_s = \frac{\varepsilon V_{g0}}{q \cdot t} \cdot \frac{V_{g0}^{-u_0} \left( \frac{\varepsilon V_{g0}}{q \cdot t} \right)^{2/3}}{q \cdot t \cdot DOS + 1} = \frac{\varepsilon V_{g0}^{-u_0} \left( \frac{\varepsilon V_{g0}}{q \cdot t} \right)^{2/3}}{q \cdot t \cdot DOS + 1}.
\]

(iii). Unified 2DEG Charge Density Model

To improve the validity of models developed in \( E_f < E_0 \) and \( E_f > E_0 \) fields, we developed a unified \( n_s \) model by combining these two fields of the models.

Now, combining the equations (10) and (14), we get

\[
n_s = \frac{\varepsilon V_{g0}}{q \cdot t} \cdot \frac{V_{g0}^{-u_0} \left( \frac{\varepsilon V_{g0}}{q \cdot t} \right)^{2/3}}{q \cdot t \cdot DOS + 1} - \frac{2}{3} \left( \frac{\varepsilon V_{g0}}{q \cdot t} \right)^{2/3}.
\]

The equation (15) is considered to be a unified 2DEG charge density model when \( V_{g0} = \frac{\varepsilon q \cdot DOS \cdot V_T}{\varepsilon} \) and \( V_{g0} = \frac{\varepsilon q \cdot DOS \cdot V_T}{\varepsilon} \).

III. RESULTS AND DISCUSSIONS

The transport is primarily by the 2DEG charge density in hetero-structure devices with drift and diffusion currents subject to the terminal biases. The 2DEG charge density is the key principle to the further heterostructures device study. The \( n_s \) model is developed separately in field 1 \( (E_f < E_0) \) and field 2 \( (E_f > E_0) \). Then these two models are combined to develop a unified 2D electron gas charge density model. The developed 2DEG charge density model results are compared with TCAD [14] simulation results to validate the models. The device structure is having a 15-nm thickness of AlInN barrier layer throughout.

Drift–diffusion numerical model including carrier continuity equation and Poisson equation is used for the simulation of carrier transport in the channel at 300 K. Newton method is used for model calculations. Mesh value of the structure is carefully chosen by the Deck Build Editor for the accurate simulation of the important regions of the device as well as to accelerate the computational efficiency. Simulations have been carried out by using the physical models such as, FLDMOB for the electric field-dependent mobility, CONMOB for the concentration dependent mobility, and CVT-a stand-alone model which incorporates all the effects required for simulating the carrier mobility, SRH and Auger for recombination and generation. The results are analysed in Tony plot and for output data extraction the Tony plot export feature is used. During simulation, the fixed oxide charges \( (V_x \) independent \) of \( 9.8 \times 10^{12} \text{cm}^{-2} \) for HfO\(_2\) at oxide-semiconductor interface is considered [15]. The polarization charges of \( 2.73 \times 10^{13} \text{cm}^{-2} \) are calculated and imposed across AlInN interface [16].

The \( n_s \) is calculated with respect to \( V_g \) as per equations (10), (14) and (15). These developed model results are shown in figure 4 and these results are compared with TCAD simulation results with respect to \( V_g \). From these results, the \( n_s \) is increasing linearly with gate voltage and the maximum charge density is in the order of \( 10^{13} \text{cm}^{-2} \) which is widely suitable for fabricated GaN based MOSHEMT devices. The figure 4 shows the developed model results and simulation results are in good agreement.

![Fig. 4. Comparison of simulation and model results of \( n_s \) with respect to \( V_g \).](image-url)
dielectric permittivity and interface charges. we consider AlInN barrier material of 15nm thickness and permittivity $\varepsilon_{AlInN} = 8.5 \varepsilon_0 F/m^2$. The HfO$_2$ material is used as oxide layer having permittivity of $\varepsilon_{Oxide} = 22.3 \varepsilon_0 F/m^2$. In view of this, we have varied the oxide thickness from 0 to 20 nm with respect to $n_s$ and shown in figure 5.

![Graph showing $n_s$ with respect to different oxide thicknesses.](image)

Fig.5. $n_s$ with respect to different oxide thicknesses.

The $n_s$ increasing linearly with positive slope when increasing the oxide thickness. When the oxide thickness is increasing, the electric field decreases due to the existence of positive interface and bulk oxide charges in HfO$_2$ material [7]. When the electric field decreases the quantum-well sub-band energy values decreases then the $E_f$ difference increases and in consequence to increase in $n_s$. From figure 5, the $n_s$ with respect to oxide thickness variation in two different fields and unified model results are compared with simulation results and are in good agreement. From all these results, it is important to note that the developed models can be useful to study the transport characteristics of III-Nitride based MOSHEMT structures.

IV. CONCLUSION

We have developed an analytical model for the unified 2D electron gas charge density of HfO$_2$/AlInN/GaN MOSHEMT device. The unified $n_s$ model is developed by solving transcendental relation of $n_s$ and $E_f$ with respect to gate voltage in field 1 ($E_f < E_0$) and field 2 ($E_f > E_0$) and combined them. This model has not required any fitting or empirical parameters. These developed models are verified with different oxide thickness and shows a linear positive increment in $n_s$ with increasing the oxide thickness. The developed model results are compared with simulation results and found in a good agreement between them. Finally, it is important to note that the developed models can be useful to study the further characteristics of III-N based MOSHEMT structures.

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