

A Physics-Based Analytical Model for 2DEG Charge Density in AlGaIn/GaN HEMT Devices

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Abstract—In this brief, we present a physics-based analytical model for 2-D electron gas density n_s in AlGaIn/GaN high-electron mobility transistors. The proposed model accounts for the interdependence between Fermi level E_f and n_s . The model is developed by considering the variation of E_f , the first subband E_0 , the second subband E_1 , and n_s with applied gate voltage V_g . The proposed model is in very good agreement with numerical calculations.

Index Terms—AlGaIn/GaN high-electron mobility transistor (HEMT), analytical models, two-dimensional electron gas (2DEG) charge density.

I. INTRODUCTION

AlGaIn/GaN high-electron mobility transistor (HEMT) devices are considered to be very promising candidates for high-speed and high-power applications [1], [2]. These devices offer advantages such as high breakdown voltage, high charge density, and good electron mobility [3]–[5]. The formation of the 2-D electron gas (2DEG) in these devices is the heart of the device operation and has been studied in great detail in the literature. For accurate and fast simulation of circuits based on these devices, an analytical expression for 2DEG density n_s is required. The expression should be also physics based, which obviates the use of a large number of empirical parameters.

To the best of the authors' knowledge, currently available models for n_s are primarily based on numerical calculations, semiempirical model expressions, or simplifying approximations [6]–[11]. Models relying on numerical calculations will be slow because of the iterative nature. Semiempirical models are fast but do not provide needed insight into the device operation. They also tend to have a large number of empirical parameters, which have to be extracted from experimental data. In contrast to these approaches, we present a physics-based analytical model with minimal empirical parameters.

The difficulty in modeling the 2DEG charge density stems from the complicated variation of E_f with n_s in the quantum

TABLE I
LIST OF SYMBOLS

Symbol	Physical meaning
n_s	Density of 2DEG
d	Thickness of AlGaIn layer 20 nm
q	The electron charge
ϵ	The permittivity of AlGaIn
D	Density of States $1.001e18 \text{ m}^{-2}\text{V}^{-1}$ [12]
V_{off}	Cutoff voltage taken as -3V [6]
k	Boltzmann's constant
T	Temperature
E_0	Position of first sub-band
E_f	Position of Fermi level
E_1	Position of second sub-band
γ_0, γ_1	Experimentally determined parameters $2.12e-12$ and $3.73e-12 \text{ V}\cdot\text{m}^{4/3}$ respectively [13]

well. This relationship is given by [7]

$$n_s = DV_{\text{th}} \left\{ \ln \left[\exp \left(\frac{E_f - E_0}{V_{\text{th}}} \right) + 1 \right] + \ln \left[\exp \left(\frac{E_f - E_1}{V_{\text{th}}} \right) + 1 \right] \right\} \quad (1)$$

where $E_0 = \gamma_0 n_s^{2/3}$ and $E_1 = \gamma_1 n_s^{2/3}$ are the levels of the two lowest subbands, E_f is the Fermi level expressed in volts, and $V_{\text{th}} = kT/q$ is the thermal voltage. The definitions of the symbols used are given in Table I. Assuming that the AlGaIn layer is completely ionized, we can write

$$n_s = \frac{\epsilon}{qd} (V_{\text{go}} - E_f) \quad (2)$$

where $V_{\text{go}} = V_g - V_{\text{off}}$, and V_{off} is the cutoff voltage. The calculations in this brief have been done for an $\text{Al}_{0.15}\text{Ga}_{0.85}/\text{GaN}$ structure and typical V_{off} of -3 V [6]. It is apparent from (1) and (2) that the variation of n_s with respect to V_g is a complicated transcendental function. Here, we propose simplifying assumptions in these equations, which allows us to develop a precise analytical expression for n_s versus V_g for the typical operating range of gate voltages and temperatures.

II. 2DEG CHARGE DENSITY MODEL DEVELOPMENT

Fig. 1 shows important quantities E_f , E_0 , and E_1 as obtained from numerical calculations based on (1) and (2) for a wide range of gate voltages from close to V_{off} and up. It is interesting to note the relative positions of the subband levels compared with E_f in this range. To accentuate the observation, we plot

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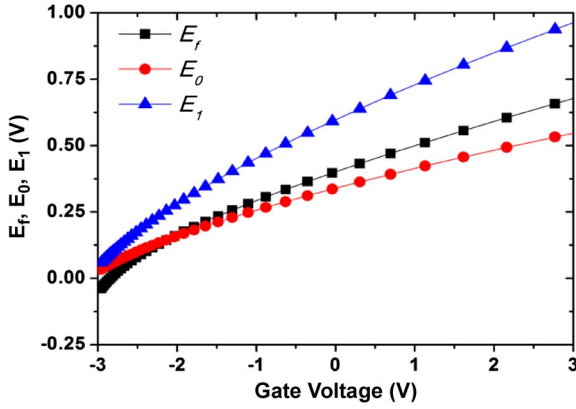


Fig. 1. Numerical calculations of E_f , E_0 , and E_1 versus gate voltage. $T = 298$ K.

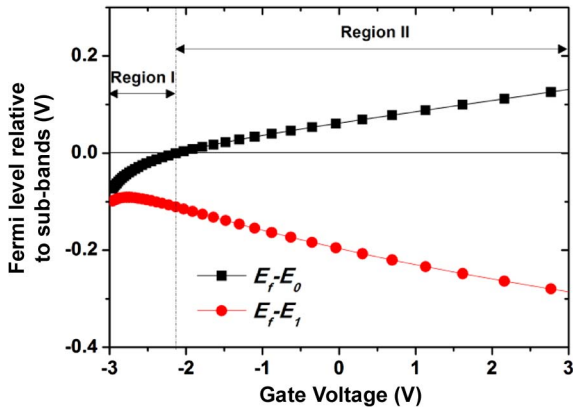


Fig. 2. Numerical calculations of $E_f - E_0$ and $E_f - E_1$ versus gate voltage. Regions I and II are marked in the figure.

$E_f - E_0$ and $E_f - E_1$ in Fig. 2 and find two observations: 1) Upper level E_1 is larger than E_f for the complete range of the gate voltages. In addition, E_1 is significantly larger than E_0 over the same range. Hence, the contribution to n_s from the second subband can be safely ignored. 2) Lower level E_0 has two distinct regions, namely, Region I, where E_0 is larger than E_f , corresponding to $V_{go} < 0.9$ V, and Region II, where E_0 is lower than E_f and $V_{go} \geq 0.9$ V. **We also note that, in the full range of gate voltages considered, except very close to cutoff, E_f will be much smaller than V_{go} .**

Next, a model for n_s is separately developed in Regions I and II. These models are then combined to give a unified model covering both regions.

A. Charge Density Model in Region I

Using the aforementioned observation for Region I, (1) can be approximated as follows:

$$E_f^I \approx \gamma_0 (n_s^I)^{2/3} + V_{th} \ln \left(\frac{n_s^I}{DV_{th}} \right). \quad (3)$$

Equation (3) is obtained by neglecting the second term in (1) and replacing E_0 by $\gamma_0 (n_s^I)^{2/3}$. Next, we apply (2) to eliminate n_s^I in (3) and expand the two terms on the right-hand side of

(3) **to first order in E_f^I/V_{go}** (see above). Thus, we obtain the following analytical expression for E_f^I versus gate voltage:

$$E_f^I = V_{go} \frac{V_{th} \ln(\beta V_{go}) + \gamma_0 \left(\frac{C_g V_{go}}{q} \right)^{2/3}}{V_{go} + V_{th} + \frac{2\gamma_0}{3} \left(\frac{C_g V_{go}}{q} \right)^{2/3}} \quad (4)$$

where $C_g = \epsilon/d$, and $\beta = C_g/(qDV_{th})$. It is important to point out here that, for vertically scaled devices with $d < 5$ nm, the 2DEG distance from the interface, i.e., δd , will become comparable with d . In such cases, d should be replaced by $d_{eff} = d + \delta d$ in the model expressions. Combining (4) and (2), we find an analytical model for n_s^I versus gate voltage in Region I, i.e.,

$$n_s^I = \frac{C_g V_{go}}{q} \frac{V_{go} + V_{th} [1 - \ln(\beta V_{go})] - \frac{\gamma_0}{3} \left(\frac{C_g V_{go}}{q} \right)^{2/3}}{V_{go} + V_{th} + \frac{2\gamma_0}{3} \left(\frac{C_g V_{go}}{q} \right)^{2/3}}. \quad (5)$$

B. Charge Density Model in Region II

In Region II, observations 1) and 2) applied to (1) result in the following approximate expression for n_s^II :

$$n_s^II \approx D (E_f^II - E_0). \quad (6)$$

Combining this with (2) using the same approximation as was used for Region I, we now obtain

$$E_f^II = V_{go} \frac{\beta V_{th} V_{go} + \gamma_0 \left(\frac{C_g V_{go}}{q} \right)^{2/3}}{(1 + \beta V_{th}) V_{go} + \frac{2\gamma_0}{3} \left(\frac{C_g V_{go}}{q} \right)^{2/3}} \quad (7)$$

$$n_s^II = \frac{C_g V_{go}}{q} \frac{V_{go} - \frac{\gamma_0}{3} \left(\frac{C_g V_{go}}{q} \right)^{2/3}}{(1 + \beta V_{th}) V_{go} + \frac{2\gamma_0}{3} \left(\frac{C_g V_{go}}{q} \right)^{2/3}}. \quad (8)$$

C. Unified Model for Charge Density

In order to find a unifying expression for E_f and n_s applicable for the full range of gate voltages, we observe that the respective expressions for Regions I and II differ only in one term in the numerator and one term in denominator, both with a factor of V_{th} . Hence, both the regional models are expected to provide a fairly reasonable approximation for most of the voltage range considered, except near cutoff. In fact, similar accuracy can be obtained by removing all terms with factor V_{th} in (4), (5), (7), and (8), resulting in approximate unified expressions for E_f and n_s . However, to improve accuracy, we propose to use a unified form that combines the two regional models. Considering specifically the expression for n_s , we can write

$$n_s = \frac{C_g V_{go}}{q} \frac{V_{go} + V_{th} [1 - \ln(\beta V_{gon})] - \frac{\gamma_0}{3} \left(\frac{C_g V_{go}}{q} \right)^{2/3}}{V_{go} \left(1 + \frac{V_{th}}{V_{god}} \right) + \frac{2\gamma_0}{3} \left(\frac{C_g V_{go}}{q} \right)^{2/3}}. \quad (9)$$

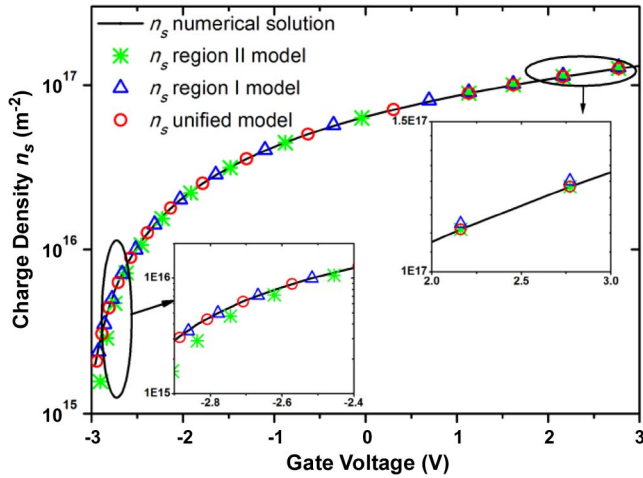


Fig. 3. Comparison of numerical calculations and the unified and regional analytical models of n_s versus gate voltage. $T = 298$ K.

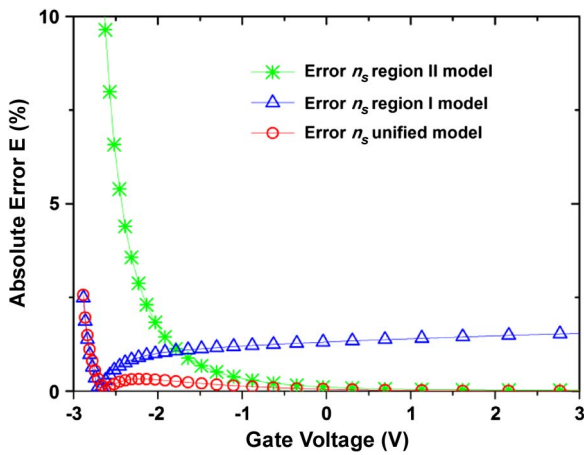


Fig. 4. Percentage absolute error between numerical calculations and analytical models of n_s versus gate voltage.

Here, V_{gon} and V_{god} are functions of V_{go} given by the interpolation expression

$$V_{gox} = \frac{V_{go}\alpha_x}{\sqrt{V_{go}^2 + \alpha_x^2}} \quad (10)$$

where $\alpha_n = e/\beta$, and $\alpha_d = 1/\beta$. We observe that (9) has the proper limiting form corresponding to that of (5) for Region I and (8) for Region II. A similar unified expression can be also easily established for E_f by applying (9) in (2).

III. RESULTS AND DISCUSSIONS

The model developed for n_s is compared with numerical calculations in Fig. 3, where the two regional models are indicated along with the unified model at room temperature. It is apparent from this figure that all three models agree quite well with the simulations for most of the gate voltage range considered, but the unified model has higher precision everywhere with typically less than 1% error for $V_{go} > 0.1$ V, as shown in Fig. 4. Since the assumption that $E_f^I/V_{go} \ll 1$ does not apply very close to cutoff, the error tends to steeply increase in this region, as indicated in Fig. 4. Region I model actually performs quite

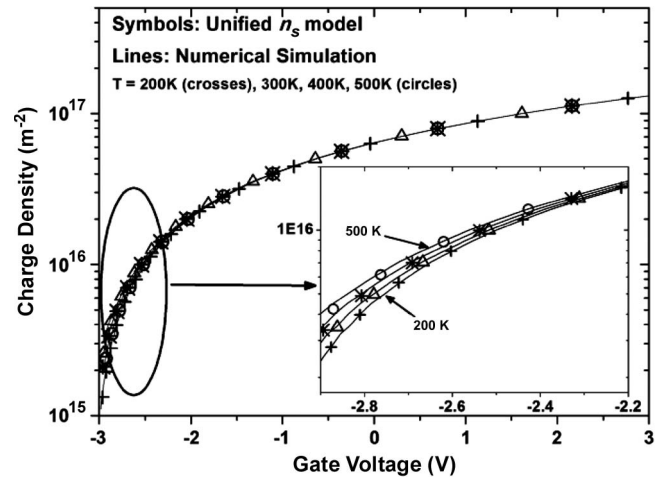


Fig. 5. Comparison of numerical calculations and the unified analytical model of n_s versus gate voltage for $T = 200, 300, 400$, and 500 K.

well also in Region II, with an error of less than 2% in that region. Region II model performs relatively poorly in Region I, with a rapidly increasing error for $V_{go} < 1$ V.

Since GaN devices often operate at high power, it is also of interest to assess the precision of the present model at elevated temperatures. In Fig. 5, the unified model for n_s is compared with numerical calculations at different temperatures up to 500 K. It is apparent from the results that the model agrees quite well with the numerical calculations throughout this temperature range, although the error tends to increase somewhat near cutoff with increasing temperature. The increase in error is found to be almost linear with increasing temperature for bias point $V_{go} = 0.2$ V. However, it can be argued that high temperatures due to self-heating will occur only well above cutoff, where the error is very small.

IV. CONCLUSION

We have presented a physics-based fully analytical model for the dependence of 2DEG density n_s on gate bias. The model is developed by simplifying the basic device equations in different regions of operation and combining them. The proposed model does not have any empirical or fitting parameters. The modeling results are in excellent agreement with numerical calculations for a wide range of temperatures. This model can be used to develop physics-based compact models of GaN HEMT devices.

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