Compact Modeling of Intrinsic Capacitances in AlGaN/GaN HEMT Devices

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ABSTRACT

We present an analytical model for intrinsic gate-source and gate-drain capacitances in AlGaN/GaN HEMT devices. A physics-based analytical expression for 2-DEG charge density developed previously by our group along with the Meyer capacitance formulations is used to derive the intrinsic capacitances. The model is in excellent agreement with experimental data.

Keywords: AlGaN/GaN HEMTs, MODFETs, Compact Models

1 INTRODUCTION

AlGaN/GaN HEMT devices are being actively pursued for high power and high frequency applications [1-2] in industry and academia, owing to their excellent characteristics like high breakdown voltage, high charge density, and high electron mobility [3-5]. To explore and exploit the full potential of these devices, accurate and fast simulation of circuits based on these devices is required. The speed and accuracy of such simulations depend heavily on the compact model used to describe behavior of the device, which underlines the importance of an analytical physics-based model for these devices.

To the best of the authors’ knowledge, currently available models for these devices are primarily based on numerical calculations, semi-empirical model expressions, and/or simplifying approximations [6-11]. Models relying on numerical calculations will be slow because of the iterative nature. Semi-empirical 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 for intrinsic capacitances in these devices with a minimal parameter set.

An analytical physics-based expression for 2-DEG charge density \( n \), developed previously by our group is used to derive the gate-channel capacitance \( C_{ch} \) valid in all the regions of device operation. We use the developed \( C_{ch} \) model in conjunction with the Meyer capacitance model to derive continuous expressions for intrinsic gate-source and gate-drain capacitances valid in all the regions of device operation. With long channel approximation all the nine trans-capacitances in the device can be obtained from the present model.

The paper is arranged as follows. In section 2, we present the details of the model for intrinsic capacitances. The developed model is verified by comparing with experimental data in section 3. In section 4, we conclude the paper.

2 MODEL DESCRIPTION

A cross-sectional view of the AlGaN/GaN HEMT device discussed here is shown in Fig. 1. The equations derived in this work are for the channel region under the gate contact. The source-gate and drain-gate gap regions are treated as parasitic resistances.

Figure 1. Cross sectional view (not drawn to scale) of AlGaN/GaN HEMT. UID is a thin un-intentionally doped AlGaN layer commonly used for mobility enhancement.

The 2-DEG charge density is one of the principal entities governing the performance and operation of AlGaN/GaN HEMT devices. It can be calculated from the solution of Schrodinger’s and Poisson’s equations in the quantum well assuming a triangular potential profile. A self-consistent solution of \( n_s \) considering the two important energy levels is expressed as [7],

\[
\left\{ \begin{array}{l}
\ln \left[ \exp \left( \frac{E_f - E_0}{V_{th}} \right) + 1 \right] + \ln \left[ \exp \left( \frac{E_f - E_i}{V_{th}} \right) + 1 \right] \\
E_0 = \gamma_0 n_s^{2/3}, E_i = \gamma_1 n_s^{2/3}
\end{array} \right.
\]

(1)

\[
n_s = \frac{e}{qd} \left( V_{go} - E_f - V_x \right)
\]

(3)

where \( V_{go} = V_g - V_{off} \) and \( V_x \) is the potential at any point \( x \) in the channel. A description of all the other symbols used is
given in Table 1. It is apparent that to obtain an analytical solution from (1) – (3), we need to make simplifications. This is done by subdividing the variation of \( n_s \) versus the applied gate voltage into different operating regions, allowing us to derive explicit expression in each one. This subdivision is determined by the position of the Fermi level \( E_f \) relative to the energy levels \( E_0 \) and \( E_1 \). The regional analytical solutions are then combined to provide a continuous model for \( n_s \) valid across all the regions.

The various regions of the subdivision are identified in Fig. 2, together with the numerical solution for \( E_f, E_0 \) and \( E_1 \) versus \( V_g \). The regions are: (i) \( V_g < V_{off} \), the sub-\( V_{off} \) region, where \(|E_f| \) is comparable to \(|V_{off}| \); (ii) \( V_g > V_{off} \), and \( E_f > E_0 \), the moderate 2-DEG region; (iii) \( V_g > V_{off} \) and \( E_f > E_0 \), the strong 2-DEG region. In the sub-\( V_{off} \) region, \(|E_f| \gg E_0 \) and \( E_1 \) (see Fig. 2) and therefore \( E_f - E_0 \) and \( E_f - E_1 \approx E_f \). Applying this observation and using the approximation \( \ln(1 + x) \approx x \) for \( x \ll 1 \) to (1), and invoking (3), the solution for \( n_s \) can be written in terms of a Lambert’s function as,

\[
q n_s V_{th} \exp \left( \frac{q n_s}{C_g V_{th}} \right) = 2QD \exp \left( \frac{V_{go}}{V_{th}} \right) \tag{4}
\]

Performing a Taylor series expansion of (4) and neglecting higher order terms, we obtain the following explicit function for \( n_s \) in the sub-\( V_{off} \) region,

\[
n_{s,sub-V_{off}} = 2DV_{th} \exp \left( \frac{V_{go}}{V_{th}} \right) \tag{5}
\]

This expression is valid when \(|E_f| \gg E_0, E_1 \) and \( E_f < 0 \).

The model for \( n_s \) valid in the moderate 2-DEG and strong 2-DEG regions can be written as [12],

\[
n_{s,above-V_{off}} = \frac{C_g V_{go}}{q} H(V_{go}) \tag{6}
\]

where

\[
H(V_{go}) = \frac{V_{go} + V_{th} \left[ 1 - \ln \left( \frac{\beta V_{go}}{V_{th}} \right) \right] - \frac{\gamma_f}{3} \left( \frac{C_g V_{go}}{q} \right)^{2/3}}{\left( \frac{V_{go}}{V_{th}} \right)^2 + \frac{2\gamma_f}{3} \left( \frac{C_g V_{go}}{q} \right)^{2/3}} \tag{7}
\]

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

\[
V_{go} = \frac{V_{go} \alpha_s}{\sqrt{V_{go}^2 + \alpha_s^2}} \tag{8}
\]

and \( \beta = C_g / qDV_{th} \), \( \alpha_o = e/\beta \) and \( \alpha_s = 1/\beta \).

For the purpose of developing a compact model, a continuous unified expression for \( n_s \) valid in all regions of operation is desirable. This is possible by combining (5) – (7) in the following manner,

\[
n_{s,unified} = \frac{2V_{th} (C_g / q) \ln \left[ 1 + \exp \left( \frac{V_{go}}{2V_{th}} \right) \right]}{1 / H(V_{go}) + (C_g / qD) \exp (-V_{go} / 2V_{th})} \tag{9}
\]

From this expression we readily observe that (6) is recovered when \( V_g > V_{off} \), and (5) results in the sub-\( V_{off} \) region. Hence (9) describes the variation of the 2-DEG charge density with the applied voltage in all the regions of operation.

The material system in HEMT devices is metal-AlGaN-GaN. For a useful operating range the Schottky junction (metal-AlGaN) is reverse biased and the AlGaN layer is fully depleted. This makes the system a non-linear capacitor as only displacement current is expected. The displacement current is due to the variation in the 2-DEG and the GaN layer charge. The 2-DEG operation is desirable. This is possible by combining (5) – (7) in the following manner,

\[
H(V_{go}) = \frac{V_{go} + V_{th} \left[ 1 - \ln \left( \frac{\beta V_{go}}{V_{th}} \right) \right] - \frac{\gamma_f}{3} \left( \frac{C_g V_{go}}{q} \right)^{2/3}}{\left( \frac{V_{go}}{V_{th}} \right)^2 + \frac{2\gamma_f}{3} \left( \frac{C_g V_{go}}{q} \right)^{2/3}} \tag{7}
\]

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

\[
V_{go} = \frac{V_{go} \alpha_s}{\sqrt{V_{go}^2 + \alpha_s^2}} \tag{8}
\]

and \( \beta = C_g / qDV_{th} \), \( \alpha_o = e/\beta \) and \( \alpha_s = 1/\beta \).
The capacitance model presented in the previous section is correlated with experimental data for gate-source and gate-drain capacitances for a device with channel length 0.35 μm from [11]. In Fig. 3, we show the comparison between the model and experimental data for $C_{gs}$. The cut-off voltage for this device is -2.8 V. When $V_g$ is below $V_{off}$, the 2-DEG charge density is very small and the capacitance is mainly due to fringing field. The value of the fringe capacitance is found to be 0.37 pF/mm. When $V_g$ goes above but close to $V_{off}$, the 2-DEG charge density rapidly increases with $V_g$ causing the observed rise in $C_{gs}$. For $V_g$ well above $V_{off}$ the 2-DEG charge density becomes close to a linear function of $V_g$ causing the saturation of $C_{gs}$. It is apparent from Fig. 3 that the model captures all the regions of device operation quite well.

$$C_{gs} = C_{xg} + C_{sd} = C_{ds} + C_{gs} \quad (16)$$

$$C_{gg} = C_{gx} + C_{gd} = C_{xg} + C_{dg} \quad (17)$$

### 3 RESULTS AND DISCUSSIONS

In Fig. 4, we compare the model with experimental data for $C_{gd}$ versus $V_d$. A steady decrease in $C_{gd}$ with $V_d$ is apparent from Fig. 4, which indicates that the drain loses control of the channel charge. This happens because increasing the drain voltage after saturation only moves the point of saturation slightly without causing substantial change to the charge in the channel. An excellent correlation between the model and experimental data verified the developed modeling methodology.

### 4 CONCLUSIONS

We have presented an analytical physics-based model for intrinsic capacitances in AlGaN/GaN HEMT devices. An analytical 2-DEG charge density model valid in all the regions of device operation is used to derive gate-channel...
capacitance model. The gate-channel capacitance model is used in conjunction of Meyer capacitance model to derive the intrinsic capacitances in AlGaN/GaN HEMT devices. The model is in excellent agreement with experimental data. The proposed model can serve as basis for development of a complete compact model for AlGaN/GaN HEMT devices.

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