1. INTRODUCTION

The wide band gap AlGaN/GaN high electron mobility transistors (HEMTs) show great promise for applications such as high frequency wireless base stations and broad-band links, commercial and military radar and satellite communications [1-5]. The outstanding properties of nitride material system such as high electron mobility, high saturation velocity, low thermal impedance, and high breakdown field make them extremely promising devices for high power and high temperature microwave applications. GaN-based materials are usually grown in [0001] and [111] directions, and since these axes are polar, they cause GaN-based materials to exhibit strong lattice polarization effects. Because of the piezoelectric and spontaneous polarization fields, AlGaN/GaN-based HEMTs have the ability to achieve two dimensional electron gas (2-DEG) with sheet carrier densities of the order of $10^{12} - 10^{13}$ cm$^{-2}$ even without intentional doping. This mechanism of polarization leads to unprecedent high power densities and high current drive capability that are one order of magnitude higher than their silicon or GaAs counterparts [6, 7]. The development of new generations of AlGaN/GaN field-effect transistors (FETs) requires low gate leakage and superior pinch-off characteristics, specifically at elevated temperatures for high temperature microwave power electronics [8]. These properties directly impact the device drain breakdown voltage, radio frequency (RF) performance, and noise figure. In the past, several groups have attempted to achieve gate leakage suppression and superior pinch-off characteristics by using the metal-insulator-semiconductor FETs (MISFETs) [9, 10] or metal-oxide-semiconductor FETs (MOSFETs) [11] device approach. However, the performance level of all these insulated gate devices is well below that of the state-of-the-art AlGaN/GaN HFETs. Recently Khan et al. [12] reported the dc characterization results of AlGaN/GaN metal-insulator-semiconductor heterostructure field-effect transistors (MISHFETs) on sapphire substrates. The built-in channel of MISHFET is formed by the high density 2-DEG at the AlGaN/GaN interface as in regular AlGaN/GaN HFETs. However, in contrast to HFETs, the metallic gate is isolated from AlGaN barrier layer by a thin Si$_3$N$_4$ film. This insulator layer provides extremely low gate leakage current and allows for a large negative to positive gate voltage swing (GVS) [12]. Thus MISHFET combines the advantages of the MIS structure that suppresses the gate leakage current and AlGaN/GaN heterointerface, which provides high-density high-mobility 2-DEG channel. Although piezoelectric polarization results in large values of sheet carrier density, it also gives rise to charged surface states within the device. These surface states are considered responsible for DC to RF current collapse or dispersion, because these electron traps act as a negatively charged virtual gate and limit maximum current available during microwave operation. Good insulator can passivate these surface states and also reduce gate leakage. Thus, the same dielectric can be used both as a gate insulator as well as the surface passivation layer [13]. The MISHFET approach also allows for application of high positive gate voltages to further increase the sheet carrier density in the 2-DEG channel and hence the device peak currents. These features make MISHFETs extremely promising for high power microwave applications. However, there are many milestones to be achieved and the work in this field is far from complete. Physics-based analytical modeling, which reflects the mechanism of device operation, is an essential requirement to fully explore the performance enhancements of MISHFET.

To characterize and optimize the device performance, an accurate charge control relation between 2-DEG sheet carrier density $n_s$ and the controlling gate voltage $V_{gs}$ is desirable. Various models...
have been proposed; some of these models take the approximation of Fermi energy level $E_F = 0$, which transforms into a linear dependence of $n$ on $V_{gs}$. But a linear $n - V_{gs}$ relation fails in the near threshold and deep saturation regions [14-17]. The region near threshold, where carrier density is quite low, is very important for circuit operation in VLSI circuit design and hence demands special attention. Till date, no analytical model considering the variation of sheet carrier density with gate voltage (valid from near threshold to high conduction region) for AlGaN/GaN MISHFET has been reported so far. In this work, we, for the first time, propose a nonlinear analytical model to characterize the dc and microwave performance of MISHFET structure with Si$_3$N$_4$ as gate dielectric on conventional AlGaN/GaN HFET structures. The new MISHFET exhibits high current levels and large gate voltage swing. The model provides good insight into the physical operation of device and aids in device structure optimization and performance evaluation. The proposed model includes $E_F$ as a function of $n_i$ by a simple polynomial in the $n_i - V_{gs}$ expression. Our model incorporates the highly dominant effect of spontaneous and piezoelectric polarization to accurately predict the 2-DEG sheet charge density at the AlGaN/GaN interface. The proposed analysis can also predict the performance of HFETs by adjusting few parameters. The results when compared with experimental data show excellent agreement. The effects of parasitic source drain resistances and velocity saturation have also been included to accurately develop the dc model. To generalize the model, the pulse-doped structure comprising the schottky cap layer, dopant layer, and spacer layer is employed. The model is extended to calculate small signal parameters, viz. transconductance and unity current gain cut-off frequency, so as to predict the microwave performance of device. The details of the proposed model are discussed in Section 2. The results in Section 3 show that insulated gate HFETs have higher drive currents and operating voltages than conventional HFETs, while still maintaining slightly higher cut-off frequency and thus are suitable for high power microwave applications. Finally, the conclusions are drawn in Section 4.

2. MODEL FORMULATION

The basic structure of an AlGaN/GaN MISHFET is shown in Figure 1. It consists of SiC substrate, an undoped GaN layer to form 2-DEG channel, an undoped AlGaN spacer layer of thickness $d_s$, a n-doped AlGaN layer of thickness $d_d$ to provide 2-DEG sheet carrier density, and an undoped schottky cap layer of thickness $d_c$. The gate insulator of thickness $t_{ins}$ and dielectric permittivity $\varepsilon_{ins}$ is deposited beneath the gate length $L$. The whole structure can be viewed as two separate isolated structures brought into contact, one is the metal-insulator-semiconductor and the other is the heterostructure. When the two regions are coupled, the depletion regions at both sides will overlap and interpenetrate before parallel conduction starts thus raising the potential ($\Delta$) at the interface of overlapped depletions and forming Region I and Region II as shown in conduction band diagram of Figure 2. The 2-DEG results from the transfer of free carriers from the undepleted region to the quantum well and is formed at AlGaN/GaN interface.

2.1. Analysis for Region I

In the band diagram, $y = 0$ represents the MIS contact and $y = d_c$ represents the heterojunction. Depletion due to MIS contact gives rise to depletion width, $w_{MIS}$ and overlapping of two regions give rise to potential, $\Delta$. The Poission equation in depletion Region I is

$$\frac{\partial^2 \psi_i}{\partial y^2} = -\frac{\rho}{\varepsilon_i \varepsilon_0}.$$  

The boundary conditions required to solve the Poisson’s equation are given as follows:

$$\psi_i = \phi_s, \quad \frac{\partial \psi_i}{\partial y} = -E_i \quad \text{at} \quad y = 0;$$

$$\frac{\partial \psi_i}{\partial y} = 0, \quad \psi_i = \Delta \quad \text{at} \quad y = w_{MIS},$$

where the effect of overlapping of two regions is considered in the boundary condition for $y = w_{MIS}$. $\phi_s$ and $E_i$ are the potential and electric field at the MIS interface, respectively, $\varepsilon_i (m)$ is the dielectric permittivity of high band gap semiconductor layer, and $\rho$ is the space charge density given by

$$\rho = q N(y) \quad \text{for} \quad y \geq w_{MIS};$$

$$= 0 \quad \text{for} \quad y < w_{MIS}.$$  

For pulsed dopant structure,

$$N(y) = 0 \quad \text{for} \quad 0 \leq y \leq d_d;$$

$$= N_d \quad \text{for} \quad d_d < y \leq d_d + d_c;$$

$$= 0 \quad \text{for} \quad d_d + d_c < y \leq d_c$$

in which $d_d = d_c + d_d$ is the channel depth and $N_d$ is the doping concentration of the dopant layer. Solving (1) leads to

![Figure 1](image1.png) Cross-sectional view of pulsed doped AlGaN/GaN MISHFET along with axes system

![Figure 2](image2.png) Conduction band profile of insulated gate AlGaN/GaN heterostructure SiC-based MISHFET along the y-axis

and from charge neutrality condition at the metal insulator semiconductor interface

$$\phi_s = V_{gs} - \phi_b(m) - V_{in}. \quad (6)$$

where $V_{gs}$ is the applied gate voltage, $\phi_b(m)$ is the schottky barrier height between bulk semiconductor and gate electrode (as given in Table 1) and $V_{in} = -q N_d t_a (w_{MIS} - d) n_i e_i$ is voltage across the insulator. Substituting value of $\phi_b(m)$ and $V_{in}$ in (6) and using (5) leads to

$$w_{\text{MIS}} = \frac{e_i t_a}{e_m} + \left( \sqrt{\left( \frac{e_i t_a}{e_m} \right)^2 + \frac{2 e_i t_a d_i}{e_m} d_i^2 - \frac{2 e_i e_m (\phi_b(m) - V_{gs} + \Delta)}{q N_d}} \right). \quad (7)$$

The free carrier density $n_{dh}$ due to barrier layer doping can thus be obtained as

$$n_{dh} = N_d (d_i + d_i - w_{\text{MIS}}). \quad (8)$$

These free carriers are transferred to the quantum well depending on the value of $\Delta$, i.e., the free carrier density will be equal to 2-DEG sheet carrier density before $\Delta = 0$. The rest of the free carriers will participate in conduction in high band gap semiconductor region (also called parasitic parallel conduction).

### TABLE 1 Parameters for the Al$_n$Ga$_{1-n}$N/GaN MISHFET Structure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$</td>
<td>Electronic charge</td>
<td>$1.6 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>$m_0$</td>
<td>Rest mass of electron</td>
<td>$9.1 \times 10^{-31}$ kg</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>Absolute permittivity</td>
<td>$8.85 \times 10^{-12}$ F/m</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Mobility</td>
<td>$800 \times 10^{-4}$ m$^2$/V·s$^{-1}$</td>
</tr>
<tr>
<td>$V_{sat}$</td>
<td>Saturation velocity</td>
<td>$9.9 \times 10^4$ m/sec</td>
</tr>
<tr>
<td>$k_1$</td>
<td>Subthreshold factor</td>
<td>$-0.1794$ V</td>
</tr>
<tr>
<td>$k_2$</td>
<td>Linear factor</td>
<td>$2.991 \times 10^{-5}$ m/V</td>
</tr>
<tr>
<td>$k_3$</td>
<td>Saturation factor</td>
<td>$-0.657 \times 10^{-8}$ V$^2$/m$^2$</td>
</tr>
<tr>
<td>$\varepsilon_{AlGaN}$</td>
<td>Permittivity of AlGaN layer</td>
<td>$9.375 \varepsilon_0$</td>
</tr>
<tr>
<td>$\varepsilon_{ins}$</td>
<td>Permittivity of insulator layer</td>
<td>$7.5 \varepsilon_0$</td>
</tr>
<tr>
<td>$\Delta E_f$</td>
<td>Conduction band discontinuity</td>
<td>$0.345$ V</td>
</tr>
<tr>
<td>$\phi_b(m)$</td>
<td>Barrier height</td>
<td>$0.725$ V</td>
</tr>
<tr>
<td>$a(0)$</td>
<td>Lattice constant at mole fraction 0</td>
<td>$3.881 \times 10^{-10}$ m</td>
</tr>
<tr>
<td>$e_{31}$</td>
<td>Piezoelectric constant</td>
<td>$-0.517$ C/m$^2$</td>
</tr>
<tr>
<td>$e_{33}$</td>
<td>Piezoelectric constant</td>
<td>$0.913$ C/m$^2$</td>
</tr>
<tr>
<td>$C_{11}$</td>
<td>Elastic constant</td>
<td>$104.25 \times 10^9$ Pa</td>
</tr>
<tr>
<td>$C_{33}$</td>
<td>Elastic constant</td>
<td>$397 \times 10^9$ Pa</td>
</tr>
<tr>
<td>$P_{sp}(m)$</td>
<td>Spontaneous polarization at mole fraction $m$</td>
<td>$-0.034$ C/m$^2$</td>
</tr>
<tr>
<td>$P_{sp}(0)$</td>
<td>Spontaneous polarization at mole fraction 0</td>
<td>$-0.292$ C/m$^2$</td>
</tr>
</tbody>
</table>

#### 2.2. Analysis for Region II

At equilibrium, relation between $\Delta$ and $V_{20}$ can be seen from Figure 2 as

$$\Delta + V_{20} = - (\Delta E_c - E_0), \quad (9)$$

where $\Delta E_c$ is the conduction band discontinuity and $E_0$ is the position of Fermi level with respect to the bottom of the conduction band in GaN.

$V_{20}$ is obtained by solving Poisson equation in the depletion Region II due to heterostructure and assuming the density of free carriers to be nonzero in the undepleted region (present after being depleted by the gate electrode), i.e., carriers obtained from Region I are given by

$$N(y) = 0 \quad \text{for} \quad d_i + d_i \leq y \leq d_i;$$

$$N(y) = N_d \quad \text{for} \quad w_{hi} \leq y \leq d_i + d_i, \quad (10)$$

in which $d_i - w_{hi}$ is the depletion width formed by transfer of carriers to the quantum well, i.e., due to the heterostructure. On solving the Poisson’s equation

$$\frac{\partial^2 \psi_2}{\partial y^2} = - \frac{\rho}{e_o \varepsilon_i}, \quad (11)$$

for depletion Region II using the following boundary conditions

$$\psi_2 = 0 \quad \text{at} \quad y = d_i;$$

$$\psi_2 = V_{20} + \Delta \quad \text{at} \quad y = d_i, \quad (12)$$

we get

$$V_{20} = -q N_d d_i^2 \frac{2 e_o \varepsilon_i}{e_m e_0} - q N_d d_i \frac{q N_d (w_{hi} - d_i) + q N_d (d_i^2 - w_{hi}^2)}{2 e_o \varepsilon_i}; \quad (13)$$

then from (9)

$$\Delta = q N_d d_i^2 \frac{2 e_o \varepsilon_i}{e_m e_0} + q N_d d_i \frac{q N_d (w_{hi} - d_i) - q N_d (d_i^2 - w_{hi}^2)}{2 e_o \varepsilon_i} - (\Delta E_c - E_0), \quad (14)$$

where the above equation is valid before parallel conduction starts; otherwise $\Delta = 0$. Before parallel conduction starts, all the undepleted charges left out from metal-insulator-semiconductor contact are transferred to the quantum well, and then $w_{\text{MIS}}$ and $w_{hi}$ are the same. Substituting the value of $\Delta$ in (7) for $w_{\text{MIS}} = w_{hi}$, we get

$$w_{\text{MIS}} = d_i + d_i + d_i^2/2 + e_i t_a d_i / e_m - e_i / e_m (V_{\text{eff}} - \phi_b(m) + \Delta E_c - E_0) / q N_d$$

$$d_i + \frac{e_i t_a}{e_m} \quad (15)$$

where $V_{\text{eff}} = V_{gs} - V(x)$ is the effective gate voltage and $V(x)$ is the channel potential at any point $x$ due to the drain voltage.
However, in AlGaN/GaN-based structures lattice mismatch between the AlGaN barrier layer and GaN epilayer leads to a very high spontaneous and piezoelectric polarization fields. As a result, a strong interface charge is induced even without intentionally doping the barrier layer. This polarization charge depends on aluminum mole fraction and the lattice and elastic constants of the materials and is given by

\[
n_{s\text{p}}(m) = \frac{\sigma_{q}(m)}{q},
\]

where \(\sigma_{q}(m)\) is the polarization induced sheet carrier density, given by [6]

\[
\sigma_{q}(m) = 2\left(\frac{a(0) - a(m)}{a(m)}\right)\left(e_{f}(m) - e_{f}(m)C_{33}(m)\right) + P_{sp}(0)
\]

\[
- P_{sp}(m),
\]

where \(a(m)\) is the lattice constant, \(e_{f}(m)\) and \(e_{f}(m)\) are piezoelectric constants, \(C_{33}(m)\) and \(C_{33}(m)\) are elastic constants, and \(P_{sp}(m)\) is the spontaneous polarization. All these mole fraction-dependent parameters are calculated and given in Table 1.

Combining Eqs. (16) and (17), the total sheet carrier density \(n_{s}\) can be written as

\[
n_{s}(x) = \frac{e_{f}e_{s}}{q\left(d_{s} + \frac{e_{f}e_{m}}{e_{m}}\right)}[V_{\text{geo}} - V_{th} - E_{i}],
\]

where \(V_{th}\) is the threshold voltage and is defined as the gate voltage at which free carriers are zero. It is obtained as

\[
V_{th} = \phi_{b}(m) - \Delta E_{c} - \frac{q N_{d}d_{s}}{2e_{f}e_{s}}\left[1 + \frac{2d_{i}}{d_{i} + \frac{e_{f}e_{m}}{e_{m}}}\right] + \frac{\sigma_{q}(m)}{e_{f}e_{s}}\left[1 + \frac{e_{f}e_{m}}{e_{m}}\right] + k_{t},
\]

\[
E_{i},
\]

in (19) is related to \(n_{s}\) and considering only the first two sub-bands \(E_{0}\) and \(E_{i}\) in the GaN conduction band, it is given by [18]

\[
n_{s}(x) = D V_{th} \ln \left[1 + \exp \left(\frac{(E_{i} - E_{0})}{V_{i}}\right)\right] \left[1 + \exp \left(\frac{(E_{i} - E_{f})}{V_{i}}\right)\right],
\]

where \(V_{th} = kT q / q\) is the thermal voltage and \(D\) is the density of states in the 2-DEG in the triangular well. To obtain \(n_{s}(x)\) in terms of \(V_{\text{geo}}\), (19) and (20) are solved simultaneously through numerical techniques. Though the assumption of linear approximation of \(E_{i} V_{n} n_{s}\) and \(E_{i} = 0\) lead to simple expressions for \(n_{s}(x)\), the results are valid for a very small range of device operation. In our model, we represent \(E_{i}\) as a nonlinear function of \(n_{s}(x)\) by the simple polynomial:

\[
E_{i} = k_{1} + k_{2} n_{s}(x) + k_{3} n_{s}(x).
\]

The values of \(k_{1}, k_{2}\), and \(k_{3}\) (given in Table 1) were obtained using the effective mass of electron (=0.22m_{e}) [6] for AlGaN/GaN system following the same approach as proposed by Dasgupta et al. [19]. It can be noted here that (16) can be used for calculating the sheet carrier density of HFETs by simply substituting \(t_{m} = 0\).

2.3. Drain Current Model

When the gate voltage exceeds a certain level (i.e., the threshold voltage), the channel is formed and contributes to conduction mechanism in the device. The expression for drain current in the channel is obtained from the following equation:

\[
I_{d}(x) = q w_{n}(x) v(x),
\]

where \(q\) is charge of an electron, \(w\) is gate width, and \(v(x)\) is the carrier velocity.

The velocity field relation is as follows:

\[
\nu(x) = \frac{\mu E(x)}{1 + \frac{E(x)}{E_{c}}}
\]

\[
= \nu_{sat}\text{ for } E > E_{c},
\]

where \(\mu\) is mobility of electron, \(E(x) = \frac{\partial V(x)}{\partial x}\) is the electric field at any point \(x\) in the channel, \(E_{c} = \frac{\nu_{sat}}{\mu}\) is critical field due to velocity saturation, and \(\nu_{sat}\) is the saturation velocity.

2.3.1. Linear Regime

For lower drain voltages, average electron velocity is less than saturation velocity \(\nu_{sat}\). Thus, substituting (24a) and (19) in (23), drain current in the linear region is expressed as

\[
I_{dL}(x) = q w_{n}(x) \frac{\mu E(x)}{1 + \frac{E(x)}{E_{c}}}
\]

Integrating (25) from the source \(x = 0\) to the drain side \(x = L\), the drain current in the linear region is obtained as

\[
I_{dL} = \frac{q^{2} \left(\frac{d_{i} + \frac{e_{f}e_{m}}{e_{m}}}{e_{m}}\right)^{2} \mu w}{16 e_{f}e_{s} \left(\frac{d_{i} + \frac{e_{f}e_{m}}{e_{m}}}{e_{m}} + e_{f}k_{i}\right)}
\]

\[
\times \left(\frac{f(y_{g}) - f(y_{g})}{L + \frac{\mu (V_{in} - I_{bd} R_{g} + R_{b})}{\nu_{sat}}}ight)
\]

}\]
where

\[ f(y) = \left( \frac{e_0 e_k k_2}{d + e_i t_m} \right)^2 + \frac{y^2}{2} - \frac{4 e_0 e_k k_2 y^{12}}{3 q \left( d + e_i t_m \right)^2}, \]

\[ y_1 = \left( \frac{e_0 e_k k_2}{q(d e_m + e_i t_m)} \right)^2 + \frac{e_0 e_k e_m}{q(d e_m + e_i t_m)} \left( 1 + \frac{e_0 e_k e_k^3}{q(d e_m + e_i t_m)} \right) \times (V_{g_s} - V_{in} - I_g R_d), \]

\[ y_0 = \left( \frac{e_0 e_k k_2}{q(d e_m + e_i t_m)} \right)^2 + \frac{e_0 e_k e_m}{q(d e_m + e_i t_m)} \left( 1 + \frac{e_0 e_k e_k^3}{q(d e_m + e_i t_m)} \right) \times (V_{g_s} - V_{in} - I_g R_d), \]

2.3.2. Saturation Regime

At the drain end of channel, the velocity becomes saturated at \( V_{dsat} \), then from (24b) and (19), we obtain the expression for drain saturation current as

\[ I_{dsat} = \frac{q w V_{sat}}{4 \left( 1 + \frac{e_0 e_k k_2}{q(d e_m + e_i t_m)} \right)^2 + y_{sat} - \frac{e_0 e_k k_2}{q(d e_m + e_i t_m)} \times (V_{g_s} - V_{in} - I_{dsat} - I_g R_d)}, \]

where

\[ y_{sat} = \left( \frac{e_0 e_k k_2}{q(d e_m + e_i t_m)} \right)^2 + \frac{e_0 e_k e_m}{q(d e_m + e_i t_m)} \left( 1 + \frac{e_0 e_k e_k^3}{q(d e_m + e_i t_m)} \right) \times (V_{g_s} - V_{in} - I_{dsat} - I_g R_d), \]

in which \( V_{dsat} \) is calculated numerically by equating (27) and (26) at \( V_{dsat} = V_{dsat} \) following the principle of current continuity.

2.4. Transconductance

For the optimization of FETs in high frequency applications, the transconductance \( g_m \) plays a significant role. It is one of the most important indicators of device quality for microwave applications and is evaluated as

\[ g_m = \frac{\partial I_m}{\partial V_m} \Big|_{V_m = \text{const}}. \]

2.4.1. Linear Regime

Differentiating (26) with respect to gate source voltage, the transconductance in linear region is obtained as

\[ g_m = \frac{-\mu w}{16 \frac{e_0 e_k e_m}{q(d e_m + e_i t_m)} \left( 1 + \frac{e_0 e_k e_k^3}{q(d e_m + e_i t_m)} \right) \left( L + \frac{\mu(V_{in} - I_g R_d)}{V_{sat}} \right) \times \left[ \frac{\partial f(y_1)}{\partial V_{g_s}} - \frac{\partial f(y_0)}{\partial V_{g_s}} \right] + \frac{\mu g_m(R_d + I_g R_d)(f(y_1) - f(y_0))}{V_{sat}} \right] \times \left[ \frac{1}{L + \frac{\mu(V_{in} - I_g R_d)}{V_{sat}}} \right], \]

where

\[ \frac{\partial f(y_1)}{\partial V_{g_s}} - \frac{\partial f(y_0)}{\partial V_{g_s}} + \frac{e_0 e_k e_m}{q(d e_m + e_i t_m)} \left( 1 + \frac{e_0 e_k e_k^3}{q(d e_m + e_i t_m)} \right) \times (V_{g_s} - V_{in} - I_g R_d), \]

\[ \frac{\partial f(y_0)}{\partial V_{g_s}} = \frac{4 e_0 e_k e_m}{q(d e_m + e_i t_m)} \left( 1 + \frac{e_0 e_k e_k^3}{q(d e_m + e_i t_m)} \right) \times (V_{g_s} - V_{in} - I_g R_d). \]

2.4.2. Saturation Regime

Differentiating (27) with respect to gate source voltage, the transconductance in saturation region is obtained as

\[ g_m(sat) = \frac{q w V_{sat} e_0 e_k e_m}{(d e_m + e_i t_m + e_0 e_k e_k^3) V_{sat}} \left[ 1 - \frac{e_0 e_k e_k^2}{q(d e_m + e_i t_m) \sqrt{V_{sat}}} \right] \left( 1 - g_m(sat) R_d \right). \]

2.5. Cut-Off Frequency

The cut-off frequency \( f_t \) is an indicator of device’s high frequency performance, and it determines the ultimate switching speed of the device. It is given as the ratio of transconductance \( g_m \) to the total gate capacitance \( C_{gt} \), i.e.,

\[ f_t = \frac{g_m}{2 \pi C_{gt}}. \]

and is written by substituting the value of \( g_m \) from (28) and \( C_{gt} \), the total gate capacitance, is calculated by the parallel combination of insulator capacitance \( C_{in} \) and bulk capacitance \( C_b \) as follows:

\[ C_{gt} = \frac{C_{in} C_b}{C_{in} + C_b}, \]

where \( C_b = \frac{e_0 e_m w L}{d i_m} \), \( C_m = \frac{e_0 e_m w L}{d i_m} \), and \( wL \) denotes the effective area under the gate. Under the normal operating conditions, the depletion region under the gate extends throughout the barrier layer keeping gate capacitance constant over most of the operating region except in the near threshold regime and the 2-DEG is controlled completely by the gate bias [20].

3. RESULTS AND DISCUSSION

An analytical model has been presented to evaluate the dc current voltage characteristics and small signal microwave parameters of AlGaN/GaN MISHFET. The behavior of device in terms of sheet carrier density, transconductance, and unity current gain cut-off frequency is also studied to assess the microwave performance. The parameters used for the study are listed in Table 1. To explore the performance enhancements of MISHFET and to prove the validity of the proposed model, the results are compared with conventional HFET structures and experimental data respectively.

Figure 3 shows the variation of sheet carrier density with gate voltage for MISHFET in comparison to HFET structures. Though the maximum sheet carrier density increases slightly, a noticeable large gate voltage swing is observed with the introduction of insulator. The slope of \( n_c - V_{gs} \) curve corresponds to the capacitance of the structure, which is directly related to the separation between
the gate and the 2-DEG, i.e., the thickness of AlGaN layer. As the AlGaN layer thickness increases, the slope of $n_s-V_{gs}$ curve beyond threshold decreases. Thus, a higher value of AlGaN layer thickness is desirable to achieve high value of 2-DEG density and lower values of gate capacitance. However, the parallel conduction in dopant layer imposes an upper limit on AlGaN layer thickness, but with the introduction of dielectric under the gate region, the slope decreases for constant value of barrier layer thickness. Curves show excellent agreement with published data [21]. Figure 4 shows the dependence of $n_s$ on Al mole fraction for different values of dopant layer thickness, as given by (19). Sheet carrier density for MISHFETs is clearly larger than conventional HFETs for a particular value of aluminum mole fraction and dopant layer thickness. In our calculations, threshold voltage does not involve any fitting parameters and is directly obtained from (20). Figure 5 shows the dependence of threshold voltage on dopant layer thickness for two different Al mole fractions. As predicted, higher values of threshold voltage are obtained for MISHFETs. The negative enhancement observed in $V_{th}$ for higher mole fractions is due to the fact that higher negative voltage is required to deplete a higher density of electrons located at a larger effective distance from gate. An increase in Al mole fraction also leads to decrease in threshold voltage due to corresponding increase in polarization induced sheet carrier density. This variation in sheet carrier density can be used to improve device performance for different set of geometrical parameters. Comparison with experimental results [22] confirms the validity of the proposed model.

Figure 6 shows the $I_{ds}-V_{ds}$ characteristics of Al0.25Ga0.75N/GaN MISHFET and HFET. $V_{gs} = +2$ to $-2V$. Gate width is 100 $\mu$m.
is clear from the figure that for same values of gate and drain bias, the drain current is higher for MISHFETs than their conventional counterparts. The MISHFETs show remarkable 36% increase in drain saturation current.

The variation of drain current with gate bias is depicted in Figure 7 over a wide range of gate bias for $0.25 \mu m \text{Si}_3\text{N}_4/\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ MISHFET and HFET. The results of proposed model fit reasonably well with experimental data in all regions of operation [23]. Because of a voltage drop at the Si$_3$N$_4$ gate insulator, the threshold voltage of the MISHFET shifts to $-7$ V as compared to $-4.5$ V of HFET. This shift is apparent in the form of large gate voltage swing for the MISHFET structures.

Figure 8 shows transconductance $g_m$ as a function of gate source voltage $V_{gs}$. The maximum transconductance $g_{m\text{max}}$ of MISHFET and HFET obtained are 190 and 240 mS/mm, respectively. Although the MISHFET have lower transconductance in comparison to HFET, they have almost constant variation of transconductance for wide range of gate source voltages, which makes it useful for high performance amplifications.

Figure 9 shows the gate bias dependencies of drain saturation current $I_{dsat}$ and drain saturation voltage $V_{dsat}$. As predicted, the drain bias required to saturate the channel increases with the introduction of insulator beneath the gate. The dc saturation drain current, which is a key parameter for controlling maximum output RF power, is also larger in MISHFETs than in HFETs. In devices with long gate, the drain saturation current depends on electron mobility, but in short gate length devices, the electron velocity under the gate saturates, which limits the maximum current. The forward gate current, which increases exponentially as a function of gate bias, plays significant role in limiting the channel current at high positive gate biases in HFETs. To limit the gate leakage current, HFET devices generally operate at gate voltages ranging between threshold voltage and values slightly above zero, but the MISHFET structures do not have the gate current limitation as is clearly shown by substantially larger values of $I_{dsat}$. Currents greater than 1 A/mm can be obtained from sub-micron gate MISHFET device, which makes them extremely attractive for high power microwave applications.

4. CONCLUSION

The device performance of AlGaN/GaN-based MISHFETs has been investigated. The proposed analysis can easily be used to predict the characteristics of HFETs as well. The MISHFET struc-
Figure 10 Variation of saturation drain voltage and saturation drain current with gate source voltage for MISHFET and HFET structures

ture shows clearly an advantage over their HFET counterparts in terms of gate voltage swing, higher saturation currents, and operating voltages, while still maintaining slightly higher cut-off frequency. With a quarter micron gate, it is found that drain saturation current and gate voltage swing of nitride-based MISHFET are 1.36 A/mm and 9 V in comparison to 1 A/mm and 6.5 V of HFETs, respectively. The developed model shows good qualitative and quantitative agreement with experimental data. This model provides a valuable tool for design, optimization, and performance prediction of microwave power devices and demonstrates clear superiority of MISHFETs over HFETs.

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REFERENCES


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