MISHEMT’s multiple conduction channels influence on its DC parameters

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Abstract — The Si₃N₄/AlGaN/AlN/GaN Metal-Insulator-Semiconductor High Electron Mobility Transistor (MISHEMT) analog performance was ascertained considering the device’s multiple channels. MISHEMTs with different gate lengths, source/drain electrodes depths, source/drain distances to the gate electrode and AlGaN aluminum molar fractions were analyzed. The total drain current has 3 different components, where one of them is related to MOS conduction and the other two are related to HEMT conduction. Due to their different transport mechanism and distance to the gate electrode, each channel conduction exhibits different threshold voltages, causing unusual transfer and output characteristics, such as transconductance multiple slopes and a steady output resistance. As a result, the MISHEMTs presents an unexpected increase in intrinsic voltage gain (Av) for high gate bias (strong conduction). The HEMT conduction and the conduction through all the AlGaN volume are responsible for sustaining drain current levels so high that it affects the Early voltage more strongly than the degradation of output conductance, ensuring a high Av values.

Keywords—MISHEMT, AlGaN, AlN, GaN, Multiple Channel, Analog Parameters, Intrinsic Voltage Gain.

1 INTRODUCTION

Silicon-based Metal-Oxide-Semiconductor Field Effect Transistors (MOSFET) evolution came across several technology limitations that are intrinsic to silicon material [1] and to MOSFET’s carrier transport mechanisms. These limitations are related to the reduction of physical dimensions, power consumption and operating speed. In order to overcome these limitations, approaches such as transistor’s structure and geometry innovation (e.g., heterostructure), and the use of material systems with different properties (e.g., III-V materials) [2] were taken.

Due to their wide bandgap, nitrides-III, among others III-V materials, have drawn attention because of their ability to withstand high magnitude electric fields, their capability to offer very high output power in power amplifiers, and operating temperatures higher than the silicon’s [3, 4]. A heterostructure of gallium based nitrides, i.e., the junction of at least two III-V semiconductors, gives rise to an internal polarization, result from the sum of spontaneous and piezoelectric polarizations [5]. The internal polarization in a heterostructure is responsible for originating at its interface a region whose conduction band energy is lower than the Fermi level, giving rise to a quantum well that traps electrons. This quantum well is called two-dimensional electron gas (2DEG), which has high carrier mobility due to the physical separation of the electrons from their original atoms [5, 6].

The High Electron Mobility Transistor (HEMT) is an III-V material heterostructure based transistor, which, together with the MOSFET, are predecessors of the Metal-Insulator-Semiconductor High Electron Mobility Transistor (MISHEMT). One of the HEMT’s main problems is the gate current leakage. In that regard, by adding a layer of gate insulator, the MISHEMT was able to offer a reduction of the gate current leakage current by three orders of magnitude [7, 8].

Since the MISHEMT is the union of HEMT and MOSFET, most of its properties are the combination of the properties of both MOSFET and HEMT devices, and so are its driving mechanisms. In a MOSFET, the electric current flows through the carrier accumulation layer (for depletion mode MOSFETs) or inversion layer (for inversion mode MOSFETs), while in a HEMT it flows through the 2DEG. On a MISHEMT with spacer layer, three current channels are formed, one at the interface between the gate insulator and the barrier layer (1st interface), one near the interface between barrier layer and spacer layer (2nd interface), and one at the interface between spacer layer and buffer layer (3rd interface). The channel at the 1st interface is an accumulation of electrons due to field effect from MIS structure, and the channels at 2nd and 3rd interfaces are 2DEGs formed by internal polarizations [9]. As an extension of [10], the goal of the current work is to investigate how each one of these channels affects the performance in the electrical behavior of the MISHEMT, focusing mainly on DC parameters. For this analysis, it will be evaluated the influence of the variation of the depth of source/drain electrodes (dSDL), the distance between gate and source/drain electrodes (LGS & LGD, with LGD = L0S and the aluminum molar fraction on AlGaN (x) on the transfer characteristics, and the influence of different gate biasing and gate length (Lg) on the DC analog parameters: Early voltage (VESA), output conductance (gD) and intrinsic voltage gain (Av).

II DEVICE CHARACTERISTICS

The simulated MISHEMTs have an AlGaN/AlN/GaN heterostructure with a Si₃N₄ gate dielectric of 2 nm and a gate width (W) of 1µm. Figure 1 shows the general simulated device, in which variable dimensions (dSDL, LGS & LGD and Lg) are represented by their symbols. Two different gate lengths were simulated: 400 nm and 200 nm.

Accounted variables were the source/drain electrodes depth, which varied between 20 nm, where they reach the AlN spacer layer, and 21 nm, where they reach the GaN buffer layer, the distance between source & drain electrodes and gate electrode (LGS & LGD), which varied between 50 nm and 800 nm, and the AlGaN aluminum molar fraction (x), which was varied between 0.25, 0.30 and 0.35. Also, when the channel length was the focus, the source/drain electrodes
depth were kept constant at $d_{SD} = 21$ nm, the distance between gate and source/drain electrodes were maintained constant at $L_{GS} & L_{GD} = 50$ nm, and the AlGaN aluminum molar fraction of 0.25.

The simulation was carried out on Atlas from Silvaco with Fermi-Dirac model for carrier statistics, Schokley-Read-Hall (SRH) model for recombination process, Lattice. Temperature model for heat transfer, Polarization + Calc. Strain models for internal polarization in gallium nitrides, Fmct.n for the low-field mobility in gallium nitrides depending on temperature and on the aluminum concentration (x) in Al$_x$Ga$_{1-x}$N, and GaNsat model for high-field mobility in gallium nitrides depending on temperature and electric field [11].

III RESULTS AND ANALYSIS

The electron concentration in the center of AlGaN/AlN/GaN MISHEMT’s is presented by Figure 2, from which one can observe that, for sufficiently gate bias ($V_{GS} = 0$ V), there is the formation of 3 conduction channels, one located at the 1st interface, between the gate insulator and the barrier layer (Si$_3$N$_4$/AlGaN), one near the 2nd interface, between the barrier and spacer layers (AlGaN/AlN), and one at the 3rd interface, between the spacer and buffer layers (AlN/GaN).

Since the electron concentration in the middle of the AlGaN layer is numerous, there is conduction through all AlGaN depth, even though the 1st and 2nd interfaces channels are 10 nm distant from each other.

Figure 3 shows the transfer curves for a low drain bias ($V_D = 50$ mV) of devices with $L_g = 400$ nm for different drain/source electrode depths and different gate to source/drain distances, while Figure 4 presents the transconductance ($g_{m}$) curves of these simulations. For a short distance between the gate to source/drain electrodes ($L_{GS} & L_{GD} = 50$ nm), the contribution to the drain current ($I_{DS})$ coming from the 1st interface is high, and for $L_{GS} & L_{GD} = 800$ nm this contribution is reduced, due to the high series resistance. Having low contribution of the MOS channel at the 1st interface means that the conduction will happen preferably through the 2nd and 3rd interfaces 2DEGs, which causes a plateau in $I_{DS} \times V_{GS}$ curves and reduces $d_{IDS}$ level. This effect can be observed comparing Figure 1’s 3A with 3B and 3C with 3D.

When analyzing the role of source/drain electrodes depth ($d_{SD}$) on conduction, different current components must be considered. For $d_{SD} = 20$ nm the source/drain electrodes do not reach GaN layer, so the drain current can only flow through the AlGaN layer, that means that the drain current is composed by MOS channel (1st interface), by AlGaN HEMT (2DEG) channel (2nd interface) and by the conduction throughout the depth of AlGaN layer. A deeper contact ($d_{SD} = 21$ nm) also adds the GaN HEMT (2DEG) channel (3rd interface) to conduction, substantially increasing the total drain current.

Multiple slopes can be seen on the transconductance curves from Figure 4, corroborating conduction through multiple channels. When $d_{SD} = 20$ nm and $L_{GS} & L_{GD} = 800$ nm (conduction through only the AlGaN layer, not including the 1st interface) it is possible to observe that the second interface 2DEG is activated for a $V_{GS}$ near to -2.5 V, while for
d_{SD} = 50 nm and L_{GS} & L_{GD} = 50 nm (same condition but including conduction through the 1st interface), the second g_m peak, related to MOS channel activation, is near to -1 V. The drain current is strongly reduced with L_{GS} & L_{GD} increment due to the high series resistance, mainly due to the attenuation of the MOS conduction. When d_{SD} = 21 nm the conduction through third interface is added to the total current. Since a strong 2DEG is formed due to the difference between AlN and GaN bandgaps combined with the distance between this 2DEG and the gate electrode, the activation voltage to this interface is more negative (V_{GS} ≈ -4 V) and the g_m growth starts earlier. In this case, L_{GS} & L_{GD} influence on g_m follows the same trend described for d_{SD} = 20 nm.

![Transconductance curves of AlGaN/AlN/GaN MISHEMTs with different distances between source & drain electrodes and the gate electrode and different source & drain electrodes depth.](image)

Note that the V_{GS} required to enable or disable each interface does not change between the different devices, so it is possible to conclude that each interface has its own threshold voltage (Vt) which are not influenced by d_{SD} or L_{GS} & L_{GD}.

As the 2DEG is created by the materials and heterostructure properties, changing the aluminum molar fraction on AlₓGa_{1-x}N (x) will affect the 2DEGs. The closer x is to unit, the more like AlN the AlGaN becomes, and the closer it is to zero the more it resembles GaN. The AlN has a larger bandgap than GaN, in addition to being more resistive and insulating. Figure 5 presents the electron concentration of the center region of the MISHEMT for different values of x.

For increasing x, it can be observed an increase on both 2DEGs electron concentrations due to an increase on the heterostructure bandgap mismatch, and a slightly decrease on the electron concentration at the 1st interface due to a reduction on the total number of electrons in the AlGaN. The total number of electrons in AlGaN and GaN layers for different x (Table I) were extracted by integrating the electron concentration regarding each layer depths and the device width of 1 µm.

Even though the 2nd interface 2DEG electron concentration increases for increasing x, more than half of the barrier layer shows a decreasing electron concentration, therefore, the total number of electrons in AlGaN shows a slight reduction.

![Electron concentration at the vertical center line of the studied MISHEMT for different AlGaN aluminum molar fraction.](image)

![Dependence of the number of electrons on the AlGaN barrier layer and on the GaN buffer layer.](image)

Table I. Total number of electrons on the AlGaN barrier layer and on the GaN buffer layer.

<table>
<thead>
<tr>
<th>x</th>
<th>Number of electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AlGaN</td>
</tr>
<tr>
<td>0.25</td>
<td>1.66 (10^{17})</td>
</tr>
<tr>
<td>0.30</td>
<td>1.62 (10^{17})</td>
</tr>
<tr>
<td>0.35</td>
<td>1.55 (10^{17})</td>
</tr>
</tbody>
</table>

Depending on the source and drain electrodes depth, they will have access to the GaN or not. The transfer curves and g_m for both d_{SD} cases with different x is shown by Figure 6.

![Transfer curves and transconductance for MISHEMTs with short L_{GS} & L_{GD}, 3 values of aluminum molar fraction and with (A & B) source/drain electrodes reaching AlN layer and (C & D) source/drain electrodes reaching GaN layer.](image)

When the source and drain electrodes reach the AlN layer (d_{SD} = 20 nm), the current decreases for increasing x, and when the electrodes reach the GaN layer (d_{SD} = 21 nm), I_{DS} increases for increasing x, due to the total number of electrons in each layer. Also, for both cases of d_{SD}, increasing the
aluminum molar fraction strongly influences $g_m$ peak at $V_{GS} = -1$ V (related to 1st interface channel), attenuating the MOS conduction.

Since for a higher $x$ the internal polarization becomes stronger, the 3rd interface’s 2DEG carriers’ depletion turns more difficult, that is why the threshold voltage of the device with $d_{SD} = 21$ nm becomes more negative.

Finally, the investigation of the MISHEMT’s analog performance was done by the analysis of its output characteristics. For this matter, two devices were chosen based on the criteria of having conduction through all the 3 channels. Both devices have $L_{GS} & L_{GD} = 50$ nm to include the 1st interface channel, $x = 0.25$ to have a considerable 2nd interface 2DEG electron concentration, and $d_{SD} = 21$ nm to include the 3rd interface 2DEG on conduction. The devices differ on the gate length: the reference one with $L_g = 400$ nm and other with $L_g = 200$ nm. Figure 7 shows the input characteristics of both devices.

![Figure 7. Input characteristics of MISHEMTs with different gate lengths.](image)

One can observe from Figure 7 that a smaller channel length presents a higher drain current level, however, while the channel length is reduced by half, the increase on $I_{DS}$ does not double, since MISHEMT devices have HEMT channels created by internal polarizations and a channel created by field effect from MIS structure.

Knowing that each channel have its own threshold voltage, the $I_{DS}$ on the output curves will account only enabled channels for a certain $V_{GS}$. The chosen gate biases were $V_{GS} = -3.5$ V, because it prioritizes the conduction through the 3rd interface, $V_{GS} = -2.0$ V which includes the conduction through the 2nd interface, and $V_{GS} = -0.5$ V when MOS conduction (through the 1st interface) is also taken into account.

The $I_{DS}$ as a function of $V_{DS}$ curves for both devices under the chosen $V_{GS}$ are presented by Figure 8, from which it is possible to notice that the drain current increases with the channel length reduction and the increment of gate bias. To better understand the influence of each channel conduction (strongly dependent on $V_{GS}$) on output behavior and visualize their status under each bias condition, the electron concentration profile can be analyzed in Figure 9.

![Figure 8. Output characteristics of AlGaN/AlN/GaN MISHEMT with different $L_g$ and under different gate biasing conditions.](image)

Figure 9 brings the electron concentration profiles of the MISHEMTs with $L_g = 200$ nm under different gate bias and for 2 different drain voltages ($V_{DS} = 0.2$ V and $V_{DS} = 4.0$ V).

From Figure 9, one can observe that, for $V_{GS} = 0.2$ V there is no saturation effects taking place, and $V_{GS}$ acts enabling or disabling the different channels. Whenever a channel is enabled, an increase on $I_{DS}$ is observed. Increasing $V_{DS}$ to 4.0 V, Figure 8 shows that the device is under saturation regime, and the channels start to show saturation effects: for $V_{GS} = -3.5$ V only the 3rd interface 2DEG is enabled and is interrupted near its drain end, similar to a MOSFET; for $V_{GS} = -2.0$ V the 3rd interface 2DEG does not show saturation effects, while the 2nd interface 2DEG shows a narrowing of its thickness throughout the gate range; and for $V_{GS} = -0.5$ V, besides both...
Table II. Analog parameters results and calculations for MISHEMTs with different Lg and under different biasing conditions.

<table>
<thead>
<tr>
<th>Lg (nm)</th>
<th>VGS (V)</th>
<th>gns (mS)</th>
<th>gD (µS)</th>
<th>VEA (V)</th>
<th>Av (dB)</th>
</tr>
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<tr>
<td>200</td>
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<td>20.3</td>
<td>6.8</td>
<td>30.7</td>
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<tr>
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<td>46.5</td>
<td>29.3</td>
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<tr>
<td></td>
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<td>21.4</td>
<td>138.4</td>
<td>34.9</td>
</tr>
<tr>
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<td>0.41</td>
<td>4.2</td>
<td>17.8</td>
<td>39.7</td>
</tr>
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<td>0.73</td>
<td>16.6</td>
<td>62.5</td>
<td>32.9</td>
</tr>
<tr>
<td></td>
<td>-0.5</td>
<td>1.07</td>
<td>18.4</td>
<td>122.4</td>
<td>35.3</td>
</tr>
<tr>
<td>400</td>
<td>-3.5</td>
<td>0.70</td>
<td>20.3</td>
<td>6.8</td>
<td>30.7</td>
</tr>
<tr>
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<td>-2.0</td>
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<td>1.07</td>
<td>18.4</td>
<td>122.4</td>
<td>35.3</td>
</tr>
</tbody>
</table>

When VGS = -3.5 V is applied, the 3rd interface’s 2DEG is barely accumulated and suffers from channel-length modulation like effect, as seen on Figure 9, that is why IDS is low, which makes VEA to be low. When decreasing Lg from 400 nm to 200 nm, this effect degrades gD more severely, which makes VEA and Av to decrease even more. Changing VGS to -2 V, although gD is worse than for VGS = -3.5 V, a higher VEA is reached due to higher current level, but it is not enough to improve Av, that is still decreasing due to be in strong conduction.

Similarly, for VGS = -0.5 V, from Lg = 400 nm to Lg = 200 nm there is an increase in IDS and gns, however, for this gate bias, the gD degradation is less important since the second and third interfaces are strongly accumulated and saturation effects are noticed only in the first interface. When VEA is evaluated, the predominant factor is the higher current level that results in higher VEA for both channel lengths. Although for VGS = -0.5 V the device is more deeply in strong accumulation, the high IDS and VEA values makes that the Av goes up again.

### IV Conclusions

In this work, the channels in the different interfaces of AlGaN/AIN/GaN MISHEMT were evaluated in regard to their formation, position and influence on the device’s analog behavior.

The studied MISHEMTs have 3 conduction components, coming from one MOS channel formed by field effect and two HEMT channels formed by internal polarization. Due to the nature and position of each channel, they have their own threshold voltage. Lastly, the electron concentration in the barrier and buffer layers are affected in opposite ways by the barrier layer material composition. As smaller is the Al concentration on barrier layer, higher is the effective threshold voltage, tending to become normally off device.

In ascending order of gate bias, the 3rd interface is the first channel to be enabled, while the 1st interface is the last one. This means that, when the first interface channel is activated, a strong carrier accumulation is observed on the entire barrier layer, and the 3rd and 2nd interfaces 2DEGs are in their full formation. Consequently, if a high drain voltage is applied, even if the 1st interface begins to suffer from channel-length modulation, the 3rd and 2nd interfaces channels are barely affected by high VDS and are able to sustain higher drain currents without suffering from saturation nor reducing their output resistances. These factors make the MISHEMT to show a new increase on the intrinsic voltage gain for more positive gate voltages (deeply strong inversion), instead of lowering it.

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**References**


