Characterization of Enhancement AlInN/GaN Hemts using Partial P-Type GaN Gate

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Abstract. This work attempts to characterize the Enhancement mode (E-mode) AlInN/GaN HEMT devices implemented using p-GaN gate for getting positive threshold voltage (VT). The device channel consists of a lattice-matched wideband Al0.83In0.17N and narrowband GaN layers, along with p-GaN layer below the E-mode device. The 2D Sentaurus TCAD simulation is done using the hydrodynamic model. The simulation model is calibrated with the initially published experimental result. A comprehensive, quantitative investigation of transfer characteristics, transconductance, gate capacitance, gate leakage and RF gain for E-mode devices is done. The E-mode device exhibit a VT of + 1.0 V. This new device exhibit almost similar transconductance characteristics. The E-mode device shows lower off-state leakage current, higher ION/IOFF ratio and lower SS. These results demonstrate the feasibility for fabricating an E-mode AlInN/GaN HEMT device which is extremely desirable for high speed and high-frequency applications.

Keywords: Enhancement mode (E-mode), HEMT, p-GaN, AlInN/GaN

I. INTRODUCTION

The AlInN/GaN heterostructures is based on High Electron Mobility Transistors (HEMTs) and metal oxide semiconductor HEMTs (MOS-HEMTs) [1-4]. By virtue of lattice matching in the AlInN/GaN structure, the devices show better performance than conventional AlGaN/ GaN heterostructure devices. AlInN/GaN devices offer higher spontaneous polarization induced two-dimensional electron gas (2DEG) density [5], higher drain current, stress-free structure with enhanced reliability, and higher thermal and chemical stability [3]. AlInN with Al composition of about 0.83 is nearly lattice-matched to GaN. The lattice matched AlInN/GaN devices have exhibited very high electron mobility (1200 to 2000 cm²/Vs) and high 2DEG sheet carrier densities (3.2x10¹¹cm⁻²) [7,8]. Considering the immense potential of AlInN/GaN heterostructure it has used in the current work. It’s reported a new approach in fabricating E-mode AlGaN/GaN HEMTs based on fluoride-based plasma treatment of the gate region in AlGaN/GaN HEMTs and post-gate rapid thermal annealing [9]. Masahito presented details of E-mode GaN MIS-HEMT device showing high drain current and complete enhancement-mode operation [10]. Fabrication of E-mode GaN/AlGaN HEMTs on SiC substrates achieved with high threshold voltage through the combination of low-damage and controllable dry gate-recessing and the annealing of the Ni/Au gates [11]. InP-based InAlAs/InGaAs E-mode HEMT’s using non alloyed ohmic contacts and Pt-based buried-gate technologies, to reduce the source resistance (RS) [12]. A low RN and high-breakdown-voltage E-mode AlGaN/AlN/GaN HEMT was fabricated [13]. Although there are many reported E-mode devices, the AlInN/GaN based e-mode device using p-GaN gate not yet explored. Thus, we have done the characterization of E-mode AlInN/GaN HEMT device implemented using p-GaN gate.

A lot of work has already been done in AlInN/GaN based HEMTs and MOS-HEMT devices, but it mostly focus on depletion mode devices [13]. As these devices are having negative threshold voltage (VT), their deployments in digital switching applications is limited despite of having high speed switching characteristics even at very low device dimensions [11,12,13]. The E-mode AlInN/GaN may prove to be excellent device for high speed digital applications. Therefore, the analysis of AlInN/GaN based E-mode using p-GaN gate device would be a significance to predict accurately its potential for high speed and high-frequency switching applications.

Thus, in this paper for the first time, we report the analysis of AlInN/GaN based E-mode using p-GaN gate low device dimensions.
The channel is formed at the interface of narrow bandgap GaN layer (30 nm) and intrinsic wide and-gap Al0.83In0.17N (1.2 nm) for calibrating the simulation model. The simulated transfer characteristics are compared with the initially published transfer characteristics. The model parameters are tuned & adjusted for achieving a close matching between simulation and experimental transfer characteristics. Once a close matching is achieved, the simulation model is applied for simulating the proposed Enhancement Mode AlInN/GaN HEMTs Using partial p-type GaN Gate device.

The 2D simulations are done using HD model of TCAD device simulator G2012.06. This model accurately considers the non-equilibrium conditions such as quasi-ballistic transport and velocity overshoot effect. The physical effects such as bandgap narrowing, variable effective mass, and doping dependent mobility at high electric fields are also considered. For high speed devices the electron can attain high energy and the resulting transport,

For considering spontaneous polarization occurring in the AlInN/GaN heterostructure device fixed charges \( n_p \) as listed in Table 3 are initiated at each interface. Effects of non-uniform distribution of the trapped electrons in the same direction horizontally with the interface are also considered for the simulation, as the current continuity equation and Poisson equation are solved self-consistently. The Al0.83In0.17N /GaN heterostructure is stacked along C-axis.

### Table 2 Parameters are necessary to compute the temp. and electron mobility of Al0.83In0.17N.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amin [cm(^2)V(^{-1})s(^{-1})]</td>
<td>75.9322</td>
</tr>
<tr>
<td>( \alpha_m )</td>
<td>2.1894</td>
</tr>
<tr>
<td>( \alpha_d )</td>
<td>5204.361</td>
</tr>
<tr>
<td>AN [cm(^{-1})]</td>
<td>2E+17</td>
</tr>
<tr>
<td>( \alpha_N )</td>
<td>7.365</td>
</tr>
<tr>
<td>( \alpha_a )</td>
<td>0.40252</td>
</tr>
<tr>
<td>aa</td>
<td>-0.20567</td>
</tr>
</tbody>
</table>

### Table 3 Polarization charge density at each interface

<table>
<thead>
<tr>
<th>Material</th>
<th>nsp(GaN)(cm(^3))</th>
<th>nsp(AlInN)(cm(^3))</th>
<th>Total (cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlInN/GaN</td>
<td>-1.81 x 10(^{13})</td>
<td>4.54 x 10(^{13})</td>
<td>2.73 x 10(^{13})</td>
</tr>
<tr>
<td>Al2O3/AlInN</td>
<td>-4.54 x 10(^{13})</td>
<td>-4.54 x 10(^{13})</td>
<td>-</td>
</tr>
</tbody>
</table>

There is a considerable matching between the experimental and simulation transfer characteristics (Fig 2), validating the approximation of the carrier transport model and other model parameters used in the simulation model.
Fig. 2 Experimental (solid lines) and simulated (symbols) transfer characteristics for Gate-Recessed Enhancement-Mode InAlN/AlN/GaN HEMT

Fig. 3 ID-VDS characteristics for E-mode devices at applied drain voltage vds = 5v

IV. RESULTS AND DISCUSSION

The transfer characteristics for E-mode HEMT device shows excellent control of gate throughout the range. The measured Vt for E-mode devices was +1.0 v approximately. The stacking of 40nm p-GaN helped in achieving a Vt shift of 4.7V approximately. The Vt shifting is caused due to the carrier depletion in the channel below the p-GaN layer. The depletion of carriers in the channel area results in E-mode operation. The maximum drain current observed was 241 mA/mm E-mode devices. The E-mode devices exhibits better off-state performances.

Fig 4 Extrinsic gm as function of gate voltage for E-mode

Fig. 4 shows the transconductance (gm) as a function of the gate voltage. Transconductance can be obtained from the ratio of variation in Id to the variation of gate voltage (Vgs), for constant drain voltage (Vds). The peak extrinsic gm,max observed was 46.1 mS/µm for E-mode device. The gate voltage swing (GVS) can be defined as the 10% drop from gm,max is about 1.7 V for E-mode device. Broader gm profile are desirable as broader profile provides an improved linear behavior from which a smaller intermodulation distortion, its a smaller phase noise and a sufficient dynamic range could be expected.

Fig 5 Dependence of Gate to Source current on gate to source voltage for E-mode device.

The capacitance versus voltage (C-V) simulations for E-mode The AC analysis was performed to extract C-V curves at 1 MHz frequency. The C-V measurements devices at applied drain voltage vds = 5v

Fig 6 Capacitance as a function of gate voltage for E-mode device at 1MHz freq.

Fig 5 represents the logarithmic scale of gate leakage current as a function of Vg, gate-to-source voltage. Both devices exhibit excellent off-state performances such as Ioff leakage and low SS. The E-mode device has a very low.

Ioff leakage of 5.4 x 10⁻⁷ mA/mm at Vgs= 0 V, high Ion/Ioff ratio of 3x10⁸ and low SS of 132 mV/decade

The capacitance versus voltage (C-V) simulations for E-mode The AC analysis was performed to extract C-V curves at 1 MHz frequency. The C-V measurements
shows negligible hysteresis. The $V_t$ shift for E-mode device can also be observed from C-V measurement.

![Fig 7](image_url)

**Fig 7.** RF characteristics of E-mode device

The E-device is of significance for high-speed digital applications and higher $f_{\text{max}}$ corresponds to the Ft at $P_{\text{max}}$ available which is a realistic parameter of the optimization of high-frequency amplifiers. These two FOMs, Maximizing RF gain, $f_t$ and $f_{\text{max}}$ are the primary goals for RF applications. Small signal AC analysis is performed over a wide frequency range using 2-D device simulator and the vertical direction parameters are calculated. Then, an advanced two port network RF extraction post processing tool is used to generate the different RF-POMs ($f_t$ and $f_{\text{max}}$) by converting admittance and capacitance to H-parameters.

The E-mode device exhibits slightly enhanced RF characteristics. The peak $f_t$ and $f_{\text{max}}$ obtained for E-mode device is 43 GHz and 48 GHz respectively.

**V. CONCLUSION**

Characterization of the novel Enhancement mode (E-mode) AlInN/GaN HEMT implemented using p-GaN gate is done using 2D Sentaurus TCAD simulation is done using the hydrodynamic model. Hydrodynamic model is used in the simulation. Comprehensive investigation of key FOMs such as Transfer characteristics, $V_t$, transconductance, capacitance and RF gain are done E-mode device. The E-mode device shows lower off-state leakage current, higher $I_{\text{on}}/I_{\text{off}}$ ratio and lower subthreshold slope (SS). The E-mode device exhibits slightly enhanced RF characteristics as compared to existing devices. These results demonstrate the potential of E-mode AlInN/GaN HEMT device for high speed and high-frequency applications.

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**REFERENCES**


