CHAPTER 5

DESIGN AND ANALYSIS OF $L_g$ 30 nm T-GATE InAlN/GaN HEMT WITH HEAVILY DOPED SOURCE/DRAIN FOR HIGH POWER MILLIMETER WAVE APPLICATIONS

In this chapter, the DC and Microwave characteristics of $L_g$ 30 nm T-gate InAlN/GaN HEMT with AlGaN back-barrier is demonstrated in both Depletion mode and enhancement mode operation by Synopsys Sentaures TCAD tool.

5.1 INTRODUCTION

For high power millimeter wave applications, the GaN-based HEMTs require both high power and high frequency performance. The high frequency performance of HEMT is achieved by allowing aggressive scaling of the device dimension. However, the reduction in the device dimensions deteriorates the breakdown voltage of HEMT. For achieving both high power and high frequency performance of HEMTs involving a trade-off between current gain cut-off frequency ($f_T$) and maximum frequency oscillation ($f_{max}$) for breakdown voltage ($V_{BR}$). Several research groups reported the high $f_T$ (Sun 2010; Shiping Guo 2010; Ronghua Wang 2011; Masataka Higashiwaki 2005; Haifeng Sun 2009) by scaling the gate length below 50 nm in GaN-based HEMT, but the less attention has been paid to improve the breakdown voltage and maximum frequency oscillation of the ultra-scaled HEMTs. For high power operation of the HEMTs, the Johnson figure of merit ($f_T \times V_{BR}$)
and maximum frequency oscillation ($f_{\text{max}}$) of the transistor are the important key factors. In this research work, a novel T-gate both enhancement and depletion mode InAlN/GaN HEMT with AlGaN back-barrier is designed for achieving high $f_{\text{max}}$ and JFOM ($f_T \times V_{BR}$) simultaneously. The proposed HEMT structure is simulated by Sentaurus TCAD tool and the results are validated with existing experimental data.

5.2 InAlN/GaN HEMT WITH AlGaN BACK-BARRIER DEVICE STRUCTURE AND BAND GAP DIAGRAM.

The vertical cross section view of depletion mode and enhancement mode InAlN/GaN HEMT with AlGaN back-barrier on SiC substrate is depicted in Figure 5.1 and 5.2 respectively. The depletion mode HEMT consists of 6 nm lattice matched In$_{0.17}$Al$_{0.83}$N barrier, 1 nm AlN spacer, 20 nm GaN channel and 800 nm Al$_{0.07}$Ga$_{0.93}$N back-barrier as the buffer. Whereas the recessed (recess depth is 5 nm) gate structure is formed by removing the part of the InAlN barrier layer for enhancement mode operation. The drain to source distance ($L_{sd}$) is kept for 585 nm and gate to drain distance ($L_{gd}$) is 165 nm & gate to drain distance ($L_{gd}$) is 400 nm. The T-shaped Schottky gate with a small footprint (30 nm length and 100 nm stem height). Ni/Au metal stack used as gate contact for depletion mode HEMT, whereas for enhance mode HEMT uses recessed T-gate with the same gate length 30 nm (100 nm stem height from the barrier and 400 nm wide) by using Pt/Au metal stack. The channel aspect ratio for depletion mode ($L_g/d$; where $d$ is the distance from channel to gate) is > 4 and for enhancement mode is > 15 (30/2). The gate width is $2 \times 25 \mu$m. In order to reduce the contact resistance, Ti/Al/Ni/Au metal stack used as ohmic contacts, which has the direct contact with Si doped ($>1 \times 10^{19} \text{cm}^{-3}$) 50nm n+ GaN source/drain region. Finally, the device surface is passivated by 60 nm Si$_3$N$_4$ passivation layer to mitigate the current collapse and parasitic capacitance (Derluyn et al. 2005).
A 1 nm Al spacer layer associated with Al$_{0.07}$Ga$_{0.93}$N back-barrier structure attenuates the short channel effects and provides the better electron confinement in 2DEG. The Al content in the back-barrier is less than 10%, to avoid excessive stress in GaN channel and rough surfaces, which will affect the mobility of the 2DEG. The access and output resistance of HEMTs limits the performance of these devices. Since the contact resistivity is a major part of such parasitic resistances. The heavily doped n+ GaN source/drain ohmic contacts allowed a significant reduction of the contact resistivity in the proposed device. The T-gate structure reduces the gate access resistance by providing large gate area while maintaining the smaller gate length and reduces the extrinsic gate capacitance. The reduction in the gate to drain space can cause the high electric field in the gate-source region which results in high $C_{gs}$ and high $g_{ds}$. In this work, gate to source ($L_{gs}$) distance is more than the gate to drain ($L_{gd}$) distance to maintain a low electrostatic field in the gate-drain space channel region for achieving high breakdown voltage. 6 nm wide bad gap InAlN barrier associated with AlN spacer layer effectively mitigates the gate leakage current.

Figure 5.1 Depletion mode InAlN/GaN HEMT with AlGaN back-barrier
The Si$_3$N$_4$ passivation layer limits the amount of electrically active traps that cause the dispersion effects. And also the passivation layer reduced the parasitic capacitive effect particularly between gate and drain ($C_{gd}$). SiC is used as a substrate for the proposed device due to their excellent thermal conductivity.

![Diagram](image)

**Figure 5.2** Enhancement mode InAlN/GaN HEMT with AlGaN back-barrier

![Diagram](image)

**Figure 5.3** (a) Polarization distribution (b) Energy band diagram
The energy band diagram of InAlN/AlN/GaN/AlGaN is depicted in Figure 5.3. The InAlN/GaN hetero-junction benefits the high 2DEG density (~$10^{13}$ cm$^{-2}$) without doping and high electron mobility (~2000 cm$^2$/V-s) because of the large conduction band discontinuity between the InAlN/GaN. The high 2DEG density is achieved by large spontaneous and piezoelectric polarization field inside the InAlN layer. The amount of 2DEG density is controlled by the thickness of the barrier layer and the Al content of InAlN. To confine the induced 2DEG electron density in the channel region and enhance the electron mobility in the quantum well, AlGaN back-barrier is used in our proposed structure, which also helped to enhance the breakdown voltage of the device by reducing the buffer leakage current. Rather than making conduction band discontinuity because of band offset, the enhanced 2DEG confinement is enabled by the negative polarization induced charges in the GaN/AlGaN interface. The induced charges make significant band bending; this creates a very high barrier. A very thin 1nm wide band gap (6.01 eV) AlN spacer presented in between the barrier and channel offering the large effective conduction band offset which also contributes to higher sheet charge with enhanced electron mobility.

5.3 DRAIN CURRENT CHARACTERISTICS

The drain characteristics of E-mode and D-mode Lg 30 nm InAlN/GaN HEMT with AlGaN back-barrier is shown in Figure 5.4 and Figure 5.5 respectively. The peak drain current density of (I$_{ds}$) of 2.3 A/mm and 2.42 A/mm is achieved for D-mode and E-mode HEMT respectively. The high drain current density is obtained due to tight carrier confinement in the channel region by AlN spacer layer and AlGaN back barrier. The obtained 2DEG density, carrier mobility and sheet resistance of D-mode HEMT (E-mode) are $2 \times 10^{13}$ ($2.3 \times 10^{13}$) cm$^{-2}$, 1478 (1583) cm$^2$/V.s and 228 (239) $\Omega$/□ respectively. The on resistance ($R_{on}$) of the transistor is the primary
source for power dissipation when the operation in active the region, the extracted low $R_{on}$ for the Depletion mode and Enhancement mode HEMT from the V-I characteristics are 0.52 $\Omega$.mm and 0.49 $\Omega$.mm respectively.

The transfer characteristics of $L_g$ 30 nm E-mode InAlN/GaN HEMT with AlGaN back-barrier is displayed in Figure 5.6. The extracted threshold voltage of the D-mode and E-mode HEMTs are -1 V and -0.2 V respectively.

![Figure 5.4 Drain characteristics of $L_g$ 30 nm D-mode InAlN/GaN HEMT with AlGaN back-barrier](image_url)

Figure 5.4 Drain characteristics of $L_g$ 30 nm D-mode InAlN/GaN HEMT with AlGaN back-barrier

The breakdown voltage GaN-based HEMT is the primary advantages for high power applications. However, scaling the gate length of HEMTs below 100 nm will lead to significant reduction in breakdown voltage due to high leakage currents. Figure 5.7 and Figure 5.8 displaying the constant breakdown characteristics of $L_g$ 30 nm InAlN/GaN HEMT with AlGaN back-barrier D-mode and E-mode HEMTs. In the proposed InAlN/GaN HEMT structure, the gate leakage current and buffer leakage currents are majorly reduced with help of wideband gap barrier, spacer layer, and AlGaN back-barrier. The off-state breakdown voltage ($V_{DS}$) of 40 V (D-
mode) and 38 V (E-mode) are extracted from the constant drain current injection breakdown characteristics for $I_d$ of 10 mA/mm.

![Figure 5.5 Drain current characteristics of $L_g$ 30 nm E-mode InAlN/GaN HEMT with AlGaN back-barrier](image)

**Figure 5.5** Drain current characteristics of $L_g$ 30 nm E-mode InAlN/GaN HEMT with AlGaN back-barrier

![Figure 5.6 Transfer characteristics of both E and D-mode InAlN/GaN HEMT with AlGaN back-barrier](image)

**Figure 5.6** Transfer characteristics of both E and D-mode InAlN/GaN HEMT with AlGaN back-barrier
Figure 5.7 $V_{ds} - V_{gs}$ breakdown characteristics of D-mode InAlN/GaN HEMT with AlGaN back-barrier

Figure 5.8 $V_{ds} - V_{gs}$ breakdown characteristics of E-mode InAlN/GaN HEMT with AlGaN back-barrier
5.4 SUBTHRESHOLD AND LEAKAGE CURRENT CHARACTERISTICS

The short channel effects are the major problem in ultra-scaled devices, particularly in sub 50 nm gate lengths. The inclusion of AlGaN back-barrier material in InAlN/GaN HEMT reduces the short channel effects. The subthreshold characteristics of both D-mode and E-mode $L_g$ 30 nm InAlN/GaN with AlGaN back-barrier are depicted in Figure 5.9 and Figure 5.10 respectively. The extracted drain induced barrier lowering (DIBL) and subthreshold slope (SS) from the log scale plot are 115 mV/V & 84 mV/dec for D-mode HEMT and 89 mV/V & 87 mV/dec for E-mode HEMT. The high channel aspect ratio of E-mode HEMT had shown better short channel effects suppression in compare with D-mode.

The gate leakage current characteristics of $L_g$ 30 nm InAlN/GaN HEMT with AlGaN back-barrier is shown in Figure 5.11 (D-mode) and Figure 5.12 (E-mode). For high voltage switching applications reverse bias gate leakage current is a series problem affecting the device performance.

![Subthreshold characteristics of D-mode InAlN/GaN HEMT with AlGaN back-barrier](image)

Figure 5.9 Subthreshold characteristics of D-mode InAlN/GaN HEMT with AlGaN back-barrier
The wide band gap (6.01 eV) AlN inter layer not only reducing the alloy scattering, which also effectively reduces the Fowler-Nordheim (FM) tunneling current at high reverse gate voltages. At zero gate bias, the gate leakage current \(I_g\) for depletion mode HEMT is \(\approx 10^{-13}\) A/mm, whereas the enhancement mode HEMT gate leakage current is \(\approx 10^{-9}\) A/mm.

Figure 5.10 Subthreshold characteristics of E-mode InAlN/GaN HEMT with AlGaN back-barrier

Figure 5.11 Leakage current characteristics of D-mode InAlN/GaN HEMT with AlGaN back-barrier
5.5 RF CHARACTERISTICS OF InAlN/GaN HEMT WITH ALGAN BACK-BARRIER

The transconductance variation with gate-source bias is displayed in Figure 5.13 and Figure 5.14 for D-mode and E-mode respectively. A peak transconductance ($g_m$) of 1.15 S/mm and 1.65 S/mm is extracted from the plot at $V_{ds} = 5$ V and $V_{gs} = -1$ V.

The expression for the current gain cut-off frequency and power gain cut-off frequency are written as follows:

Current gain Cut-off frequency:

$$f_t = \frac{g_m/g_{ds}}{2\pi \left( \left( c_{gs}+c_{gd} \right) + \left( \frac{1}{g_{ds}+(R_s+R_d)} \right) \right) + (c_{gd}g_m/g_{ds})(R_s+R_d)}$$  \hspace{1cm} (5.1)

Power gain cut-off frequency:
\[ f_{\text{max}} = \frac{f_t}{2 \sqrt{(R_s + R_d)g_{ds} + 2\pi f_t R_g C_{gd}}} \]  

(5.2)

where the source resistance \( R_s = \left( \frac{R_c}{w} \right) \left( \frac{R_{sh} + L_{ds}}{w} \right) \) and drain resistance \( R_d = \left( \frac{R_c}{w} \right) \left( \frac{R_{sh} + L_{gd}}{w} \right) \). \( R_c \) and \( R_{sh} \) are the contact resistance and channel sheet resistance respectively. \( L_{gs} \) and \( L_{gd} \) are gate to source and gate to drain spacing respectively. \( w \) is the width of the gate. \( R_g \) is the gate access resistance and \( g_{ds} \) represents drain conductance. The gate to drain capacitance is \( C_{gd} \) is an essential parameter for high frequency operation of the device.

The simulation result of current gain cut-off frequency \( (f_T) \) and power gain cut-off frequency \( (f_{\text{max}}) \) of \( L_g \) 30 nm InAlN/AlN/GaN HEMT with AlGaN back-barrier of D-mode and E-mode HEMTs for various gate-source bias are extracted from the TCAD simulation and depicted in Figure 5.15 and Figure 5.16 respectively. The proposed HEMT device exhibited a peak \( f_T/f_{\text{max}} = 262/234 \) GHz for D-mode and \( f_T/f_{\text{max}} = 246/290 \) GHz for E-mode at \( V_{ds} = 5 \) V. The Johnson figure of merit (JFoM) of D-mode and E-mode HEMTs are 10.48 and 9.348 THz respectively.

The higher \( f_T/f_{\text{max}} \) are achieved by the drastic reduction in the contacts resistances and the parasitic capacitances of the device by heavily doped (n+ GaN) source/drain regions have direct contacts with the channel, combined Si$_3$N$_4$ passivated device surface. The features of the T-gate structure is reduced gate resistances & capacitances, short channel effects (SCEs), which improves the transconductance \( (g_m) \) and attenuated drain conductance. The extracted device small signal parameters are gate-source capacitance \( C_{gs} \), gate-drain capacitance \( C_{gd} \), source resistance \( R_s \), drain resistance \( R_d \), Sheet resistance \( R_{sh} \) and on resistance \( R_{on} \) of the 30 nm T-gate D-mode (E-mode) InAlN/AlN/GaN HEMT device with heavily doped source...
and regions are 513(434) fF/mm, 174(173) fF/mm, 0.18(0.165) Ω.mm, 0.2 (0.21) Ω.mm and 435(418) Ω/□ respectively.

Figure 5.13 Transconductance variations with gate-source voltage of D-mode InAlN/GaN HEMT with AlGaN back-barrier

Figure 5.14 Transconductance variations with gate-source voltage of E-mode InAlN/GaN HEMT with AlGaN back-barrier
Figure 5.15 RF characteristics of D-mode InAlN/GaN HEMT with AlGaN back-barrier

Figure 5.16 RF characteristics of E-mode InAlN/GaN HEMT with AlGaN back-barrier
5.6 SUMMARY

In this chapter, the DC and microwave characteristics of a novel 30 nm T-gate InAlN/AlN/GaN HEMT with AlGaN back-barrier has been presented by using Synopsys TCAD tool. The device features are heavily doped (n++) source/drain regions with Al$_2$O$_3$ passivated device surface which is helped us to reduce the contact resistances and gate capacitances of the device which uplift the microwave characteristics of the HEMTs. L$_g$ = 30 nm, w=2 × 25µm D-mode (E-mode) HEMT exhibited a peak drain current density I$_{d_{\text{max}}}$ of 2.3 (2.42) A/mm, transconductance g$_m$ of 1.15(1.65) S/mm, current gain cut-off frequency $f_T$ of 262 (246) GHz and power gain cut-off frequency $f_{\text{max}}$ of 246 (290) GHz. The three terminal off-state breakdown voltages of 40 V for D-mode and 38 V for E-mode HEMT. The excellent microwave characteristics with the higher breakdown voltage of the proposed GaN-based HEMT are the expected to be the most optimistic applicant for future high power microwave millimeter wave applications.