CHAPTER 5

ANALYSIS OF BREAKDOWN VOLTAGE IMPROVEMENT USING GATE FIELD PLATE ENGINEERING TECHNIQUE IN AlGaN/GaN HEMT

5.1 Introduction

Beyond the current capability and concepts, the higher frequency along with high power devices are essential for the next generation systems. With the emerging demand for High efficiency transistor devices in high power applications, GaN based High Electron Mobility Transistor (HEMT) gained a considerable attention due to its unique properties like high mobility, high carrier density and high breakdown field strength. High voltage devices require electric field (EF) characterisation below the gate edge, where the maximum electric field is located.

Various types of breakdown enhancement techniques are available. The Schottky Source/Drain (SSD) contact technique improve the frequency as well as the breakdown voltage (Alan Brannick et al., 2009). Si$_3$N$_4$ Passivation technique has mainly two function, one is to reduce the effect of polarization variation due to the external effects and another function is to smoothen the field distribution at the drain end of the gate region to improve breakdown voltage (Prajoon.P et al., 2014, Guohao Yu et al., 2013). Further improvement in breakdown voltage is achieved by using field plate technique.

Field plate engineering technique is one of the best choice to spread the electric field (EF) along the channel. This will improve the breakdown voltage
capability of the HEMT device (Moon J.S. et al., 2011), Huili Xing et al., 2004). Different field plate structures are gate field plate, floating field plate, multiple field plate and source field plate technique (Peng et al., 2011, Guohao et al., 2013, Gang Xie et al., 2012). Though the breakdown voltage is improved in field plated HEMT, the frequency and gain of the device reduces due to the addition of extra capacitance in the channel (Wu Y.F et al., 2004). Here the extension of gate metal towards the drain helps to smoothen the gate peak electric field along the channel (Hsien-Chin et al., 2009, Aldona Mathew et al., 2014). The main advantage in using the field plate structure except the breakdown voltage is the reduced current collapse effect, since it suppresses the high field trapping effect (Guohao et al., 2013, Zhang et al., 2000).

Field plate technique influence the electric field distribution along the 2DEG channel by a capacitive action, therefore the thickness and relative permittivity of the passivation layer is very important in field plate engineering. The onset voltage for additional channel depletion under the field plate can be controlled by varying the thickness of passivation layer. So it is desirable to fix the thickness to an optimum value (Shreepad Karmalkar et al., 2006, Jae-Gil Lee et al., 2011). As the thickness reduces, the capacitance effect in the channel and field plate increases. This is one of the trade-off in using field plate but still this enhances the power capability of the device to a higher extent. For large thickness the effect of field plate vanishes. The drain and field plate separation should not go below a certain value (approximately 40% of $L_{gd}$) as it leads to premature breakdown (Ando et al., 2003). At high field condition, the gate field is predominant in deteriorating the device current due to the high field trapping effect. This current collapse effect at high field is effectively suppressed using a gate field plate. So in this thesis, the effect of Gate field plate in AlGaN/GaN structure has been analysed using sentaures TCAD for breakdown voltage analysis without affecting the frequency and drain current to large extent.
In this chapter a high-breakdown voltage GaN/AlGaN based novel High Electron Mobility Transistor (HEMT) is designed by incorporating field plate engineering technique. The field plate remoulds the electric field distribution on the drain side of the gate contact which in turn reduces the gate peak electric field. The variation in Off- state breakdown voltage is analysed by varying the length of the field plate and an optimum device dimension is obtained for the HEMT device. The device with $L_{gd}$ of 5 µm with a field plate length of 3 µm provides a high breakdown voltage of 1190 V. The obtained results are in good agreement with experimental data. In addition to this, drain current and transconductance of the device is analysed to understand the DC as well as AC characteristics of the device. This renders the field plated GaN HEMT one of the assuring candidate for high power applications.

5.2 $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ field Plated HEMT Structure

Figure 5.1 and Table 5.1 shows the field plated HEMT cross sectional schematic and parameters respectively (Bin Lu et al., 2010). In order to increase the thermal conductivity and reduce lattice mismatching in the device a Silicon Carbide material is used as the substrate (Ando et al., 2003). The six layer layered structure starting with an undoped GaN Buffer layer grown over the substrate is used to decrease the effect of lattice mismatching and associated trap effect. Buffer layer is followed by a GaN channel, undoped AlGaN spacer, n-doped AlGaN Barrier and GaN cap layer. The mole fraction of the ternary AlGaN material is fixed to 0.26 to obtain a higher polarization effect to improve the 2DEG sheet carrier density. The energy band discontinuity along with the high piezoelectric and spontaneous polarization at the GaN channel / AlGaN spacer interface creates a Two Dimensional Electron Gas Channel (2DEG) inside the GaN channel. The function of the cap layer on top of the barrier layer is to decrease the overall capacitance as well as the metal semiconductor contact resistance. Moreover the cap layer gives better gate control over the channel and increases the breakdown voltage by suppressing the gate field (Vipan Kumar et
al., 2006, Giovanni Verzellesi et al., 2014). In addition to these a passivation layer (Si$_3$N$_4$) is incorporated at the top of GaN Cap layer to prevent the device from external polarization and also to reduce the peak electric field at the drain end of the gate region.

![Figure 5.1 Proposed AlGaN/GaN HEMT device structure](image)

**Table 5.1 Device Dimension**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Al Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Plate ($L_{FP}$)</td>
<td>0.2 µm</td>
<td>-</td>
</tr>
<tr>
<td>Si$_3$N$_4$ Passivation</td>
<td>50 nm</td>
<td>-</td>
</tr>
<tr>
<td>GaN Cap</td>
<td>3 nm</td>
<td>-</td>
</tr>
<tr>
<td>AlGaN Barrier</td>
<td>16 nm</td>
<td>0.26</td>
</tr>
<tr>
<td>AlGaN Spacer</td>
<td>2 nm</td>
<td>0.26</td>
</tr>
<tr>
<td>GaN Channel</td>
<td>5 nm</td>
<td>-</td>
</tr>
<tr>
<td>GaN Buffer</td>
<td>2 µm</td>
<td>-</td>
</tr>
<tr>
<td>Gate to Drain Distance ($L_{gd}$)</td>
<td>5 µm</td>
<td>-</td>
</tr>
<tr>
<td>Gate Length ($L_g$)</td>
<td>0.8 µm</td>
<td>-</td>
</tr>
</tbody>
</table>
Finally to improve the breakdown voltage characteristics of the device the drain side edge of the gate is extended towards the drain by a length of $L_{FP}$. Which is called as the field plate (FP). The role of FP is to reduce the field distribution in the drain end of the gate region.

![Energy band profile of AlGaN/GaN HEMT](image)

Figure 5.2 Energy band profile of AlGaN/GaN HEMT.

A stacked layer of Ni/Au schottky contact is used as the source and drain contact. The lower On-resistance ($R_{on}$) and high field suppressed source carrier injection associated with the Schottky Source Drain (SSD) HEMT further improves the breakdown voltage characteristics of the FP-HEMT device.

The energy band profile of the GaN/AlGaN HEMT is shown in Figure 5.2. The basic physical parameters explained in this figure are Schottky barrier height $\phi_m$, Gate voltage $V_{gs}$, Conduction band discontinuity between AlGaN spacer and GaN channel Layer $\Delta E_C$, and Fermi energy level $E_F$. The band bending from AlGaN to GaN is in such a way that the conduction band of the GaN layer falls below the fermilevel ($E_F$) and forms a quantum well at the interface. This interface well forms a high mobility electron channel inside the GaN called the Two Dimensional Electron Gas (2DEG). The absence of doping and quantum confinement effect in the well makes the device more suitable for operation in high frequency application.
5.3 Result and Analysis of the Field Plate Engineered HEMT

The following section describes the various analysis made on the field plated HEMT device. The section describes the DC, RF and Breakdown voltage characteristics of the device in detail.

5.3.1 DC Characteristics Analysis

The improvement in breakdown voltage with various field plate dimension is analysed and an optimum dimension for high power and high frequency is achieved for the GaN/AlGaN HEMT. The Figure 5.3 shows the output current $I_d$ characteristic of the device. The device is simulated with drain voltage sweep from 0 V to 50 V with different gate voltage. The simulated result for the Field Plated (FP) HEMT shows a peak drain current of 0.91 A/mm against 1 A/mm non field plated (NFP) HEMT at gate voltage of 2 V. The drain current of NFP-HEMT device simulation is validated using experimental data at a gate voltage of 1 V (Bin Lu et al., 2010). The result also shows current improvement over NFP-HEMT device.

![Figure 5.3](image)

Figure 5.3. $I_d$-$V_{ds}$ characteristics for $L_{gd} = 5 \mu m$ and field plate length $3 \mu m$. 
The carrier density between gate and drain is modulated by the voltage applied to the FP electrode. This carrier modulation successfully reduces the effect of current collapse at high electric field. The result clearly show an extremely small current collapse at high electric field for FP (Field Plated) device. The comparative analysis between FP and NFP (non-field plated) devices is also given in the drain current analysis. It evidently shows the FP device is more stable at high field condition due to reduced trapping effect and less carrier freeze out resulted from the field plate (Ren Chunjiang et al., 2013).

![Graph showing transfer characteristics of GaN/AlGaN HEMT with and without field plate](image)

Figure 5.4. Transfer characteristics of the GaN/AlGaN HEMT with and without field plate at an $L_{gd} = 5 \, \mu m$ and $L_{FP} = 3 \, \mu m$.

The effect of field plate is clearly shown in the DC transfer characteristic of the HEMT. Figure 5.4 shows a comparative analysis to obtain drain current variation between FP and NFP-HEMT device. The device without field plate clearly shows a higher drain current of $0.86 \, A/\mu m$ at a gate voltage of $2 \, V$ compared with $0.8 \, A/\mu m$ of the field plated HEMT at $50 \, V$ drain bias.
Figure 5.5 Transconductance characteristics of GaN/AlGaN HEMT with $L_{gd} = 5 \mu m$ and $L_{FP} = 3 \mu m$.

The transconductance analysis of the FP and NFP device is also done and the interpretation is given. The Figure 5.5 shows the transconductance variation of the device FP and NFP-HEMT device. The variation in transconductance between FP and NFP device is sparingly small, 224 mS/mm and 225 mS/mm respectively. The threshold voltage of the devices are -2.1 V and -2.6 respectively. The reduction in transconductance and drain current is the result of additional depletion layer extension due to the gate field plate (Dora Y. et al., 2006).

5.4 Effects of breakdown voltage using field plate

The effect of gate electric field and gate to drain spacing in the breakdown voltage characteristics of the device is discussed in the following sections.

5.4.1 Electric field analysis in a field plate Plated HEMT

Intensive work has been done to investigate the breakdown mechanism of GaN HEMTs. The breakdown is due to an avalanche process that usually occurs
near the gate edge on the drain side. In a field-plate HEMT, the electric field originating from the field-plate contributes to the formation of a vertical depletion region in the passivation and conducting channel layers underneath. This is equivalent to providing additional negative charge at the surface of the channel, resulting in less charge in the channel. The depletion region in the x-direction is then extended by the field plate, which creates a second electric field peak at the field-plate metal edge. The second peak brings down the first peak at the gate edge, thus increasing the breakdown voltage of the device.

![Electric Field Distribution](image)

**Figure 5.6 TCAD Simulated Electric field Distribution in the field plated AlGaN/GaN HEMT.**

Now in order to understand the field plate “action” it is essential to look at the electric field profile at high field condition. Figure 5.6 shows the simulated electric field distribution of the AlGaN/GaN HEMT. Here the peak electric field is split in to two, one at the drain side gate edge and another at the field plate edge. Hence the overall electric field in the device reduces and essentially increases the device breakdown voltage.
A field profile comparison between FP and NFP HEMT device is shown in Figure 5.7. As can be seen in the figure the NFP device presents single peak located at the drain edge of the gate contact. The high electric field at the edge of the gate contact enhances electron tunnelling from the gate to the device channel. This will further increase the gate current and impact ionisation rate, which will ultimately lead to breakdown of the device. Since the breakdown mechanism is triggered by the electric field profile at the gate edge, it is clear that, to increase the device breakdown it is necessary to lower electric field values in the gate drain device region. In fact, this is the function of the field plate in HEMT device. The peak electric field in the FP-HEMT is split into two, one at the drain end of the gate edge and another at the field plate edge. So the electric field is gets distributed along the field plate and the maximum peak of the fields concentrated on the drain side edge of the FP metal. The highly controlled electric field distribution, makes the device capable of operating at high voltage condition. This results in maximum breakdown voltage for AlGaN/GaN HEMT devices.

Figure 5.7. Electric Field profile along the heterojunction interface of the FP and NFP-HEMT Device at $V_{ds} = 50$ V.
5.4.2 Analysis of Field plate length on Breakdown Voltage of HEMT

To start analysing the effects of the field plate geometry on device breakdown, it is necessary to fix the field plate length and passivation layer thickness. Figure 5.8 shows the breakdown voltage characteristics of the device with different field plate Length ($L_{FP}$). The increase of LFP, decreases electric field in the region between the two peaks (i.e. gate edge and field plate edge). This increases the breakdown voltage. But as $L_{FP}$ increases further, the peak electric field at the field plate edge merges with drain field. This effect will reduce the breakdown voltage capacity of the device (Takuma Nanjo et al., 2013).

![Breakdown Voltage variation with field plate Length](image)

Figure 5.8. Breakdown Voltage variation with field plate Length

Here a comparative analysis of GaN/AlGaN HEMT device with and without field plate is analysed. The simulated NFP device is matched with NFP experimental data (Bin Lu et al., 2010). The result shows a linear increase in breakdown voltage with increase $L_{FP}$ upto a certain limit. Beyond this limit the device breakdown voltage shows a dramatic decrease. This is because of the immature breakdown caused by the overlapping of the gate field with drain field.
due to the longer field plate (Chini et al., 2004). From the analysis results, it is clear that the device with field plate provides a higher breakdown voltage of 1190 V at field plate length $L_{FP} \ 3 \ \mu m$. As the spacing between the drain and field plate decreases the strength of electric field at the edge of the field plate increases. This will result in premature breakdown and hence shows a degradation in the breakdown voltage characteristics at higher $L_{FP}$ (Hongtao xu et al., 2004, Hongtao xu et al., 2013). The additional capacitance due to the incorporation of field plate definitely decreases the RF performance of the device. The drop-off in RF in the device is nearly compensated by cap-layer and Source/Drain Schottky Contact technology. The obtained frequency of the GaN/AlGaN gate field plated device is 12.5 GHz. This clearly shows that the device is working in the microwave frequency range.

### 5.4.3 Analysis of gate to drain distance on breakdown voltage of HEMT

The increase in gate to drain distance definitely increases the breakdown voltage as it reduces the concentrated electric field at the gate end. To obtain a clear idea on the effect of field plate and $L_{gd}$ it is necessary to simulate the device with different $L_{gd}$. Figure 5.9 shows the breakdown voltage plot as a function of $L_{gd}$.

![Figure 5.9 Breakdown Voltage Variation with Lgd.](image)
During the simulation the field Plate length is fixed to 60% of the length of gate to drain distance. Because at this $L_{FP}$, the device shows the maximum breakdown voltage. It is found that a maximum breakdown voltage of 1660 is obtained for an $L_{gd}$ of 10 µm and $L_{FP}$ of 6 µm. But any increase in device longitudinal dimension will reduce the RF characteristics of the device. Hence to obtain high power and high frequency device, it is desirable to fix an optimum dimension.

5.5 Conclusion

In this chapter, analysis of breakdown voltage characteristics is performed using gate field plate engineering technique in GaN/AlGaN HEMT. The results of drain current clearly shows the reduction in the current collapse effect, which improves stability of the field plated device. The breakdown voltage shows a nonlinear behaviour with field plate length. Hence for a high power device an optimum dimension is determined by TCAD simulation. Field plate length optimisation is carried out and found that a 3 µm field plate shows a maximum breakdown voltage of 1190 V at a gate to drain distance $L_{gd}$ of 5 µm. This device also shows a good cut-off frequency of 12.5 GHz. The breakdown voltage of the device is improved without much effecting the frequency and output current of the device. So this gate field plated HEMT device is very much encouraging for future high power microwave applications.