Effect of Field Plate on the RF Performance of AlGaN/GaN HEMT Devices

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Abstract

This paper examines the effect of the field plate structure on the RF performance of AlGaN/GaN High Electron Mobility Transistor (HEMT) devices. While the field plate structure helps to increase the breakdown voltage of the device through modulating the electric field locally, it induces additional feedback capacitance from drain to gate. Such feedback capacitors may impact the overall RF performance of the device especially at high frequencies. Systematic investigations on the small signal as well as power performance as functions of the drain biases are presented.

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Keywords: field plate; AlGaN/GaN; HEMT; feedback; capacitors.

1. Introduction

Modern wireless communication systems have put extremely stringent requirements on both power and linearity performance of power amplifiers for base stations operating at microwave frequencies. In a lot of phased-array radar systems, highly reliable power amplifiers with good linearity are critical to guarantee the overall system performance since such systems always operate under harsh environmental conditions. Silicon LDMOS power transistors have dominated such applications over the past years. However, with the approaching limits of operability for such devices, there will be a need for other semiconductor materials to fulfill the high-power and high-linearity requirements of the next generation wireless technology. Gallium nitride (GaN) has been acknowledged as prime candidate for high-power
microwave applications due to their high breakdown field (3MV/cm), high electron saturation velocity (2.5×10⁷cm²/V-s), and high operating temperature. [1] The associated AlGaN/GaN HEMT structure further features relatively high electron mobility due to the existence of the two-dimensional electron gases (2 DEGs). Such superior electronic properties of the structure have generated record-high output power densities at X- and Ku-band. [2,3]

Recently, a field plate structure has been widely used in AlGaN/GaN HEMTs for power application. It was believed that the field plate cannot only enhance breakdown voltage but also suppress the surface state, which markedly affected the power performance of GaN HEMTs. [4,5] The effects of insulator thickness and geometry of the field plate on breakdown voltage and frequency response were discussed. [4,6,7] Meanwhile, the extension gate of the field plate increases the gate capacitance (Cgd) and results in degraded transconductance (gm) and gain characteristics. While studies have been focused on the effect of field plates to increase the breakdown voltage, not much research effort has been devoted to the impact on the overall RF performance of the field-plated (FP) AlGaN/GaN HEMT. [7,8] From the circuit point of view, the field plate behaves as a drain-to-gate feedback capacitor which provides additional modulation on the signals at the input and output of the device. Under such circumstances, impact on the RF performance is expected especially at high frequencies due to the additional phase variations provided through the feedback path. Thus, this study focuses on the systematic comparisons of the RF performance between field-plated and non field-plated devices under different bias conditions.

2. Device Fabrication

The AlGaN/GaN HEMT epitaxy structure in this study was grown on sapphire by metal organic chemical vapor deposition. The structure included 3-μm-thick undoped GaN buffer and 30-nm-thick undoped Al0.25Ga0.75N layers. The Hall mobility and sheet carrier concentration were 1300 cm² V⁻¹ s⁻¹ and 1 × 10¹³ cm⁻², respectively. Fig. 1 shows a schematic cross section of the field-plated AlGaN/GaN HEMT.

Mesa etching was performed by ICP-RIE with a Cl₂/BCl₃ gas mixture. Ohmic alloy Ti/Al/Ni/Au was deposited by e-beam evaporation and annealed in nitrogen atmosphere at 800 °C for 60 s. The spacing between source and drain was 7 μm. The ohmic contact resistance was 3 × 10⁶ Ω cm². After ohmic
formation, the sample was dipped in dilute HCl for 1 min for cleaning. After cleaning, a Ni/Au gate \((L_g = 1 \ \mu m)\) was deposited and subsequently the device was passivated with a 100-nm-thick SiN\(_x\) layer grown by plasma-enhanced chemical vapor deposition. Finally, Ti/Au was deposited as the field plate structure \((L_{FP} = 1 \ \mu m)\), which was connected to the gate electrode. The device was 100 \(\mu m\) FET with gate finger widths of 50 \(\mu m\). In this study, both FP and non-FP (nFP) AlGaN/GaN HEMTs were fabricated to observe the effect of the field plate structure on the RF characteristics at microwave frequencies.

3. Results and Discussions

3.1. DC Characteristics

Fig. 2 shows the DC I-V curves of the FP and nFP HEMT devices. Fig. 3 compares the \(G_m\) and drain current as a function of gate biases for both types of devices. As observed, the maximum drain current at \(V_{GS} = 0\) was 610 mA/mm and the maximum transconductance was 160 mS/mm for the nFP HEMT, compared to those of 545mA/mm and 140mS/mm for the FP HEMT, respectively.

Clearly, a 11% reduction of saturation drain current in the FP-HEMT is observed which is mainly due to the gate extension from the field plate structure. Such extension together with the thin SiNx passivation layer yields to a larger effective gate length causing degradation in the drain saturation current. Despite the degradation in saturation current, the FP-HEMT exhibited an improved breakdown voltage of 160 V compared with 90 V for the nFP-HEMT. The improvement in breakdown voltage makes higher drain bias possible leading to better power and linearity performance with good reliability.

3.2. Small Signal RF Performance

S-parameters of the 100 \(\mu m\) FP and nFP-HEMT devices were measured from 1 to 40 GHz using a Cascade Microtech on-wafer probing system with an HP8510XF vector network analyzer. Additionally, a standard load-reflection-reflection-match (LRRM) calibration method was used to calibrate the measurement system, and the calibrated reference planes were at the tips of the corresponding probes. The parasitic effects (mainly capacitive) from the probing pads have been carefully removed from the measured S-parameters using the same method as Yamashita et al. and the equivalent circuit model
reported by Dambrine et al. [9,10] Fig. 4 shows the extracted RF $G_m$ and drain-to-gate capacitance ($C_{gd}$) as functions of the drain bias for the FP and nFP devices. Fig. 5 correspondingly shows the extracted gate-to-source capacitance ($C_{gs}$) as a function of the drain bias. The dependence of the cutoff frequency ($f_T$) on the drain biases for the FP and nFP devices is included in Fig. 6. In order to have a fair comparison, the gate biases for generating the three figures were chosen at the peak DC transconductance to accommodate for the slight shift in the threshold voltage for device with field plate.

![Fig. 4 Dependence of equivalent model parameters on drain bias for FP and nFP devices](image1)

![Fig. 5. Dependence of $C_{gs}$ on drain bias for FP and nFP devices](image2)

![Fig. 6. Dependence of $f_T$ on drain bias for FP and nFP devices](image3)
As expected, the extracted \( C_{gd} \) of FP device exhibited a major increase compared with that of nFP one. Moreover, the gate-to-source capacitance showed a minor increase with increasing drain bias. Fig. 6 shows the dependence of \( f_T \) on the drain bias for FP and nFP devices. Clearly, the FP devices showed a lower \( f_T \) due to the major increase in \( C_{gd} \) compared to the nFP devices. However, it is also relevant that the dependence of \( f_T \) on drain bias is very weak for FP devices.

### 3.3. RF Power Performance

The power performance was characterized using a FOCUS on-wafer load-pull system. The devices were tuned for the maximum output power. Fig. 7 shows the output power, gain, and PAE as a function of input power for both devices at 2 GHz when biased at 30 V with a 15 mA/mm current density. The optimum load reflection coefficients were \( \Gamma_{opt} = 0.886 \angle 9.9^\circ \) and \( \Gamma_{opt} = 0.885 \angle 7.5^\circ \) for FP and nFP devices, respectively. A higher output power of 25.36 dBm and PAE of 43\% were achieved for the FP device. Meanwhile, \( \text{P}_{1dB} \) for the FP and nFP devices when biased at a 30V drain bias were 18.52 and 16.26 dBm, respectively. The softer gain compression of the FP device is believed to be the reason for the linearity improvement at high output power levels even beyond \( \text{P}_{1dB} \). Such superior performance is mainly attributed to the reduction of trapping in surface states due to the field plate structure.

![Fig. 7. The measured RF power performance at 2GHz when both devices were biased at 30V.](image.png)

### 4. Conclusion

In this study, a field-plated AlGaN/GaN HEMT device has been fabricated and characterized. Measurement results revealed an output power of 25.36 dBm with a linear gain of 15.39 dB achieved for the FP-HEMT at 2 GHz when biased at \( V_{ds} = 30 \) V. An improvement in breakdown voltage from 90 to 160 V was observed. The major impact of the field plate on the device performance was the degradation in the cutoff frequency mainly due to the increase in the gate-to-drain capacitance. The softer gain compression of the FP devices was mainly attributed to the phase compensation provided through the feedback capacitance. Such observation has highlighted possible optimization on the field plate geometries for specific applications at the desired frequencies.
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