Effect of the gate structure on the kink phenomenon in $S_{22}$ of AlGaN/GaN HEMT

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For the first time, the effect of the gate structure on the kink phenomenon in $S_{22}$ of the AlGaN/GaN HEMT is investigated in this study. To provide critical understanding into the $S_{22}$ kink effect, the kink effect in $S_{22}$ of the AlGaN/GaN HEMTs is investigated with transistors that have various gate lengths ($L_g$) and gate connected field plate lengths ($L_{gfp}$). The HEMTs are fabricated and charaterised at the same conditions, and the equivalent circuit models are used to get consistent results. The experimental results show that the gate structure can play an important role on kink effect in $S_{22}$. The results present valuable information on the development of the AlGaN/GaN HEMT technology and the MMIC design regarding kink effect.

Introduction: The GaN HEMT technology has gained importance in defense, space, and communications industries due to its superior material properties [1, 2]. Therefore, understanding the parameters such as the kink effect (KE) in the output reflection coefficient ($S_{22}$), which can degrade the device performance, has become more important; and multiple studies have been conducted to analyse the origin of the kink [3–18].

The KE in $S_{22}$ is defined as an abrupt dip in $S_{22}$ behaviour at a specific frequency as a result of the transition of the output impedance ($Z_{ou}$) of the transistor from a low-frequency series RC circuit to a high-frequency parallel RC circuit [3]. The origin of the KE has been debated, and it has been studied by poles and zeros [4, 5] and circuit models [6, 7]. Moreover, the KE has been attributed to the feedback resistance [4], the substrate resistance [5–9], the low-frequency dispersion [10], the open dummy structure [11, 12], and the high values of transconductance ($g_m$) [3, 13, 14]. However, the KE in $S_{22}$ depends on the intrinsic elements [14, 15], and the extrinsic elements change its behaviour [1, 7].

The KE in $S_{22}$ of GaN HEMTs has been attributed to the high values of $g_m$, but the other technologies such as GaAs and Si also suffer from the kink phenomenon [4, 11, 15, 16]. Besides, the effect of the gate width ($W_g$), the bias condition and the temperature effect on the scattering ($S_{22}$) parameters have been studied, and the results are reported in [13, 15, 17, 18].

The AlGaN/GaN HEMT technology offers various $L_g$ options such as 0.4–0.5 mm, 0.25 mm, and 0.15 mm for S-Band, X-Band, and Ka-Band applications, respectively. The $L_g$ is not the only difference between those technologies. The device sizes, the drain-source spacing, the wafer properties, and the bias conditions are other possible differences. Therefore, direct comparison of those transistors would not be meaningful.

In this study, to evaluate the effect of the gate structure, represented in Figure 1, on the KE in $S_{22}$ of AlGaN/GaN HEMTs, eight HEMTs with different $L_g$ and $L_{gfp}$ values are fabricated. HEMTs with 0.2 mm, 0.25 mm, 0.30 mm, and 0.35 mm $L_g$ with 0.9 mm $L_{gfp}$ are fabricated to investigate the effect of $L_g$ on KE. The HEMTs with 0.5 mm, 0.7 mm, and 0.9 mm $L_{gfp}$ with 0.25 mm $L_g$ are fabricated to investigate the effect of $L_{gfp}$ on KE. All HEMTs, used in this study, are fabricated with $L_g$ and $L_{gfp}$ (scfp: source-connected field plate).

Experimental study and results: The devices used for the tests have $8 \times 125$ mm ($W_{g,p} = 1.0$ mm) configuration. The HEMTs with different $L_g$ and the HEMTs with 0.7 mm and 0.9 mm $L_{gfp}$ are fabricated on the same wafer with the GaN technology T1. On the other hand, the HEMTs with 0.5 mm and 0.7 mm $L_{gfp}$ are fabricated on the same wafer with the GaN technology T2. The HEMT with 0.7 mm $L_{gfp}$ is common in both technologies to be used as the normalisation reference for the comparison. The $S$-parameter measurements of the devices are performed with 28 V drain voltage ($V_D$) and 100 mA/mm drain current ($I_D$) at 25°C chucks temperature from 0.5 GHz to 25.0 GHz.

The equivalent-circuit model, illustrated in Figure 2, is used to develop the models of the HEMTs. The developed models are used for accurate analysis and the results of the models are compared with the measured $S_{22}$ data, and are presented in Figure 3.

The kink parameters (KPs): the kink frequency band (KFB), the kink frequency point (KFP), the kink size (KS), and the kink figure of merit (KFM) are calculated from the second derivative (D2) of $\text{Im}(S_{22})$ with respect to $\text{Re}(S_{22})$ as explained in [15]. Since the results of D2 from the measured data can be very noisy to evaluate the parameters properly, the simulation results of the models are used for the rest of the analysis. The KFP is the frequency point where KE occurs in $S_{22}$ and can be determined from the negative peak of D2. The KS is defined as the value of the negative peak in D2. The KFB is the frequency range between two zero crossing of D2. The KFM is the ratio of KFB.

Figure 4 shows the $\text{Im}(S_{22})$ versus $\text{Re}(S_{22})$ and its corresponding first (D1) and second (D2) derivatives from 0.5 GHz to 25.0 GHz for the whole and the intrinsic HEMTs with different $L_g$. Figure 5 illustrates the kink parameters for the HEMTs with different $L_g$.
The KPs in Figure 5 for different $L_g$ values are calculated from the D2s in Figure 4. From Figures 3(a) and 4, one can evaluate that KFP is moving to lower frequency points by the increase in $L_g$. Excluding the HEMT with 0.25 $\mu$m $L_g$, the increase in $L_g$ results with the reduction in KPs of intrinsic HEMT, while there is no significant change in KS of whole HEMT. Thus, it is clear that the extrinsic parameters have major impact on KE [1, 7].

SET1 HEMTs with 0.7 $\mu$m and 0.9 $\mu$m $L_{g_{H}}$ from T1 and SET2 HEMTs with 0.5 $\mu$m and 0.7 $\mu$m $L_{g_{H}}$ from T2 are analysed separately; and the normalised KP results according to HEMTs with 0.7 $\mu$m $L_{g_{H}}$ from technology T1 and T2 are used to compare the changes in the KPs with respect to $L_g$. Figure 6 shows the Im($S_{22}$) versus Re($S_{22}$), D1, and D2 from 0.5 GHz to 25.0 GHz for the intrinsic HEMTs with different $L_g$. Figure 7 illustrates the KPs for the intrinsic HEMTs with different $L_{g_{H}}$. The actual KP values of SET1 and SET2 HEMTs, and $g_m$, $C_{gd}$, and $C_{gs}$ are shared in Table 1. Although KFP change is clear from the $S_{22}$ data of varying $L_g$ case, it is not clear for the varying $L_{g_{H}}$ case from Figures 3(b) and 6. The KPs in Figure 5 for different $L_{g_{H}}$ values are calculated from the D2s in Figure 6. The increase in $L_{g_{H}}$ results with increase in KFB, KS, and KFM, while there is no significant change in KFP. The changes in $L_g$ and $L_{g_{H}}$ directly affect the depletion region properties of the HEMTs. Therefore, the gate-to-drain capacitance ($C_{gd}$), the gate-to-source capacitance ($C_{gs}$), and $g_m$ are directly affected by the gate structure. Although $C_{gd}$ is $\sim 10\times$ larger than $C_{gs}$, the change in $C_{gd}$ becomes critical with the change in the gate structure. Moreover, it is clear from Table 1 that KS can be negligible even with large gate widths unlike stated in [3, 15].

Figure 8 shows $S_{22}$ results of the HEMT with $L_g = 0.25$ $\mu$m and $L_{g_{H}} = 0.9$ $\mu$m. To investigate the effect of $C_{gd}$, $C_{gs}$, and $g_m$, $C_{gd}$ and $C_{gs}$ values are varied, and $g_m$ is varied by excluding $C_{gd}$ from the model. The results are compared with the whole HEMT and the intrinsic HEMT results, and the KP results are shared in Table 2. Since $C_{gd}$ is related with the isolation of the HEMT, $S_{12}$ results of those configurations are also given in Table 2. The $S_{12}$ comparison shows that the increase in $C_{gd}$ results with lower isolation. Furthermore, the KPs are directly affected by the change in the isolation as a result of the change in $C_{gd}$. Although doubling $C_{gs}$ has minor effect on KS, KFP is lowered, and KFB becomes narrow, which results with worse KFM. Excluding $C_{gd}$ from the model eliminates the kink in $S_{22}$ by increasing the isolation between the gate and the drain.

![Image](image-url)
Table 2. Kink parameters of Whole HEMT (WH) and Intrinsic HEMTs (IH) (Lg = 0.25 μm and Lgrf = 0.9 μm)

| DUT | $g_m$ | $C_{gd}$ | $C_{gs}$ | KS | KFP | KFB | KFM | $S_{11\text{max}}$ |
|-----|-------|---------|---------|----|-----|-----|-----|------------------|
| WH  | $g_m$ | $C_{gd}$ | $C_{gs}$ | -9.84 | 5.4  | 6.1 | -1.61 | -23.8 |
| IH  | $g_m$ | $C_{gd}$ | $C_{gs}$ | -20.27 | 6.6  | 8.3 | -2.44 | -23.2 |
| IH  | $g_m$ | $C_{gd}$ | $C_{gs}$ | -55.03 | 7.1  | 10.4 | -5.29 | -20.6 |
| IH  | $g_m$ | $C_{gd}$ | $C_{gs}$ | -10.61 | 5.7  | 6.5 | -1.63 | -26.9 |
| IH  | $g_m$ | $C_{gd}$ | $C_{gs}$ | -19.88 | 3.2  | 3.9 | -5.09 | -27.2 |
| IH  | $g_m$ | no $C_{gd}$ | no $C_{gs}$ | no KS | no KFP | no KFB | no KFM | no $S_{11\text{max}}$ |
| IH  | $g_m$ | no $C_{gd}$ | no $C_{gs}$ | no KS | no KFP | no KFB | no KFM | no $S_{11\text{max}}$ |
| IH  | $g_m$ | no $C_{gd}$ | no $C_{gs}$ | no KS | no KFP | no KFB | no KFM | no $S_{11\text{max}}$ |

Thus, it reveals that the limited isolation between the gate and the drain caused by the high values of $C_{gd}$ leads to the kink in $S_{22}$. Since the feedback capacitance $C_{gs}$ is a strong function of $V_D$, the KE can be also controlled with $V_D$.

A HEMT that has $10 \times 125 \mu m$ ($W_{gs,rf} = 1.25 \text{ mm}$) configuration with $340 \text{ mS} \ g_m$ is preferred to evaluate the effect of $C_{gd}$ change that is caused by $V_D$ change. Thus, $V_{DD}$ is kept constant at $-3.25 \text{ V}$ and $V_{DS}$ is swept from $12 \text{ V}$ to $32 \text{ V}$ with 4 V steps. Moreover, S-parameter measurements are performed with $0.8 \text{ ms}$ pulse width and 0.8% duty cycle to eliminate thermal effects.

Fig. 9. Intrinsic HEMT results of $10 \times 125 \mu m$ ($W_{gs,rf} = 1.25 \text{ mm}$). (a) $S_{22}$ results with respect to $V_{DS}$ from 0.5 GHz to 25.0 GHz. (b) Kink parameters versus $C_{gd}$.

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Conclusion: The effect of the gate structure on the kink in $S_{22}$ is investigated with the transistors that have different $L_g$ and $L_{grf}$ configurations. This study shows that the KPs also depend on the gate structure besides the gate width, the bias point, and the thermal conditions. The KS is also affected by the change in $C_{gd}$.

As a result of the change in $C_{gd}$, the isolation of the transistor is also affected. A proper feedback technique and a proper $V_D$ can be useful to suppress the kink in $S_{22}$ associated with $C_{gd}$. Thus, the gate structure has to be studied carefully to develop a proper kink-free technology, and a proper feedback has to be studied in the design process to minimise the kink in $S_{22}$. Considering the transistor as a whole, KE exists as a combined effect of the parameters such as $C_{gd}$, $C_{gs}$, $g_m$, the bias conditions, and the operating temperature. Moreover, the study of the KE in $S_{22}$ can be extended by investigating the epitaxial structure of the wafers and the process parameters.

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