Low Noise AlGaN/GaN MODFETs with High Breakdown and Power Characteristics

Shawn S.H. Hsu, Dimitris Pavlidis
Department of Electrical Engineering and Computer Science,
The University of Michigan, Ann Arbor, MI 48109-2122, USA
Tel: (734) 647-1778, Fax: (734) 763-6132, email: pavlidis@umich.edu, http://www.eecs.umich.edu/dp-group
J. S. Moon, M. Micovic, C. Nguyen, and D. Grider*
HRL Laboratories, 3011 Malibu Canyon Road, Malibu, CA 90265, USA
* Currently at GCS Systems, CA

Abstract

AlGaN/GaN MODFETs (0.25×200 μm^2) with low noise, high breakdown and power characteristics have been evaluated. A noise figure of 1.9 dB with 16.2 dB associated gain was obtained at a quiescent point of I_{DS}= 30 mA and V_{DS}= 10 at 10 GHz. The maximum power measured was 22.9 dBm (~ 1 W/mm) and PAE was 21.9 % at 8.4 GHz at the same bias condition. In addition, a maximum breakdown voltage (V_{BD}) of ~ 115 V at I_D= 20 µA and I_G ~ 30 µA was measured. A MODFET noise model and its correlation with gate leakage current are also investigated.

I. Introduction

Devices with low noise figure, and high breakdown voltage can be used in RF front-ends with no need for protection circuitry, therefore greatly simplifying system designs. GaN-based devices are promising for such applications and impressive microwave power and low noise figure characteristics have been demonstrated from AlGaN/GaN MODFETs [1-2]. However, little has been reported on both noise and power characteristics of the same devices. In this work, noise and power characteristics of AlGaN/GaN MODFETs were studied. Moreover, the device breakdown mechanism and gate leakage current was also investigated. Results indicate that AlGaN/GaN MODFETs exhibit relative high output power under bias conditions corresponding to the minimum noise figure. In addition, devices show excellent breakdown voltage and small gate leakage current, which may contribute to their low noise figure.

II. GaN MODFET DC and Microwave Characteristics

The AlGaN/GaN MODFET layers studied in this work, were grown on 4H-SiC substrates using RF-assisted MBE. The measured devices had two fingers, each with a gate length of 0.25 µm, and a gate width of 0.1 mm. The device structures consist starting from the substrate of an undoped GaN buffer, an NID $Al_{0.22}Ga_{0.78}N$ spacer, n-$Al_{0.22}Ga_{0.78}N$ donor layer and an NID $Al_{0.28}Ga_{0.78}N$ cap layer. The fabricated devices exhibited excellent DC and microwave characteristics. A maximum drain current density of ~ 1.35 A/mm and a peak transconductance of ~ 320 mS/mm were obtained. Fig. 1 shows the device's maximum oscillation frequency (f_{max}) and cut-off frequency (f_T) under various bias conditions. As can be seen, the devices show a maximum f_{max} of ~ 81 GHz (V_{GS}=-3.4 V, V_{DS}=15 V), and f_T of ~ 57 GHz (V_{GS}=-2.6 V, V_{DS}=15 V). Moreover, the devices present high f_{max} and f_T in a wide range of bias conditions, which is an advantage for circuit applications.

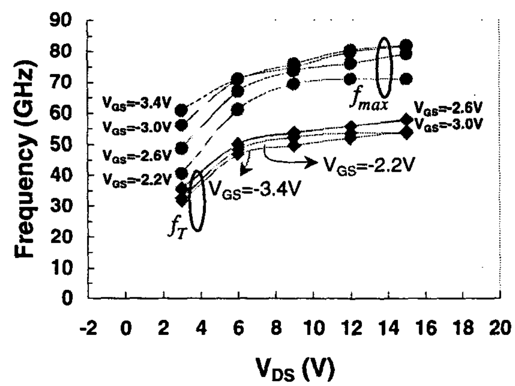

Fig. 1: Maximum oscillation frequency (f_{max}) and cut-off frequency (f_T) under different bias conditions

III. Microwave Noise Characteristics and Equivalent Circuit Model

The minimum noise figure (F_{min}) and associated gain (G_a) were characterized at 10

GHz under V_{DS}= 10 V as a function of drain current and the results are shown in Fig. 2. A noise figure of 1.9 dB with 16.2 dB associated gain were obtained at a quiescent point of I_{DS}= 30 mA. The variation of F_{min} was found to be relatively small in the measured current range. In addition, F_{min} was also found to be relatively independent of drain bias voltages within the measured range of 5-15 V. The results indicate that AlGaN/GaN MODFETs can maintain a small value of F_{min} over a wide bias range, which is a good feature for relaxed circuit design. F_{min} as a function of frequency was also evaluated. The results are shown in Fig. 3. Within the measured frequency range (6- 14 GHz), F_{min} varied from 1.47 to 2.92 dB. The associated gain (G_a) values were found to decrease monotonically from 16.5 to 12.0 dB. Smaller minimum noise figure values can be achieved (< 1 dB at X-band) with similar technology [2].

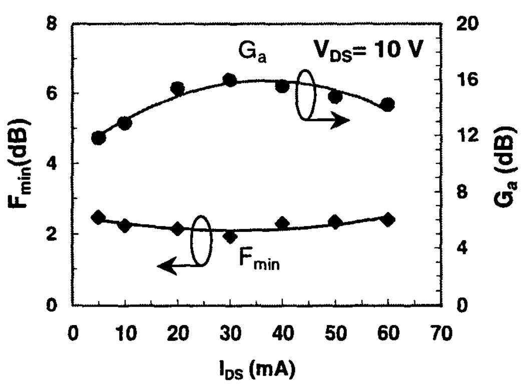

Fig. 2: F_{min} and G_a as a function of drain current at 10 GHz

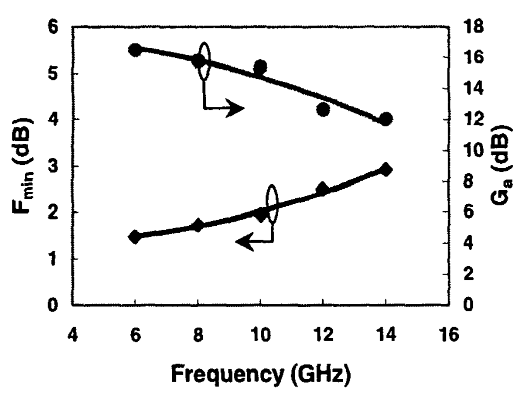

Fig. 3: F_{min} and G_a as a function of frequency at I_{DS}= 30 mA and V_{DS}= 10 V

The equivalent circuit of AlGaN/GaN MODFETs was extracted in order to further understand the contribution from various noise sources to device noise characteristics. "Cold" *S-parameters* were used to extract parasitic components such as pad capacitances and inductances [3]. Multi-bias *S-parameters* were then used to obtain the bias dependent parameters such as transconductance (g_m) and transit time (τ). Measured and simulated *S-parameters* from 0.5 GHz to 25.5 GHz are shown in Fig. 4. As can be seen, excellent agreement is obtained.

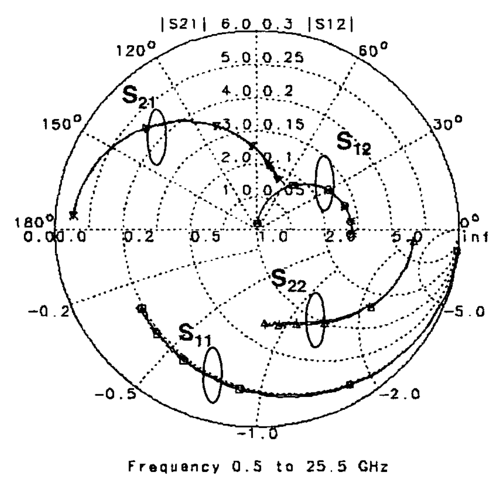

Fig. 4: Measured and modeled *S-parameters* for AlGaN/GaN MODFETs at V_{GS}=-3V, V_{DS}= 10V and I_{DS}= 30 mA

Once the small-signal model was established, the noise sources can be calculated. The equations used were reported earlier [4-5]. Three noise voltages are used to describe the thermal noise generated from parasitic resistances. The shot noise resulting from the gate leakage current is also included. In addition, the equations take into account the correlation between the gate and the drain noise currents. The noise model adapted in this study is shown in Fig. 5. Noise parameters were obtained by fitting the noise parameters (*P, R, C*) to the measured results under the same bias condition and source impedance. The optimization procedure was performed in HPADS. Table I shows the extracted small-signal and noise parameters. Fig. 6 compares measured and modeled results. Good agreement between experimental and simulated noise and associated gain characteristics was obtained as a function of frequency from 6 to 14 GHz.

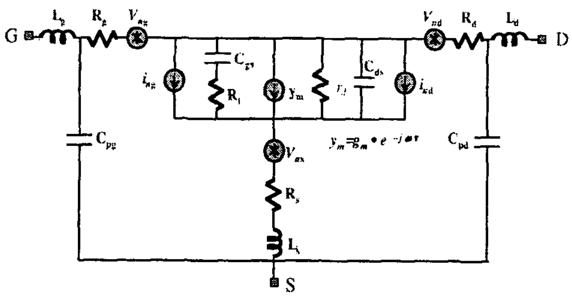

Fig. 5: AlGaN/GaN MODFETs noise equivalent circuit noise model

C_{pg}(fF)	C_{pd}(fF)	L_s(nH)	L_g(nH)	L_d(nH)	R_s(Ω)
15	45	0.031	0.016	0.002	1.48
R_g(Ω)	R_d(Ω)	C_{gs}(fF)	C_{gd}(fF)	g_m(mS)	r_d(Ω)
3.69	3.97	206	33	69.2	350.2
R_i(Ω)	τ(ps)	P	R	C	
2.03	1.2	1.38	0.23	0.41	

Table I AlGaN/GaN MODFETs small-signal and noise equivalent circuit model parameters

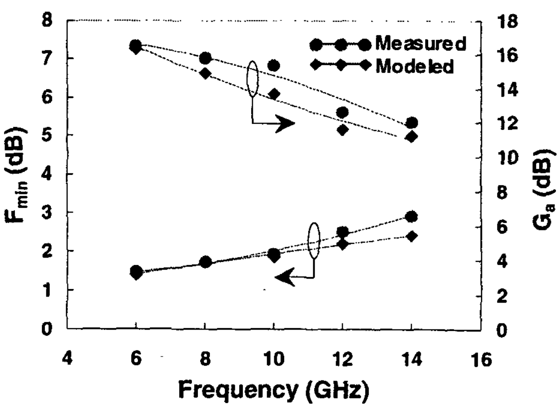

Fig. 6: Measured and modeled F_{min} and G_a from 6- 14 GHz

IV. GaN MODFET Power and Breakdown Characteristics

The power characteristics of the devices close to low noise biases were investigated at 8.4 GHz under bias conditions corresponding to low noise operation. Fig.7 shows the results of output power (P_{out}), gain and power-added efficiency (*PAE*). The device was biased at V_{GS}=-3 V, V_{DS}= 15 V and I_{DS}= 34.2 mA. The maximum power obtained was 22.9 dBm (~ 1 W/mm) and PAE was 21.9%. The breakdown voltage of the AlGaN/GaN MODFETs was investigated by employing the current-injection technique, which offers a systematic and non-destructive way of FET breakdown evaluation [6]. During this measurement, the drain current is forced to a preset level corresponding to OFF-state breakdown conditions. At the same time, the gate-source bias is swept between open and pinch-off channel conditions. The results of current-injection testing are shown in Fig. 8. As can be seen, the gate-drain voltage measured at different drain current densities was independent of V_{GS} as the device entered the deep pinched-off operation regime. Such characteristics indicate that the breakdown in the measured devices is limited by the gate-drain diode rather than source-drain channel breakdown mechanism.

The measured device was found to exhibit a high breakdown voltage and a low leakage current simultaneously (maximum V_{BD} ~ 115 V at I_D= 20 μA, I_G ~ 30 μA). It has been reported that the noise performance of FETs is strongly dependent on the gate leakage current value due to the shot noise contributed from the gate leakage current [4]. Thus, the observed small gate leakage current of the devices of this study under high bias conditions could be a key contributor to the observed low noise figure.

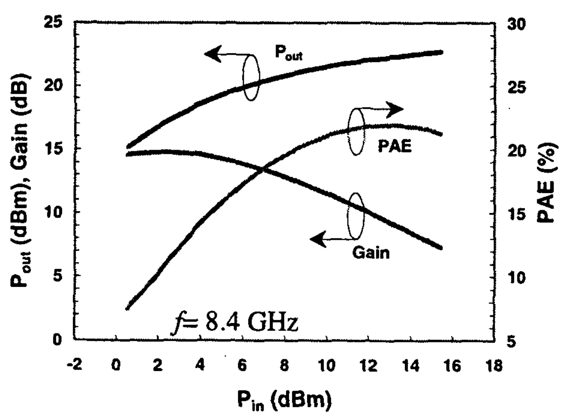

Fig. 7: Power characteristics of a 0.25×200 μm^2 device at 8.4 GHz

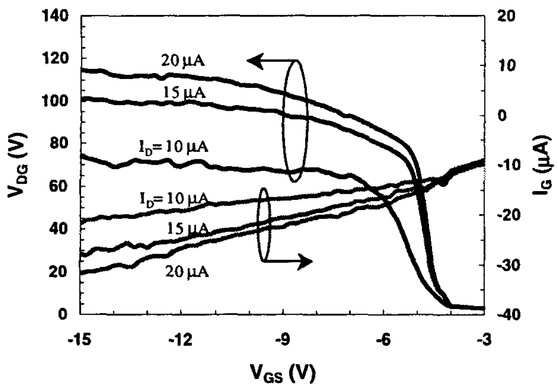

Fig. 8: Gate-drain breakdown characteristics and gate leakage current of AlGaN/GaN MODFETs

V. Discussion

In order to further investigate the impact of gate leakage current on device noise characteristics, simulations were performed using the developed noise model. The equivalent circuit model of the device was terminated with 50 ohms at both input and output ports in a common-emitter configuration. The gate leakage current level was varied from 2 μA to 200 μA and the rest of parameters were kept identical. Note that the tested device shows a measured gate leakage current as 2.2 μA at V_{GS}=-3 V, V_{DS}= 10 V, which is similar to the low gate leakage case in our simulation. The results obtained from this study show that the ratio of noise contributed from gate leakage current to total noise figure increases dramatically as the gate leakage current level increases (from 0.4 % to 26 % at 10 GHz). It appears that the gate current shot noise becomes an important portion of the overall device performance when its level increases. Therefore, gate leakage current of low level is essential for low noise characteristics.

The study also showed that at high gate leakage level, the impact of gate leakage on noise figure decreases as the operation frequency increases. This is due to the fact that the gate shot noise is frequency independent. However, certain other noise sources increase with frequency, such as for example the gate diffusion noise. Therefore, the ratio of S_{IG} (gate current shot noise)/ S_{total} decreases as the frequency increases.

VI. Conclusion

In summary, the microwave noise and power performance of AlGaN/GaN MODFETs were characterized. The devices present a low noise figure and relatively high output power concurrently. The breakdown characteristics of the devices were investigated by the current injection technique and were found to be limited by gate-drain breakdown. In addition, the importance of gate leakage current to device noise characteristics was studied using equivalent circuit model.

Overall, the results indicate that the AlGaN/GaN MODFETs have excellent breakdown voltage and low gate leakage current, which contribute to the low noise figure of these devices. The good noise figure, high breakdown voltage and relatively high output power obtained from these devices demonstrate the suitability of AlGaN/GaN MODFETs for robust RF LNA applications.

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