Large-Signal Characteristics of AlGaN/GaN Power MODFETs

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Abstract—**This work addresses the scalability of power performance of AlGaN/GaN MODFETs with large gate periphery, as necessary for microwave power devices. High-frequency large-signal characteristics of AlGaN/GaN MODFETs have been studied for devices with gate widths from 0.2 to 1 mm. 1-dB gain compression occurred at input power levels varying from -1 to +10dBm as the gate width increased, while gain remained almost constant at ~17dB. Output power density was maximum (1.3W/mm) for devices with 0.6mm gates and maximum output power (29.9dBm) occurred in devices with 1mm gates, while power-added-efficiency remained almost constant at ~30%.**

I. Introduction

AlGaN/GaN heterojunction FETs grown by RF-assisted MBE have a high potential for high-power electronics as previously reported by the authors [1]. A record output power density of 3W/mm at 18GHz and 5.3W/mm at 10GHz [2] was recently obtained using AlGaN/GaN MODFETs. The DC and small-signal high-frequency performance of $Al_{0.3}Ga_{0.7}N$/GaN MODFETs with gate widths ranging from 200μm to 800μm was also recently reported [3] and excellent uniformity of drain current across the wafer and scalability of drain current and transconductance with the gate width was demonstrated. However, there is lack of detailed information on the scalability of power saturation characteristics for large-gate-periphery power devices. In this work, an automatic load-pull system is employed to obtain and compare the power performance and large-signal impedance of AlGaN/GaN power MODFETs with gate widths up to 1 mm.

The AlGaN/GaN layers were grown on sapphire substrates using RF-assisted MBE. The layer growth and fabrication details of 0.25μm-long gate MODFETs on such layers have been reported elsewhere [4]. Power devices with 2, 4, 6, 8, and 10 100μm-wide gate fingers (maximum width of 1.0 mm) have been investigated. The thermal effects were reduced by employing 30μm-thick Au-plated heat sinks. AlGaN/GaN MODFETs demonstrated typical $I_{DSS} \approx$ 500mA/mm and $g_m \approx$ 100mS/mm.

II. Small-Signal Performance

Small-signal S-parameters of AlGaN/GaN MODFETs with varying gate widths were measured between 0.5 and 25.5GHz. Current-gain cutoff frequency (f_T) and maximum oscillation frequency (f_{MAX}) extrapolated from the S-parameters for different bias conditions are shown in Figure 1. The figure shows that f_T and f_{MAX} were maximum for V_{GS} between –4 and -6V (V_{DS}=15V). f_T and f_{MAX} slowly increased with drain-source voltage for V_{DS}>5V when V_{GS} was fixed at -5V. f_T was 27GHz for most devices while f_{MAX} varied between 45 and 70GHz.

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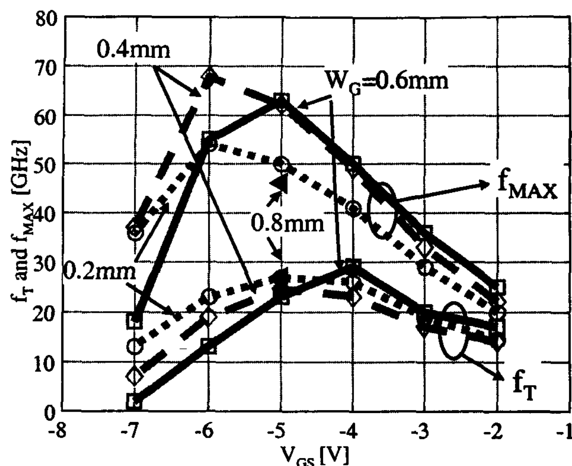

Figure 1. Bias dependence of f_{MAX} and f_T for AlGaN/GaN MODFETs with varying gate widths

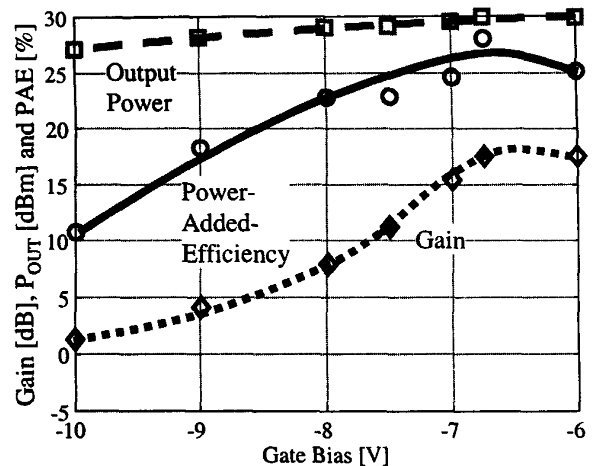

Figure 2. Dependence of output power and power-added-efficiency on gate bias

Small-signal S-parameters were also used to extract equivalent circuit elements under optimal biasing conditions (V_{DS}=15V and V_{GS}= -5V). The small-signal RF transconductance demonstrated notable scaling with the gate width ($G_M \approx$ 100mS/mm) and agreed well with the transconductance extracted from DC measurements. It was observed that the output drain-source capacitance C_{DS}, the input gate-source capacitance C_{GS}, and the feedback drain-source capacitance C_{GD}, also scale linearly with the gate width. The values of C_{GD}, C_{GS}, and C_{DS} capacitance are 120fF/mm, 540fF/mm, and 440fF/mm respectively. This good scalability of the devices is very important for circuit design applications.

III. Bias Dependence of Large-Signal Characteristics

An automatic on-wafer load-pull system with electromechanical tuners has been employed to obtain P_{OUT}-P_{IN} characteristics of GaN-based MODFETs at 8GHz. Both source and load tuners were positioned to obtain best matching and therefore maximum gain at an input power level corresponding to ~1dB gain compression The bias-dependence of output power, power-added-efficiency, and gain was investigated. Devices with 1-mm gate width demonstrated maximum output power (30dBm), PAE (28%), and gain (17.6dB) when the gate bias was set to -6.75V as shown in Figure 2.

Limitations imposed by current handling of the microwave probes and bias tees used in characterization did not allow reducing the gate bias below -6V as this led to drain current in excess of 500mA. Maximum output power and large-signal performance is therefore expected to be higher than described by the results of Figure 2.

The dependence of output power, PAE, and gain of 1-mm gate devices on the drain-bias was also investigated. Maximum PAE (32%) was obtained for drain bias of 15V, while maximum output (30dBm) occurred at 18V. Thermal effects are suggested as a cause for reduced efficiency and output power at drain bias exceeding 18V.

IV. Gate Width Dependence of Large-Signal Characteristics

The dependence of power performance on the gate width was investigated using AlGaN/GaN MODFETs with 2, 4, 6, 8, and 10

100μm-wide gate fingers. All devices were first biased for maximum gain at an input power level corresponding to ~1dB gain compression and load terminations corresponding to small-signal matching conditions. Then the source and load tuners were adjusted improve matching and maximize the gain.

P_{OUT}-P_{IN} characteristics of devices with different gate widths are shown in Figure 3. Biasing conditions, gain, output power, and power-added-efficiency are listed in Table 1. The largest gain (18.2dB) and power density (1.3W/mm) were obtained for devices with 0.6-mm gate width. The largest output power (29.9dBm) with associated gain of 4dB was obtained for devices with 1-mm gate width.

Table 1. Power Saturation Characteristics of AlGaN/GaN Power MODFETs

Gate Width [mm]	V_{DS} [V]	V_{GS} [V]	Gain [dB]	$P_{IN\ -1dB}$ [dBm]	Max P_{OUT} [dBm]	P_{OUT} [W/mm]	PAE_{1dB} [%]
0.2	15	-4.5	15.9	-0.8	22.5	0.89	30.3
0.4	12	-4.5	17.4	3.2	26.0	1.00	28.9
0.6	15	-5.5	18.3	7.8	28.9	1.31	29.5
0.8	12	-5.0	15.9	10.3	28.5	0.87	31.5
1.0	18	-6.75	17.6	7.3	29.9	0.99	28.1

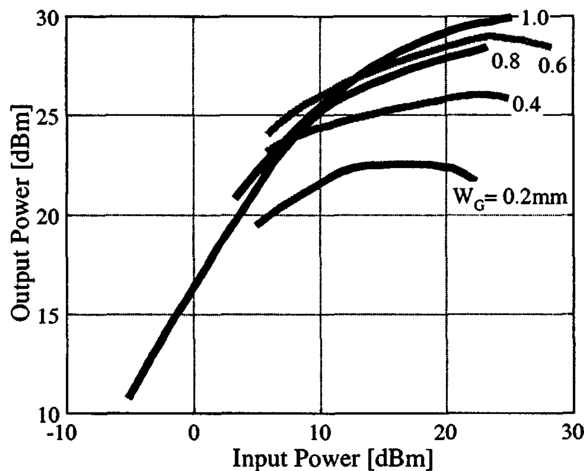

Figure 3. Power saturation characteristics of AlGaN/GaN MODFETs with varying gate width

Devices with wider gates showed delayed onset of gain compression, as demonstrated by higher input power at 1-dB gain compression P_{IN1dB} for gate widths up to 0.8mm.

When the width is increased from 0.2mm to 0.8mm P_{IN-1dB} is increased from -1 to 10dBm, P_{OUT1dB} is increased from 20 to 25dBm, and P_{OUTMAX} is increased from 23 to 30dBm. The output power density (~1W/mm), power-added-efficiency (~30%) and gain (~17dB) remained in general constant.

P_{IN1dB} and P_{OUT1dB} showed a small decrease in 1-mm devices compared with 0.8-mm MODFETs. This is probably caused by the limitations in current handling described earlier, which did not allow operation of the 1-mm devices at their maximum power capacity.

Constant output power (P_{OUT}) and constant power-added efficiency (PAE) contours of AlGaN/GaN MODFETs were evaluated using the load-pull system and allowed to obtain loading conditions for maximum output power and efficiency as necessary for circuit design.

The contours of AlGaN/GaN MODFET with 0.8mm gate under high input power conditions (P_{IN}=22dBm) are shown in Figure 4. The contours were found to remain circular up to power levels corresponding to severe gain compression (~10dB). Moreover, the positions of the optimal loads for maximum P_{OUT}=28dBm and maximum PAE=32% are located close to each other on the Smith Chart. The latter suggests the possibility of power amplifier realization without a considerable tradeoff between output power and power-added-efficiency.

The dependence of the optimal load on the gate width is shown in Figure 5. When the gate width is increased from 0.2 to 1mm, the position of optimal load on the Smith Chart (complex conjugate of the device output impedance) moved along a line corresponding to increased

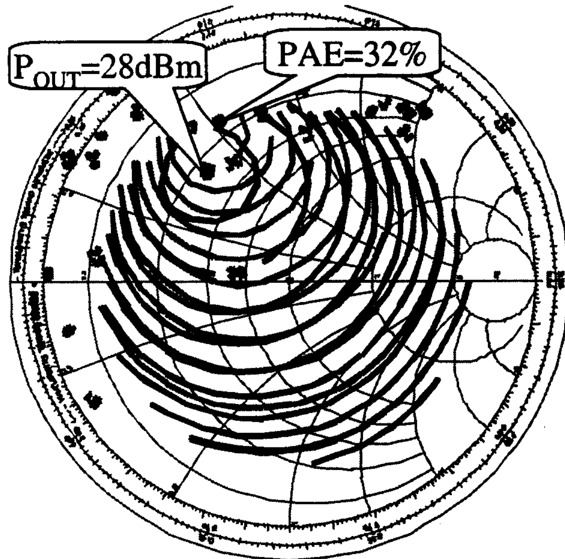

Figure 4. Constant output power (P_{OUT}) and constant power-added efficiency (PAE) contours for GaN MODFET with 0.8mm gate width under P_{IN}=22dBm

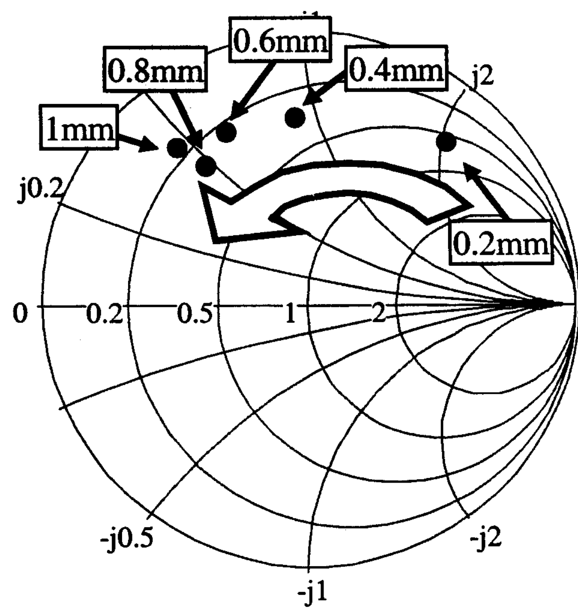

Figure 5. Dependence of position of the matched load tuner on the gate width of GaN MODFETs

output capacitance and decreased output resistance. The large-signal output capacitance was in good agreement with extracted small-signal values, while the large-signal output resistance was significantly reduced under large-signal conditions.

The results illustrate a notable scalability of AlGaN/GaN MODFET power characteristics and demonstrate their excellent potential for power applications.

V. Conclusions

Overall, AlGaN/GaN power-MODFETs with gate widths up to 1mm have been characterized using an automatic load-pull system. High output power (29.9dBm) with high power-added-efficiency (32%) was obtained from discrete devices with 1.0mm gate width. The optimal loads for output power and efficiency were located close to each other as necessary for power amplifier applications. Excellent scalability of small- and large-signal characteristics was observed for devices with gate widths varying from 0.2 to 0.8mm. Very high output power and power-added efficiency were obtained from discrete AlGaN/GaN MODFETs grown on sapphire indicating the high potential of GaN-based technology for power applications.

Acknoledgments

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References

1. Y.F.Wu et al., "Short-Channel $Al_{0.5}Ga_{0.5}N$/GaN MODFETs with power density >3W/mm at 18GHz", Electronics Letters, Vol. 33, n.20, 1997, p 1742-1743
2. T.S.Sheppard at al.,"High power microwave GaN/AlGaN HEMTs on Silicon Carbide", in Late News 1998 56th Annual Device Research Conference, avail. at http://schof.colorado.edu/~drc/drc1998/lateprog.htm
3. N.X.Nguyen et al, "Device characteristics of scaled GaN/AlGaN MODFETs", Electronics Letters, Vol.34, n.8, 1998, p 811-812
4. N.X.Nguyen et al.,"GaN/AlGaN MODFET with 80GHz f_{MAX} and >100V gate-drain breakdown voltage", Electronics Letters, Vol.33, n.4, 1997, p 334-335