High Linearity, Robust, AlGaN-GaN HEMTs for LNA & Receiver ICs

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1. Introduction

AlGaN-GaN HEMTs have not only been identified as the technology of choice for next generation high-power, high frequency applications but recently have also garnered interest for low noise receiver applications[i,ii]. These devices have shown one-order higher power density over conventional GaAs-based HEMTs at X band and exhibit comparable cut-off frequencies for similar gate-lengths[iii]. The high power capability directly translates into the ability to handle a high input power or energy spike without failure in a receiver front-end.

For low-noise applications at microwave frequencies, the most important factors include: 1) channel sheet resistance and, 2) saturation velocity. Traditionally, InGaAs-channel HEMTs excel in both aspects and have been the champion of low-noise devices, with a representative device noise figure of 0.45 dB and circuit noise figure of 1.2 dB at X band.[iv] However these devices are typically limited by the small breakdown voltages and are susceptible to failure due to energy spikes at the input of the receiver, requiring an input protection diode that increases the system complexity as well as noise figure. Inspection of the properties of GaN-channel HEMTs shows that the very high 2-DEG density well compensates the lower mobility leading to a low channel resistance approaching InGaAs HEMTs, thereby enabling low noise figure operation.

In this paper, we will discuss the noise figure and linearity of robust GaN HEMTs for LNA integrated circuits. GaN HEMTs with a low noise figure of 0.75 dB at X-band are presented. We believe this is the first comprehensive report combining all major requirements of a Robust LNA-receiver technology: low noise figure, high linearity and high survivability.

2. Epistructure Growth and Device Fabrication

AlGaN-GaN HEMTs on SiC substrate were grown by MOCVD. An AlN nucleation layer was grown on the SiC substrate followed by an insulating GaN buffer and an AlGaN barrier layer with Al composition greater than 30%. The schematic of the AlGaN-GaN HEMT is shown in Figure 1. Subsequently, AlGaN-GaN HEMTs were fabricated using our standard process described elsewhere[v] and a T-Gate E-beam lithography technology. The gate-length of the fabricated HEMTs was ~ 0.18 μm for the low NF devices. The SEM photograph of a typical AlGaN-GaN HEMT device is shown in Figure 1.

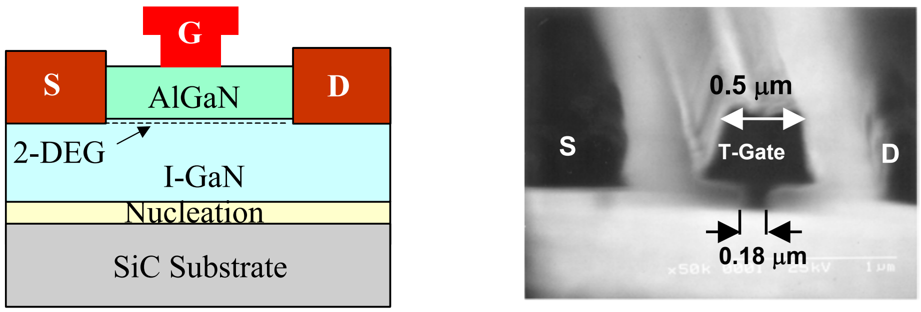

Figure 1. Schematic of the AlGaN-GaN HEMT on SiC & SEM of the 0.18 μm T-Gate

3. Noise Characterization

Noise characterization was done on an ATN Noise measurement system from 2-18 GHz. Noise figure performance was comprehensively studied as a function of gate-length/cut-off frequency, AlGaN barrier thickness, bias current and bias voltage. This resulted in complete mapping of the I-V plane for NF as well as indicated the trends that result from different device designs.

The 0.18-μm gate length devices exhibited a high small-signal gain of 17 dB at X band with an f_τ of 70 GHz and f_{max} of 105 GHz, on par with pHEMTs of the same gate length. The best NF obtained at 10 GHz was 0.75 dB, with a gain of 12 dB. By observing the trends in NF vs. gate-length (f_t), it is expected that a NF could be reduced to the 0.5-0.6 dB range for a device with >100 GHz f_τ. The small-signal frequency and the noise characterization data are shown in Figure 2. The V_{ds} was 15 V and V_{gs} was –4.5 V (~ 10% I_{dss}).

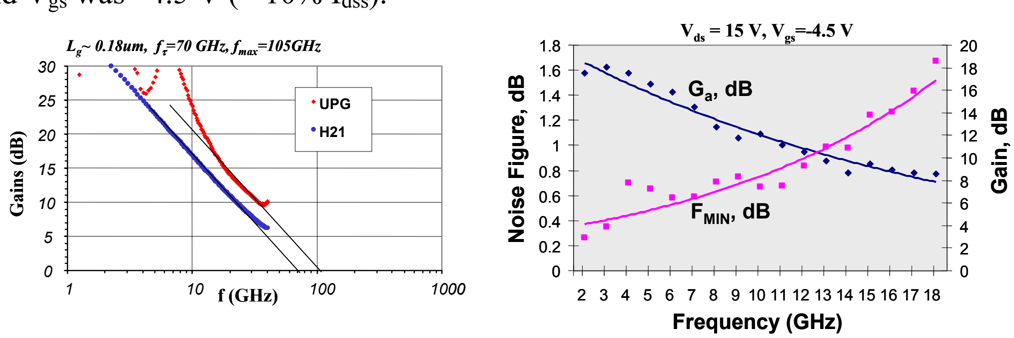

Figure 2. Small-signal characterization and Noise Figure measurement

The four-parameter noise model was also determined for this device giving F_{min} of 0.75 dB, R_n of 40 ohms, the real and imaginary parts of the optimum generator impedance being 0.76 (magnitude) and 14.4 (angle) respectively (W_g=150 μm).

The results of NF versus bias are shown in Figure 3. As a function of gate bias (drain current), the NF is high near pinch-off due to lower gain. As the device comes out of pinch-off, the gain increases and the NF drops. As the drain current further increases, the noise contribution from the drain current increases the NF. The best NF is obtained at about 10-15 % I_{dss}. This also happens to match the range of bias for obtaining high efficiency. With respect to the drain bias, NF is relatively insensitive, as long as the bias is above the knee voltage, in the high gain regime. Thus for the AlGaN-GaN HEMT, drain bias can be chosen to optimize other parameters of interest, such as linearity.

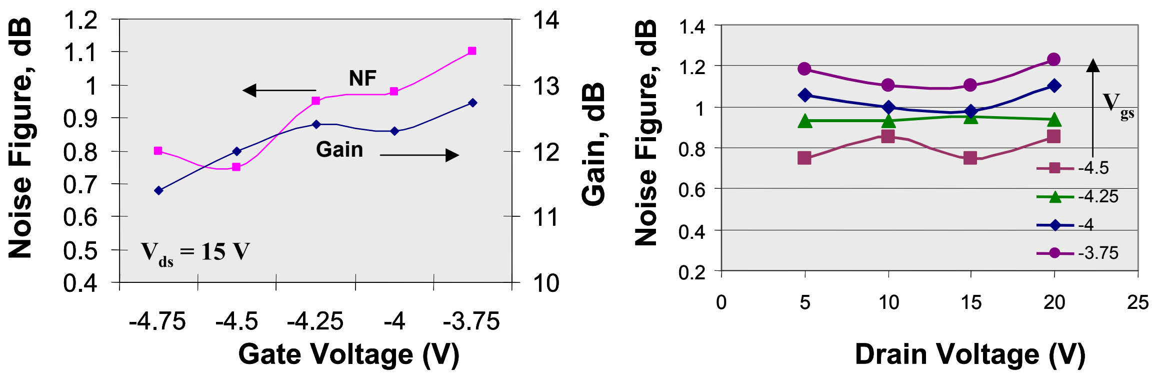

Figure 3. Characterization of NF as a function of bias at 10 GHz. The gate voltage range represents drain current from 5% to 30% I_{dss}.

For another set of devices (with longer gates), we also studied the NF behavior with respect to device parameters such as AlGaN barrier thickness and cut-off frequency. Figure 4 shows the effect of AlGaN barrier thickness (higher AlGaN barrier thickness implies lower transconductance and a higher pinchoff voltage for a fixed charge density). It is observed that for a given current level, it is desirable to have a lower AlGaN barrier thickness. This leads to higher gain and lower noise figure. However if the AlGaN barrier thickness is increased and the charge is also increased then the impact on NF could be different (for example the device resistances would be decreased, positively impacting the NF). It is clearly seen that a high f_τ is essential for lower NF.

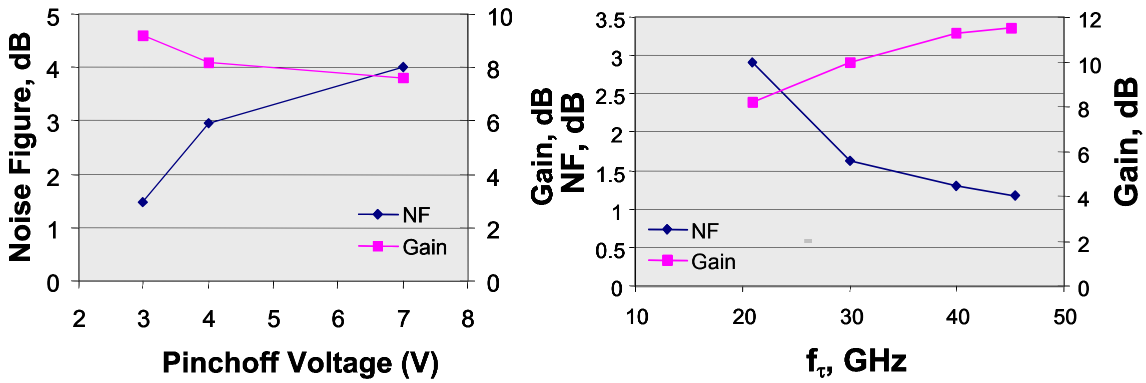

Figure 4. Noise figure as a function of AlGaN thickness/pinchoff voltage and f_t/gatelength

4. Linearity Characterization

Linearity characterization was performed with a two-tone intermodulation test at 10 GHz with an offset frequency of 100 kHz. The performance benchmark for a typical receiver application is the third order output intercept, referred to as the OIP_3. C is the carrier power and I3 is the power in the third order intermodulation product. G_p is the power gain. IP_3 is the power at which the level of I3 is equal to the carrier power. For a theoretical power sweep with class A bias, the I3 has a well-defined slope of 3 and the IP_3, which is the intersection of the two curves, is a fixed value. In most cases, especially for Class AB, and Class B, the IP_3 changes with input power since the I3 may not exhibit a fixed slope of 3. In such cases, extrapolations for IP_3 are more meaningful if taken from the region in which the C and the I3 conform to their expected slopes. The IP_3 is quite relevant for receiver devices like LNAs, which typically operate in the linear regime. A rule of thumb is that for high linearity devices, the separation between OIP_3 (Output Power corresponding to the IP_3 point) and P_{1dB} (1 dB Saturation power) is about 9-10 dB or higher. The results are shown in Figure 5 illustrating an OIP3 of 41 dBm and a LFOM (Linearity Figure of Merit = OIP3/DC Power) of 8.4. The P_{1dB} (single tone) was 29 dBm with a PAE of 30%.

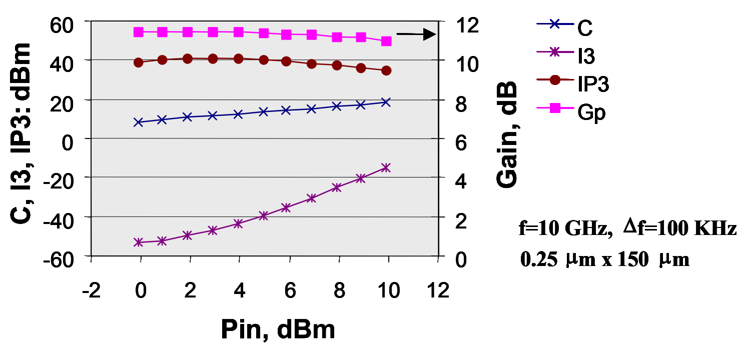

Figure 5. Linearity characterization at 10 GHz

Classic behavior is observed as a function of gate bias where Class AB-Class A operation results in high linearity. As a function of drain bias, linearity degraded at higher drain biases (> 20V). This could be the result of degradation or trapping effects at higher drain voltages and will be investigated in future. The results are shown in Figure 6.

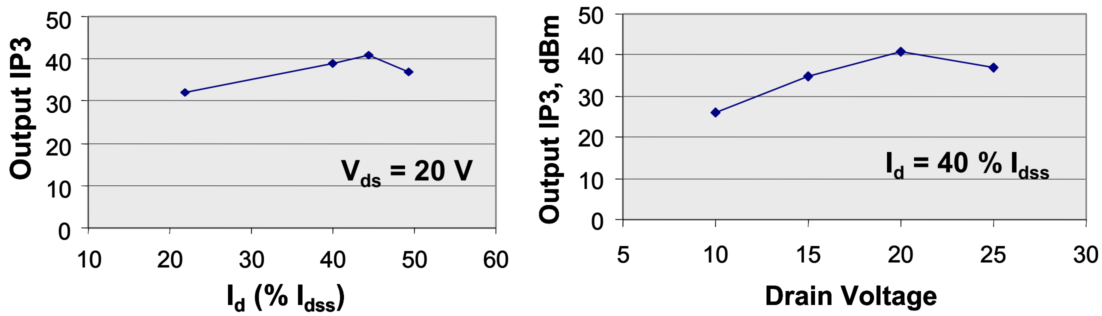

Figure 6. OIP3 (measure of receiver linearity) as a function of bias

5. Survivability Characterization

As stated earlier, the high survivability of GaN based HEMTs is an important feature making these devices attractive for robust LNA applications. We characterized low noise AlGaN-GaN HEMTs for sustaining high input power without failure. For the test device of 0.25 µm x 100 µm, the input survivability (we used maximum CW power with input of 50 ohms, that leads to failure as shown in Figure 7) ranged from 32-37 dBm depending on the bias conditions.

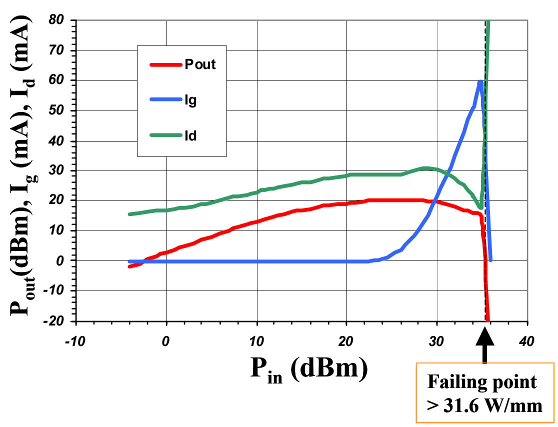

Figure 7. Typical Survivability test

The detailed results as a function of bias are shown in Figure 8. An interesting observation is that the survivability peaks around drain voltages of 25-30 V. At lower voltage, the failure seems to be dominated by the gate current while at higher drain voltages, it is dominated by conventional channel breakdown. These effects have to be investigated in detail and could lead to ways of further improving the survivability.

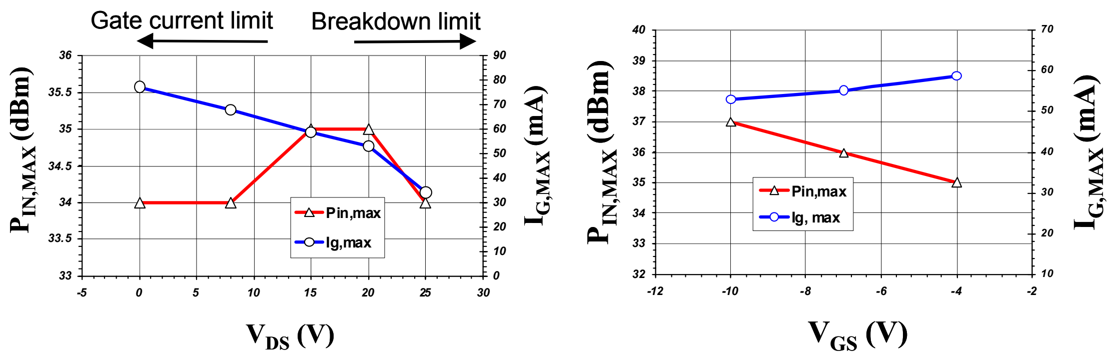

Figure 8 Input survivability as a function of drain and gate bias

While AlGaN-GaN HEMTs promise robust operation for LNA receiver applications, more detailed measures of survivability such as degradation of gain following an input pulse have to be developed and device structures optimizing the same need to be demonstrated.

6. Summary

We have demonstrated 0.18-µm AlGaN-GaN HEMTs with X-band noise figure of 0.75dB and gain of 12 dB. The key to achieving the low noise figure is realizing high f_t with minimized gate leakage. 0.25-µm AlGaN-GaN HEMT devices exhibited OIP3 (2-Tone linearity) of 37-40 dBm, which was about 8-10 dBm higher than P_{1dB}, with the best OIP3 being 41 dBm (12 dBm higher than P_{1dB}) indicating very linear operation. An input survivability capability of 32-50 W/mm (~ 10-15x higher than GaAs/InP) was demonstrated. The high survivability can help eliminate the input protection diode in LNA receivers improving the overall system noise.

With the careful optimization of linearity, noise figure and survivability, AlGaN-GaN HEMTs are very attractive for robust, high dynamic range LNA ICs for receiver applications. Future work will focus on further optimization of the device performance and the development of GaN HEMT LNA ICs. Already the leading candidate for next generation transmit power amplifiers, GaN-based HEMTs have the potential of delivering a complete transmit-receive solution.

Acknowledgments

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