# Power GaN-based Microwave Devices for Wireless Communications

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## Abstract

**Gallium Nitride (GaN) based HEMTs have the potential for being the highest performance power compound semiconductor microwave transistors. In this paper, we review the performance and present results on device scaling for the AlGaN-GaN HEMTs. In particular, 1 and 2 mm wide HEMTs resulted in 8.5 W and 14.5 W output power respectively at X-band with close to 40 % power added efficiency.**

## INTRODUCTION

The wide bandgap, high breakdown field, and high saturation velocity of Gallium Nitride (GaN) based semiconductors enable very high power and high efficiency microwave transistors with several advantages that are well suited for the above applications. Power densities over 9 W per millimeter of gate width, and power added efficiencies in the 40-60% range have been reported[i]. This power density is 10X that of conventional GaAs based transistors. Single stage amplifiers made with these devices have output powers of over 50 W at 6 GHz for relatively small transistors[ii]. High efficiency CW operation with 20 W output power has also been demonstrated[iii]. The next few years will bring much higher powers and improved operation at both microwave and millimeter-wave frequencies. This paper discusses the technology trends and the applications for the devices, with an emphasis on efficient scaling for high yield devices and circuits. 8-15 W Power Devices from 1-2 mm wide GaN HEMTs with ~ 40-50 % PAE are demonstrated

## TECHNOLOGY AND FABRICATION

In this work, high Al content AlGaN/GaN HEMTs on SiC substrates are the baseline devices. The epistructures were grown by metal-organic-chemical-vapor deposition (MOCVD) on semi-insulating SiC substrates. The epi-layers consisted of an insulating GaN buffer and a modulation-doped AlGaN layer to supply charge for the 2-dimensional gas as well as to offer a Schottky-gate barrier. The Al composition was greater than 30%. The processing flow was similar to what was published before[iv]. The gate lengths were 0.5-0.6 μm, defined by optical stepper lithography. For efficient thermal management, device scaling and circuit topology, we have developed the Flip-Chip IC (FC-IC) technology. The

GaN HEMT Epilayers are grown and the individual HEMTs are fabricated on a S.I Silicon Carbide Substrate. The passive circuits elements and the bonding pads, which complete the IC, are fabricated on a thermally conductive IC substrate (e.g. AlN, SiC). The devices are flip-chip bonded onto the circuit/sub-mount to finish the IC. The thermal management achieved by the flip-chip topology is shown in Figure 1. In this work SiC was also used as the flip-chip substrate for the 1 and 2 mm AlGaN-GaN HEMTs on SiC. At the present time, the FC-IC is a promising approach to maximize both device and circuit yield. We are also pursuing a MMIC on SiC (micro-strip with via hole process) technology that has resulted in state of the art performance[v].

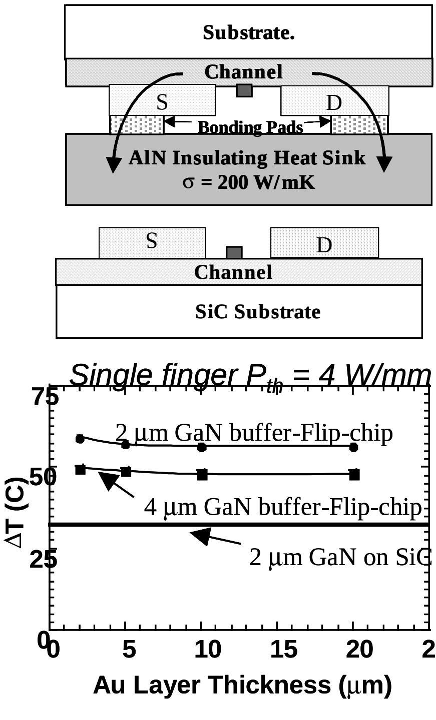

**Figure 1. Flip-Chip IC for Scaling and Thermal Management**

## RESULTS AND DISCUSSION

The power measurements were done on a focus load pull system at 8 GHz. The pulse width used was 5 µs with a 5 % duty cycle. The 1 mm devices exhibited record high power of 8.5 W at a PAE of 38 % (Figure 2) and under conditions for maximum efficiency resulted in 53 % PAE with over 6 W output power. The 2 mm chips delivered 14.5 W with close to 40 % PAE (Figure 3) and 10.7 W with close to 50 % PAE. As a comparison, small devices (100-150 µm) resulted in output power between 8-9 W/mm, demonstrating the efficacy of scaling when going towards larger gate periphery. Amplifier ICs fabricated in this technology have been reported elsewhere[ii]. Fabrication of further scaled devices and amplifier ICs is in progress.

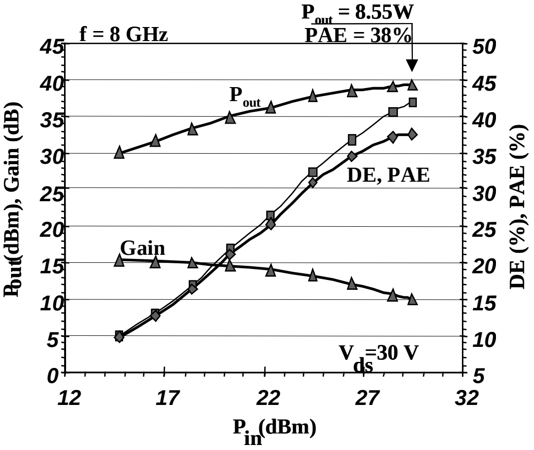

**Figure 2. Power measurements for 1 mm wide HEMT (Optimized for maximum power)**

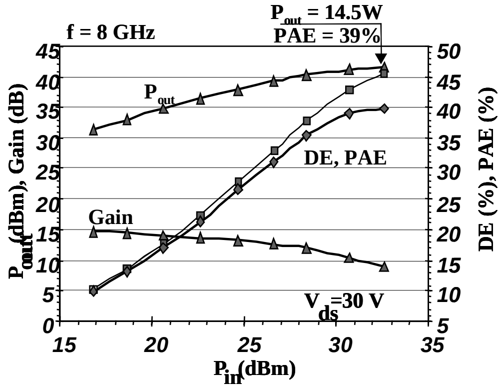

**Figure 3. Power measurements for 2 mm wide HEMT (Optimized for maximum power)**

We also characterized the linearity of the 1 mm HEMTs with 2-tone inter-modulation measurements. The frequency was 10 GHz, with an offset of 100 KHz. The drain voltage was 15 V. The C/I (Carrier to 3'rd order inter-modulation power separation) at peak PAE (~ 25-30 %) ranged from 15-20 dBc, as the bias was varied from Deep Class AB (Figure 4) to Class A. Under Class A conditions, the Output IP3 point was determined to be 44 dBm. It should be noted that the output IP3 is more meaningful for receiver applications while C/I separation or IM3 at a given PAE is more meaningful for transmitter applications. The comparison with 1.2 mm pHEMTs will also be presented. For a similar size device, GaN HEMT maintains a similar C/I ratio at about 7 dB higher output power indicating suitability for high dynamic range applications. We believe that the linearity of the GaN HEMTs can be still significantly improved by addressing the gain compression at higher powers, commonly observed in these types of devices.

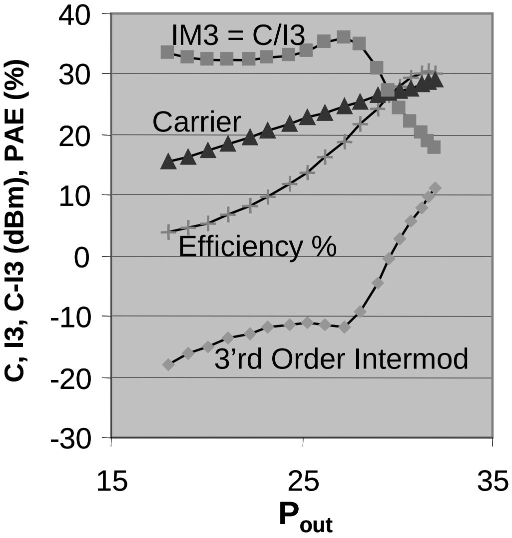

**Figure 4. Two Tone IMD measurements, Deep Class AB bias, $V_{ds}$ = 15 Volts**

## TARGET APPLICATIONS & MARKETS

Device Applications for this new generation of microwave power amplifiers range from wireless communication base stations to broadband access applications such as WLL, MMDS, LMDS, gateway terminals for satellite communications to communication satellite transponders to radar systems and microwave radios. GaN based power amplifiers would target the following rapidly growing communication market segments:

1. L-S bands (0.9 - 4 GHz): Cellular base stations, MMDS, WLL
2. C-X bands (4 -12 GHz): Transceiver modules, Hiperlan, Satcom, VSAT.
3. Ka-Ku bands (12 - 35 GHz): Satcom, LMDS, Digital Radios.

Besides the superior electronic properties of GaN for high power microwave applications, some distinct features make GaN MMICs attractive from a systems perspective. First, with potentially higher efficiency and higher power than GaAs devices, GaN-based MMICs can improve system and product performance. Second, they operate at high voltages (up to 50 V). This eliminates the need for dc-dc power converters in applications such as avionics and satellites. This increases the efficiency and lowers the system cost. Third, high temperature operation opens up the possibility of un-cooled operation, which alleviates system cooling needs required for high power GaAs MMICs, thereby reducing system weight and complexity.

Gallium Nitride HEMTs and MMICs can replace potentially not only traditional GaAs MMICs in several growing wireless infrastructure markets, but also can meet some of the stringent high power, high efficiency and requirements currently not being addressed by GaAs technology. This includes the replacement of microwave power tubes such as TWTs.

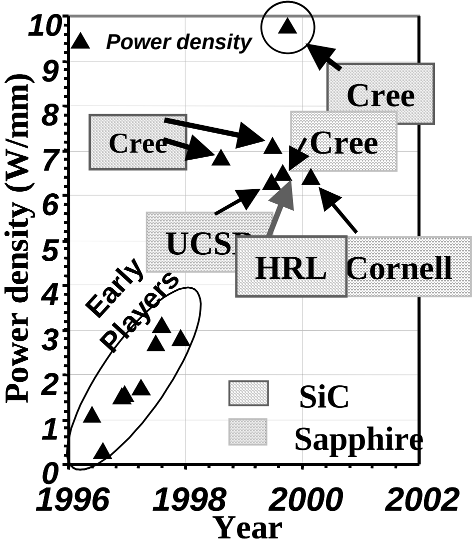

**Figure 5. Progress in Power Density for GaN HEMTs**

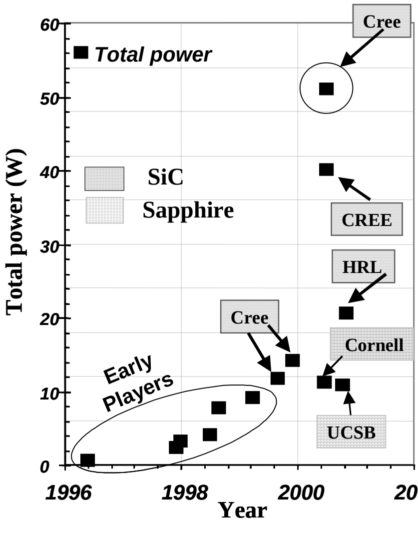

**Figure 6. Progress in Total Output Power from GaN HEMT Devices and ICs**

Finally, the rapid progress in the GaN HEMT arena is summarized in the historical chart in Figure 5 and Figure 6 (the results from Cree include those of Cree Inc., Durham and Cree Lighting Co., Santa Barbara), indicating significant current interest and future promise in this field.

## CONCLUSION

In this paper we have discussed applications of high power microwave AlGaN-GaN HEMTs. Efficient device scaling with the Flip-Chip IC scheme resulted in 1 and 2 mm devices with output power in excess of 8.5 W and 14.5 W respectively. Initial linearity measurements are presented indicating potential of high efficiency operation with high Carrier-Intermodulation separation. Finally the rapid progress in the field of materials (indicated by power density) as well as devices and circuits (indicated by total power output) is surveyed, establishing promise for a high performance manufacturable technology.

## ACKNOWLEDGEMENTS

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