# High-Efficiency and Low-Noise AlGaN/GaN HEMTs for K- and Ka-Band Applications

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## Abstract

**The development of recessed 0.25-µm gate length AlGaN/GaN HEMTs on 3-inch SiC substrates for high power, high power-added efficiency (PAE) and low-noise applications at microwave and millimeter-wave frequencies will be presented. In this work, we have demonstrated 200-µm wide GaN-based recessed HEMTs with PAE of 62, 57 and 41 percent at 10, 20 and 35 GHz, respectively. Furthermore, low minimum noise figures of 1.0 and 1.4 dB were achieved at 18 and 26 GHz, respectively, for 100-, 200- and 300-µm gate-width devices. To the best of our knowledge, this is the first demonstration of GaN HEMTs with state-of-the-art noise and power performance simultaneously. We have developed GaN HEMTs with PAE, gain and noise performance similar to that of best reported GaAs-based pHEMTs but exhibiting 4-5 times of output power densities of pHEMTs.**

## INTRODUCTION

GaAs-based Pseudomorphic HEMT has been the dominant device technology for X-band and up through Q-band power MMIC applications over the last decade. In recent years, Ka-band power performance for GaN-based devices and MMICs (Monolithic Microwave Integrated Circuits) have been reported [1-3]. J. Moon et al. have demonstrated measured maximum PAE of 50% and 45% at 10 and 30 GHz, respectively, in 2005 [1]. Minimum noise figures of 0.98 dB at 18 GHz of 0.25-µm GaN HEMTs were reported by J. Lee et al. [4]. But there is no report yet on AlGaN/GaN HEMT with both excellent low-noise and power characteristics to date. In this study, we would like to present the development of 0.25-µm AlGaN/GaN HEMT on SiC substrate demonstrating outstanding power performance at 10, 20 and 35 GHz and low-noise characteristics at 6 to 26 GHz.

It is a common but not a cost-effective practice for compound semiconductor foundries to develop and maintain several device processes that are individually optimized for achieving best noise, gain, power, and linearity performance separately. For the similar reason, MMIC designers have little choice but compromise at least one aspect of performance specifications for the benefit of high-level circuit integration. Therefore, it is highly desirable to develop this GaN FET on SiC technology capable of producing good noise, gain and power performance simultaneously.

## EPITAXIAL STRUCTURE AND PROCESSING

The AlGaN/GaN HEMT epitaxial layers were grown on 3-inch semi-insulating 6H-SiC substrates by MOCVD (Metal Organic Chemical Vapor Deposition). The first layer of the epitaxial growth is an AlN nucleation layer, followed by a sequence of an undoped GaN layer, an AlN sub-Schottky layer, a 220-Å $Al_{0.28}GaN$ Schottky layer and a GaN cap. Major active device fabrication steps are mesa isolation, Ti/Al-based ohmic metals, rapid thermal anneal (RTA), silicon nitride deposition, gate opening defined by e-beam lithography, reactive-ion-etch (RIE) etching, optional gate recessing, Pt/Au gate metal, overlay metal, silicon nitride passivation and air bridge metal, in that order. RTA was done at 850 degrees C and contact resistances were measured to be about 0.5 ohm-mm. Gate openings were defined by e-beam lithography followed by RIE etch on nitride film using $SF_6$ gas chemistry. Portion of the wafer were gate recessed in an ICP etch tool using $BCl_3$ for 3 to 8 minutes.

## DC CHARACTERISTICS

GaN HEMTs with source-drain gaps of 2-, 3- and 4-µm were fabricated on a 3-inch epitaxial wafer. Fig. 1 shows DC transfer characteristics as a function of gate voltage at a drain voltage of 10 volts of three 50-µm devices with 2- to 4-µm spacing. 2-µm source-drain device exhibits highest maximum transconductance of close to 400 mS/mm and drain current of 1.2 A/mm. At $V_d$ = 10 V and $V_g$ = 1.5 V, device maximum drain current densities ($I_{max}$) were measured to be 1.0 to 1.2 A/mm. Compared with typical pHEMT's $I_{max}$ of 600 mA/mm, GaN HEMTs offer 2X improvement in current drive capability in addition to up to 10-time increase in drain operating voltages.

Transconductance versus gate voltage of a 200-µm GaN HEMT that was recessed for 8 minutes and a non-recess device are plotted in Fig. 2. Recessed devices exhibited 50% higher in $g_m$ compared to the control devices with no gate recess. Typical pinch-off voltage range for non-recessed, 3-minute recessed, 5-minute recessed devices are -4.6 to -4.1, -3.0 to -2.5 and -1.6 to -1.1 volts, respectively.

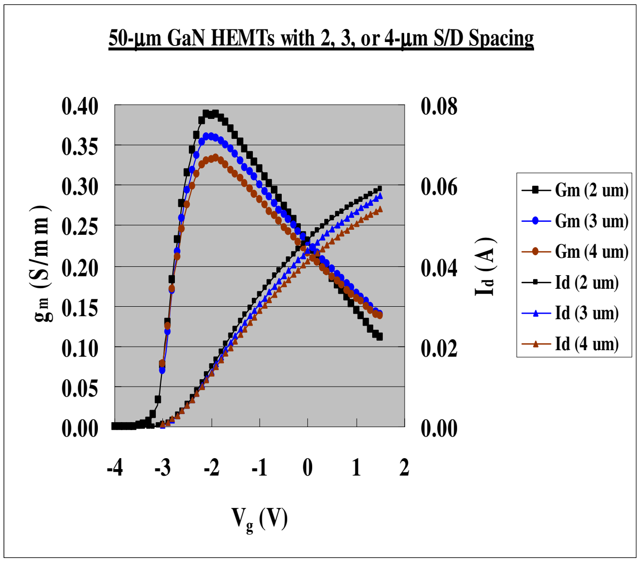

Fig. 1 Pots of $g_m$ (S/mm) and drain current (A) vs. gate voltage of GaN HEMTs with 2-, 3- and 4-µm source/drain spacing.

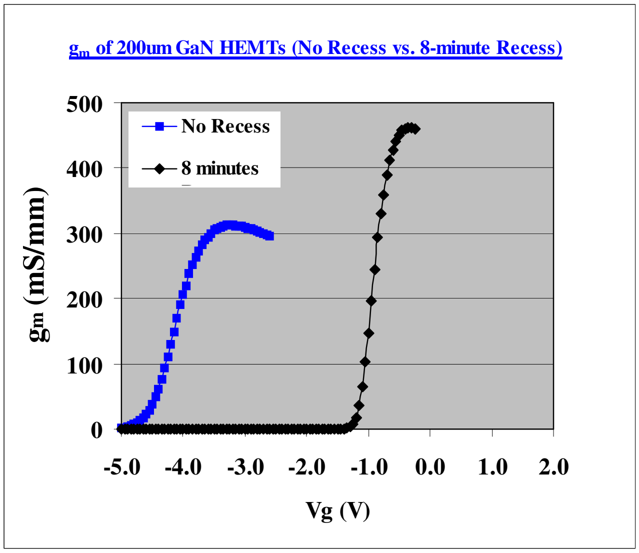

Fig. 2 Transconductance versus gate voltage plots of GaN HEMTs with 8-minute ICP gate recess and without recess.

LOAD-PULL RESULTS AT 10, 20 AND 35 GHZ

We have load-pulled 200-µm (4x50-µm) at 10, 20 and 35 GHz. The 28 V power characteristics at 10 and 20 GHz of 200-µm GaN HEMTs with a 3-µm source-drain spacing are illustrated in Figs. 3 and 4. Very high PAE of 62 and 57%, power gain of 11.1 and 9.9 dB as well as power density of 6.1 and 6.5 W/mm at 10 and 20 GHz were measured respectively.

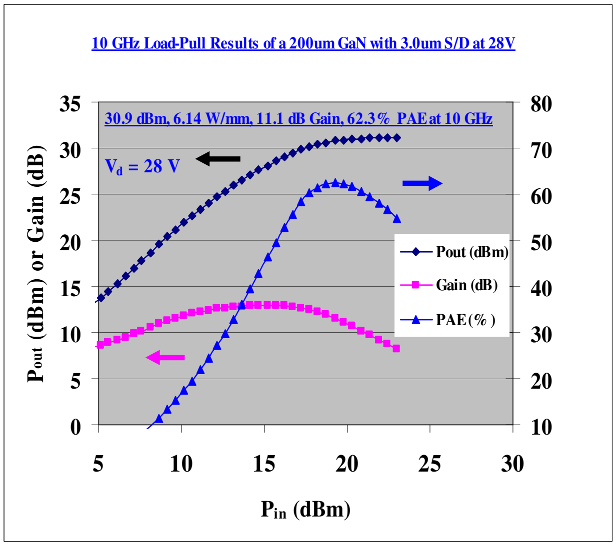

Fig. 3 10 GHz loadpull power characteristics versus input power of a recessed 200-µm GaN HEMT. Bias Conditions: $I_{dq}$ = 25 mA/mm and $V_d$ = 28 V.

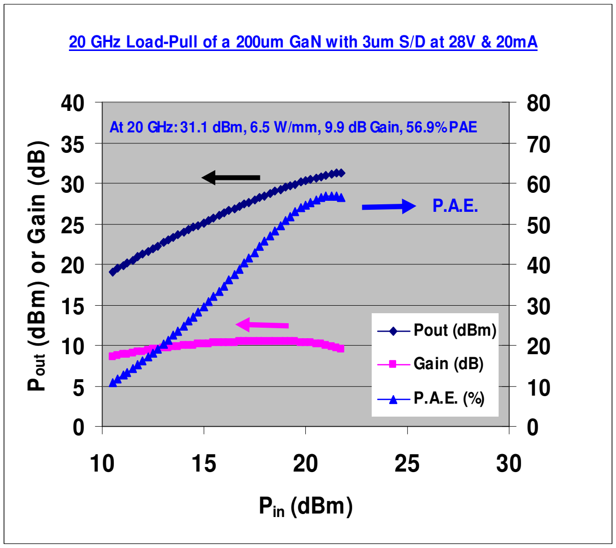

Fig. 4 20 GHz power performance (6.5 W/mm $P_{out}$, 9.9 dB gain & 57% PAE) for a 4 x 50-µm GaN HEMT at 28 volts.

As shown in Fig. 5, 35 GHz load-pull measurements of 0.25x200-µm GaN HEMT with a 2-µm source-drain spacing demonstrated power density of 3.84 W/mm, power gain of 5.8 dB and PAE of 37.2 % at $V_d$ = 20 V and $I_{d,\ quiescent}$ = 20 mA (100 mA/mm). Devices were not saturated during the 35 GHz load-pull measurement due to the limitation of the input drive level. When device was biased at 15 V, higher PAE of 41% but lower power density of 3.0 W/mm were also achieved. Compared to that of one of best reported power pHEMTs at X-, K- and Ka-Band [5], we have achieved GaN HEMTs with comparable gain and PAE performance but with 4 to 5 times of output power density.

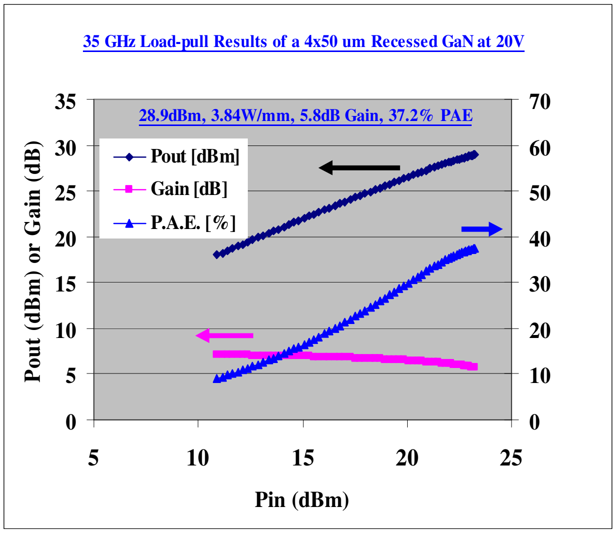

Fig. 5 35 GHz output power (28.9 dBm = 3.84 W/mm), gain and PAE for a 0.25-µm x 200-µm GaN HEMT.

## NOISE PERFORMANCE OF ALGAN/GAN HEMT

100-, 200- and 300-µm GaN HEMT unit cells with 4 gate fingers each from the same wafer were also characterized by on-wafer measurement for noise figure and gain performance. Fig. 6 shows 6-26 GHz minimum noise figure and associated gain characteristics of a 200-µm GaN device at $V_d$ of 5 volts and $I_d$ of 72 mA/mm. Minimum noise figure ($NF_{min}$) were measured to be 0.5, 1.0 and 1.4 dB at 10, 18 and 26 GHz, respectively. Associated gain of 9.1, 6.9, and 5.3 dB at 10, 18 and 26 GHz were also achieved, respectively. We have consistently measured 1.4 to 1.6 dB $NF_{min}$ at 26 GHz for 100- to 300-µm GaN HEMTs. When devices were biased at 10 volts, we have measured comparable minimum noise figures with slightly higher associated gains.

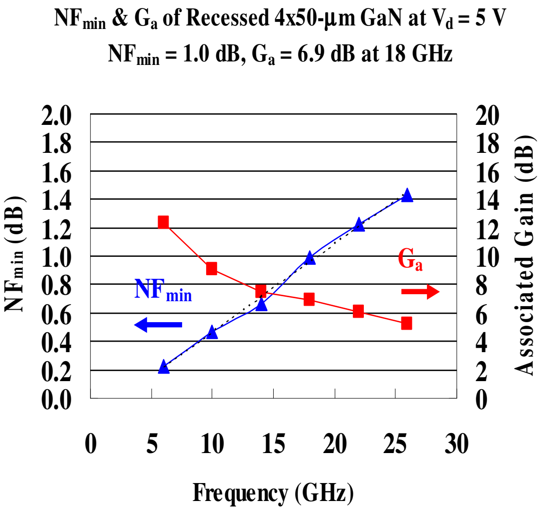

Fig. 6 Minimum noise figure ($NF_{min}$) and associated gain ($G_a$) as a function of frequency for a 4 x 50-µm GaN HEMT at $I_d$ = 72 mA/mm and $V_d$ = 5 V.

## COMPARISONS OF GAN HEMT AND GAAS-BASED PHEMT

Comparisons of dual-recessed 0.15-µm GaAs pHEMTs [5] and recessed GaN HEMTs in this study in terms of minimum noise figures at 26 GHz and power performance at 35 GHz are summarized in Table I. Both device technologies have similar noise, PAE and gain performance, but GaN HEMT produces at least 4 times more output power per millimeter gate width due to its much higher drain voltage capability and drain current density. Silicon carbide also has 7X of GaAs substrate's thermal conductivity ($3.60x10^{-4}$ vs. $5.15x10^{-5}$ W/µm-C) to accommodate higher heat dissipation.

TABLE I
COMPARISONS OF PHEMT AND ALGAN/GAN HEMT

| Device | NFmin 26 GHz (dB) | PAE 35 GHz (%) | Gain (dB) | Power Density (W/mm) |
|---|---|---|---|---|
| PHEMT | 1.1-1.5 | 38 - 44 | 5.5-6 | 0.7-0.9<br>at 6 V |
| GaN HEMT | 1.3-1.5 | 37 - 41 | 5.0-6 | 3.0- 6.1<br>at 15-28 V |
| Comparison | Similar | Similar | Similar | 4-6X |

## CONCLUSIONS

In this study, we have demonstrated recessed 0.25-µm GaN HEMTs with both excellent noise and power characteristics at microwave frequencies. It will simplify compound semiconductor foundry's GaN process offerings since power GaN devices are also well suited for low noise applications. From performance perspective, GaN HEMT would be an excellent device technology to replace GaAs pHEMT or HBT for producing HPA, transmit/receive and multi-function MMICs for S- to Q-band applications.

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## ACRONYMS

PAE: Power-Added Efficiency
HEMT: High Electron Mobility Transistor
MMIC: Monolithic Microwave Integrated Circuit
MOCVD: Metal Organic Chemical Vapor Deposition
RTA: Rapid Thermal Anneal
RIE: Reactive Ion Etch
ICP: Inductively Coupled Plasma