

# AlGaIn/GaN HEMTs with PAE of 53% at 35 GHz for HPA and Multi-Function MMIC Applications

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**Abstract** — We would like to report on AlGaIn/GaN HEMTs on SiC substrate with state-of-the-art power performance at Ka-band. Power gains of 5.6, 6.3 and 6.7 dB and peak PAE of 53, 53 and 51% were measured at 35 GHz when 200- $\mu\text{m}$  GaN HEMTs were biased at 10, 15 and 20 volts, respectively. At 10 GHz, 400- $\mu\text{m}$  GaN HEMTs exhibited maximum PAE of 67%, power gain of 11.3 dB and power density of 5.6 W/mm when devices were biased at 30 volts. Furthermore, we have also achieved 36 to 38.7 dBm TOI at a wide range of 10 to 26 dBm total output power for a 400- $\mu\text{m}$  GaN HEMT. Very low noise figures of 1.4 dB at 26 GHz were measured on 100, 200 and 300- $\mu\text{m}$  wide GaN HEMTs as well. In this work, we have demonstrated that GaN HEMTs on SiC substrate is a much superior device technology to GaAs-based pHEMT for microwave applications up through Ka-band.

**Index Terms** — HEMT, microwave FETs, millimeter wave FETs, MMIC power amplifiers.

## I. INTRODUCTION

It has been demonstrated that GaAs-based pHEMTs can produce close to 1 W/mm output power density, low 40-percent PAE, and 5.3-6 dB power gains at 35 GHz [1]. In recent years, GaN-based HEMTs for Ka-band power amplification applications have been reported [2]-[4]. J. Moon et al. have published on GaN HEMTs with PAE of 45 and 50% at 30 and 10 GHz, respectively, in 2005 [2]. It is also well documented that GaN FETs are capable of generating several to ten times more power than pHEMTs of same size because of its wide band-gap (WBG) properties. But what remains to be answered is that can GaN-based FETs be operated at millimeter wave frequencies efficiently so transistor's junction temperature won't rise over preferred application limit of 150 degree C. In this study, we have substantially advanced the state-of-the-art addressing the efficiency issue of GaN-based FETs at Ka-band. Specifically, we have developed 0.25- $\mu\text{m}$ x200- $\mu\text{m}$  GaN HEMTs with greater than 50% PAE, 5.4 W/mm output power densities and 6.3-7.0 dB power gains at 35 GHz. To the best of our knowledge, these results represent the best reported power performance for any FETs at 35 GHz. Additionally, excellent

noise performance with minimum noise figures ( $NF_{\min}$ ) of 1.3-1.4 dB at 26 GHz for 100, 200 and 300- $\mu\text{m}$  gate-width GaN HEMTs was also achieved. Furthermore, a 400- $\mu\text{m}$  GaN unit cell exhibited 18 GHz Third-Order-Intercept (TOI) values of 36.1-38.7 dBm across a wide range of output power levels when biased at class A operation. In this paper, we would like to present the development of 0.25- $\mu\text{m}$  gate length AlGaIn/GaN HEMTs on 3-inch semi-insulating SiC substrates that are well suited for high efficiency, low-noise and multi-function MMIC applications at microwave and millimeter wave frequencies.

## II. DEVICE FABRICATION AND TRANSFER CHARACTERISTICS

The AlGaIn/GaN HEMT epitaxial layers were grown on 3-inch semi-insulating 6H-SiC substrates in an MOCVD reactor. The material growth was started with an AlN nucleation layer on top of SiC substrates. The subsequent epitaxial layers consist of an un-doped GaN channel layer, an AlN sub-Schottky-barrier layer, an un-doped AlGaIn Schottky layer of 31.5% Al mole fraction and a GaN cap layer. Device isolations were formed by mesa etch in a reactive-ion-etch (RIE) machine. Ti/Al-based metal stack and RTA (Rapid Thermal Anneal) at 850 degree C were used for fabricating source-drain ohmic contacts. Contact resistances were measured to be less than 0.4 ohm-mm. Gate openings were defined by e-beam lithography followed by RIE etch on dielectric film using SF<sub>6</sub> gas chemistry. Portion of the wafer were gate recessed in an ICP etch tool using BCl<sub>3</sub> before Pt/Au metals were put down.

Drain current density of 1,400 mA/mm was achieved at  $V_d = 10$  V and  $V_g = 1.5$  V. Transfer curves of a 0.25- $\mu\text{m}$ x100- $\mu\text{m}$  GaN HEMT are plotted in Fig. 1. Maximum  $g_m$  was measured to be of 501 mS/mm at a gate voltage of - 2.5 volts, a drain current density of 276 mA/mm and a drain voltage of 10 volts.

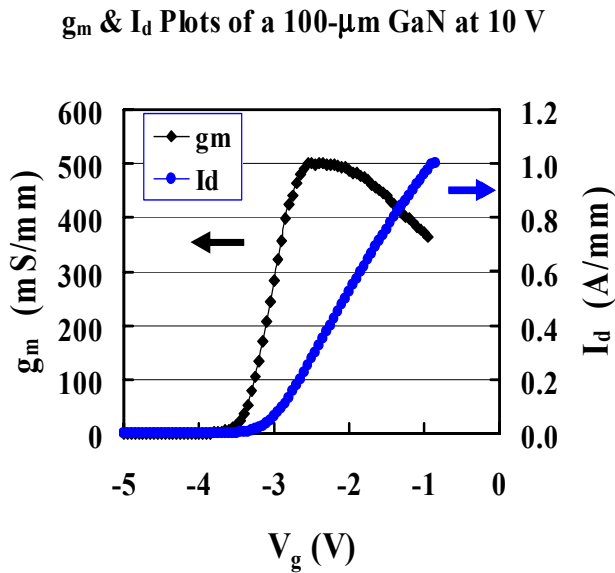


Fig. 1. Plots of  $g_m$  and  $I_d$  as a function of gate voltages at  $V_d = 10$  V. At a gate voltage of  $-2.5$  V, peak  $g_m$  of  $501$  mS/mm was measured for a  $2 \times 50$ - $\mu$ m GaN HEMT.

### III. POWER PERFORMANCE AT 10 AND 35 GHz

We have load-pulled GaN HEMTs at 10 and 35 GHz. As shown in Fig. 2, 35 GHz load-pull measurements of a  $200$ - $\mu$ m ( $4 \times 50$ - $\mu$ m) GaN HEMT with a  $1.8$ - $\mu$ m source-drain spacing demonstrated power density of  $4.5$  W/mm, power gain of  $6.7$  dB and PAE of  $51\%$  at  $V_d = 20$  V and  $I_{d, \text{quiescent}} = 10$  mA ( $50$  mA/mm). Devices were not saturated in the 35 GHz load-pull measurement system due to the limitation of the input drive levels.

$200$ - $\mu$ m devices from same wafer were biased at a reduced drain voltage of  $15$  V, very high PAE of  $53\%$  with lower output power density of  $3.5$  W/mm and power gain of  $6.3$  dB were measured. At a drain voltage of  $10$  volts, measured maximum PAE was still greater than  $50\%$  while output power density and gain were decreased to be  $2.0$  W/mm and  $5.6$  dB, respectively. Comparing these 35 GHz load-pull results at  $15$  and  $20$  V with that of GaAs-based pHEMT operated at  $6$  V, we have demonstrated 3-4 times increase of output power and 5-10 points higher in power-added efficiencies for GaN HEMT.

35 GHz Power Performance of a  $200$ - $\mu$ m GaN HEMT at  $20$  V

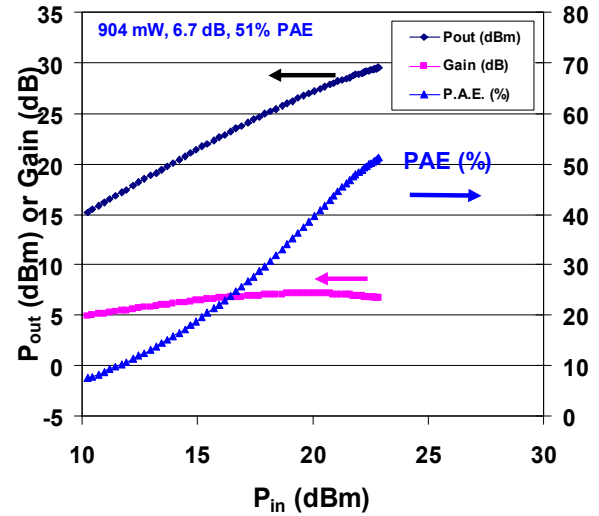


Fig. 2. Plots of output power, PAE and gain versus input power at 35 GHz.  $P_{\text{out}} = 4.5$  W/mm and gain =  $6.7$  dB at maximum PAE of  $51.2\%$ . Bias conditions:  $V_d = 20$  V.  $I_d = 10$  mA.

In addition, we have load-pulled  $400$ - $\mu$ m ( $8 \times 50$ - $\mu$ m) GaN HEMTs with a  $3$ - $\mu$ m source-drain spacing from the same wafer at  $10$  GHz. As illustrated in Fig. 3, when device's drain voltages were increased from  $20$  to  $30$  then  $40$  V, power densities were significantly increased from  $3.1$  to  $5.6$  and  $8.6$  W/mm. Excellent PAE values of  $62$ - $67\%$  and gains of  $11.3$  to  $11.7$  dB were also achieved at  $10$  GHz for this  $400$ - $\mu$ m GaN HEMT. We have successfully demonstrated GaN HEMTs on SiC with better PAE performance and 4 to 5 times of output power densities compared to that of best reported power pHEMTs at both X- and Ka-band.

PAE, Gain & P vs.  $V_d$ ,  $f = 10$  GHz,  $400$ - $\mu$ m,  $25$  mA/mm

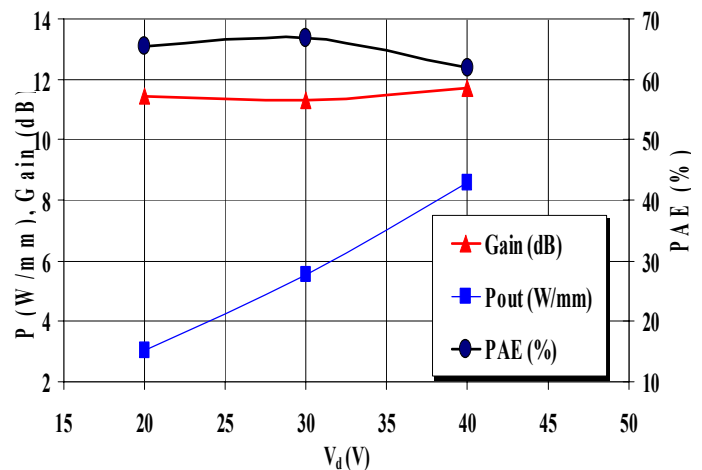


Fig. 3. PAE, gain and output power density at  $10$  GHz as a function of drain voltages from  $20$  to  $40$  V. GaN device:  $8 \times 50$ - $\mu$ m. Quiescent current density:  $25$  mA/mm.

#### IV. TOI, CUT-OFF FREQUENCY AND NOISE PERFORMANCE

Two-tone load-pull measurements at 18 GHz were performed on 400- $\mu\text{m}$  wide GaN HEMT. We have optimized the source and load impedances for achieving the best combination of gain, IMD3 (Third-order Inter-Modulation Distortion) and output TOI characteristics at drain current densities of 100 - 200 mA/mm. As shown in Fig. 4, a gain of 9.1 dB and high TOI values of 36-38.7 dBm across a broad range of total output power of 10 to 26 dBm were demonstrated at  $V_d = 15\text{V}$   $I_{d,\text{quiescent}} = 200$  mA/mm. TOI degradations of this GaN device are much less significant as compared with that of pHEMT [1] going into power saturation.

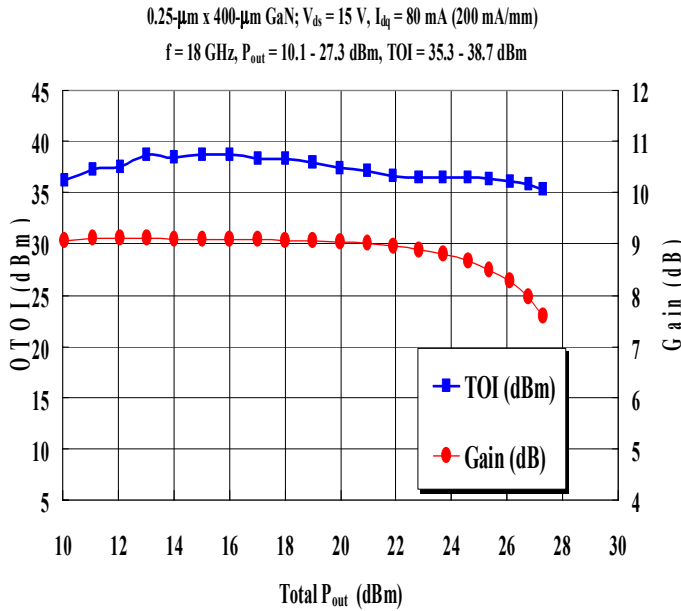


Fig. 4. Output TOI and gain plots at 18 GHz as a function of output power. Flat TOI of 36.0 – 38.7 dBm at a wide range of 10 – 26 dBm total output power. Bias Conditions:  $I_{dq} = 200$  mA/mm and  $V_d = 15\text{V}$ .

Cut-off frequencies of 4x50- $\mu\text{m}$  devices were calculated to be 53, 48 and 46 GHz at  $V_d$  of 10, 15 and 20 V, respectively, based on an equivalent circuit model.

4x25-, 4x50- and 6x50- $\mu\text{m}$  GaN unit cells were also characterized by on-wafer measurement for noise figure and gain performance. Fig. 5 shows 2-26 GHz minimum noise figures and associated gains of a 300- $\mu\text{m}$  GaN device at  $V_d$  of 10 volts and  $I_d$  of 80 mA/mm. Minimum noise figure ( $NF_{\text{min}}$ ) were measured to be 0.54 and 1.38 dB at 10 and 26 GHz, respectively. We have consistently measured 1.3 to 1.5 dB  $NF_{\text{min}}$  at 26 GHz for 100, 200 and 300- $\mu\text{m}$  GaN HEMTs. These GaN devices exhibit noise characteristics similar to that

of pHEMTs while offer substantial improvements in microwave power performance.

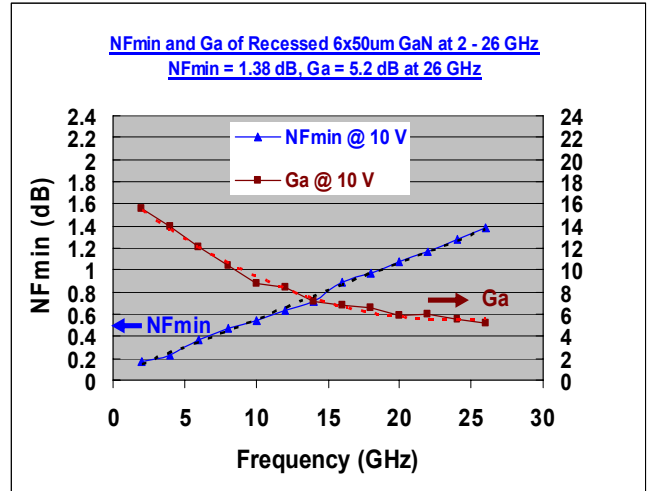


Fig. 5. Minimum noise figure ( $NF_{\text{min}}$ ) and associated gain ( $G_a$ ) as a function of frequency for a 6x50- $\mu\text{m}$  GaN HEMT at  $I_d = 80$  mA/mm and  $V_d = 10\text{V}$ . Measured  $NF_{\text{min}}$  are 0.54 and 1.38 dB at 10 and 26 GHz, respectively.

#### V. CONCLUSION

In summary, we have developed 0.25- $\mu\text{m}$  AlGaIn/GaN HEMTs on 3-inch SiC substrates with state-of-the-art power performance at 10 and 35 GHz as well as excellent noise and TOI characteristics at microwave frequencies. It has great potential to be a superior device technology to replace GaAs pHEMT for HPA, LNA, transmit/receive and multi-function MMICs for microwave and Ka-band applications.

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