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**Authors**

Palacios, T
Chakraborty, A
Rajan, S
et al.

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# High-Power AlGaN/GaN HEMTs for Ka-Band Applications

T. Palacios, *Student Member, IEEE*, A. Chakraborty, S. Rajan, C. Poblenz, S. Keller,
S. P. DenBaars, *Senior Member, IEEE*, J. S. Speck, and U. K. Mishra, *Fellow, IEEE*

***Abstract*—We report on the fabrication and high-frequency characterization of AlGaN/GaN high-electron mobility transistors (HEMTs) grown by molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD). In devices with a gate length of 160 nm, a record power density of 10.5 W/mm with 34% power added efficiency (PAE) has been measured at 40 GHz in MOCVD-grown HEMTs biased at $V_{\mathrm{DS}} = 30$ V. Under similar bias conditions, more than 8.6 W/mm, with 32% PAE, were obtained on the MBE-grown sample. The dependence of output power, gain, and PAE on gate and drain voltages, and frequency have also been analyzed.**

***Index Terms*—Gallium nitride, high-electron mobility transistor (HEMT), high-frequency performance, millimeter-wave (mm-wave) devices, output power.**

SINCE the first demonstration of an AlGaN/GaN high-electron mobility transistor (HEMT) in 1993 [1], the performance of these devices has continuously improved [2]. More than 32 W/mm have already been reported at 4 GHz [3]. However, the use of nitride-based transistors at higher frequencies faces many challenges including: relatively low electron velocity; high access resistances; unreliable passivation; and challenges associated with the fabrication of deep-submicrometer gate length devices. Although good progress has been made in the last years, and output power densities of 5.7 [4] and 2.8 W/mm [5] have already been reported at 30 and 40 GHz respectively, these numbers are still far from the theoretical limit of AlGaN/GaN HEMTs at those frequencies. In this letter, we report on the fabrication and characterization of AlGaN/GaN HEMTs with output power in excess of 10 W/mm at 40 GHz.

Two different samples have been used in this work. Sample A was grown by metal–organic chemical vapor deposition (MOCVD) while in sample B, we used molecular beam epitaxy (MBE). Both samples have similar epitaxial structures consisting of a GaN buffer followed by an AlGaN barrier (25 nm of $\mathrm{Al_{0.32}Ga_{0.68}N}$ in the MOCVD sample and 34 nm of $\mathrm{Al_{0.28}Ga_{0.72}N}$ in the MBE sample). The GaN buffer for the MBE sample was grown utilizing a modulated growth method to yield morphological uniformity. Details on this method of growth will be published elsewhere [6]. The MOCVD sample showed an electron density of $1.4 \times 10^{13}$ cm$^{-2}$ and a mobility of 1350 cm$^2$/V · s from Hall measurements; the MBE sample had a carrier density of $1.0 \times 10^{13}$ cm$^{-2}$ and a mobility of 1500 cm$^2$/V · s. Further information regarding the growth of these samples can be found in [7] for the MBE material and in [8] for the MOCVD samples.

Both samples were processed simultaneously following our standard submicron gate process. A Ti/Al/Ni/Au multilayer was deposited by e-beam evaporation to form the ohmic contacts. The evaporation was followed by rapid thermal annealing at 870 °C in $\mathrm{N_2}$ atmosphere for 30 s. $\mathrm{Cl_2}$-based dry etch was used for mesa isolation. Then, the sample was passivated with a 130-nm-thick $\mathrm{Si}_x\mathrm{N}_y$ layer deposited by plasma-enhanced chemical vapor deposition. A JEOL JBX-5DII e-beam lithography system was used to define the foot of the submicron gates in Zeon ZEP520A e-beam resist. The $\mathrm{Si}_x\mathrm{N}_y$ below the gates was removed by a $\mathrm{CHF_3}$ and $\mathrm{CF_4/O_2}$ two-step dry etch. This etch was followed by a $\mathrm{BCl_3/Cl_2}$ etch to recess the AlGaN barrier with an aim to achieve gate to channel separation of 12 nm in both samples. After the recess, a second e-beam lithography defined the top of the mushroom-shaped gates. MMA copolymer was used as e-beam resist in this second e-beam lithography. A Ni/Au/Ni multilayer was deposited for the Schottky contact. In all the devices the gate length and width are 160 nm and $2 \times 75$ $\mu$m, respectively.

After the processing, good pinch-off characteristics were achieved in both samples, although the output conductance was high ($\sim 30$ mS/mm) due to short channel effects. A maximum drain current (at $V_{\mathrm{GS}} = 2$ V) of 1200 and 1400 mA/mm was measured in the MBE and MOCVD sample, respectively. The difference in maximum current between the two samples has been attributed to the slightly different carrier density and mobility. The maximum transconductance was similar in both samples and it was in the 400–450 mS/mm range. Negligible dispersion was seen under 200–ns gate pulsed conditions with a 50 Ω load line and a maximum $V_{\mathrm{DS}} = 20$ V. The two-terminal breakdown voltage in all the devices was higher than 80 V. In both samples, the maximum current gain, $f_T$, varied from 65 to 70 GHz while the maximum power gain $f_{\max}$ ranged from 85 to 100 GHz at $V_{\mathrm{DS}} = 9$ V. The small-signal high-frequency performance of these devices was limited by the parasitic $C_{\mathrm{GD}}$ capacitance introduced by the $\mathrm{Si}_x\mathrm{N}_y$ passivation. In some devices, the $\mathrm{Si}_x\mathrm{N}_y$ passivation was removed with a buffered HF wet etch to test the effect of the passivation on $f_T$ and $f_{\max}$. After removing the $\mathrm{Si}_x\mathrm{N}_y$ layer, the high frequency performance of these devices increased to $f_T = 130$ GHz with $f_{\max}$ varying from 140 to 170 GHz. According to simulations and

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The authors are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106-9560 (e-mail: tpalacios@ece.ucsb.edu).

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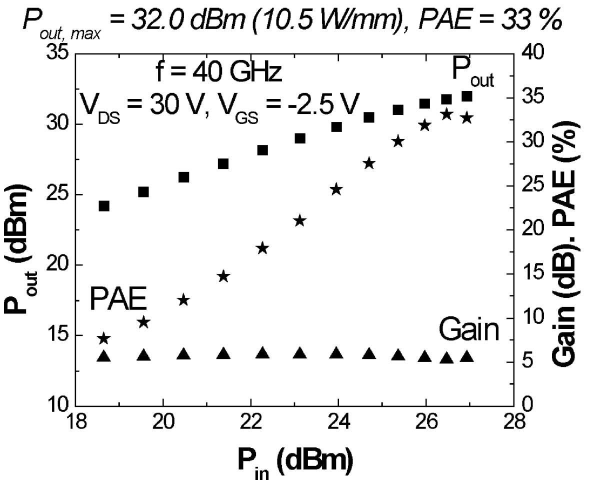

Fig. 1. Power sweep of a mm-wave MOCVD AlGaN/GaN HEMT showing a maximum power of 10.5 W/mm and PAE of 33% at 40 GHz. The drain voltage was 30 V and the drain bias current was 500 mA/mm.

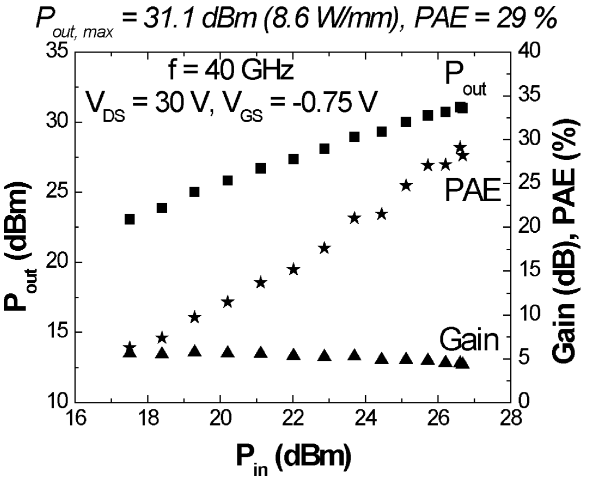

Fig. 2. Power sweep of a mm-wave MBE AlGaN/GaN HEMT with a maximum power of 8.6 W/mm and PAE of 29% at 40 GHz. The drain voltage was 30 V and the drain bias current was 500 mA/mm.

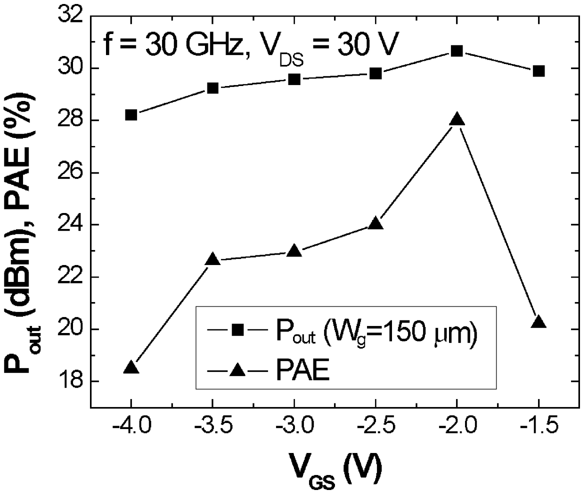

Fig. 3. Variation of maximum output power and PAE with gate bias voltage in a MOCVD transistor at 30 GHz. Similar results were obtained in MBE samples.

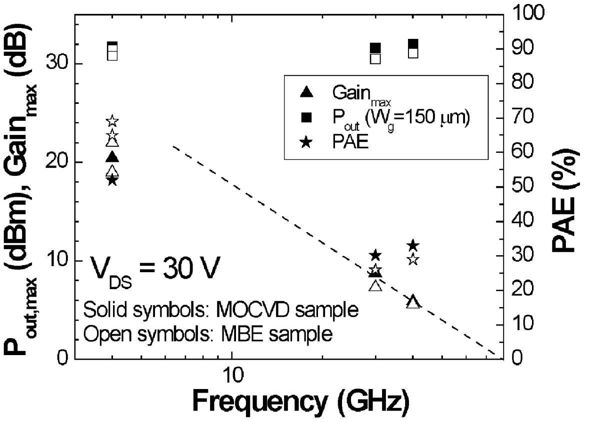

Fig. 4. Dependence of the power performance of mm-wave AlGaN/GaN HEMTs grown by MOCVD (solid symbols) and MBE (open symbols) on the frequency of operation. The dashed line decreases at a rate of 20 dB/decade and it is only a guide to the eye to follow the evolution of the maximum gain. The slightly higher power and PAE at 40 GHz than at 30 GHz is believed to be related to device variations and a slightly better load match at 40 GHz.

small-signal equivalent circuit extractions, this improvement is the result of the lower parasitic capacitances (especially $C_{\mathrm{GD}}$) in the unpassivated devices.

A Maury Microwave load pull system was used to measure the output power at 4 GHz, while a Focus Microwaves load pull system was used at 30 and 40 GHz. Figs. 1 and 2 show the output power and power-added efficiency (PAE) at 40 GHz of typical devices in the MOCVD and MBE samples, respectively. A maximum power of 32 dBm (10.5 W/mm) was measured at 40 GHz in the MOCVD sample, when biased at $V_{\mathrm{DS}} = 30$ V. Due to its lower current density, the MBE sample had a slightly lower output power of 31.1 dBm (8.6 W/mm). It must be noted that in both cases, the output power was still increasing at the highest measured input power. These very high output power results are the result of the combination of both very high current densities and breakdown voltages with negligible knee walk-out and current collapse. In the two samples, the PAE ranged from 29% to 34% and the relatively low $f_{\max}$ limited the gain to 5–7 dB at 40 GHz. Part of our ongoing work is focused on optimizing the gate geometry, passivation thickness and parasitic resistances of these devices to improve their large-signal gain at mm-wave frequencies. Also, the effect of multifinger structures ($> 2$ fingers) on the large-signal gain will have to be studied in the future.

All the power measurements in Ka-band were performed under near-class A operation ($I_{\mathrm{DS,bias}} \approx 500$ mA/mm) with the output match being optimized for maximum power at each bias point and frequency. Very little improvement in PAE was observed when trying to bias the devices closer to pinch-off (see Fig. 3). The low gain, nonoptimum load match for PAE and the difficult coupling of the power transmitted by the harmonics into the power sensor at these high frequencies are believed to be the main causes for the relatively low PAE.

As expected, at lower frequencies the power density did not change but the gain and PAE significantly increased (Fig. 4). More than 22 dB of large signal gain was recorded at 4 GHz. Due to the large available gain, the combination of high output power and PAE was achieved. For example, in the MBE sample,

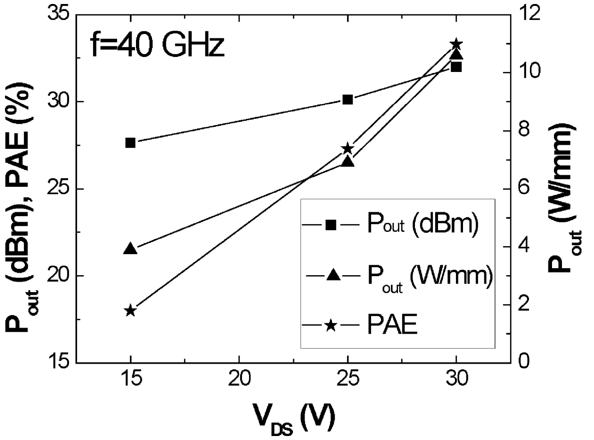

Fig. 5. Change of output power with drain voltage at 40 GHz in a MOCVD AlGaN/GaN HEMT. In each measurement, $V_{\text{GS}}$ and the matching conditions were optimized for maximum output power. A similar behavior is obtained in MBE samples (not shown).

an output power of 8 W/mm with a PAE of 69% was obtained under 3 dB compression and a drain bias voltage of 30 V.

The evolution of output power with drain voltage is shown in Fig. 5 for the MOCVD sample at 40 GHz. The continuous increase in output power when increasing $V_{\text{DS}}$ certifies the good passivation and the low damage of our two-step $\text{Si}_x\text{N}_y$ etch technique. A similar behavior was obtained in the MBE sample (not shown in Fig. 5). PAE also increases with $V_{\text{DS}}$. This increase in power efficiency is the result of the higher gain, lower contribution of the knee voltage to the PAE and a better matching for PAE at higher drain voltages. Due to limitations of the high-frequency bias-tees, the maximum drain voltage that could be applied at Ka-band was 30 V. However, at 4 GHz the devices showed a continuous increase in output power up to 42 V. A maximum output power of 33.1 dBm (13.7 W/mm) with 55% PAE was measured in the MBE sample under these conditions.

In conclusion, we have reported record power performance at Ka-band in transistors grown by MBE and MOCVD techniques. Output powers in excess of 10 W/mm, combined with more than 30% PAE at 40 GHz confirm AlGaN/GaN devices as the most important option for solid-state power amplifiers operating in this frequency range. At lower frequencies (i.e., 4 GHz), the combination of very high breakdown voltage and gain allows the combination of unprecedented high output power levels and efficiency ($P_{\text{out},3\text{ dB}} = 8\ W/\text{mm}$, PAE= 69% for $V_{\text{DS}} = 30$ V).

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