Millimeter-Wave High-Power 0.25-μm Gate-Length AlGaN/GaN HEMTs on SiC Substrates

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***Abstract*—We report on the CW power performance at 20 and 30 GHz of 0.25 μm × 100 μm AlGaN/GaN high electron mobility transistors (HEMTs) grown by MOCVD on semi-insulating SiC substrates. The devices exhibited current density of 1300 mA/mm, peak dc extrinsic transconductance of 275 mS/mm, unity current gain cutoff (f_T) of 65 GHz, and maximum frequency of oscillation ($f_{\max}$) of 110 GHz. Saturated output power at 20 GHz was 6.4 W/mm with 16% power added efficiency (PAE), and output power at 1-dB compression at 30 GHz was 4.0 W/mm with 20% PAE. This is the highest power reported for 0.25-μm gate-length devices at 20 GHz, and the 30 GHz results represent the highest frequency power data published to date on GaN-based devices.**

***Index Terms*—GaN, high electron mobility transistors (HEMTs), microwave power, SiC.**

I. Introduction

GALLIUM nitride-based high electron mobility transistors (HEMTs) are excellent candidates for high power and high frequency applications at elevated temperatures [1]–[3]. This is due to the advantageous material properties such as wide bandgap (3.4 eV for GaN to 6.2 eV for AlN) leading to high breakdown fields (1–3 × 10^6 V/cm) and high saturated electron drift velocity (2.2 × 10^7 cm/s). Also, the AlGaN/GaN heterostructure with its high conduction band offset and high spontaneous and piezoelectric polarizations exhibits high sheet carrier densities in the 10^{13} cm^{-2} range. As a result of these superior material properties and improving material growth and processing technologies, microwave power densities have been demonstrated that are five to ten times greater than that of GaAs-based devices. A CW power density of 10.7 W/mm with 40% power added efficiency (PAE) has been reported at 10 GHz for a device with 0.3-μm gate length [4]. At 20 GHz, 3 W/mm CW with 22.5% PAE has been attained for 0.3-μm gate-length devices [5] and 6.6 W/mm CW with 35% PAE for 0.15-μm gate-length devices [6]. The highest-frequency power data published to date is a pulsed-power density of 1.6 W/mm with 26% PAE at 29 GHz for a 0.2-μm gate-length device [7]. In this letter, we present our results on 0.25-μm gate-length AlGaN/GaN HEMTs on SiC substrates. These 0.25-μm gate-length devices exhibited 6.4 W/mm CW saturated output power at 20 GHz and 4.0 W/mm CW at 1-dB compression at 30 GHz. This performance indicates the potential for very high power solid-state amplifiers employing 0.25-μm gate-length GaN-based HEMTs to replace TWT amplifiers in space-based millimeter-wave communications systems.

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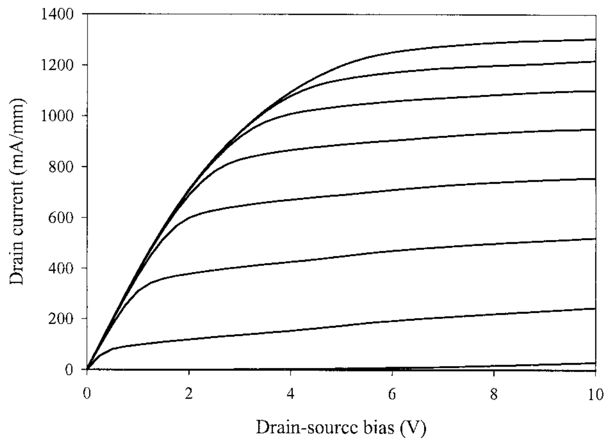
II. Device Structure and Fabrication

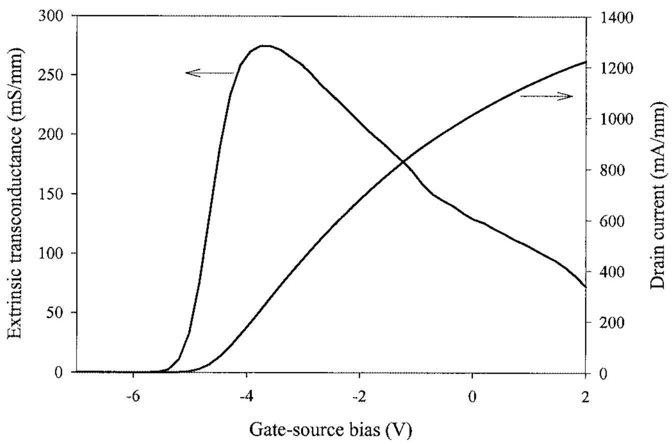
The layer used in the present study was grown on semi-insulating (0001) 4H-SiC substrates by metal-organic chemical vapor deposition (MOCVD). The epilayer consists of a 100-nm AlN buffer, 2-μm undoped GaN, a 5-nm undoped $Al_{0.25}Ga_{0.75}N$ spacer, a 10-nm Si-doped ($\sim$5 × 10^{18} cm^{-3}) $Al_{0.25}Ga_{0.75}N$ charge supply layer, and a 10-nm undoped $Al_{0.25}Ga_{0.75}N$ barrier layer. Hall measurements showed a sheet carrier concentration of 1.1 × 10^{13} cm^{-2} and an electron mobility of 1300 cm^2/volt-s at room temperature on as-grown wafers. The first step for device fabrication was mesa-isolation using Cl_2/Ar plasma in an inductively-coupled-plasma reactive ion etch (ICP-RIE) system. Ohmic contacts were formed by rapid thermal annealing of evaporated Ti/Al/Mo/Au at 840 °C for 30 s [8]. Using on-wafer transfer-length-method (TLM) patterns, the ohmic contact resistance was measured to be $\sim$0.35 ohm-mm typically. T-shaped gates (Ni/Au) with gate-length (L_g) of 0.25 μm were defined using electron-beam lithography. The devices had a gate-width of 100 μm and a source-drain spacing of 3 μm. Finally, the devices were passivated with 120-nm thick silicon nitride.

III. DC and Small Signal Characteristics

The dc measurements were carried out using an Agilent 4142B modular dc source monitor. Fig. 1(a) shows typical drain current-voltage (I_D–V_{DS}) characteristics for a device. The gate was biased from 2 to −7 V in −1-V increments. The maximum drain current density is 1300 mA/mm at a gate bias of 2 V and drain bias of 10 V. The excellent nature of the ohmic contacts is shown in the fact that the knee voltage is less than 4 V. Fig. 1(b) shows typical dc extrinsic transconductance and drain current at a drain-source voltage of 6 V. The peak extrinsic transconductance is 275 mS/mm at −3.76-V gate bias. The threshold voltage $V_{\rm th}$ is −4.6 V, where $V_{\rm th}$ is defined



(a)



(b)

Fig. 1. (a) Drain current-voltage (I_D–V_Ds) characteristics for 0.25 pm × 100 pm AlGaN/GaN HEMT on SiC substrate. The gate bias was swept from 2 to -7 V in -1-V increments. (b) DC extrinsic transconductance and drain current versus gate bias of the 0.25 μm × 100 μm AlGaN/GaN HEMT. The drain bias was 6 V.

as the gate bias for which the drain current extrapolates to zero from the maximum transconductance point.

Small signal RF performance is shown in Fig. 2. S-parameter data was taken on an Agilent 8510B network analyzer from 1 to 40 GHz at the device's peak-f_T bias point of 12 V drain-source voltage and -3.75 V gate-source voltage. The f_T of the device is 65 GHz, as determined by extrapolating the short-circuit current gain $| h_{21}|$ at -20 dB/decade. The maximum frequency of oscillation $f_{\max}$ is 110 GHz and is determined by extrapolating the maximum stable gain (MSG) at -20 dB/decade.

IV. Large Signal Characterization

Large signal CW measurements were performed using a Focus Microwaves automatic load pull system. The data was taken on-wafer at room temperature without any thermal management. The large signal performance of a device at 20 GHz is shown in Fig. 3. The device was biased with a drain source voltage of 30 V at a drain current of 620 mA/mm. The device has a saturated output power of 6.4 W/mm with an associated gain of 2.9 dB and PAE of 16%. The peak efficiency is 22% with an output power of 5.8 W/mm and gain of 6.1 dB. Fig. 4 shows the large signal performance at 30 GHz. With a drain

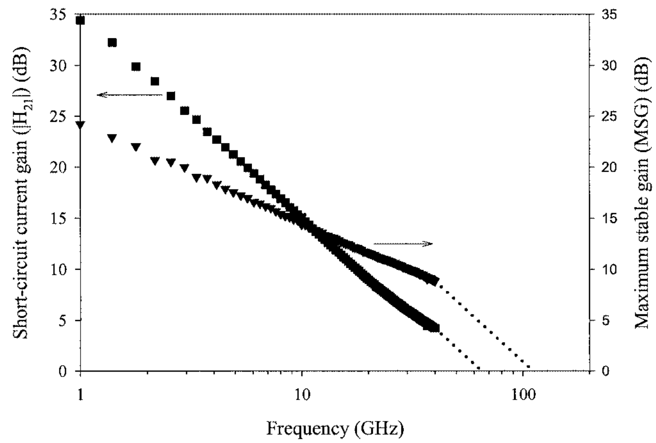


Fig. 2. Short-circuit current gain ($|h_{21}|$) and maximum stable gain (MSG) versus frequency. Extrapolating at -20 dB/decade yields f_T of 65 GHz and $f_{\max}$ of 110 GHz. The device was biased for maximum f_T with $V_{DS} = 12$ V and $V_{GS} = -3.75$ V.

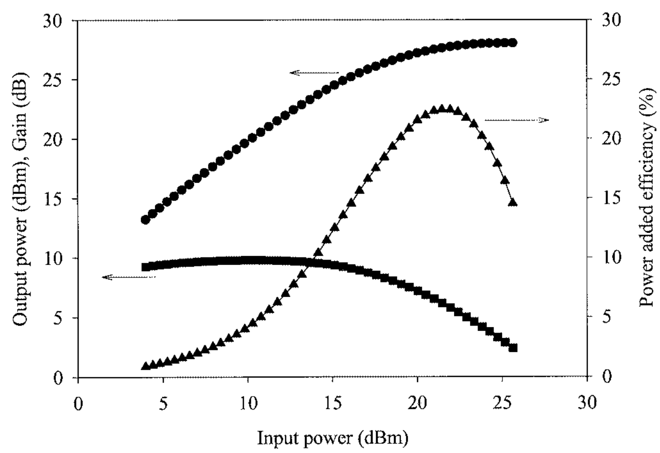


Fig. 3. Large signal performance of the 0.25 μm × 100 μm AlGaN/GaN HEMT at 20 GHz. The device was biased with $V_{DS} = 30$ V and $V_{Gs} = -1.87$ V. Saturated output power is 6.4 W/mm with 2.9-dB gain and 16% PAE. Maximum PAE is 22% with 5.8 W/mm and 6.1-dB gain.

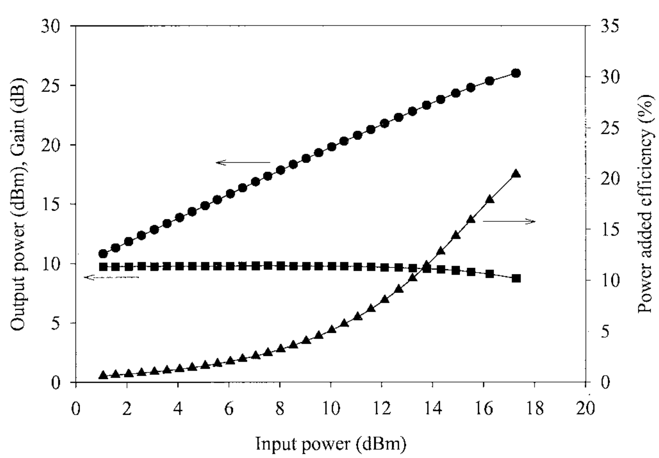


Fig. 4. Large signal performance of the 0.25 μm × 100 μm AlGaN/GaN HEMT at 30 GHz. The device was biased wth $V_{DS} = 25$ V and $V_{GS} = -2.22$ V. Output power at 1-dB compression at 30 GHz is 4.0 W/mm with 8.7 dB gain and 20% PAE.

voltage of 25 V and drain current of 670 mA/mm, the device output 4.0 W/mm at 30 GHz at 1-dB compression with 8.7-dB gain and 20% PAE. The device was not tested beyond the 1-dB compression level at 30 GHz because the drive capability of the load pull system was reached. To the best of the authors' knowledge, 6.4 W/mm is the highest power density reported at 20 GHz for a 0.25-μm gate-length GaN-based HEMT. This is also the first reported CW power performance at 30 GHz for a GaN-based HEMT.

V. Conclusion

This letter reports on the CW power performance at 20 GHz and 30 GHz of 0.25 μm $\times$ 100 μm AlGaN/GaN HEMTs on SiC substrates. The devices exhibited high current density, transconductance, f_T, $f_{\max}$, and millimeter-wave output power density. Saturated output power at 20 GHz was 6.4 W/mm with 16% PAE, and output power at 1-dB compression at 30 GHz was 4.0 W/mm with 20% PAE, representing the highest power reported for 0.25 μm gate-length devices at 20 GHz and the highest frequency power data published to date on GaN-based devices. These results indicate the potential of 0.25-μm gate-length GaN-based HEMTs for very high power solid-state amplifiers to replace TWT amplifiers in space-based millimeter-wave communications systems.

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