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AlGaN/GaN HEMTs—Operation in the K-Band and Above

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***Abstract*—We report on the power and microwave noise performance of AlGaN/GaN high electron-mobility transistors (HEMTs) at frequencies $f > 18$ GHz (K- and Ka-bands). At 20 GHz, a record continuous-wave output power of 1.6 W has been achieved on an eight-finger 500-μm total gate-periphery device. At 29 GHz, a 120-μm gate-periphery device showed a pulsed output density of 1.6 W/mm with an associated gain of 6.7 dB and power-added efficiency of 26%. Minimum noise figure of 1.5 dB has been achieved on a 0.2 μm $\times$ 200 μm device at 26 GHz. The data demonstrate the viability of AlGaN/GaN HEMTs for high-frequency power and low-noise amplifier applications.**

***Index Terms*—GaN, high electron-mobility transistor (HEMT), K-band, microwave noise, microwave power.**

I. Introduction

GaN AND related alloys have established themselves as very promising candidates for high-power high-frequency applications. Large energy gaps and resulting high breakdown fields, high electron saturation velocity, and high electron densities in AlGaN/GaN high electron-mobility transistor (HEMT) structures have led to microwave power performance significantly exceeding the performance of state-of-the-art GaAs and InP-based devices. Continuous-wave (CW) power densities as high as 11.2 W/mm have been demonstrated on the AlGaN/GaN devices at 10 GHz [1]. AlGaN/GaN HEMT X-band power amplifiers showed CW output power levels of 22.9 [2] and 38 W [3]. In the Ku-band, a GaN monolithic microwave integrated circuit (MMIC) operating at 16 GHz has recently been demonstrated with the total CW output power of 24.2 W [3].

Excellent input power-handling capabilities also make AlGaN/GaN HEMTs very attractive for use in low-noise amplifiers (LNAs). This application is getting more attention after a number of recent reports on the relatively low noise in AlGaN/GaN HEMT devices [4], [5]. GaN HEMT devices in LNA front-ends will eliminate the need for extraneous RF limiting circuitry, which degrades the noise performance of the LNA and overall system performance.

While the performance of GaN HEMTs in the L–Ku-bands has been thoroughly investigated in recent years, very few reports are available on the operation of these devices at frequencies $f \geq 18$ GHz [2], [6] that are important for satellite communication and high-performance radar applications. In this paper, we report on the power and noise performance of AlGaN/GaN HEMTs in the K- (18–27 GHz) and Ka-bands (27–40 GHz).

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II. Device Structure and Fabrication

The AlGaN/GaN structure was grown by metalorganic chemical vapor deposition (MOCVD) on top of a semi-insulating SiC substrate at the University of South Carolina, Columbia. The structure consisted of a 0.1-μm AlN layer, 1.5-μm-thick GaN buffer layer, and a 25-nm-thick $Al_{0.2}Ga_{0.8}N$ barrier. Transmission-line matrix (TLM) measurements yielded an average sheet resistance of 380 Ω/sq for the wafer used in this study.

The AlGaN/GaN HEMT fabrication process is based on the TRW's mature GaAs and InP HEMT processes designed for high-volume production [7], [8]. Therefore, it typically demonstrates excellent uniformity and reproducibility. The device mesa etch was performed using the HBr/BCl_3 electron cyclotron resonance (ECR) plasma etching technique. Ti/Al/Ni/Au ohmic contacts with an average contact resistance of 0.65 $\Omega \cdot$ mm were formed by alloying at 880 °C in a nitrogen atmosphere. Electron beam lithography was utilized to fabricate 0.2-μm Pt/Au T-gates in a 2-μm source–drain region. The devices were passivated with PECVD SiN and two levels of interconnect metal including air bridges were used for external connection. The process also includes thin-film resistors and metal–insulator–metal capacitors.

III. DC and Small-Signal Performance

Fig. 1 shows the transfer characteristics of a four-finger 40-μm total gate-periphery (4×40) AlGaN/GaN HEMT biased at $V_{\rm ds} = 8$ V. The maximum drain current density measured at $V_{\rm g} = +1$ V was 1.14 A/mm. The peak transconductance of 293 mS/mm was achieved at $V_{\rm gs} = -2.1$ V. Drain current densities in excess of 1 A/mm and peak transconductance around 300 mS/mm were typical for devices on the wafers used in this study. The typical on-state breakdown of these devices was ∼40 V.

Small-signal RF performance of AlGaN/GaN HEMTs was characterized by on-wafer S-parameter measurements in the 1–49-GHz range. Fig. 2 shows the small-signal current gain, $|h_{21}|$, and the unilateral power gain U of a typical four-finger 200-μm total gate-periphery GaN HEMT. At $V_{\rm ds} = 20$ V and $I_{\rm ds} = 425$ mA/mm, the device demonstrated the current gain cutoff frequency (f_t) of 44 GHz. A maximum oscillation

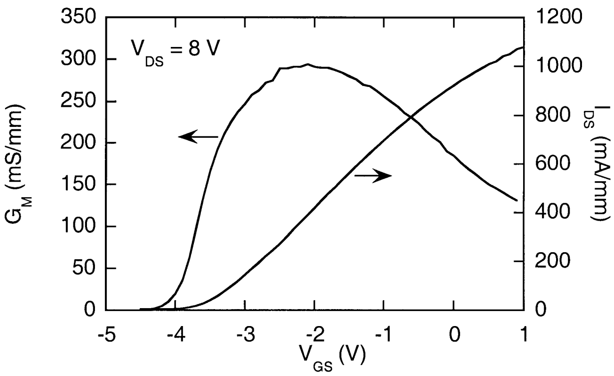

Fig. 1. Transfer characteristics of a typical four-finger 40-μm total gate-periphery AlGaN/GaN HEMT at a source–drain bias of 8 V.

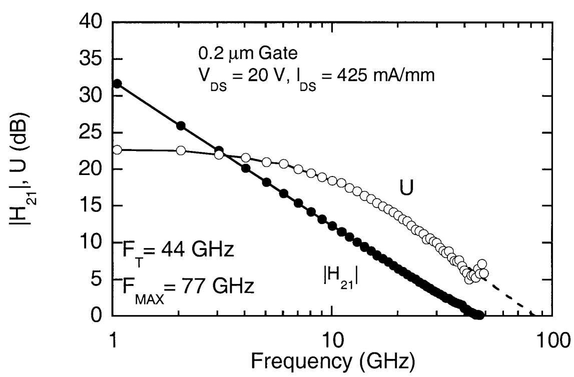

Fig. 2. Small-signal RF performance of a four-finger 200-μm total gate-periphery AlGaN/GaN HEMT. The unity current gain cutoff frequency (f_t) and maximum oscillation frequency $(f_{\max})$ were determined to be 44 and ~80 GHz, respectively.

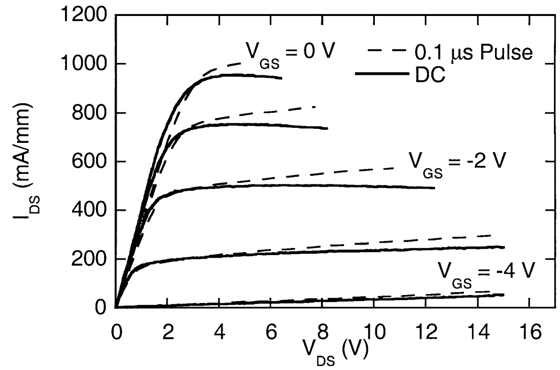

Fig. 3. DC (solid lines) and pulsed (dashed lines) *IV* characteristics of a ten-finger 1-mm total gate-periphery AlGaN/GaN HEMT. The pulsewidth was 0.1 μs with 1-ms separation.

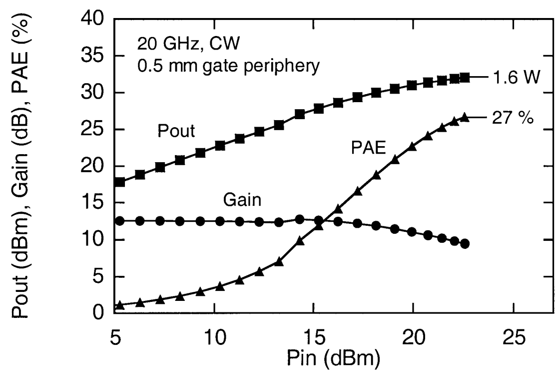

Fig. 4. Power performance of a 500-μm gate-periphery AlGaN/GaN HEMT showing a total CW output power of 1.6 W at 20 GHz. The device was biased at $V_{\rm ds} = 25$ V and $I_{\rm ds} = 200$ mA.

frequency $(f_{\max})$ of ~80 GHz was obtained by extrapolating the part of the unilateral gain curve having a ~20-dB/decade slope (15–30 GHz) toward the abscissa axis. The measured f_t is believed to be limited by high channel access resistance and parasitic capacitances that will be mitigated by further improvements in the HEMT profile and the existing AlGaN/GaN HEMT process.

The high levels of dc current in AlGaN/GaN HEMTs are not always easily reproducible under fast ac or pulsed gate drives. The reduction of drain current and increase in the knee voltage in AlGaN/GaN HEMTs under RF conditions caused by the presence of both bulk and surface electron traps have been discussed in many recent publications devoted to GaN devices [11]–[13]. Ultimately they lead to a reduced RF output power and poor efficiency. However, the right choice of the device passivation scheme, as well as careful epitaxial growth optimization, have been shown to solve this problem. Fig. 3 shows dc and pulsed (0.1-μs pulse) current–voltage characteristics of a ten-finger 1-mm total gate-periphery device used in this study. The negligible difference between dc and pulsed *IV* characteristics, which is observable only below the knee voltage, clearly indicates the absence of trapping effects in the processed devices. The difference between the dc and pulsed *IV* curves at high drain biases is simply a manifestation of self-heating.

IV. Large-Signal Characteristics of GaN HEMTs

CW power measurements at 20 GHz were performed on eight-finger devices with the total gate periphery of 500 μm (8 × 500) using a Q-band Focus load–pull system. The results of the on-wafer load–pull measurements are shown in Fig. 4. When biased and tuned for the maximum output power, the device under investigation showed a total output power of 1.6 W with an associated power-added efficiency (PAE) of 27% and gain of 10 dB (Fig. 4). To the best of our knowledge, this is the highest output power reported for AlGaN/GaN transistors at 20 GHz. The corresponding power density was 3.2 W/mm. This relatively low value of the power density in comparison to the power densities reported for small devices at 20 GHz (6.6 W/mm for a 2 × 50 μm device [6]) is related to the compact device geometries used in this experiment. The gate pitch of the devices was 40 μm, which we believe is insufficiently wide to mitigate severe self-heating. Wider gate pitches will reduce the thermal resistance of the devices and lead to more ideal operation.

We also performed on-wafer power measurements on AlGaN/GaN HEMTs at 29 GHz. Fig. 5 shows the results of the pulsed load–pull measurements at 29 GHz using a 4-μs pulse and a 400-μs duty cycle. The pulsed output power density of 1.6 W/mm with an associated gain of 6.7 dB and PAE of 26%

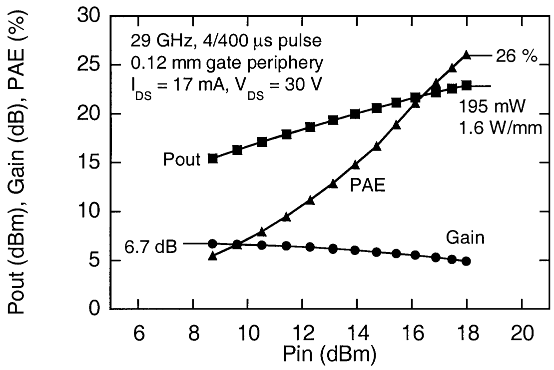

Fig. 5. Power performance of a 120-μm gate-periphery AlGaN/GaN HEMT at 29 GHz. The pulsed on-wafer power measurements were performed using 4-μs pulses and a 400-μs duty cycle.

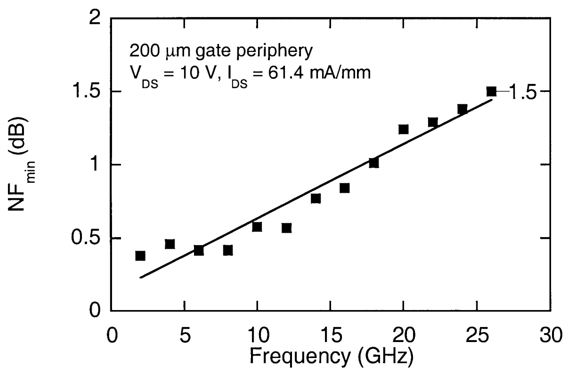

Fig. 6. Minimum noise figure versus frequency for the typical 0.2-μm AlGaN/GaN HEMT with a gate periphery of 200 μm. The solid line represents a linear fit to experimental $\mathrm{NF}_{\min}$ data.

was achieved on a 120-μm total gate-periphery device. Our load–pull system was unable to achieve optimal tuning for this size device, which resulted in lower power density.

V. Microwave Noise Performance

High-frequency noise performance of the devices was measured using an ATN noise parameter test set. Noise-figure measurements have been performed from 2 to 26 GHz. A plot of the noise characteristics as a function of frequency for a four-finger 200-μm total gate-periphery device is shown in Fig. 6. The minimum noise figure increases linearly as a function of frequency and reaches 1.5 dB at 26 GHz. This is comparable to the $\mathrm{NF}_{\min}$ of 1.4–1.6 dB typically demonstrated by GaAs HEMTs at this frequency. By going to shorter gates, the f_t of the devices can be significantly increased and much better noise performance is expected. This data clearly demonstrate that AlGaN/GaN HEMTs are excellent candidates for high performance and highly survivable microwave LNAs.

VI. Summary

In this paper, we have investigated the power performance of AlGaN/GaN HEMTs at frequencies $f \geq 20$ GHz. At 20 GHz, a record-total CW output power of 1.6 W has been achieved on a 500-μm gate-periphery device when the device was tuned for the maximum output power and a maximum PAE, respectively. At 29 GHz, the 120-μm gate-periphery AlGaN/GaN HEMT exhibited a pulsed output power density of 1.6 W/mm with a gain of 6.7 dB and PAE of 26%. These results indicate that nitride-based devices are well suitable for high-power operation in the K-band and above in different commercial, military, and space applications. Future improvements in the AlGaN/GaN performance at high frequencies is feasible through better thermal effect management. This would involve the optimization of device topology, as well as development of efficient packaging techniques. In addition, initial microwave noise measurements performed in the frequency range of 2–26 GHz demonstrate the possibility for building robust low-noise GaN-based LNAs.

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