High-power Density W-band MMIC Amplifiers using Graded-channel GaN HEMTs

Jeong-sun Moon[1], Bob Grabar[1], Joel Wong[1], Joe Tai[1], Ignacio Ramos[1], Erdem Arkun[1], Chuong Dao[1], Dave Fanning[1], Nicholas C. Miller[2], Michael Elliott[2], Ryan Gilbert[2], Nivedhita Venkatesan[3], Patrick Fay[3]
[1]HRL Laboratories, USA
[2]The Air Force Research Laboratory Sensors Directorate, WPAFB, USA
[3]Department of Electrical Engineering, University of Notre Dame, USA
jmoon@hrl.com

***Abstract* —We report the W-band amplifier performance of graded-channel GaN HEMTs with f_T and f_{MAX} of 170 GHz and 347 GHz, respectively. Graded-channel GaN HEMTs with a gate periphery of 0.15 mm show a peak power-added-efficiency of 50% at 94 GHz at 2.2 W/mm associated power density after de-embedding of the matching network loss of 0.3 dB. Pre-matched power cells with 0.6 mm total gate periphery yielded 2.1 W output power and 3.5 W/mm power density at 94 GHz. Finally, we report three-stage W-band amplifiers with a peak gain of 22.5 dB at 92.5 GHz, yielding 7.5 dB gain per stage.**

***Keywords*—GaN, MMIC, mm-wave, W-band, communications, 5G, 6G.**

I. INTRODUCTION

Advanced millimeter-wave transceiver systems, including future 5G FR2 and 6G mobile networks, are of great interest to support high data rate communications (e.g., 10 Gbps or higher) and backhaul communications with > 50 Gbps. Since E-band and W-band can also support multi-GHz bandwidths, there is also growing interest in phased-array implementations. With its inherent integration advantage, SiGe phased arrays with excellent performance were demonstrated at W-band [1, 2] with the latest result of > 10 Gbps data rate using 16 QAM with up to 60 dBm effective isotropic radiated power [2]. In the case of point-to-point wireless links, III-V technologies (e.g., pHEMT) have also been utilized in full-duplex W-band links; for example, a peak data rate of 10 Gbps over 2 GHz bandwidth with 128 QAM was demonstrated [3].

For high-power W-band applications, GaN HEMTs have been evaluated also. For instance, several ~1 – 2 Watt W-band GaN MMIC PAs were reported with PAE of about 21% [4-7]. In 2020, a state-of-the-art 6 Watt GaN PA was reported at 95 GHz with an associated PAE of 18% [8]. Also, a 100 W W-band GaN SSPA was demonstrated with low-loss waveguide power combining [9]. Additionally, Niida et al., reported 1.15 Watt (3.6 W/mm power density) MMIC power amplifiers at 86 GHz using InAlGaN/GaN HEMTs [10]. Despite these developments, there is a trade-off between the PAE and output power of these W-band amplifiers with current device technologies.

Very recently, graded-channel (GC) GaN HEMTs demonstrated leading-edge RF and mm-wave power performance at 30 GHz and 94 GHz [11-18], due to a reduced peak electric field and improved saturation velocity [14, 15]. Excellent low-noise and linearity performance (0.5 dB NF_{min} at 30 GHz) was demonstrated with graded-channel HEMTs with f_T/f_{MAX} of 170 GHz/360 GHz [11], as were Ka-band low-noise amplifiers with a record linearity figure-of-merit, OIP3/Pdc, of 17.5 dB [16]. In terms of RF/mm-wave power applications, graded-channel GaN HEMTs demonstrated a record device-level PAE of >70% at 30 GHz [12], and linear Ka-band power scaling up to 6 W/mm [16], and 50% device level PAE at 94 GHz at 2.2 W/mm from a small 0.15 mm GaN HEMT devices [18]. In this paper, we report W-band MMIC amplifiers fabricated in graded-channel GaN HEMT technology.

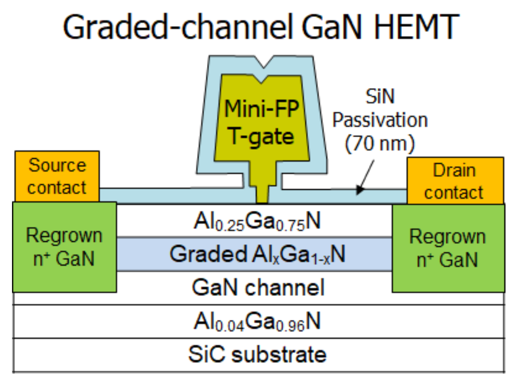

Fig. 1. Schematic of mini-field-plate T-gate graded-channel GaN HEMT with 50 nm gate-length

II. LINEAR AND HIGH-SPEED GAN DEVICE

Figure 1 shows a cross-sectional schematic diagram of a graded-channel GaN HEMT. A SiC substrate was used for efficient heat extraction, and a 50 nm gate-length T-gate with integrated mini-field-plate (mini-FP) was used to enhance lateral electric field control [17]. The HEMT channel consists of a GaN layer and a graded AlGaN layer, below an AlGaN barrier layer to linearize the device transconductance and the gate-to-source capacitance. To reduce the device ohmic loss, the source and drain ohmic contacts were formed using an n^+ GaN regrowth layer, in conjunction with a Ti/Pt/Au ohmic metallization layer. The measured ohmic contact resistance with this approach was about 0.1 ohm-mm.

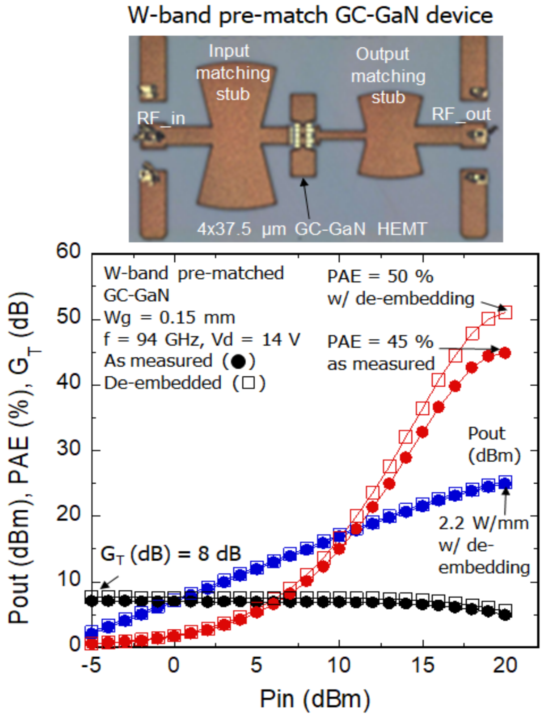

Fig. 2. (a) Optical micrograph of a fabricated W-band pre-matched GC-GaN HEMT, and (b) Measured power performance of the pre-matched graded-channel GaN device at 94 GHz at V_{ds} = 14V.

The small-signal RF performance of 4x37.5 µm device with source – drain spacing of 1.5 µm was measured on-wafer from 0.1 – 67 GHz and the pad parasitics were de-embedded with conventional open and short structures. The device's f_T was estimated to be 170 GHz, and the f_{MAX} was estimated to be 347 GHz from both the measured maximum stable/available gain (MSG/MAG) and Mason's unilateral gain U.

III. W-Band High-PAE GaN HEMTs

Figure 2(a) shows an optical image of a fabricated pre-matched W-band graded-channel (GC)-GaN HEMT embedded in a microstrip Thru-Reflect-Line (TRL) launcher. The pre-matched 4 x 37.5-µm-wide GC-GaN HEMTs bring the source and load matching points close to 50 ohms. A W-band scalar Maury load-pull system with on-wafer TRL calibration was used to establish the reference plane at the GaN transistor manifold during the in-situ tuner characterization. The delta-G_T values were within 0.15 dB, which is a good validation of 94 GHz large-signal measurements. Figure 2(b) shows the 94 GHz power performance of the pre-matched GC-GaN device with and without the de-embedding. After de-embedding the metal losses, the transistor linear gain becomes 8 dB at V_{ds} = 14V with a peak PAE of 50% at a power density of 2.2 W/mm, which is a state-of-the-art performance at 94 GHz. We note that the de-embedding done here only compensates for the metallic losses of the input and output matching stubs; to be conservative and not to overestimate the device-level performance, our de-embedding does not include the mismatch loss between the matching stubs and GC-GaN HEMT.

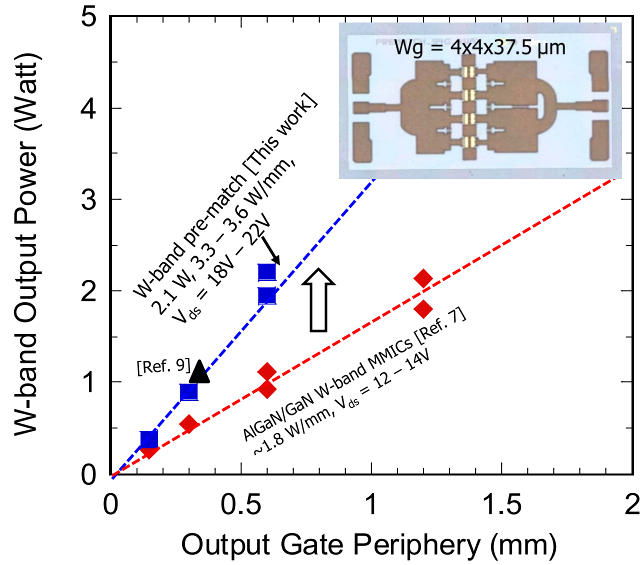

Fig. 3. Measured power performance of the pre-matched graded-channel GaN devices at 94 GHz, outputting 2.1 W with 3.5 W/mm power density.

IV. W-Band Power Amplifiers

To characterize the GC-GaN HEMTs for high-power applications in W-band, both 0.3 mm and 0.6 mm periphery pre-matched GC-GaN HEMT devices were designed and fabricated, as shown in the inset of Figure 3. Figure 3 shows the measured continuous-wave (CW) power performance of the pre-matched GC-GaN HEMT devices versus the total gate periphery at 94 GHz, compared with the prior work reported with conventional AlGaN/GaN HEMTs. At V_{ds} = 18V, the output power of the 0.6 mm wide GaN power cell was 1.95 W with 3.3 W/mm power density. At V_{ds} = 20V, the output power was 2.1 W with a power density of 3.5 W/mm. At V_{ds} = 22V, the output power was 2.2 W with a power density of 3.67 W/mm at 94 GHz. This illustrates that the GC-GaN HEMTs can deliver the MMIC power density of >3 W/mm from large output cells.

Figure 4 shows an optical micrograph of 3-stage W-band MMIC PA, where the output stage has a 0.6 mm total gate periphery. The drive ratio was 2:1 in this design.

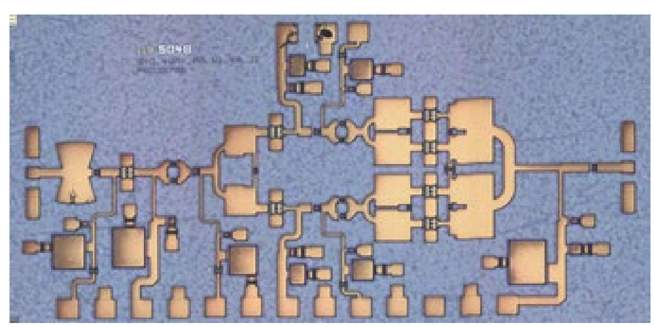

Fig. 4. An optical micrograph of the fabricated 3-stage W-band MMIC PA with the graded-channel GaN HEMT, where the output stage has 0.6 mm total gate periphery.

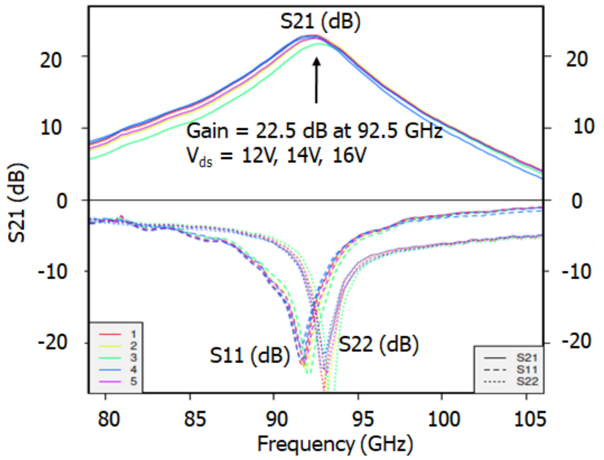

Fig. 5. Measured small-signal gain of the 3-stage W-band MMIC PAs, yielding 22.5 dB at 92.5 GHz with 7.5 dB gain per stage.

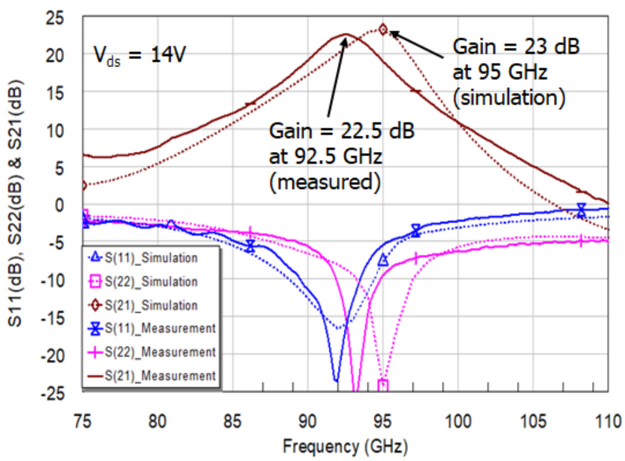

Fig. 6. Measured and modeled small-signal gain of the 3-stage W-band MMIC PAs, showing an excellent agreement. The simulation predicts a peak gain of 23 dB at 95 GHz with 7.6 dB gain per stage.

Figure 5 shows the measured small-signal S-parameters at V_{ds} = 12 V, 14V, and 16V. The MMIC DC bias current density was 200 mA/mm. The peak gain is 22.5 dB at 92.5 GHz with S_{11} and S_{22} well below -10 dB.

Figure 6 shows the measured and modeled small-signal gain of the 3-stage W-band MMIC PAs, showing an excellent agreement. The simulation predicts a peak gain of 23 dB at 95 GHz with 7.6 dB per stage, while the measurements show a gain of 22.5 dB and 7.5 dB per stage.

V. Conclusion

In summary, emerging graded-channel GaN HEMTs are reported for W-band power applications with the 3-stage MMIC PAs with a peak gain of 22.5 dB at 92.5 GHz. An output power cell with 0.6 mm gate periphery demonstrated 2.1 Watt and 3.5 W/mm power density at 94 GHz. Combined with the previously reported linear low-noise amplifiers, this demonstrates that graded-channel GaN HEMTs are promising for mm-wave amplifiers for 5G and future communication systems.

Acknowledgment

This material is based upon work supported by DARPA under contract number FA8650-18-C-7802. The views expressed are those of the author and do not reflect the official policy or position of the DARPA or the U.S. Government. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Government. Approved for public release, distribution unlimited.

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