

Highly-Linear and Efficient mm-Wave GaN HEMT Technology

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Abstract — Realizing high-performance mm-Wave 5G and beyond communication systems will require transistors with higher linearity and efficiency than current technology options. While GaN HEMTs offer excellent power density, their limited linearity and efficiency compromise overall system performance; this requires substantial DC power consumption and power back-off to circumvent. Here, we report the linearity of graded-channel GaN HEMTs at 30 GHz and compare their performance to that of conventional AlGaIn/GaN HEMTs. For low-noise amplifier applications, the graded-channel GaN HEMTs offer the linearity figure-of-merit, OIP3/P_{DC}, of 20 dB at 30 GHz, well beyond the 10 dB rule of thumb. For power amplifier applications, a two-tone PAE of 62% was obtained experimentally, which is a state-of-the-art result. We find that ~3 dB back-off from peak PAE is sufficient to achieve a carrier to third-order intermodulation (C/IM3) ratio of 30 dBc. Further, the efficiency under this back-off condition provides an associated PAE of 55% at 30 GHz. Hence, the graded-channel GaN HEMTs are promising for mm-wave linear and efficient amplifiers, including 5G applications.

I. INTRODUCTION

GaN is a wide bandgap semiconductor with a 3.4 eV bandgap with a corresponding breakdown field as high as 3.4 MV/cm, compared with Si's critical field of 0.3 MV/cm. While Si LDMOS has been the historical choice for cellular base station power amplifiers, GaN power amplifiers (PA) made a sizable in-road to the 4G base station PAs when Huawei deployed GaN PAs in their 4G base stations. The currently deployed sub-6 GHz 5G network provides a peak data rate of 20 Gbps, which is a 10x improvement in peak data rate, compared with 4G network performance. The next-generation mm-wave 5G network will provide a peak data rate of 20 Gbps with 1 msec latency. As the wireless network frequencies move to higher and millimeter-wave (mm-wave) in a 5G network, GaN PAs offer clear advantages over Si LDMOS [1].

The 5G transceiver systems utilize bandwidth-efficient modulation schemes such as 64-quadrature amplitude modulation (QAM) with massive MIMO antennas. As a consequence of the signal complexity, a high level of linearity both for low-noise amplifiers (LNA) and PAs is

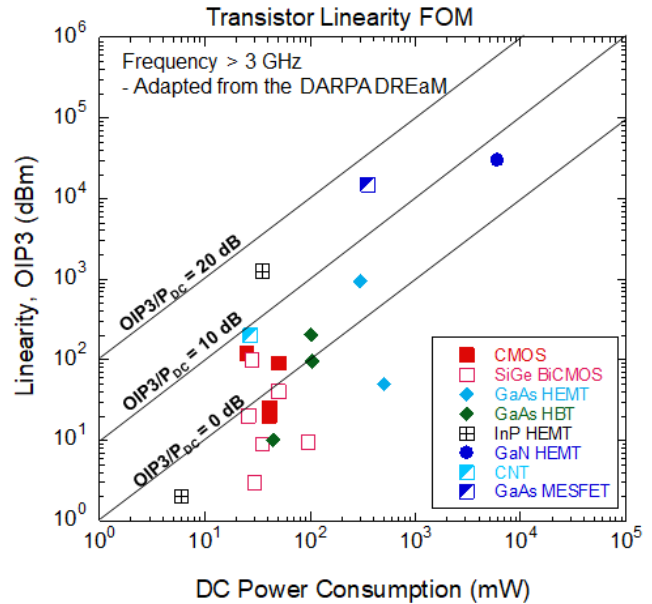


Fig. 1. Transistor technology challenge for linearity figure-of-merit, OIP3/P_{DC}.

needed. Figure 1 shows a survey of high-speed transistor technologies in terms of their device linearity defined as the third-order output intercept point (OIP3) under two-tone modulation versus the DC power consumption [2]. As can be seen, the linearity figure of merit (OIP3/P_{DC}) of most of the semiconductor transistors is less than 10 dB. Thus, the amplifier linearity requirements are commonly achieved by using higher DC power consumption for LNAs or operating with reduced PAE and power density for PAs.

Figure 2 shows a survey of PAs in terms of their average PAE versus the average output power, illustrating the output backed-off (OBO) operation results in greatly reduced average PAE when operated under conditions needed to support complex modulation schemes. Recent SOA CMOS-SOI amplifiers [3] demonstrated an associated PAE of 16% compared to the peak PAE of 40.5% at 28 GHz. A multi-band Doherty PA has also been demonstrated using SiGe technology; in this case, the PAE at 6 dB output backed-off point was 13.9% for a PA with a saturated output power of 16.8 dBm [4]. Various GaN-based Doherty PAs were demonstrated also [5, 6], which include an average PAE of 20.5 % at the 8-dB backed-off output power of 27.6 dBm with

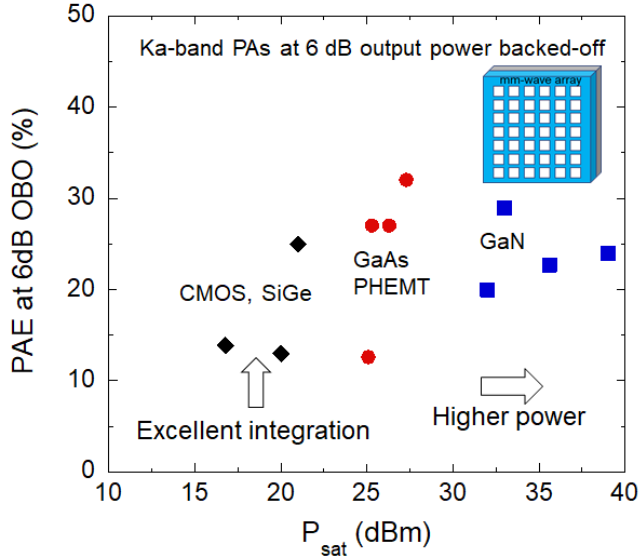


Fig. 2. Power amplifier technology challenge for mm-wave communications.

the adjacent channel leakage ratio of $-25 \sim -17$ dBc under the 64-QAM at 28 GHz [5].

Recently, GaN transistors have made significant improvements in mm-wave. These include a 61% PAE at a power density of 3.2 W/mm at 40 GHz with 110 nm gate length GaN HEMTs [7], a 60.8 % PAE at a power density of 2 – 2.3 W/mm at 35 GHz with 90 nm gate length GaN HEMTs from Qorvo [8], and a 70 % - 48 % PAE at a power density of 2.5 – 5.5 W/mm at 30 GHz with 60 nm gate length graded-channel GaN HEMTs [9]. These high-speed T-gate GaN devices offer improved gain and PAE at Ka-band, but their power densities are less than the power density of 10 W/mm of the field-plated GaN HEMT devices [10, 11]. In W-band, a 27 % PAE at the power density of 7.9 W/mm was demonstrated at 94 GHz with 75 nm gate length N-polar GaN

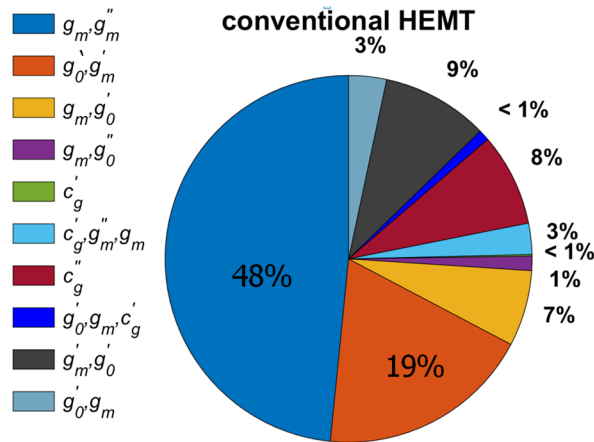


Fig. 3. Breakdown of intermodulation contributions of conventional AlGaIn/GaN HEMT

MISHEMTs [12]. On the other hand, linearity is still challenging in GaN transistors.

To address these trends, the exploration of advanced GaN transistor engineering concepts to improve linearity and efficiency has become a very active area of research. Some of the device approaches being explored include the use of graded III-N channel structures by polarization-doping [9] to mimic the charge distribution in highly-linear GaAs MESFETs, N-polar GaN MISHEMTs [12], buried dual-gate FETs (BRIDGE FETs) that leverage sidewall gates [13], and multi-channel GaN FinFETs [14]. So far, the graded-channel approach has resulted in promising performance; graded-channel HEMTs with f_T/f_{MAX} of 170 GHz/360 GHz with 50-nm gate lengths have been demonstrated [15], as has a record device-level PAE of $>70\%$ at 30 GHz [16], and the small-signal linearity of these graded-channel devices is improved by 20 dB [17-18] over that of conventional AlGaIn/GaN HEMTs. Recently, the graded-channel GaN HEMTs have demonstrated promising mm-wave power scaling with a device speed*power density product of 858 GHz*W/mm, as well as reduced current collapse [9].

In this paper, we report both the small-signal and large-signal linearity and PAE of graded-channel GaN-based HEMTs at 30 GHz. The high-speed graded-channel GaN HEMTs offer 20 dB OIP3/ P_{DC} linearity FOM from small-signal two-tone tests. Under the large-signal conditions, these graded-channel GaN HEMTs exhibit a peak PAE of 62% at 30 GHz under class AB bias conditions. Furthermore, when backed off to establish a carrier-to-third-order intermodulation ratio of 30 dBc, a PAE of 55% was obtained. This combination of measured peak PAE and linearity at 30 GHz represents a substantial improvement in the state of the art over conventional AlGaIn/GaN HEMTs.

II. LINEAR AND HIGH-SPEED GAN DEVICE

Figure 3 shows a breakdown of the nonlinear contributions for conventional AlGaIn/GaN HEMT, showing that they are dominated by the g_m'' , and interaction between the g_m' and the first derivative of the output conductance, with the second-derivative of gate capacitance also playing an important role.

Figure 4(a) shows a cross-sectional schematic diagram of a graded-channel AlGaIn/GaN HEMT of the type explored here. A SiC substrate was used for efficient heat extraction, and a T-gate with integrated mini-field-plate (mini-FP) was used to enhance lateral electric field control. The HEMT channel consists of a GaN layer and a 6-nm-thick compositionally-graded AlGaIn layer, below an $Al_{0.25}Ga_{0.75}N$ barrier layer. Figure 4(b) shows a comparison of the calculated conduction band energy diagrams and electron distributions for a comparable conventional AlGaIn/GaN heterostructure HEMT (i.e. a HEMT with the same barrier, but without the compositionally-graded layer in the channel) and graded-channel device. The graded structure spreads the channel charge over a larger thickness, locally reducing the

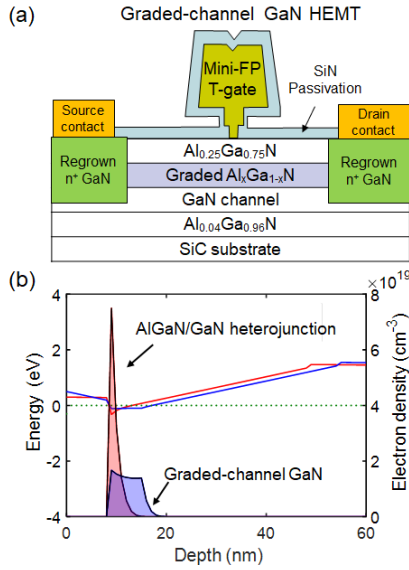


Fig. 4. (a) Schematic of graded-channel GaN HEMT with gate-integrated mini-field-plate, and (b) Comparison of computed conduction band diagram and charge distribution for conventional AlGaIn/GaN HEMT and graded-channel devices showing a distributed charge for the graded channel structure.

charge density. This is in stark contrast with the conventional HEMT, where the carriers are confined largely to the AlGaIn/GaN heterojunction interface. With a 6-nm-thick graded AlGaIn layer, the graded-channel GaN HEMT exhibits electron mobility of $1531 \text{ cm}^2/\text{Vs}$ with a sheet carrier density of $7.5 \times 10^{12} \text{ cm}^{-2}$. This level of carrier concentration and mobility is comparable to that achieved in a reference AlGaIn/GaN heterostructure.

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

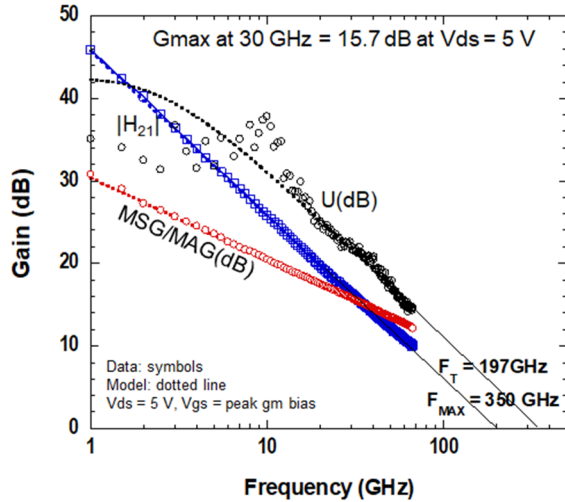


Fig. 5. Measured f_t and f_{\max} of 40 nm gate length graded-channel AlGaIn/GaN HEMT at $V_{ds} = 5 \text{ V}$.

with this approach was found to be less than $0.1 \text{ ohms} \cdot \text{mm}$. An important aspect of the device fabrication that controls device performance is the gate. In the devices reported here, a low-parasitic T-gate was fabricated with an integrated mini-field plate (Fig. 4(a)) instead of the conventional T-gate.

The small-signal RF performance was measured on-wafer from $0.1 - 67 \text{ GHz}$ and the pad parasitics were de-embedded with conventional open and short structures. Figure 5 plots the measured short-circuit current gain $|h_{21}|^2$ versus frequency at $V_{ds} = 5 \text{ V}$ and I_d of 320 mA/mm . The device's extrinsic f_t was estimated to be 197 GHz , and the extrinsic f_{\max} was estimated as 350 GHz from both the measured maximum stable/available gain (MSG/MAG) and Mason's unilateral gain U .

Figure 6 shows measured 2-tone OIP3 and gain versus average tone power P_{in} of conventional AlGaIn/GaN HEMT and graded-channel GaN HEMT at the same DC power. The graded-channel GaN HEMT shows OIP3 of 36 dBm with a 18 dB reduction in IM3. As a result, the OIP3/ P_{DC} ratio was also improved by 9 dB in the graded-channel GaN HEMT over the AlGaIn/GaN HEMT. The OIP3/ P_{DC} ratio is 20 dB at 30 GHz , which is the highest ever reported in GaN HEMTs.

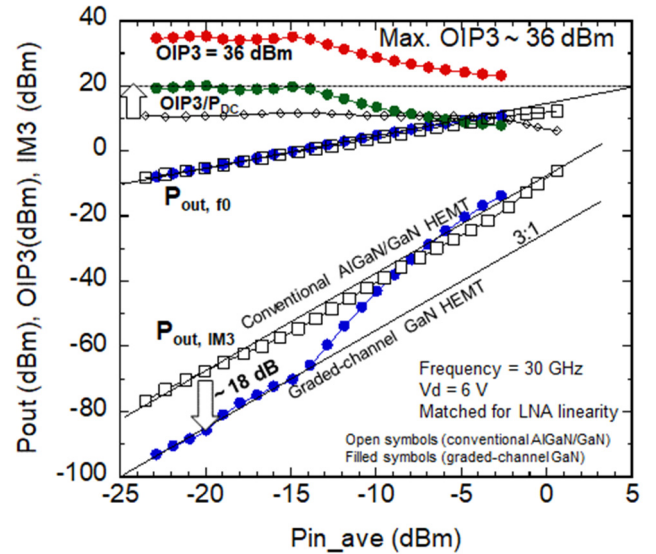


Fig. 6. Measured OIP3 and gain of graded-channel GaN HEMTs at $V_{ds} = 6 \text{ V}$ at 30 GHz , showing a record linearity FOM of 20 dB with about 18 dB reduction in IMD over conventional AlGaIn/GaN HEMTs.

III. LARGE-SIGNAL LINEARITY

To evaluate the large-signal linearity of these devices, two-tone power testing was performed. Figure 7 shows the measurement results achieved with a 4 finger, $37\text{-}\mu\text{m}$ -wide graded-channel AlGaIn/GaN HEMT at 30 GHz . The devices were biased in class AB, a quiescent drain current of $\sim 70 \text{ mA/mm}$. The output load impedance was tuned for a maximum PAE with a peak PAE of 62% . By backing off the output power, the intermodulation ratio exceeding 30 dBc can be achieved with the measured PAE of 55% . This is a state-

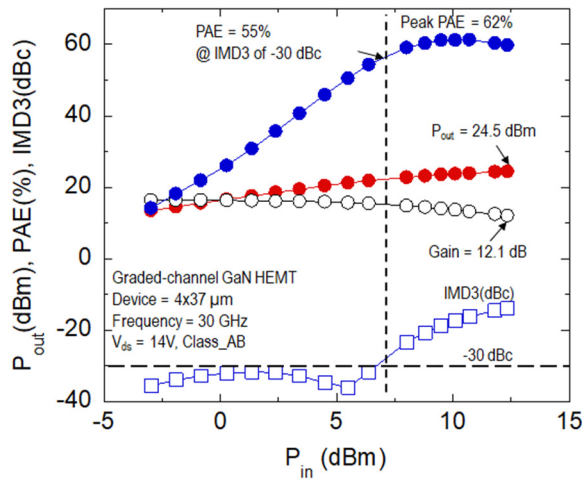


Fig. 7. Measured two-tone linearity of graded-channel HEMTs at 30 GHz in class AB bias, showing a broad reduction in the third order intermodulation (IM3) over a wide range of RF input levels.

of-the-art result for simultaneous efficiency and linearity and demonstrates the potential of the graded-channel GaN HEMT mm-wave frequency linear amplifier operation.

IV. SUMMARY

In summary, high-speed linear AlGaIn/GaN-based graded-channel HEMTs have been demonstrated with record linearity at 30 GHz, showing that the graded-channel AlGaIn/GaN HEMTs are promising for achieving the high PAE and linearity needed for mm-wave amplifiers in 5G and beyond communication systems.

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