2021 Device Research Conference (DRC) | 978-1-6654-1240-7/20/$31.00 ©2021 IEEE | DOI: 10.1109/DRC52342.2021.9467196

Large Signal Response of AlN/GaN/AlN HEMTs at 30 GHz

Austin Hickman[1], Reet Chaudhuri[1], Neil Moser[2], Michael Elliott[2], Kazuki Nomoto[1], Lei Li[1],
James C. M Hwang[3], Huili Grace Xing[1,3,4], and Debdeep Jena[1,3,4]
[1]*ECE,* [3]*MSE,* [4]*Kavli Institute at Cornell University, Ithaca, NY 14853*
[2]*Air Force Research Laboratories, Wright-Patterson Air Force Base, Dayton, OH 45433*
Email: alh288@cornell.edu / Phone: (304)-208-2333

Power amplifier (PA) technology is essential to the future of millimeter-wave (mm-wave) communication systems in defense and commercial sectors. High atmospheric attenuation at these mm-wave frequencies has led to demand for high power PAs able to offset this effect. Gallium nitride high-electron-mobility-transistors (GaN HEMTs) have emerged as leading contenders to supply high power at mm-wave frequencies due to its wide bandgap and high electron velocity. To improve upon conventional GaN HEMT heterostructures, we previously introduced HEMTs on the aluminum nitride (AlN) platform [1], using an AlN/GaN/AlN heterostructure. The maximized bandgap of binary AlN prevents buffer leakage current and increases HEMT breakdown voltage, while also providing a higher thermal conductivity for enhanced channel temperature management. Additionally, the increased polarization offset with GaN allows for highly scaled top barriers that still induce large density two-dimensional electron gases (2DEGs). We recently showed high breakdown voltage of up to 2 MV/cm in RF AlN/GaN/AlN HEMTs [2] and RF power operation of these HEMTs at 6 GHz, with an power added efficiency of 55% and output power (P_{out}) of 2.8 W/mm [3]. **In this work, we demonstrate the first mm-wave frequency operation of AlN/GaN/AlN HEMTs, showing a peak PAE = 29%, with associated P_{out} = 2.5 W/mm and G_T = 7 dB at 30 GHz.**

The AlN/GaN/AlN heterostructure was grown on a 6H-silicon carbide via plasma-assisted molecular beam epitaxy. The fabrication flow began with a patterned Cr/SiO_2 hardmask. The exposed surface was etched via a Chlorine-based inductively-coupled plasma (ICP), and n++ ([Si] ~ 10^{20} cm^{-3}) GaN was regrown to form ohmic contacts to the 2DEG. The HEMTs were then isolated via another Chlorine-based ICP dry etch, and ohmic contacts (Ti/Au) were deposited via e-beam evaporation on top of the regrown regions. The T-gate gate contacts (Ni/Au) were defined via e-beam lithography. Finally, the devices were passivated with 100 nm of PECVD silicon nitride.

The regrown ohmic contact resistance was 0.23 Ω·mm. The majority of devices showed on-currents exceeding 3 A/mm. The HEMT shown in this work demonstrated I_D = 3.2 A/mm with an on-resistance of 0.8 Ω·mm and a transconductance of 0.72 S/mm, as seen in Fig. 1. Pulsed $I_D V_D$ measurements, shown in Fig. 2(c), showed a dispersion of less than 10% percent. Small-signal characteristics for this device demonstrated a cutoff frequency (f_t) and maximum oscillation frequency (f_{max}) of 140 and 239 GHz, respectively (Fig. 2(d).

Large signal measurements were performed at AFRL using a scalar Ka-band load-pull test bench with two 50 GHz Maury Microwave passive tuners. When tuned for peak PAE and biased at a quiescent drain voltage (V_{DSq}) of 12 V, the power sweep measurement showed P_{out} = 2.5 W/mm, PAE = 29%, and G_T = 7 dB at 30 GHz (Fig. 3(a)). With an uncompressed gain of 14 dB, the output power of the HEMT is limited by early onset gain compression. This is thought to be the result of the passivation-last process flow. Efforts are currently underway to develop in-situ passivated AlN/GaN/AlN HEMTs to prevent the observed gain compression. Two-tone linearity measurements were also performed on the same device. When tuned for third order intercept point (OIP3), the HEMT demonstrated a maximum OIP3 of 28 dBm, with an OIP3/P_{DC} of 8 dB (Fig. 3(b)). This high linearity can be partially attributed to the heterostructure, which provides a strong backbarrier to confine the 2DEG and prevents short channel effects.

These results represent the first large signal performance at mm-wave frequencies for HEMTs on the AlN platform. The high uncompressed gain of 14 dB and PAE of 29% are promising, with the current devices limited by the soft gain compression. The development of in-situ passivated AlN/GaN/AlN HEMTs will allow future generations of devices to take advantage of this high gain heterostructure, increasing the observed output power and efficiency.

The authors would like to thank Keisuke Shinohara and Teledyne Scientific and Imaging, Thousand Oaks, CA, for providing PECVD SiN passivation. This work was supported by Semiconductor Research Corporation (SRC) Joint University Microelectronics Program (JUMP), AFOSR (FA9550-20-1-0148), and NSF DMR (1710298). The work was performed at Cornell NanoScale Facility (NNCI member supported by NSF ECCS-1542081), and Cornell Center for Materials Research, supported by NSF MRSEC DMR-1719875.

[1] G. Li et al., IEEE-EDL, vol. 33, p. 661, (2012).
[2] Hickman et al., IEEE-EDL, vol. 40, p. 1293, (2019).
[3] Hickman et al., Semicond. Sci. Technol., (2021).

978-1-6654-1240-7/21/$31.00 ©2021 IEEE

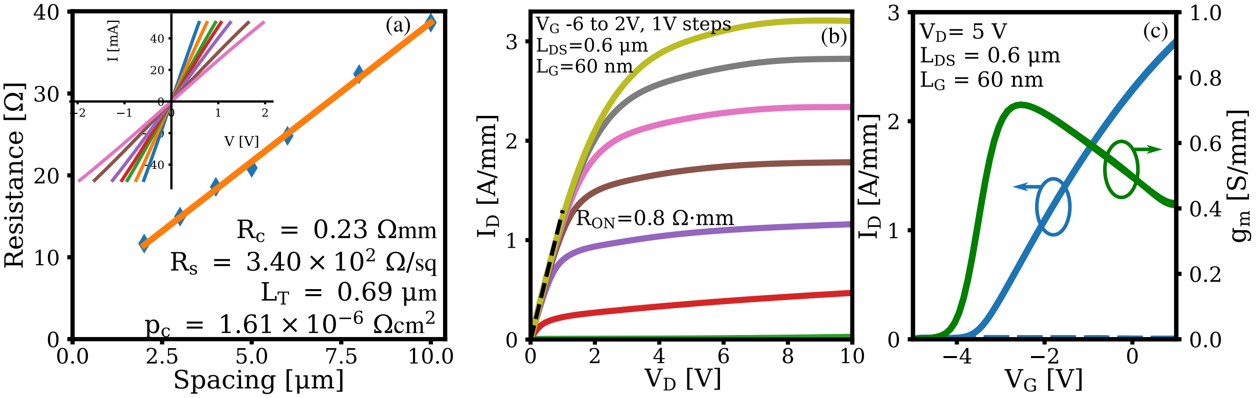

Fig. 1: (a) TLM measurements of the ohmic contact to the 2DEG, showing $R_C = 0.23\ \Omega \cdot \text{mm}$. (b) Family of curves with over 3.2 A/mm and $R_{ON} = 0.8\ \Omega \cdot \text{mm}$. (c) The transfer curve for the same device with $L_G = 60$ nm, demonstrating a peak transconductance of 0.72 S/mm.

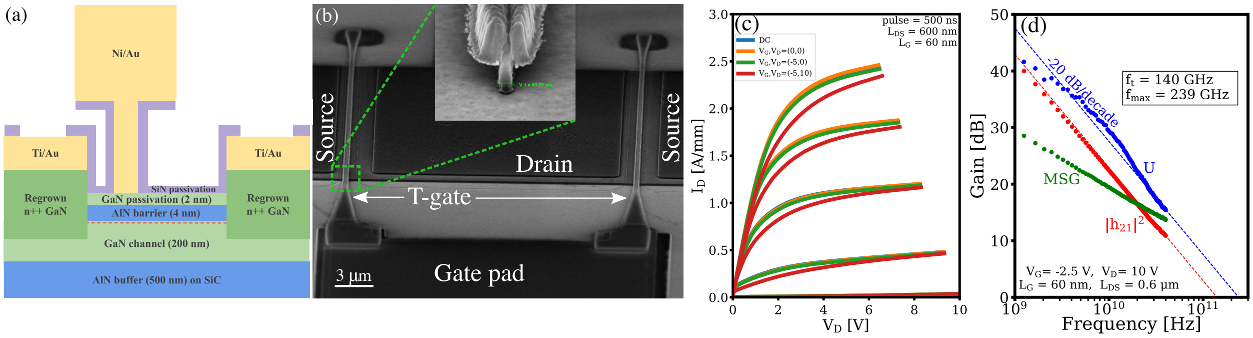

Fig. 2: (a) A representative cross-section of a fully processed AlN/GaN/AlN HEMT. (b) A scanning electron microscope (SEM) image showing a processed device prior to passivation. The inset image shows a 60 nm T-gate. (c) The pulsed characteristics for the HEMT, demonstrating a dispersion of less than 10%. (d) The small-signal characteristics for the HEMT when biased to max transconductance, with f_t/f_{max} = 140/239 GHz.

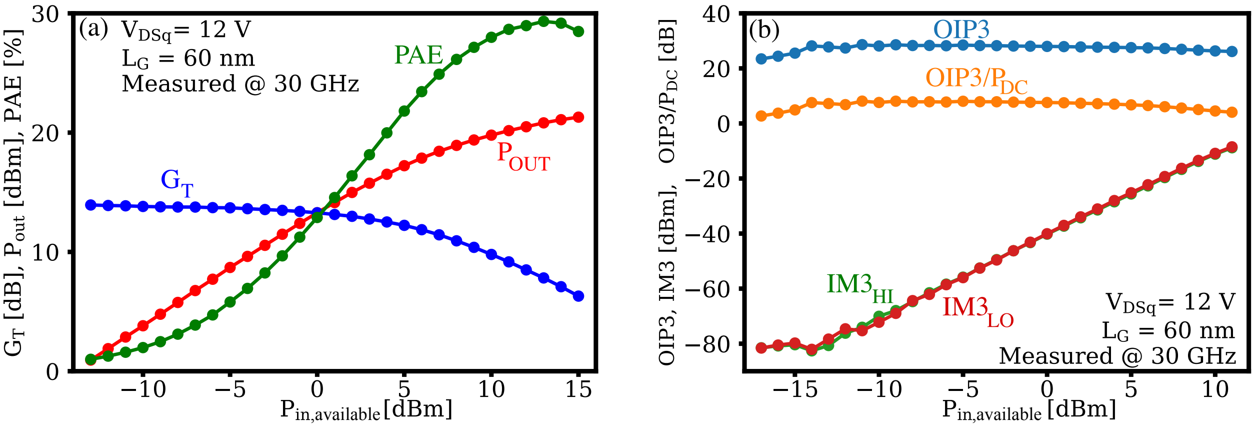

Fig. 3: (a) The power sweep for the AlN/GaN/AlN HEMT at 30 GHz. At the peak PAE of 29%, P_{out} = 2.5 W/mm and G_T = 7 dB. The uncompressed gain is 14 dB, the HEMT is limited by the gain compression at low $P_{in,available}$. (b) Two-tone linearity measurement demonstrating a max OIP3 of 28 dBm and OIP3/P_{DC} = 8 dB.