Record-performance N-polar GaN Schottky barrier gate HEMTs on low-cost sapphire

University of California, Santa Barbara reports record large-signal gain and record power-added efficiency at W-band frequencies.

N-polar gallium nitride (GaN) deep-recess high-electron-mobility transistors (HEMTs) have demonstrated excellent power density and efficiency at W-band frequencies. The utilization of a GaN cap on the GaN channel layer in N-polar orientation enables high-power-density operation with excellent DC-to-RF dispersion control and high access region conductivity. In addition, unlike Ga-polar GaN devices, the wider-bandgap barrier layer is under the channel, which enables the independent tuning of the channel charge density and gate aspect ratio, thereby enabling high gain and power simultaneously. Traditionally, deep-recess N-polar GaN HEMTs have employed SiN gate dielectric layer to suppress the gate leakage current. Although this effectively minimizes the gate leakage current, it comes with the cost of reduced gate aspect ratio, which prevents exploiting the advantages of the N-polar GaN technology to its fullest extent.

To tackle the reduced gate aspect ratio with the inclusion of a gate dielectric, Dr Emre Akso and Dr Henry Collins, the main contributors in the project, studied the formation of Schottky barrier junctions on the AlGaN cap, which is situated right above the GaN channel. Choosing the correct gate material was the key, as it had to not

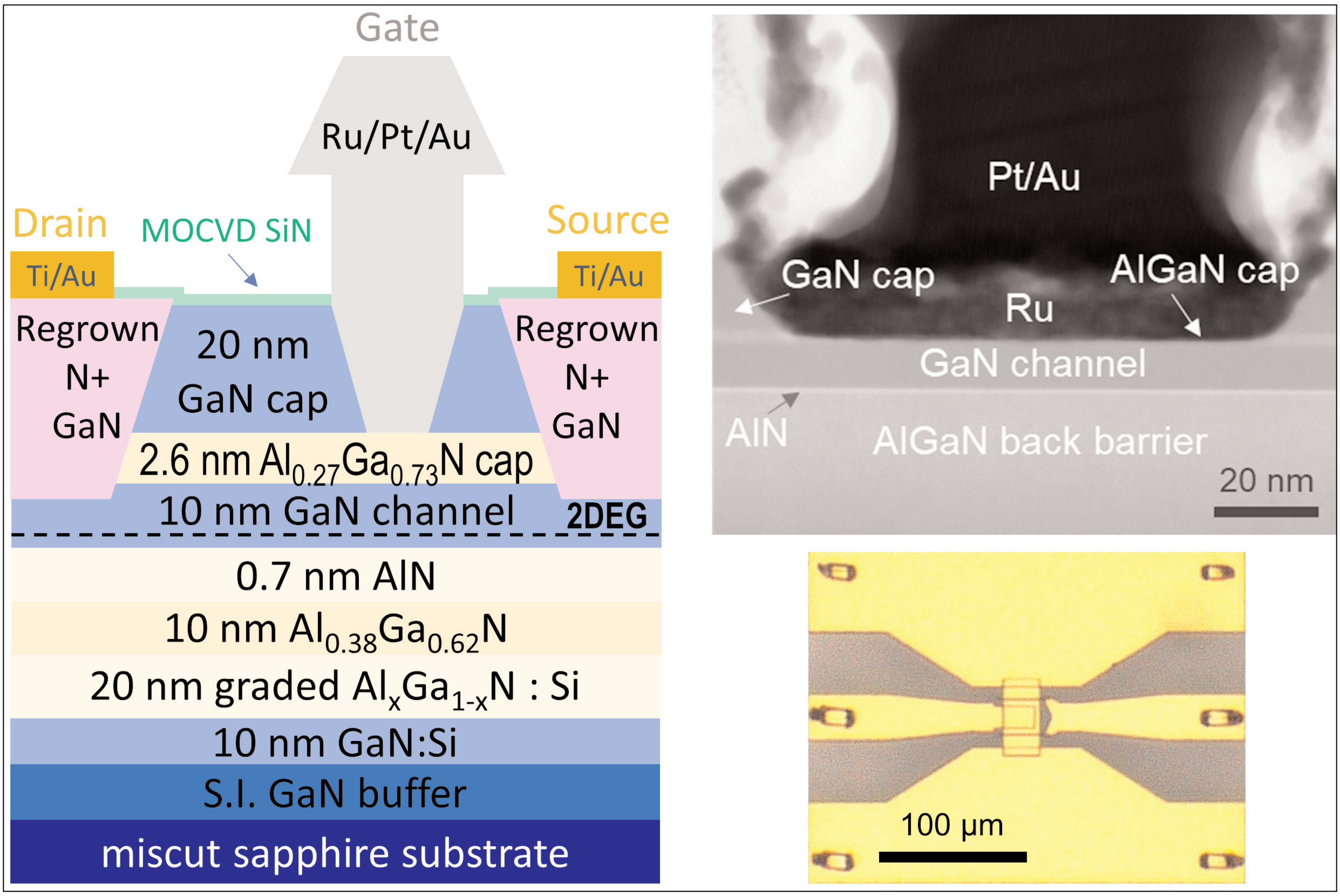

Figure 1. (a) Device structure and epitaxial layers (b) TEM image of a recessed Schottky barrier gate structure with 90nm L_G. (c) Fabricated devices with CPW pads (W_G:2x25µm). Figure © [2024] IEEE [1].

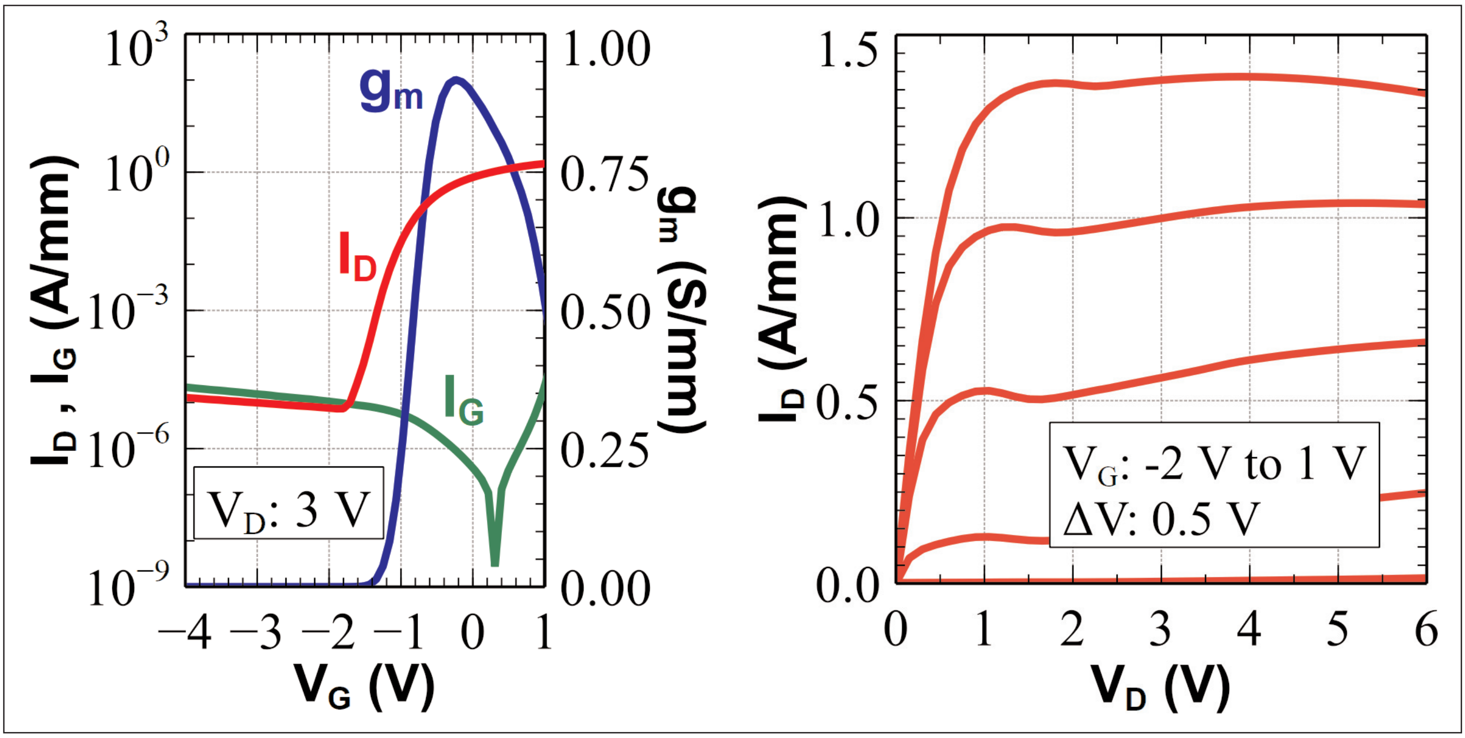

Figure 2. (a) DC characteristics at 3V V_D. (b) DC output characteristics for V_G of −2V to +1V with 0.5V step. Figure © [2024] IEEE [1].

only form a low-leakage Schottky barrier junction with no Fermi-level pinning, which can impede the channel charge modulation, but also should be deposited with a technique compatible with filling narrow gate trenches. That's why our focus was on the materials available in the UCSB atomic layer deposition (ALD) system.

Dr Akso and Dr Collins first studied Schottky barrier gate HEMTs with ALD ruthenium (Ru) gates. The HEMTs were built on N-polar GaN-on-sapphire epitaxy with a scaled channel thickness of 10nm and GaN cap thickness of 20nm, as shown in Figure 1.

Along with transistors, the team fabricated diodes on the recessed HEMT structure to evaluate the reverse leakage current against the previous diode studies with ALD Ru fabricated on 600nm-thick n-GaN with no 2DEG (two-dimensional electron gas). The reverse leakage current from the diode on a recessed HEMT structure was 43A/cm^2, as opposed to the 2μA/cm^2 from a traditional Schottky barrier diode on thick n-GaN. The increased leakage for the diode on the recessed HEMT structure could be attributed mainly to the increased tunneling current with a metal-to-2DEG spacing of only 13nm. Despite this, for a scaled transistor with a gate length of 100nm, this per-area leakage would correspond to 43μA/mm reverse current, which is excellent to ensure a current modulation of more than four decades for an on-current greater than 1A/mm.

As a result of improved gate aspect ratio and low expected reverse leakage current from the diodes, the transistors demonstrated remarkable DC, RF and large-signal performance. The particular transistor reported in the paper had a source–drain spacing (L_{SD}) of 540nm, gate length (L_G) of 77nm, gate–source spacing (L_{GS}) of 100nm, and 2x25μm gate periphery. DC characterization showed that the transistor has a peak transconductance (g_m) of 917mS/mm, which is the highest reported g_m from N-polar GaN/AlGaN devices to date. The extraordinary improvement in the g_m corresponds to almost twice as much as the g_m of previously reported deep-recess HEMTs with gate dielectrics. Additionally, as expected from the diode characterization, the reverse gate leakage for the transistor remained below 40μA/mm, which ensured more than five decades of on-to-off ratio, as shown in Figure 2.

As expected from the improved aspect ratio, despite the increased fringe capacitance through the sidewalls of the recess with Schottky contact, the transistor showed a significant RF performance improvement over MISHEMTs with gate dielectric, as illustrated in Figure 3.

The key to high power-added efficiency (PAE) is to make a transistor that has high gain at low current density. The ALD Ru-gated Schottky barrier HEMTs demonstrated larger than 1S/mm RF g_m at a current density of as low as 0.3A/mm. Additionally, the increased aspect ratio improved the output resistance (r_{DS}), which culminated in an intrinsic gain (g_m*r_{DS}) of 50.6. This is one of the highest reported intrinsic gains reported from scaled GaN HEMTs.

The large-signal characterization was done with a W-band active load-pull system operating at 94GHz. Biased at $V_{DS,Q}$ of 10V and $I_{DS,Q}$ of 0.25A/mm, the transistor demonstrated record transistor-level gain of 10.5dB and record combined PAE and power of 50.2% with 2.8W/mm, as shown in Figures 4.

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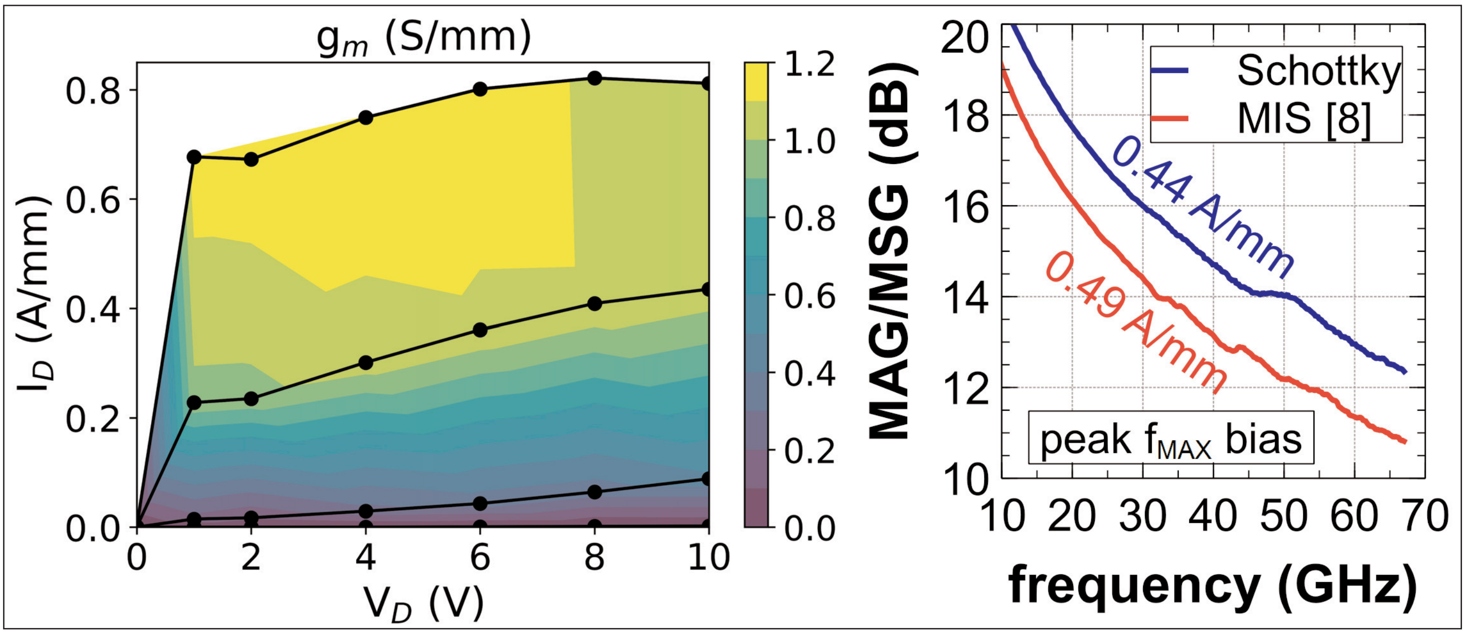

Figure 3 . (a) Bias-dependent RF g_m extracted at V_G of −2V to 0V with a 0.5V step. (b) Comparison of MAG/MSG of Schottky barrier gate versus MISHEMT at peak f_{MAX} bias. Figure © [2024] IEEE [1].

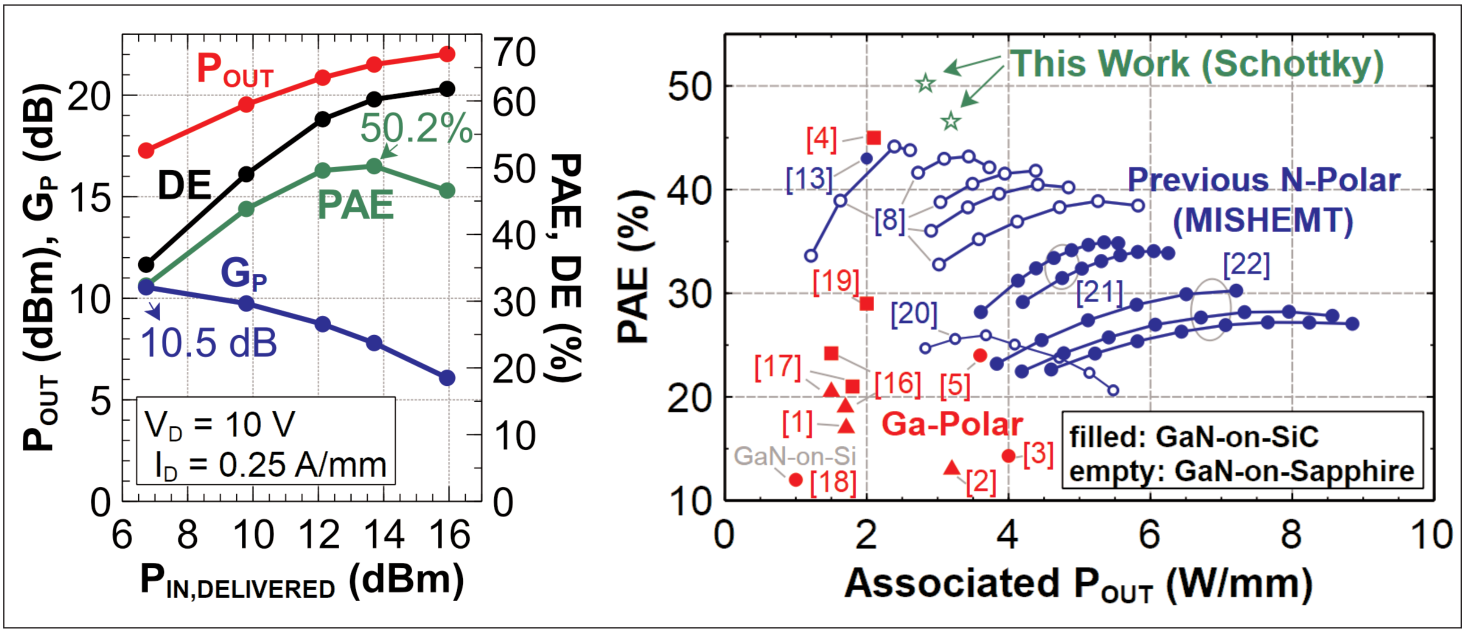

Figure 4. Power sweep at V_D = 10V and I_D = 0.25A/mm at 94GHz (b) PAE versus associated P_{OUT} at W-band (83–95GHz) for GaN, circle: load pull, square: pre-matched device, triangle: MMIC Figure © [2024] IEEE [1].

Furthermore, the team explored another ALD material as a Schottky barrier contact material: titanium nitride (TiN). TiN was used to establish the contact with the AlGaN surface, so the thickness was kept at 2nm because of the limited conductivity of the TiN. On top of TiN, an ALD Ru layer was deposited to fill the narrow gate trenches further with a more conductive material.

The team fabricated diodes and transistors as in the case of the samples with ALD Ru only. The diodes alone showed an improvement in the reverse leakage current compared with ALD Ru only. Furthermore, the breakdown voltage measured by the drain current injection (DCI) method showed a significant improvement with the inclusion of TiN.

The transistors with TiN gates showed a comparable DC performance to that of those with Ru gates. However, the TiN contact improved the RF performance of the transistors, as shown in Table 1. This improvement in f_{max} and f_T can be attributed to the lower gate resistance (R_G) with better filling of the trench associated with TiN, and reduction in the fringing capacitance, respectively.

The peak f_{max} of 362GHz and peak f_T of 193GHz are again record numbers for the deep-recess N-polar GaN HEMTs. With the increased breakdown voltage, the team was able to bias the transistor at a higher quiescent voltage of 12V for large-signal characterization. The TiN-gated transistor, biased at 0.25A/mm quiescent current density, showed another record large-signal performance with

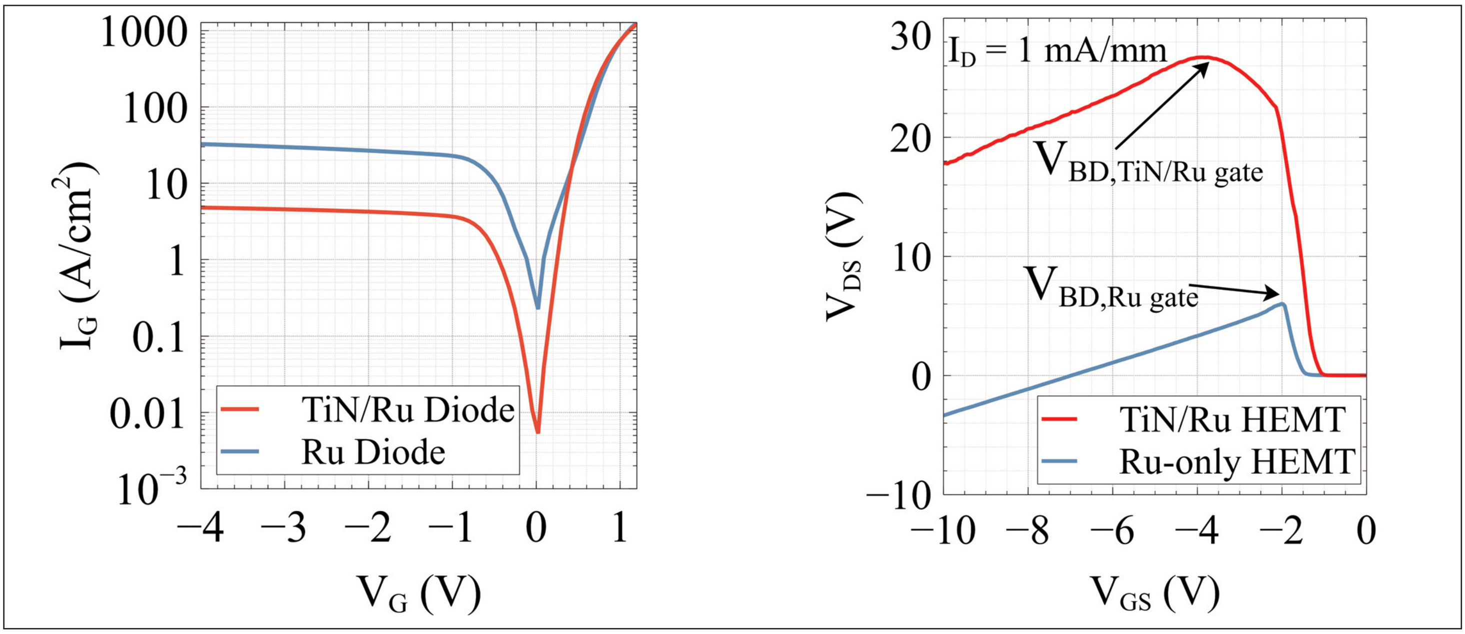

Figure 5. (a) I–V sweep comparing TiN and Ru-only Schottky diodes on N-polar deep-recess GaN epitaxy. (b) Breakdown measurement via DCI. Figure © [2024] IEEE [2].

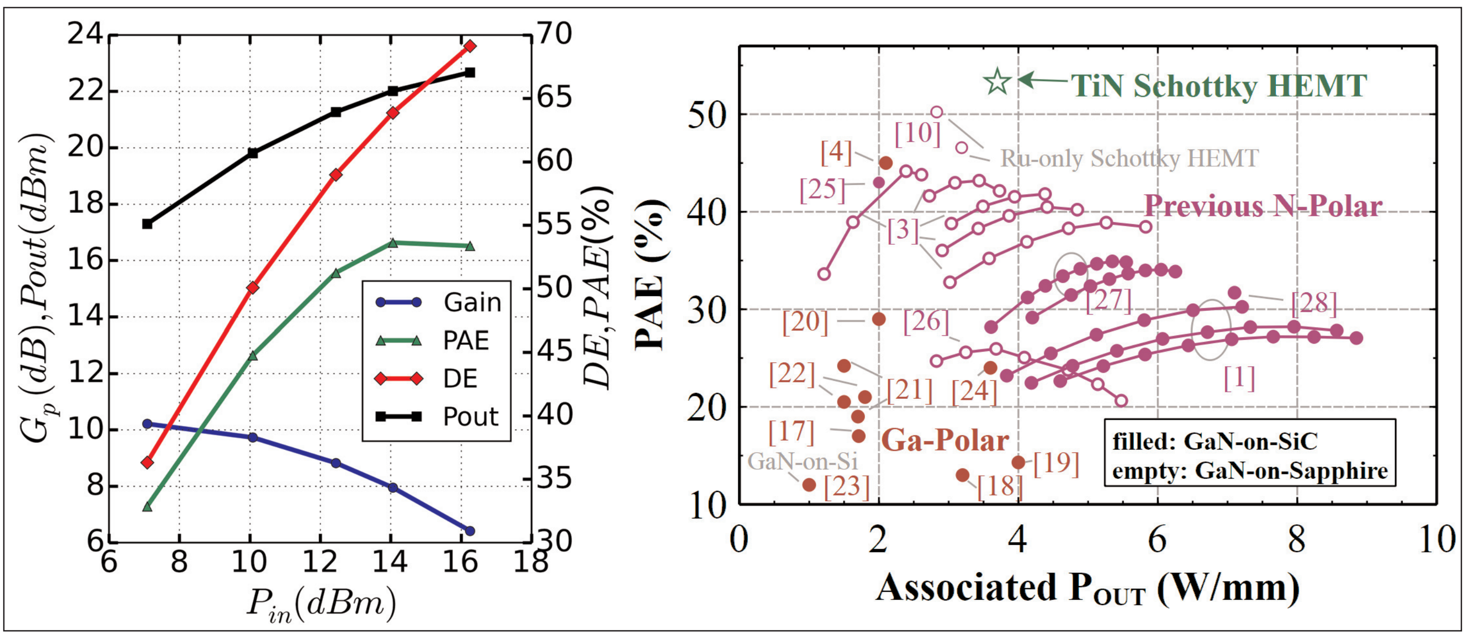

Figure 6. (a) 94GHz load-pull power sweep of the TiN Schottky gate HEMT. (b) Benchmark comparison of W-band load-pull performance showing the excellent combination of PAE and P_{out} attained by the TiN Schottky HEMT (this work). Figure © [2024] IEEE [2].

	L_g (nm)	Peak f_t (GHz)	Peak f_{max} (GHz)	$g_{m,RF}$ (S/mm)	$c_{g,fringe}$ (pF/mm)	R_G (Ω)
Ru-gated MIS	57	132	306	N/A	N/A	N/A
Ru-only Schottky	50	176	307	1.13	0.42	3.4
TiN Schottky	50	193	362	1.03	0.21	1.8
	60	169	339	1.07	0.21	1.6

Table 1. Peak f_T and f_{max} for MIS and Schottky HEMTS and small-signal parameter extraction at peak f_T bias. Table © [2024] IEEE [2].

3.7W/mm associated with 53.4% PAE, as illustrated in Figure 6.

This work presented the first successful demonstration of Schottky barrier gate N-polar GaN deep-recess HEMTs in the literature with record large-signal performance at W-band frequencies. These devices with extraordinary performance were demonstrated on low-cost sapphire substrate, unlike the state-of-the-art Ga-polar GaN devices on costly silicon carbide (SiC). This record performance on a low-cost substrate platform will pave the way for low-cost yet high-performance wireless communication and radar systems.■

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[1] Akso et al, IEEE Microwave and Wireless Technology Letters, vol.34, no.2 (February 2024), p183–186
[2] Collins et al, IEEE Microwave and Wireless Technology Letters, vol.34, no.7 (July 2024), p907–910