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GaN-Based Multiple 2DEG Channel BRIDGE (Buried Dual Gate) HEMT Technology for High Power and Linearity

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We report on a GaN-based field effect transistor with laterally-gated multiple 2DEG channels, called BRIDGE (buried dual gate) HEMT. Unique operation principle of the transistor enables unprecedented device characteristics suitable for efficient and linear millimeter-wave power amplifier applications. The lateral gate simultaneously modulate multiple 2DEG channels formed in an Al(Ga)N/GaN hetero-structure. A higher electron saturation velocity measured for a lower 2DEG density suggests that the multiple 2DEG channel structure is ideal for obtaining a high current density, and simultaneously enhancing high frequency performance of the transistor. The BRIDGE HEMTs built on a 16-channel HEMT epitaxial structure with a net 2DEG density of 3.3×10^{13} cm^{-2} exhibited a record high knee current density of 3.7 A/mm. The absence of the top contact gate results in negligible current collapse by eliminating a high electric field region at the drain end of the gate – another key feature of the BRIDGE HEMT.

Introduction

A unique combination of high mobility, high velocity and high sheet density of the 2DEG formed in GaN-based hetero-structures and high critical field of the GaN material has enabled GaN-based HEMTs to be used in a wide range of applications from RF power amplifiers to efficient power converters. Today's complex communication systems require transceivers to process RF signals efficiently with large bandwidth and high fidelity. While GaN-based HEMT technology has advanced to reach higher power densities, it has not fundamentally changed the power requirements for the linearity performance. This stems from the HEMT device structure and its operation principle. In this paper, we present a new type of GaN-based transistor structure designed to break the traditional performance tradeoff observed in conventional GaN-based HEMTs.

BRIDGE HEMT Technology

To address fundamental limitations of HEMT's power/linearity/efficiency/frequency tradeoff, we proposed a transistor structure called BRIDGE (buried dual gate) HEMT where gate feet are buried into AlGaN/GaN heterostructures and contact laterally with multiple 2DEG channels as illustrated in Figure 1 [1,2]. A deliberate elimination of a conventional top-contact gate leads to a unique device operation principle and performance advantages for improved linearity and efficiency during large signal

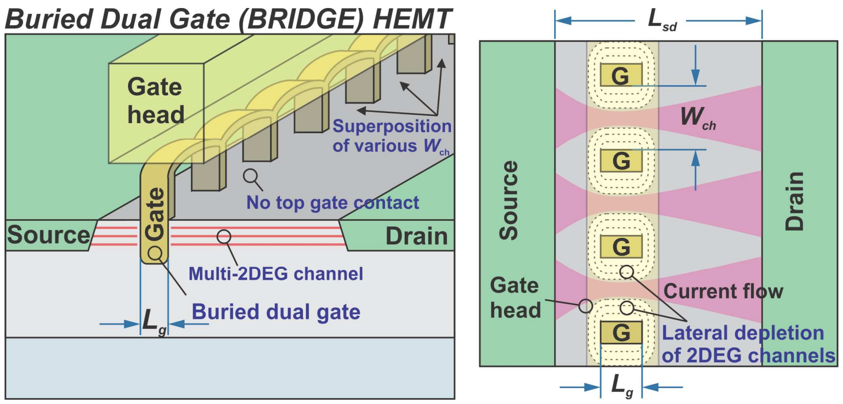

Figure 1. Schematic illustration of GaN HEMT with buried dual gates (BRIDGE HEMT).

operation; (1) The drain-source current is controlled solely by modulating the width of the 2DEG channels by the lateral gate electric field while maintaining a constant 2DEG density. (2) The MESFET-like device operation enables gradual pinch-off, greatly reducing g_m derivatives near pinch-off. (3) Lack of 2DEG density modulation with V_{gs} leads to a constant electron velocity at high electric field, eliminating a typical g_m roll-off at high V_{gs}. This results in a constant gain along a resistive load line. (4) The buried gates forms Schottky contacts to the GaN channels below the 2DEG layers. This enhances electron confinement and improves electrostatic isolation between the source and drain, significantly reducing g_d at high V_{ds}. (5) Elimination of the top-contact gate prevents electrons from being trapped on the surface, suppressing current collapse at high voltage operations. (6) An absence of inverse piezoelectric effect due to the reduced vertical electric field at the drain-side of the gate improves device reliability under high voltage stress.

Device Characteristics

Due to the ohmic contact width (W_g) being wider than the active 2DEG width (W_{2DEG}), the applied drain voltage (V_{ds}) is concentrated in the channel between the buried gates. This enables (1) an early velocity saturation at a low V_{ds}, resulting in a low knee voltage (V_{knee}) of 1V, and (2) an effectively low on-resistance (R_{on}) of 1.1 Ω·mm. The buried gates that contact the GaN layer below the 2DEG enhances electron confinement, leading to an improved electrostatic isolation between source and drain, and therefore, good pinch-off characteristics and small output conductance (g_d) (Fig 2(a)). Deliberate elimination of a top-contact gate reduces the density of trapped electrons at a high field region near the surface and alleviates capacitive coupling between the trapped electrons and the 2DEG. The pulsed I-V measurement confirmed a large reduction of knee current collapse: only 7% at a quiescent drain voltage of 50V (Fig. 2(b)). One of the key linearity enhancing attributes of the BRIDGE HEMT is the gradual transfer characteristics due to its MESFET-like device operation. In conventional top gated HEMTs, g_m peaks at about 20-30% of the maximum drain current and decreases with increasing the gate bias (V_{gs}), which is due to a reduction of the electron velocity caused by n_s modulation [2]. The abrupt reduction of g_m near threshold voltage (V_{th}) is inherent to the vertical gate electric field in parallel to the direction of the 2DEG confinement in the channel. On the other hand, the gradual pinch off characteristics of the BRIDGE HEMT result in a greatly reduced the first and the second g_m derivatives (g_m', g_m") (Fig. 3(a)). The V_{th} of the BRIDGE HEMT can be precisely controlled by the channel width (W_{ch}), which allows

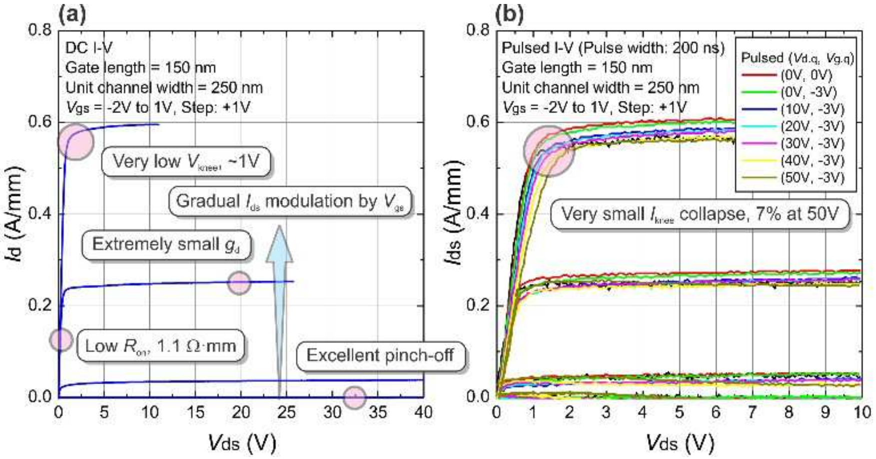

Figure 2. Output (a) and pulsed I-V (pulse width = 200 ns) characteristics (b) of a single-channel 150-nm-gate BRIDGE HEMT.

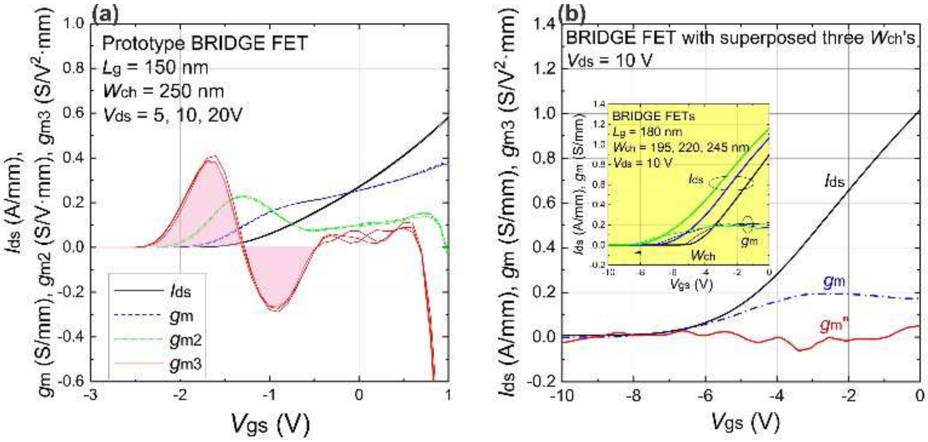

Figure 3. Transfer characteristics of a single-channel 150-nm gate BRIDGE HEMT (a) and engineered transfer characteristics with negligible gm" (second derivative of gm) peaks realized in a BRIDGE HEMT consisting of three channel widths (b).

for engineering a g_m profile by superposing three different W_{ch}'s to cancel g_m" peaks for improved large signal linearity performance (Fig. 3(b)).

RF performance of the BRIDGE HEMTs was improved through reduction of parasitic resistances and capacitances. A 180-nm-gate BRIDGE HEMT demonstrated a maximum oscillation frequency (f_{max}) of 250 GHz at 25V (Fig 4(a)). Soft gain compression is a known problem with GaN HEMT amplifiers and a significant cause of nonlinearity. To realize constant large signal gain over a wider range of input power, a uniform small-signal gain along the load line is desired. Figure 4(b) shows a contour plot of maximum stable gain (*MSG*) measured at 30 GHz for a BRIDGE HEMT. Owing to its unique g_m profile, low V_{knee}, and small g_d in combination with the reduction of the reduced gate-drain capacitance (C_{gd}) at higher V_{ds}, the BRIDGE HEMT exhibits almost constant *MSG* along the load line over a wide V_{ds} range.

The buried gate structure of the BRIDGE HEMT allows for simultaneous modulation of stacked 2DEG channels, enabling proportional power scaling with the net 2DEG density. Figure 5 illustrates electrical properties of AlGaN/GaN and AlN/GaN epitaxial structures consisting of a single and multiple 2DEG channel(s). Large net 2DEG densities of 5.2×10^{13} cm^{-3} and 3.2×10^{13} cm^{-3} with a high electron mobility of >1600 cm^2/V·s and

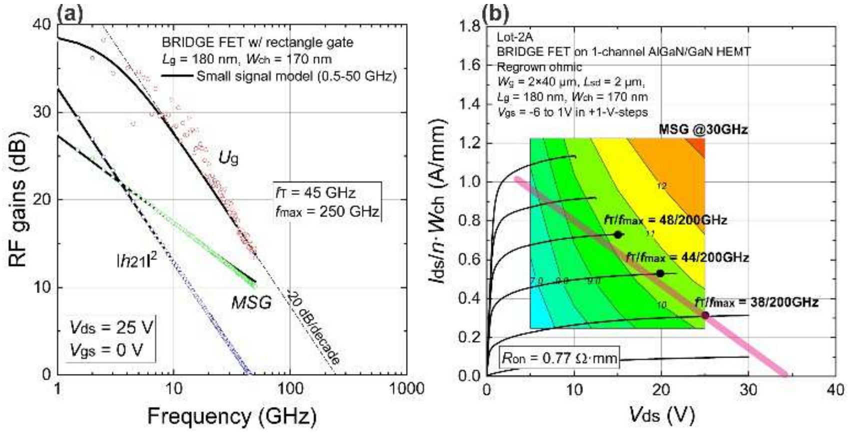

Figure 4. RF characteristics and MSG contour of a single-channel 180-nm-gate BRIDGE HEMT.

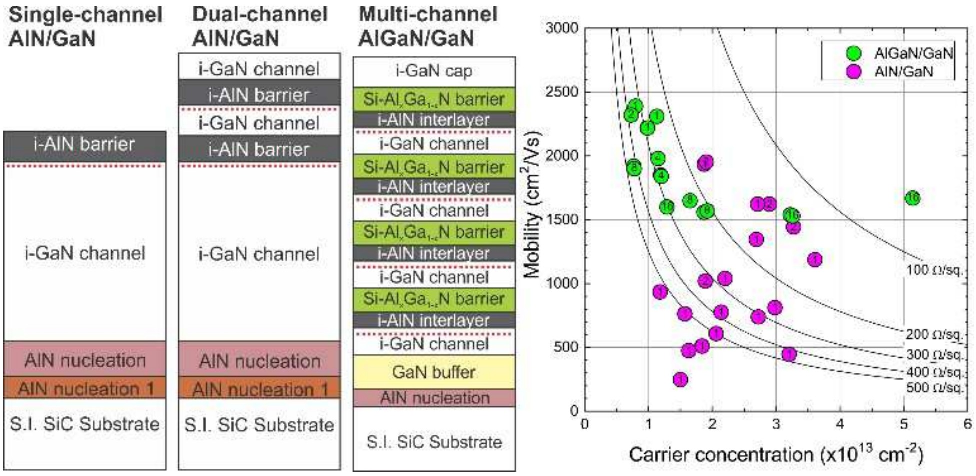

Figure 5. Electrical properties of multiple 2DEG channel AlGaN/GaN and AlN/GaN HEMT epitaxial structures.

>1400 cm^2/V·s have been obtained in a 16-channel AlGaN/GaN and a 2-channel AlN/GaN epitaxial structure, respectively. Electron velocities were extracted experimentally from two-terminal *I-V* characteristics of a TLM test structure fabricated on a single-, 2- and 4-channel HEMT epitaxial structures. Fig. 6(a) illustrates extracted electron velocity plotted as a function of the electric field. At low electric fields, electron velocities are similar among three structures, reflecting their similar electron mobility (~1600 cm^2/V·s). Electron velocities at high electric fields (> 20 kV/cm), on the other hand, are higher for the 2- and 4-channel epi structures. This result is attributed to the density-dependent electron saturation velocity in GaN-based HEMTs, which is caused by a strong interaction between electrons and LO phonons [2,3]. The extracted electron velocities at a high electric field of 100 kV/cm are plotted as a function of the net 2DEG density (solid circles) as well as the 2DEG density per channel (open circles), which are compared with experimental and theoretical data for a single-channel HEMT structure reported by S. Bajaj *et al*. [3]. The data suggest that the higher electron saturation velocity in the multi-channel structures is due to a reduced 2DEG density per channel while maintaining their high net 2DEG densities enabled by stacking multiple channels. It should be noted that higher electron velocities obtained in multi-channel epi structures are beneficial for achieving not only high drain current density (= $q \cdot n \cdot v_s$) but also improved frequency performance of the transistors.

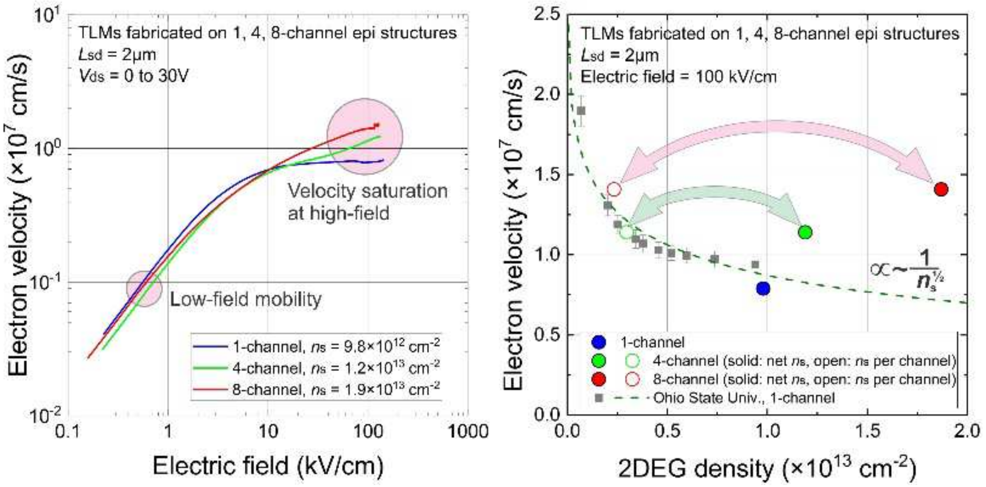

Figure 6. Experimentally extracted electron velocity as a function of the electric field for a single-, 4-, and 8-channel AlGaN/GaN HEMT epitaxial structures (a). Electron saturation velocity at a high field of 100 kV/cm plotted as a function of the 2DEG density (b).

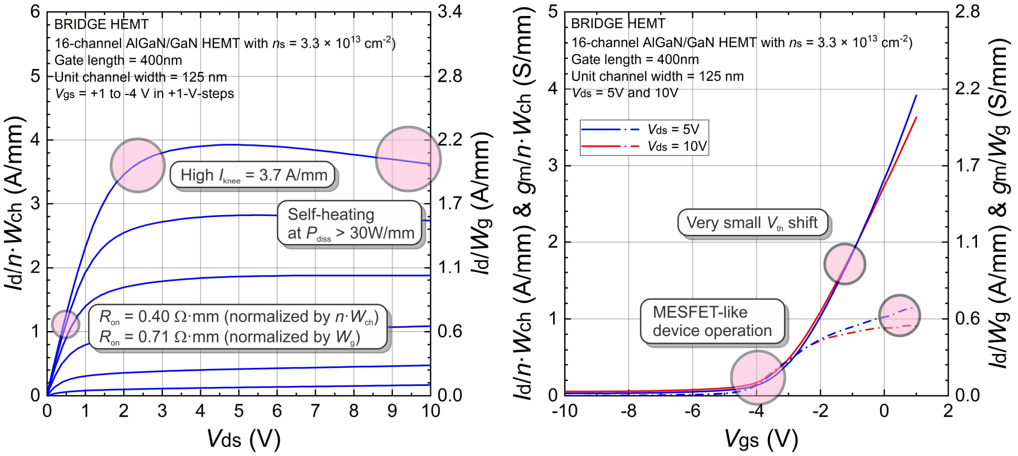

Figure 7. Output and transfer characteristics of a 16-channel 400-nm-gate BRIDGE HEMT.

Fig. 7 shows DC characteristics of a 16-channel 400-nm-gate BRIDGE HEMT with a net 2DEG density of 3.3×10^{13} cm^{-2}. The device exhibited a high knee current density of 3.7 A/mm, a peak g_m of 1.1 S/mm, and a low R_{on} of 0.4 Ω·mm. These results indicate high scalability of the BRIDGE HEMT technology through multiple 2DEG channel design, i.e., the number of channels and a 2DEG density of each channel.

Conclusion

GaN-based HEMTs with buried dual gate (BRIDGE HEMTs) were fabricated using a single- and 16-channel HEMT epitaxial structures. The unique operation principle of the BRIDGE HEMTs in combination with multi-2DEG-channel epitaxial structures offers performance advantages and design flexibility for efficient and linear operations in millimeter-wave power amplifiers.

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