Neutral Beam Etching: A Pathway to High-performance E-mode Recessed-Gate GaN MOSHEMTs for Power and RF Applications

Abstract

GaN-based E-mode transistors are highly demanded for power and RF applications due to their fail-safe property and compatibility with single-polarity voltage driving circuits. Along with p-GaN gate HEMTs, GaN recessed-gate MOSHEMTs have been regarded as another promising approach for normally-off operations, featuring wide gate swing voltages and maturity of the starting AlGaN/GaN epi-layers. Inductively coupled plasma (ICP) was commonly deployed for barrier layer thinning, however, etching damage resulting from ion bombardment and ultraviolet photons tends to degrade the device's performance. Ar-based neutral beam etching (NBE) which features focused beam of inert gas ions for precise material removal shows great potential for fine control of gate foot and mitigation of plasma-induced damage. In this work, GaN recessed-gate MOSHEMTs enabled by NBE are explicitly investigated, for both power electronics and low-noise amplifier (LNA) applications. By partially recessing AlGaN barrier, MOSHEMT show V_{th} of 1.68V, large on/off current ratio of 10^9, and low gate leakage current for both positive and negative biases. The breakdown voltage of MOSHEMTs were increased from 208 V to 701 V as L_{gd} was extended from 2 μm to 10 μm. By recessing the AlGaN barrier at different depths via Ar-based NBE, the MOSHEMTs achieved V_{th} of 1.68/2.93/4.29 V, $I_{D,sat}$ of 803/661/545 mA/mm, and small R_{on} of 5.85/6.06/7.23 Ω·mm, leading to FOM of 701/640/567 MW/cm^2, respectively. Compared to other state-of-the-art recessed-gate MOSHEMTs with similar V_{th} reported in the literature, the GaN MOSHEMTs in this study demonstrated the highest $I_{D,\ sat}$ in its class and superior FOM. For LNA applications, recessed-gate MOSHEMT (L_g = 1.2 μm & V_{th} = 0.5 V) showed cut-off frequency (f_t/f_{max}) of 9.6/27.8 GHz, along with a minimum noise figure (NF_{min}) of 1.48 dB, an associated gain (G_a) of 14.43 dB, an equivalent noise resistance (R_n) of 40.2 Ω, and an input 3rd-order interception point of 10.3 dBm at 2 GHz, benefiting from mitigation of surface defects generated during etching. At 3.5 GHz, NF_{min} slightly increased to 1.95 dB. In summary, this work highlights that Ar-based NBE gate recessing offers a promising pathway to achieving high performance E-mode GaN MOSHEMTs for power conversion and LNA applications. Ref. [1] Gao *et al*., IEEE EDL, Vol.45, Iss.6, 2024. [2] Ye *et al*., IEEE TED, Vol.72, Iss.3, 2025.

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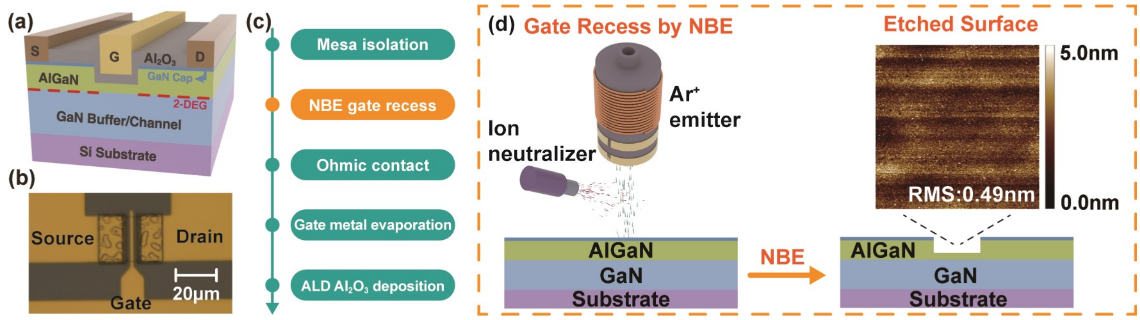


Fig.1 (a) Schematic, (b) microscopic photograph, and (c) process flow of the recessed-gate MOSHEMT. (d) NBE schematic diagram and 5 μm×5 μm surface morphology by AFM.

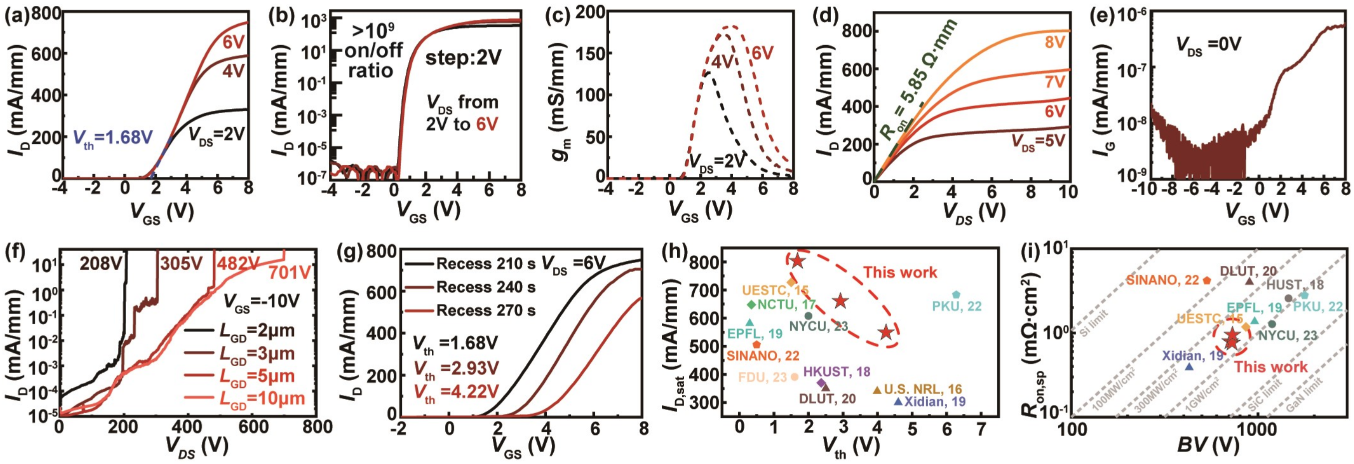
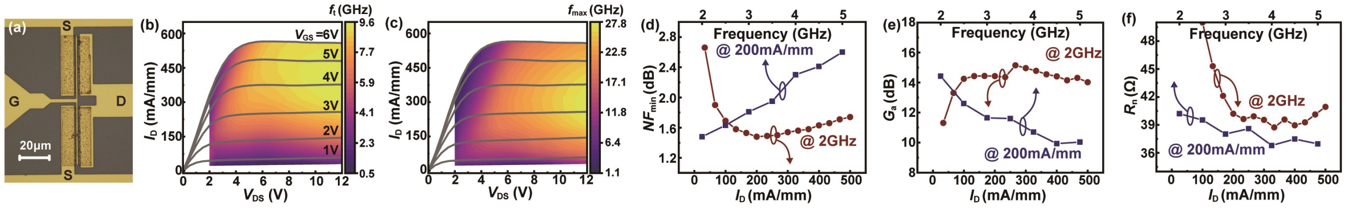
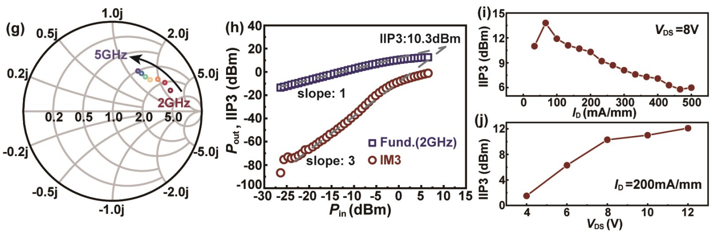


Fig.2 (a) Linear and (b) log scale transfer curves, (c) transconductance, (d) output characteristics, and (e) gate leakage of the recessed-gate MOSHEMT. (f) Breakdown characteristics of recessed-gate MOSHEMTs in off-state. (g) Devices with graded threshold voltages were achieved by controlling the etching depth. Benchmark of (h) $I_{D,sat}$ versus V_{th} and (i) $R_{on,sp}$ versus breakdown voltage for state-of-the-art recessed-gate GaN MOSHEMTs.





(k)

Param. /Ref.	V_{th} (V)	L_G (μm)	I_G (mA/mm)	g_m peak (mS/mm)	V_{DS} (V)	f_t/f_{max} (GHz)	$I_D/I_{D,MAX}$ (%)	NF_{min} (dB)@f (GHz)	G_a (dB)@f (GHz)
This Work	**0.5**	**1.2**	**≤10^{-6}**	**148**	**8**	**8.8/23.9**	**33**	**1.48@2 1.95@3.5**	**14.4@2 11.6@3.5**
p-GaN gate HEMT [a]	2.7	1	≥10^{-5}	78	8	6.1/10.3	2.4	0.90@2 4.4@3.5	12.8@2 10.1@3.5
Recessed-Gate MOSHEMT [b]	-1	0.06	≤10^{-7}	653	5	183/191	21.2	1.94@40 2.56@54	7.43@40 5.61@54

Fig.3 (a) Microscopic photograph of the recessed-gate MOSHEMT with a double-finger structure. Contour charts of V_{DS}- and I_D-dependent (b) f_t and (c) f_{max} for the recessed-gate MOSHEMT. I_D- or frequency dependence of (d) NF_{min}, (e) G_a, and (f) R_n of the recessed-gate MOSHEMT. (g) Frequency dependence of Γ_{opt} and +0.2 dB noise circles for 2 GHz at I_D of 200 mA/mm and V_{DS} of 8 V. (h) Two-tone third-order load-pull measurements for the recessed-gate MOSHEMT biased at I_D of 200 mA/mm and V_{DS} of 8V with source impedance matched at the Γ_{opt} for 2 GHz. (i) I_D - and (j) V_{DS} -dependence of IIP3 for the recessed-gate MOSHEMT. (k) A comparison of device parameters and RF performance for the E-mode p-GaN gate HEMT and D-mode recessed-gate MOSHEMT enabled by NBE. [a]. Zhou *et al.*, IEEE EDL, Vol.44, Iss.9, 2023. [b]. Lin *et al.*, IEEE EDL, Vol.38, Iss.6, 2017.