PALMA DE MALLORCA
7-10 SEPTEMBER
ESSERC 2026

UNIVERSITAT ROVIRA i VIRGILI

UIB Universitat de les Illes Balears

Compact Modeling of GaN MIS-HEMTs for Open PDKs

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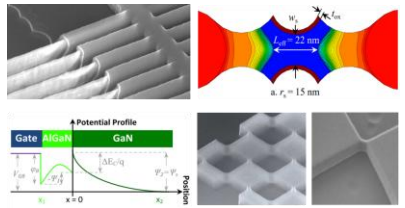

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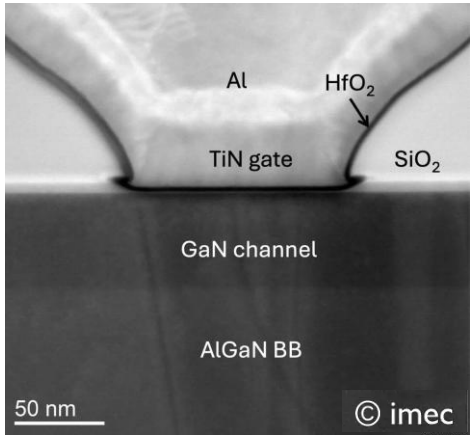
In collaboration:

Dr. Farzan Jazaeri

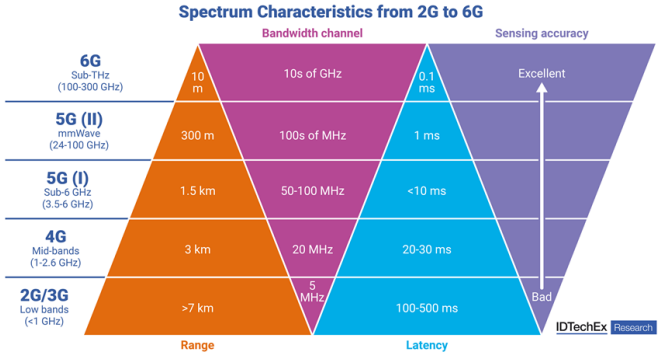
Why GaN?



https://www.marketsandmarkets.com/blog/SE/gan-semiconductor-device-technology-innovation



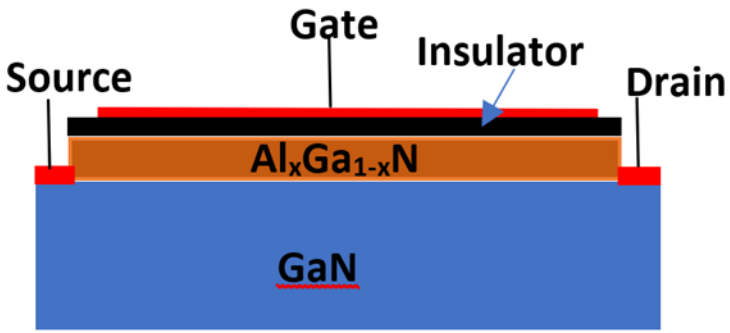
GaN-on-Si transistor for 6G power amplifiers



Outline

- Metal-Insulator-Semiconductor –High Electron Mobility Transistor (MIS-HEMT)
  - MIS-HEMT: Structure and Applications
- Intrinsic Limitations of 2DEG Density in MIS-HEMTs
- Compact drain current model of MIS-HEMT
  - 2DEG channel charge density
  - Explicit formulations
  - Charge Based Drain Current Model
- Compact Model Implementation
- Compact Model Validation
- Compact model: HEMT Biosensor Application
- Conclusion

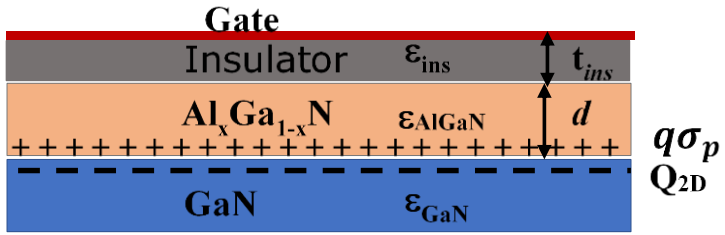
MIS-HEMT: Structure and Applications



Typical MIS-HEMT structure

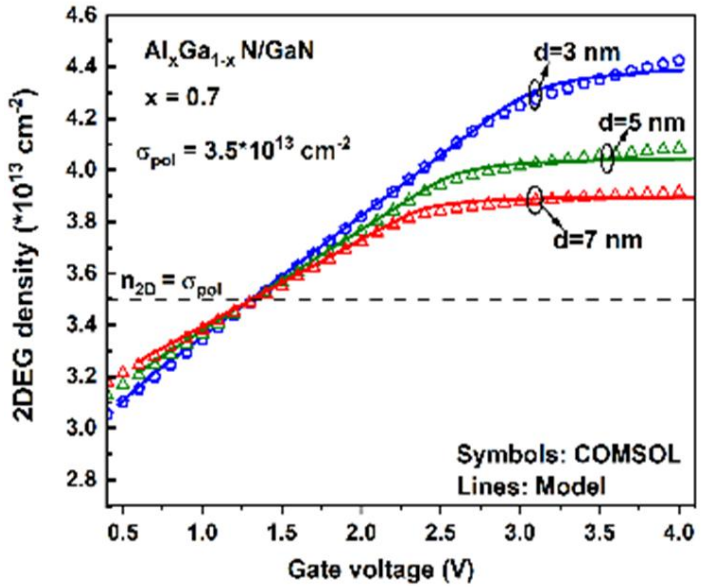
- Metal–Insulator–Semiconductor High-Electron-Mobility Transistors (MIS-HEMTs) are promising for:
  - high-frequency applications
  - high-power applications
  - next-generation wireless communication systems.
- Dielectric layer suppresses gate leakage, improving device performance and reliability.

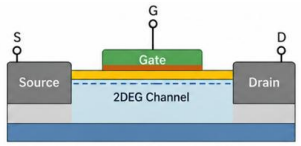
MIS-HEMT typical structure

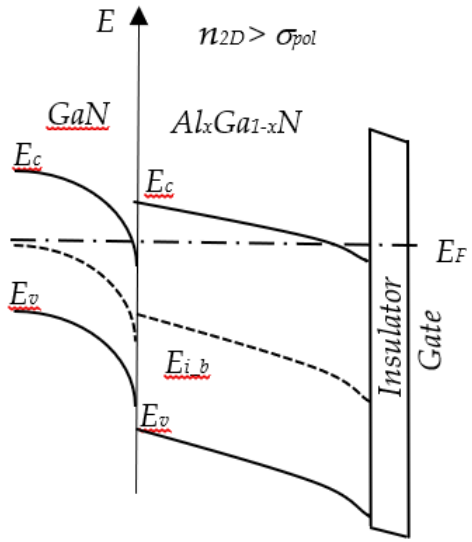


- Polarization-induced charges form at the $Al_xGa_{1-x}N$/GaN heterointerface, $q\sigma_{pol}$.
- A high 2DEG carrier density, Q_{2D}, is induced without intentional doping of the $Al_xGa_{1-x}N$ barrier layer.
- The gate voltage controls the 2DEG density through the electric field across the insulator and barrier.

Intrinsic Limitations of 2DEG Density in MIS-HEMTs



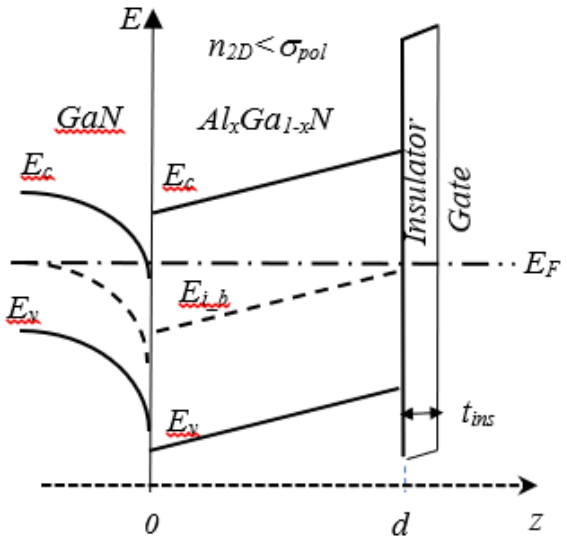


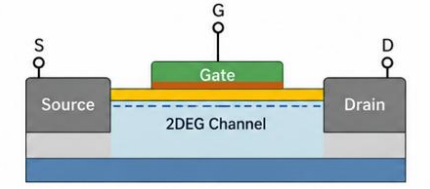


- The insulating layer enables the 2DEG density to exceed σ_{pol}.
- However, the maximum achievable 2DEG density is limited by the barrier thickness.*

* A. Yesayan, F. Jazaeri, B. Parvais and J. M. Sallese, "Intrinsic Limitation of 2DEG Modulation in GaN-MISHEMT," in *IEEE Trans. Electron Devices*, vol. 72, no. 11, pp. 5919-5925, Nov. 2025.

2DEG channel charge density, n_{2D}





- Below charge neutrality, the AlGaN barrier behaves as an insulator with an approximately constant electric field.
- An analytical 2DEG density expression is derived, valid from deep subthreshold to above-threshold operation:

$$U_T \, ln\left(exp\left(\frac{n_{2D}}{D\ kT}\right) - 1\right) + \frac{q n_{2D}}{C_{eff}} + \gamma\, {n_{2D}}^{\frac{2}{3}} = f\left(V_G, V_{ch}, \sigma_p\right)$$

Compact model: Explicit formulations

$$Q_{2D} = qn_{2D2}\, f_{sm} + q(1 - f_{sm})\, n_{2D1}$$

$n_{2D1} = f_{1_explicit}(V_G, V_{ch}, \sigma_p)$ Below threshold

$n_{2D2} = f_{2_explicit}(V_G, V_{ch}, \sigma_p)$ Above threshold

$$f_{sm} = 0.5 + 0.5\, tanh(V_{Go}/(\delta\, U_T)),$$

$$V_{Go} = V_G - V_{off} - V_{ch},\ V_{off} = \phi_{Bn} - q\sigma_p/C_{eff} - \Delta E_C/q\ ,\quad C_{eff} = \frac{C_{ins}\, C_b}{C_{ins}+C_b}$$

- Explicit equation for 2DEG charge density, valid from deep subthreshold to above-threshold operation
- Unified 2DEG density equation has compact form and suitable for Verilog-A implementation

Charge Based Drain Current Model

❑ Charge based drain current equation for GaN HEMT*:

$$I = I_o \left(\frac{Q_{ch}}{2C_{eff}\, U_T} - \left(\frac{Q_{ch}}{2C_{eff}\, U_T} \right)^2 \right) \Bigg|_S^D, \; I_o = 2\mu C_{eff}\, U_T{}^2 W/L \quad *$$

- Channel length modulation

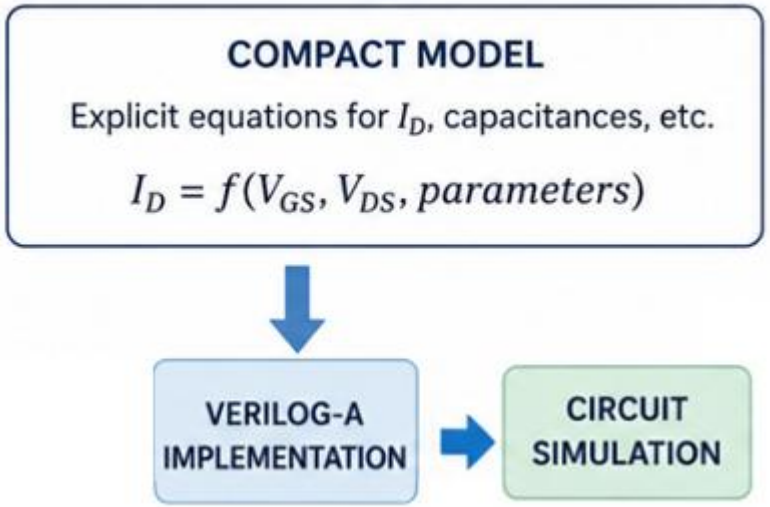
$$\Delta L = L_C ln \left(1 + \frac{V_D - V_{Deff}}{L_C E_{cr}} \right)$$

$$V_{Dsat} = V_G - V_{off}$$

$$V_{Deff} = \frac{V_D}{(1 + (V_D/V_{Dsat})^m)^{1/m}}$$

* F. Jazaeri and J-M. Sallese, "Charge-Based EPFL HEMT Model" IEEE Trans. on Electron Devices, vol. 66, no.3, pp. 1218-1229, 2019.

Compact Model Implementation

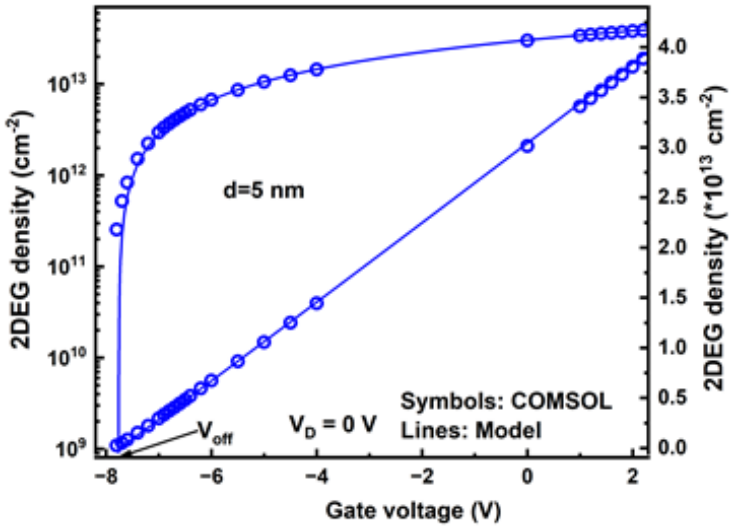


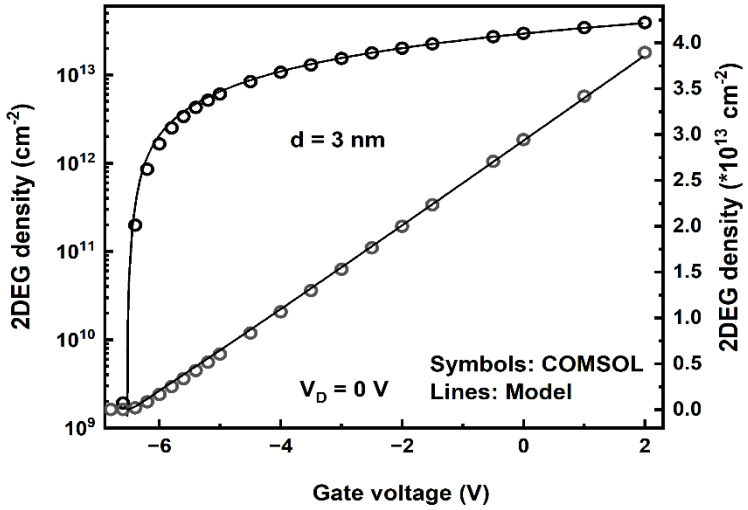
- Accurate, physics-based compact models are essential for transistor-level circuit design and simulation.
- Explicit model formulations facilitate efficient and robust implementation in Verilog-A.
- FOSS implementation: Verilog-A code → OpenVAF → ngspice

Variable Parameters Used in Calculations

Symbol	Definition	Magnitude
x	Aluminum content	0.3, 07
σ_{pol}	Polarization charge density (varying with x)	0.016, 0.056 (C/m^2)
T	Temperature	300 (K)
U_T	Thermal voltage	0.026 (V)
ε_{AlGaN}	Relative permittivity of AlGaN	8.8
t_{ins}	Insulator thickness	5 (nm)
ε_{ins}	Insulator relative permittivity	7 (for Si_3N_4)
C_{ins}	$C_{ins} = \varepsilon_{ins}\,\varepsilon_0/t_{ins}$	0.01 (F/m^2)
d	Thickness of AlGaN layer	3÷20 (nm)
C_b	$C_b = \varepsilon_{\mathrm{AlGaN}}\,\varepsilon_0/\mathrm{d}$	
D	Two-dimensional density of states in GaN	$9{\cdot}10^{19}$ ($eV^{-1}{\cdot}cm^{-2}$)
γ	Parameter for ground subband	$2.09{\cdot}10^{-31}$ ($C{\cdot}V{\cdot}m^{4/3}$)
ΔE_C	Conduction band offset (depends on x)	0.55, 1.38 (eV)

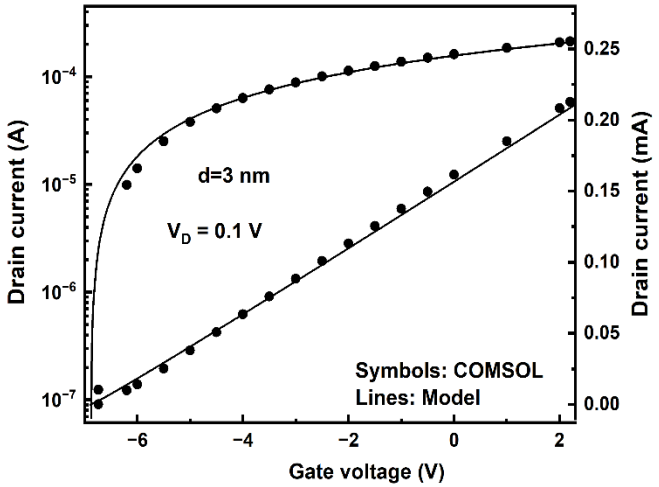
Validation of the 2DEG Charge Density

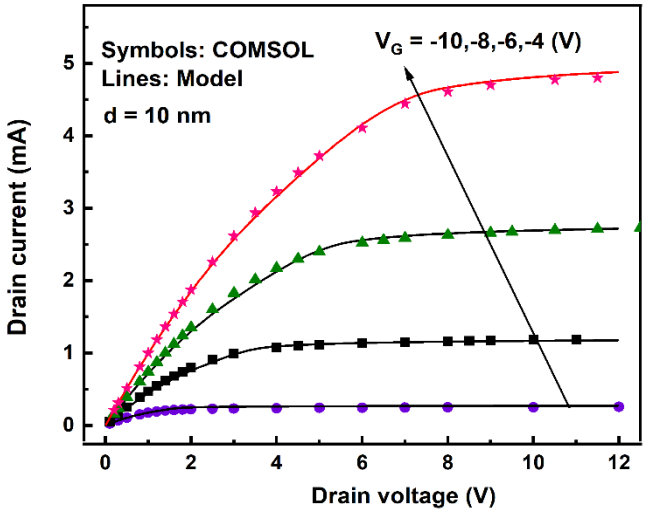


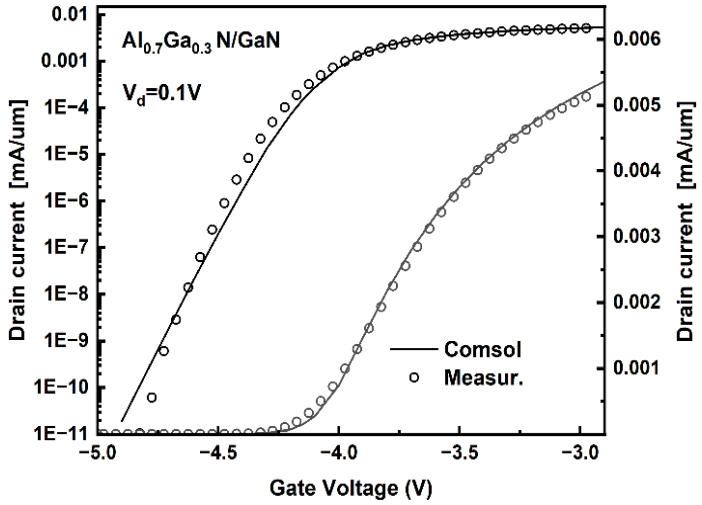


- The explicit 2DEG charge density expression is validated against 2D COMSOL Multiphysics simulations.
  - $Al_{0.7}Ga_{0.3}N$ is considered as a barrier and 5 nm thick Si_3N_4 as insulator layer.
- The model shows good agreement with simulations on both linear and logarithmic scales.

Drain Current Model Validation

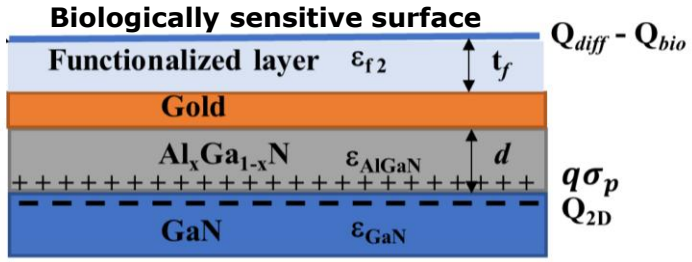






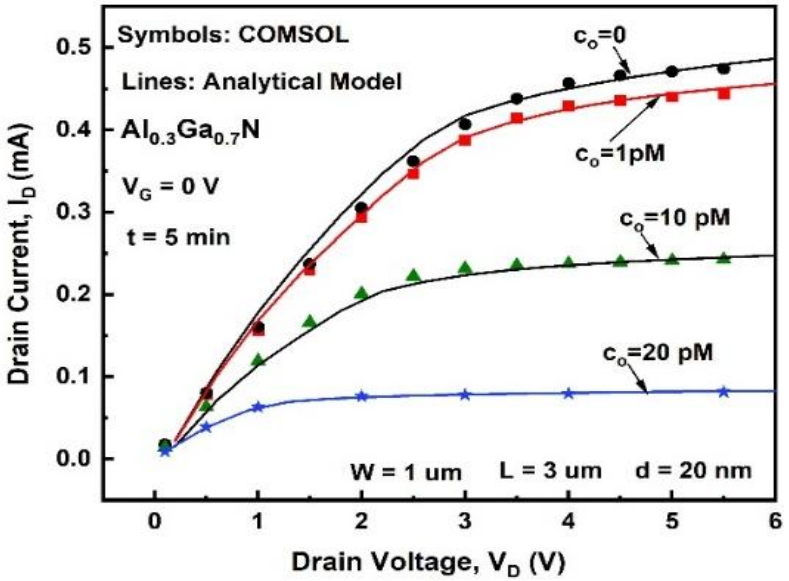
- Good agreement between the model and simulated transfer characteristics is observed on both linear and logarithmic scales.
- The accuracy of the model is further validated using the output characteristics.
  - Good agreement with COMSOL simulations confirms the accuracy of the channel-length modulation approach.
- COMSOL simulations have, in turn, been validated against experimental measurements.

Compact Model: HEMT Biosensor Application



- GaN MIS-HEMT biosensors enable highly sensitive, label-free detection of biomolecules.
  - The gold sensing surface is typically functionalized with a self-assembled monolayer
  - Biomolecular recognition results in adsorption of target analytes and formation of a charged layer above the gate.
- The bio-charged layer modulates the electrostatic potential at the sensing interface and, consequently, the 2DEG concentration.
- The change in 2DEG concentration modulates channel conductivity and drain current.

Compact Model: HEMT Biosensor Application



- The explicit analytical expressions enable direct investigation of the effects of electrostatic, biochemical, and structural parameters on sensor characteristics.
- The analytical model reproduces the numerical results with good accuracy.
- The accurate reproduction of sensing-charge-induced drain current modulation further validates the proposed drain current compact model.

Conclusion

- An explicit drain-current model was developed for an AlGaN/GaN MIS-HEMT and validated against COMSOL simulations.
- Good accuracy is achieved below and above threshold, as well as in linear and saturation operation, including channel-length modulation.
- The physics-based approach requires minimal fitting parameters.
- The explicit formulation enables simple and accurate implementation in circuit simulators, including the FOSS Open PDK environment.
- The model is applied to GaN MIS-HEMT biosensors, serving as a foundation for integrated, real-time biosensing platforms.

Thank you!