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Physics-Based Modeling and Charge Density Saturation in GaN/AlGaN MIS-HEMTs

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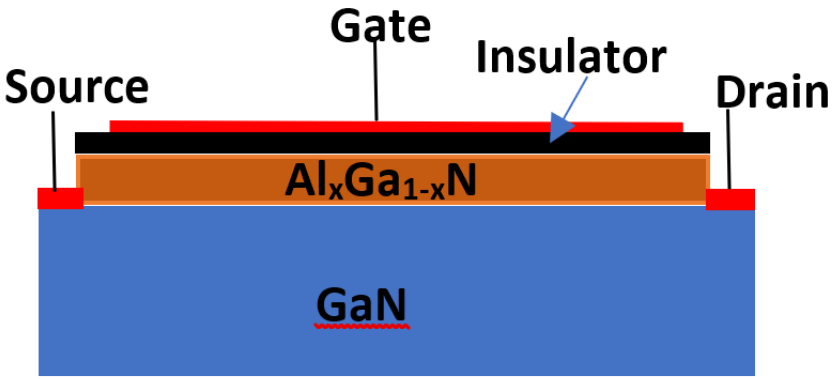
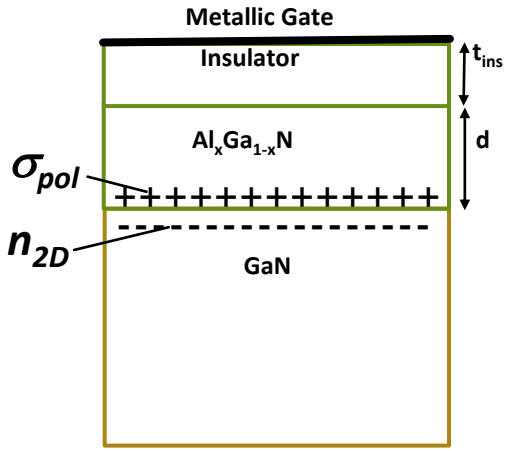
Outlines:

- Introduction to GaN MIS-HEMTs
- Increasing demand for advances in MIS-HEMTs
- charge density saturation in undoped GaN MIS-HEMTs
- Analytical model of charge saturation
- Model validation with COMSOL simulations
- Conclusion

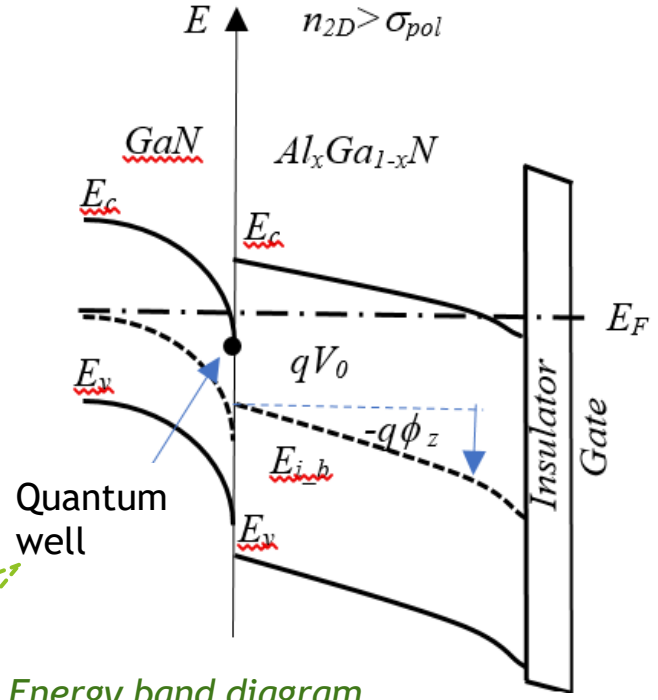
Metal-Insulator-Semiconductor –High Electron Mobility Transistor (MIS-HEMT): typical structure



Typical MIS-HEMT structure



vertical cut of MIS_HEMT structure



Energy band diagram

The polarization induced fixed charge induces a 2D electron gas (2DEG) in the quantum well (QW) created by the conduction band discontinuity at the AlGaN/GaN interface.

n_{2D} is two-dimensional electron gas density and σ_{pol} is polarization charges density

❑ Increasing demand for advances in MIS-HEMTs

What are driving forces today?

- *High data-rates*
- *Low energy consumption*

✓ **As a result, the wireless communication industry has gradually increased operating frequencies to meet this demand!**

✓ **5G products are being rolled out in sub-6GHz frequency bands, and products targeting 28/39GHz are already showcased.**

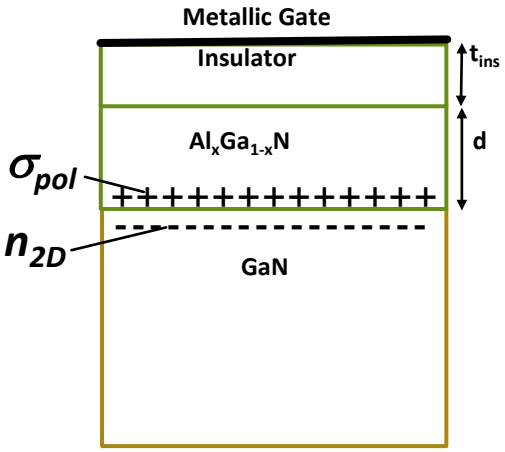
The remaining challenges are the reduced output power and lower efficiency of most technologies at these frequencies.

GaN semiconductors are the best candidates for these technologies due to their higher mobility, charge density and breakdown voltage.

However, the gate leakage current remains an issue for HEMTs.

In order to suppress the gate leakage current, the introduction of an additional dielectric layer in form of MIS-HEMT offers significant improvement in terms of gate leakage.

❑ Core analytical model: channel charge saturation



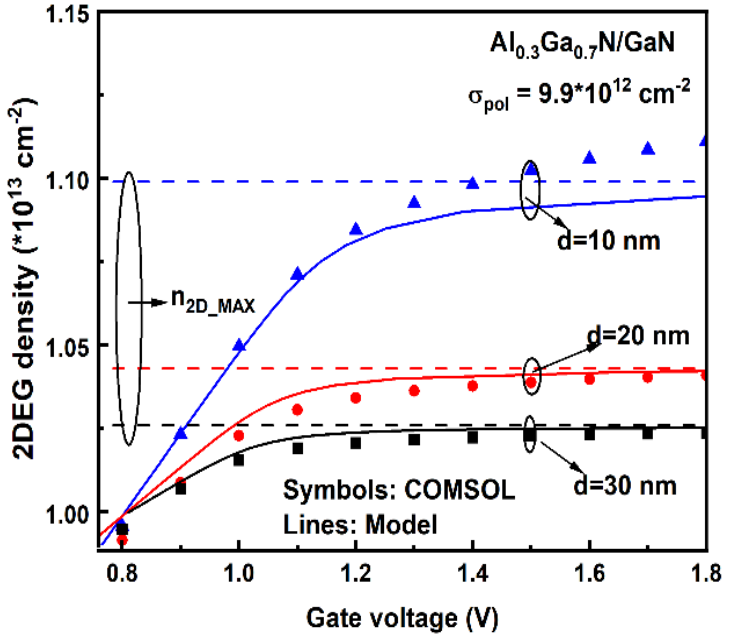
The insulating layer beneath the gate enables operation at high gate voltages, effectively mitigating conventional gate leakage issues.

One would expect that the 2DEG density under high gate voltages would continuously increase, however..

Charge neutrality reaches when $n_{2D} = \sigma_{pol}$

Operation beyond the charge neutrality point leads to the accumulation of mobile charges under the gate insulator. These charges screen the gate voltage, resulting in the saturation of the 2DEG density in the quantum well. The barrier thickness and aluminum content determine the maximum achievable, n_{2D_max} for the given structure

This effect was first observed and modelled by our modelling group [1].



1. A. Yesayan, F. Jazaeri, B. Parvais and J. M. Sallese, "Intrinsic Limitation of 2DEG Modulation in GaN-MISHEMT," in *IEEE Trans. Electron Devices*, doi: 10.1109/TED.2025.3610338. (2025).

❑ Core analytical model $n_{2D}=f(V_G, V_D)$

Poisson-Boltzmann equation in the barrier region has been analytically solved and following charge density -voltage dependencies have been derived:

$$V_G{}^{*} = \frac{\varepsilon_b}{C_{ins}} F_{b\_s} + \varphi_s$$

$$\varphi_s = U_T \, ln\left[\frac{F_{b\_s}{}^{2} - C_o}{\alpha}\right] + V_o$$

$$F_{b\_s} = \sqrt{C_o}\, coth\left(acoth\left(\frac{q(n_{2D}-\sigma_{pol})}{\varepsilon_b\sqrt{C_o}}\right) - \frac{\sqrt{C_o}}{2U_T} d\right) \quad for \quad C_o>0$$

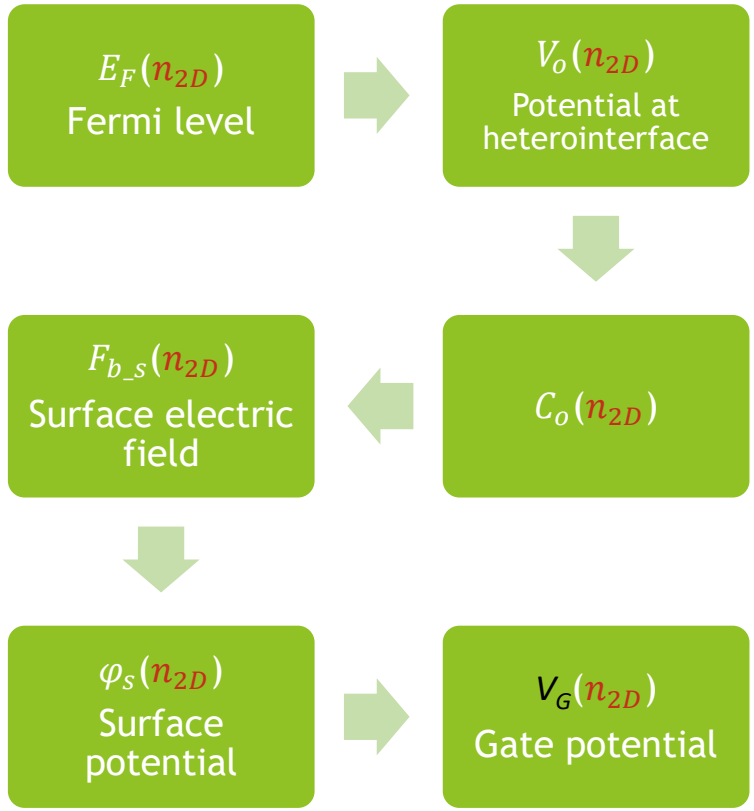
$$F_{b\_s} = \sqrt{-C_o}\, tan\left(z\frac{\sqrt{-C_o}}{2U_T} + \text{atan}\left(\frac{q(n_{2D}-\sigma_{pol})}{\varepsilon_b\sqrt{-C_o}}\right)\right) for \quad C_o<0$$

$$C_o = \left(\frac{q(n_{2D}-\sigma_{pol})}{\varepsilon_b}\right)^2 - \alpha \exp\left(-\frac{V_o}{U_T}\right)$$

$$qV_o = \Delta E_c - \frac{E_{G_b}}{2} + kT\, ln\left(\frac{N_{V_b}}{N_{C_b}}\right) - E_F$$

$$E_F = kT\, ln\left(exp\left(\frac{n_{2D}}{DOS\, kT}\right) - 1\right) + \gamma\, n_{2D}{}^{\frac{2}{3}}$$

Calculation method

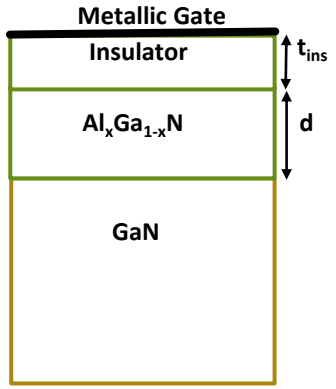


The outcomes of presented model

- We developed a physics-based analytical model that explains how electrons accumulating at the insulator/AlGaN interface screen the electrostatic potential and thereby modify the charge density in the AlGaN/GaN MIS-HEMT quantum well.
- The presented method enables quick and explicit estimation of the asymptotic (maximum) 2DEG density (n_{max}) at given system parameters.
- An accurate evaluation of charge saturation is critical for distinguishing the respective contributions of the ungated access regions and charge saturation to drain current saturation at high gate voltages.
- This model can be further expended for calculations of gate leakage current in HEMTs.

Variable parameters used in calculations

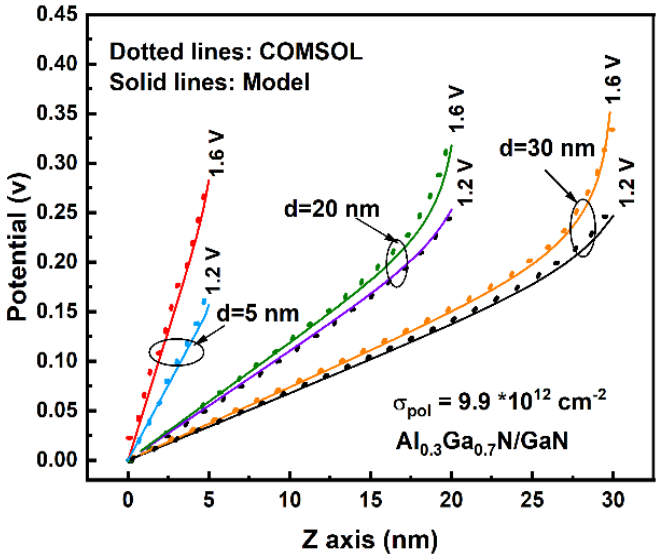
Symbol	Definition	Magnitude used in calculations
x	Aluminum content	0.3, 07
σ_{pol}	Polarization charge density (varying with x)	0.016, 0.056 (C/m^2) [4]
T	Temperature	300 (K)
U_T	Thermal voltage	0.026 (V)
ε_{AlGaN}	Relative permittivity of AlGaN	$3.4 \cdot 10^{-16}$ (cm^{-3})
t_{ins}	Insulator thickness	5 (nm)
ε_{ins}	Insulator relative permittivity	7 (for SiN_4)
C_{ins}	$C_{ins} = \varepsilon_{ins}\,\varepsilon_0/t_{ins}$	0.01 (F/m^2)
d	Thickness of AlGaN layer	3÷20 (nm)
DOS	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)
n_{i_AlGaN}	Intrinsic concentration of AlGaN	~$3 \cdot 10^{-25}$ (cm^{-3})
E_{AlGaN}	Band gap of AlGaN (depends on x)	4.15, 5.26 (eV)
α	$\alpha = 2qU_T\, n_{i\_AlGaN}/\varepsilon_{i\_AlGaN}$	$4.06 \cdot 10^{-20}$ (V^2/m^2)



The same set of parameters were used in COMSOL Multiphysics and MATHCAD calculations.

Model validation with COMSOL simulations

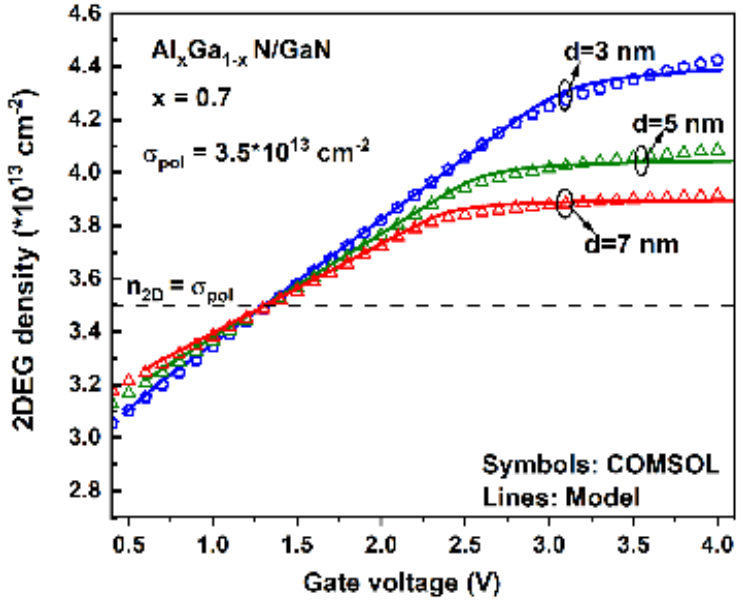
- The potential distribution in the $Al_{0.3}Ga_{0.7}N$ barrier layer along the Z axis (vertical direction) for different barrier thicknesses, namely 30, 20 and 5 nanometers. Calculations are done for two gate voltages: V_G=1.2V and 1.6V, which are chosen well above of threshold voltage (-2V for this structure).



- ✓ The curvature of the potential means that a charge builds up in the barrier layer and suggests that the AlGaN barrier cannot be treated anymore as an insulator, but behaves as a semiconductor.
- ✓ The increase of gate voltage is causing accumulation of electrons in the barrier, close to barrier/insulator interface ($z = d$).
- ✓ The onset of charge enhancement in the barrier is higher for thicker barrier layers.
- ✓ Charge accumulation in the barrier screens the gate voltage. As a result, the curvature of the potential in the barrier indicates also the saturation of the 2DEG density in the QW.

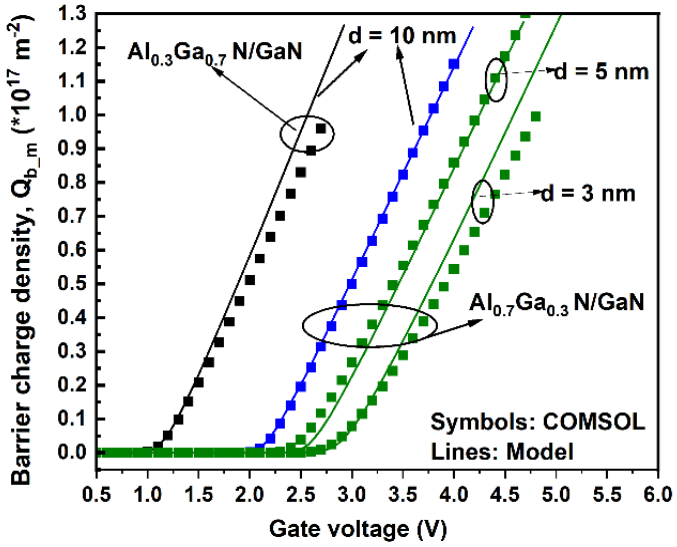
Model validation with COMSOL simulations

- 2DEG density versus the gate voltage for 7, 5, and 3 (nm) AlGaN barrier thicknesses, with 70% aluminum content.



For each barrier thickness, as it is predicted by the model, there is a maximum charge density in the quantum well.

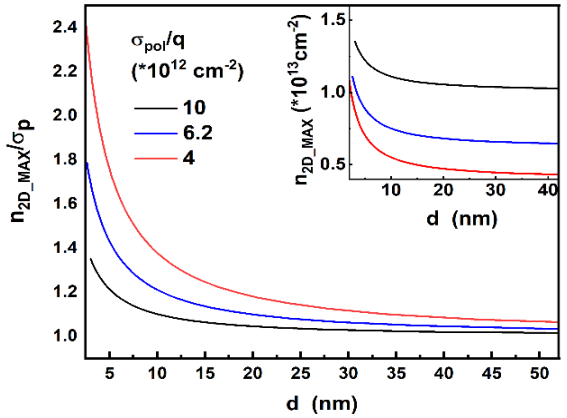
- Mobile charge density in $Al_xGa_{1-x}N$ barrier layer for x=0.3 and x=0.7 with different barrier thicknesses.



The mobile charge density in the AlGaN layer increases above certain value of the gate voltage.

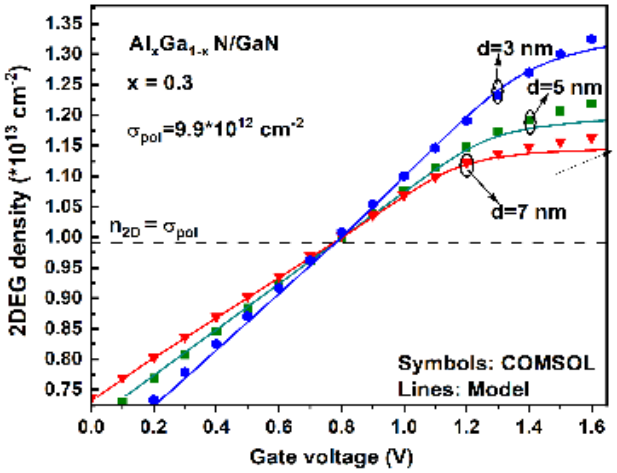
Model validation with COMSOL simulations

- Maximum 2DEG density normalized to the polarization charge density versus the barrier thickness for different σ_{pol}. The Inset illustrates the same plots with non-normalized n_{2D_MAX}.



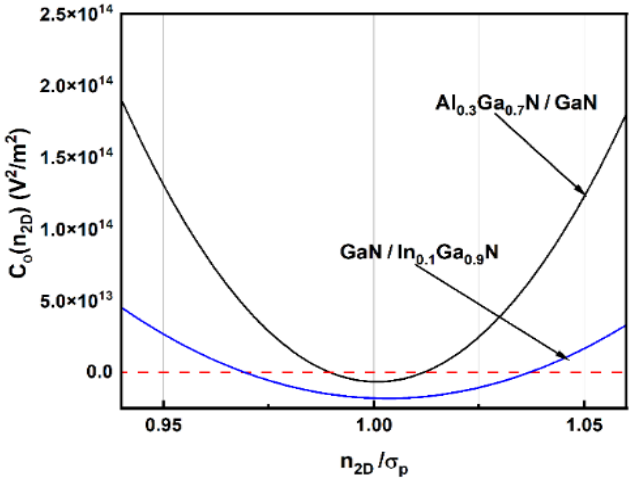
- We observe that the lower is σ_{pol}, the higher is n_{2D_MAX}/σ_{pol}.
- For thick barriers, larger than 40nm, n_{2D_MAX}/σ_{pol} is even close to unity, which is not the case for ultrathin AlGaN barriers.

- 2DEG density versus the gate voltage for 7, 5, and 3 (nm) AlGaN barrier thicknesses, with 30% aluminum content.



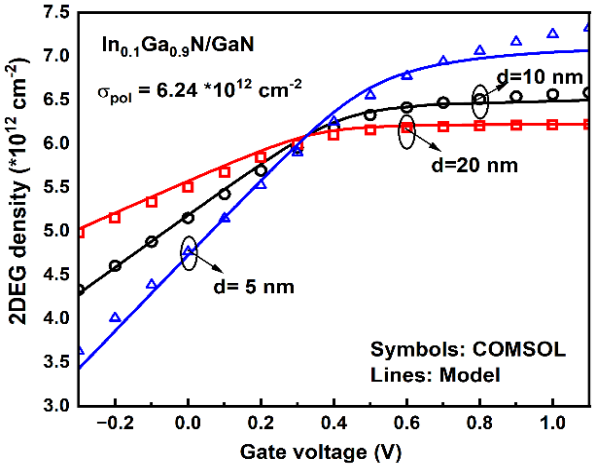
- Whatever the barrier thickness, all the curves cross at almost the same gate voltage which corresponds to the channel neutrality state at the heterojunction, i.e. $n_{2D} = \sigma_{pol}$. Below this value, the charge in the QW varies almost linearly with the gate voltage.

- Calculation of $C_o(n_{2D})$ for two heterostructures: $Al_{0.3}Ga_{0.7}N$/GaN and GaN /$In_{0.1}Ga_{0.9}N$.



We see that for practical values of n_{2D}, i.e. close to the polarization σ_{pol}, the coefficient $C_o(n_{2D})$ changes sign for both materials.

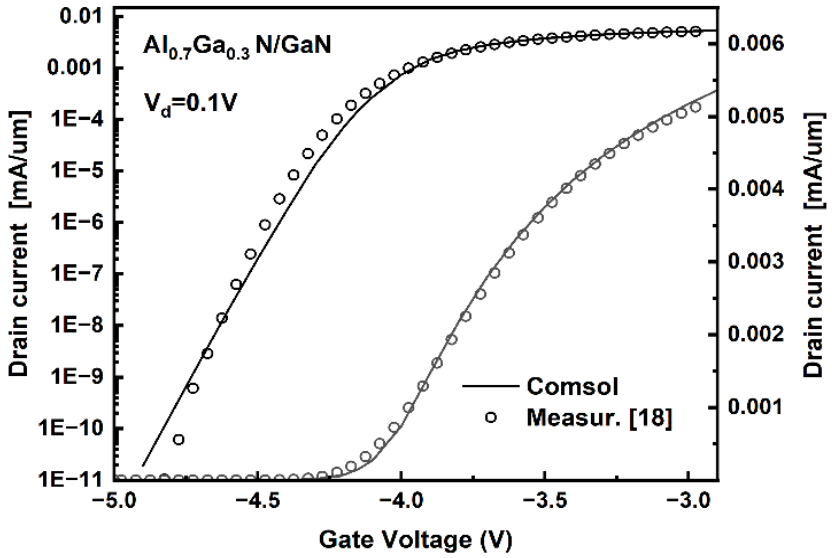
- 2DEG density versus gate voltage for 20, 10, and 5 (nm) GaN barrier thicknesses for GaN/InGaN MISHEMT.



-well above the neutrality condition, a slight mismatch between the numerical simulations and the analytical model is observed for the thinner barrier layer (5 nm), which is attributed to the use of Fermi-Dirac statistics in COMSOL, while Boltzmann statistics are used in the model.

Validation with experimental data

- Comparison of experimental data [1] with COMSOL simulations.



The device measured in [1] consist of

- 3 nm barrier layer with 70% aluminum content,
- 5 nm thick Si_3N_4 insulating layer,
- source and drain access regions of 0.75 um and 1.5 um length respectively,
- the gate length is 0.5 μm.

1. S. Yadav, et al. "High Performance mm Wave AlN/GaN MISHEMTs on 200 mm Si Substrate," 2023 International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 2023, pp. 1-4, DOI. 10.1109/IEDM45741.2023.10413712.

CONCLUSION

- The analytical model determines the charge densities in both the quantum well and the barrier of an MIS-HEMT.
- The calculations demonstrate that high barrier charge densities arise above a certain gate voltage.
- The model contains no fitting parameters, while it exhibits very good agreement with numerical simulations performed using COMSOL Multiphysics.
- The analytical model is design-oriented and the calculations highlight the key parameter dependencies.
- The model is also validated against experimental data.

Thank you for your attention