Compact Quasi-Static Small-Signal Model for GaN HEMTs

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Goal

- Development of a physical-based compact model for GaN HEMT with analytical expressions of the drain current and the small-signal parameters

Outline

- Introduction
- Charge control model
- DC model
- Charge and capacitance models
- Results
- Conclusion

Introduction

- Since the use of wide band-gap materials for FETs started, GaN based HEMTs have demonstrated to be one of the best devices for high power and high frequency applications
- Accurate modeling of GaN HEMTs is therefore critical in high power RF circuit design
- The fact that most physical models are computationally complex and time consuming restricts their application in circuit simulations.
- A Call for a standard GaN HEMT model has been opened by the Compact Modeling Council

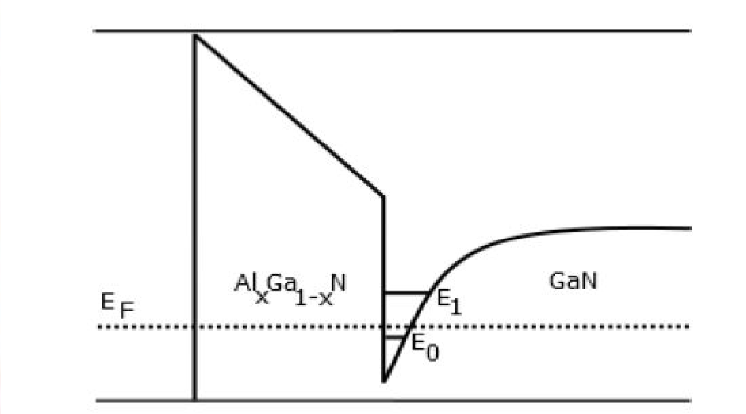
Introduction

- We developed a compact and explicit GaN HEMT model based from a charge control model derived from the band structure at the AlGaN/GaN interface
- Analytical expressions, valid for all operating regimes, of the drain current, total charges and small-signal parameters, have been obtained
- Short-channel effects were included
- The modeled characteristics agree very well with experimental data

Charge control model

- In AlGaN/GaN and AlGaAs/GaAs heterostructures the charge density per unit area accumulated in the potential well at the interface can be calculated with the assumption of a quasi-constant electric field in the potential well (triangular well approximation) and considering that only the contribution of the first subband is important:

$$n_s = DV_{th} \ln\left(\exp\left(\frac{E_f - E_0}{V_{th}} \right) + 1 \right)$$



Where $E_0 = \gamma_0 n_s^{2/3}$

This results in the following charge control model:

$$V_{g0} = \frac{qdn_s}{\varepsilon} + \gamma_0 n_s^{2/3} + V_{th} \ln\left[\exp\left(\frac{n_s}{DV_{th}} \right) - 1 \right]$$

Drain current model

- The drain current expression is obtained from:

$$I_{ds} = W\mu q n_s \frac{dV}{dx}$$

- Applying the charge control model

$$dV = -\left(\frac{qd}{\varepsilon} + \frac{2}{3}\gamma_0 n_s^{-1/3} + V_{th} n_s^{-1}\right) dn_s \, .$$

- After integration from source to drain, we obtain:

$$I_{ds} = -\frac{q\mu W}{L}\left[\frac{qd}{2\varepsilon}\left(n_D^2 - n_S^2\right) + \frac{2}{5}\gamma_0\left(n_D^{5/3} - n_S^{5/3}\right) + V_{th}\left(n_D - n_S\right)\right]$$

Drain current model

- We use unified and analytical expressions for the charge sheet densities at the source and drain, valid and continuous through all operating regimes

$$n_S = \frac{2V_{th}\left(C_g/q\right)\ln\left(1+\exp\left(V_{g0}/2V_{th}\right)\right)}{1/H\left(V_{g0}\right)+\left(C_g/qD\right)\exp\left(-V_{g0}/2V_{th}\right)}$$

$$H\left(V_{go}\right) = \frac{V_{go}+V_{th}\left[1-\ln\left(\beta V_{gon}\right)\right]-\frac{\gamma_0}{3}\left(\frac{C_g V_{go}}{q}\right)^{2/3}}{V_{go}\left(1+\frac{V_{th}}{V_{god}}\right)+\frac{2\gamma_0}{3}\left(\frac{C_g V_{go}}{q}\right)^{2/3}}$$

Drain current model

- The main short-channel and second order effects are included in the model.
  - Velocity saturation
  - Channel-length modulation
  - DIBL
  - Self-heating
- To take into account velocity saturation, a saturation voltage is found from a relation between velocity and lateral field. An effective drain-source voltage is used in the model.

Charge model

- The gate charge expression is derived by integrating the gate charge density and using our unified charge control model

$$Q_G = W\int_0^L q n_s(x)\,dx\,.$$

$$Q_G = \frac{W^2 q^2 \mu}{I_{ds}}\int_{V_s}^{V_d} n_s^2\,dV$$

- The final expression is:

$$Q_G = WLq\left(\frac{\frac{qd}{3\varepsilon}\left(n_D^3 - n_S^3\right) + \frac{1}{4}\gamma_0\left(n_D^{8/3} - n_S^{8/3}\right) + \frac{1}{2}V_{th}\left(n_D^2 - n_S^2\right)}{\frac{qd}{2\varepsilon}\left(n_D^2 - n_S^2\right) + \frac{2}{5}\gamma_0\left(n_D^{5/3} - n_S^{5/3}\right) + V_{th}\left(n_D - n_S\right)}\right)$$

Gate capacitance model

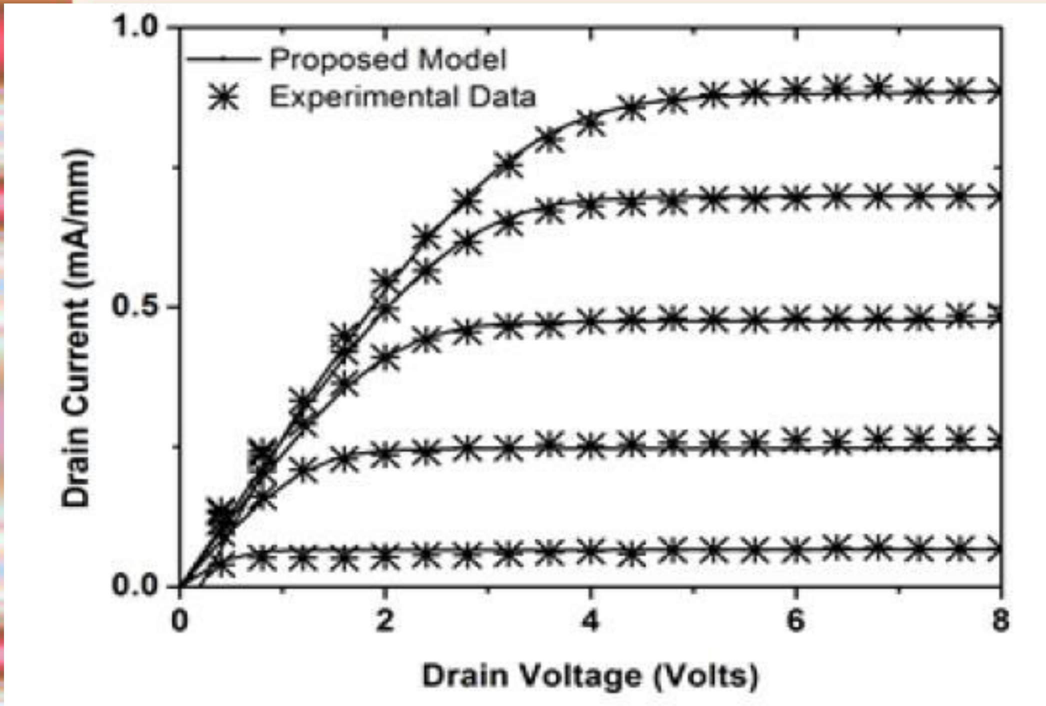
- The gate-source and gate-drain capacitances are obtained by partially differentiating the gate charge with respect to the source and drain voltages

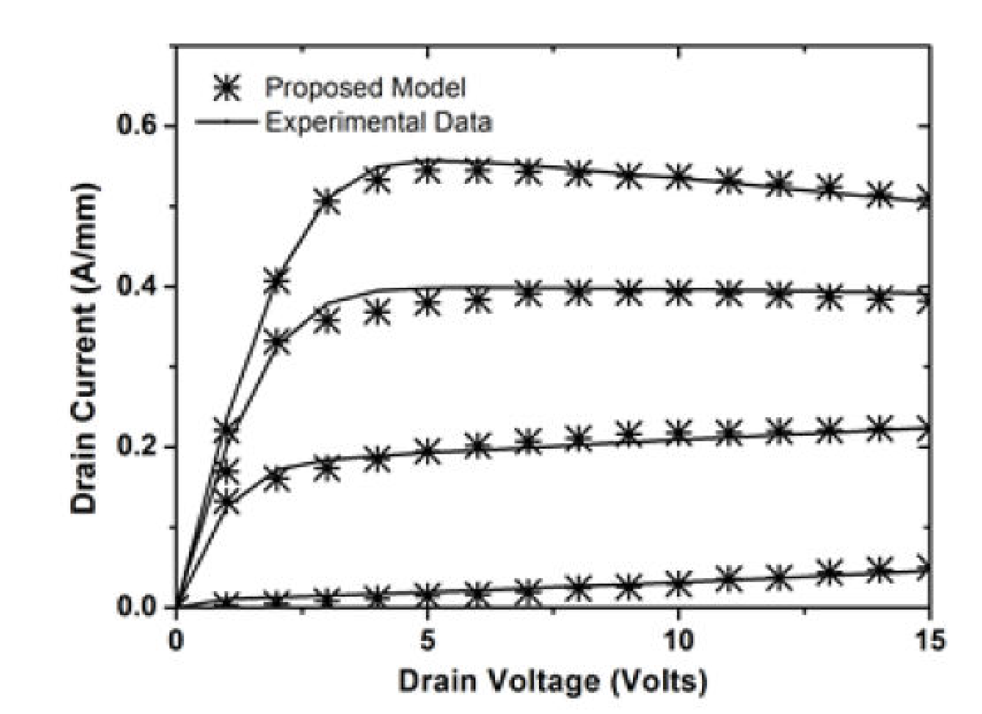
$$C_{Gx} = WLq\left(\frac{\frac{\partial f(n_s)}{\partial V_x} g(n_s) - f(n_s)\frac{\partial g(n_s)}{\partial V_x}}{(g(n_s))^2}\right)$$

$$f(n_s) = \frac{qd}{3\varepsilon}\left(n_D^3 - n_S^3\right) + \frac{1}{4}\gamma_0\left(n_D^{8/3} - n_S^{8/3}\right) + \frac{1}{2}V_{th}\left(n_D^2 - n_S^2\right)$$

$$g(n_s) = \frac{qd}{2\varepsilon}\left(n_D^2 - n_S^2\right) + \frac{2}{5}\gamma_0\left(n_D^{5/3} - n_S^{5/3}\right) + V_{th}\left(n_D - n_S\right).$$

Results

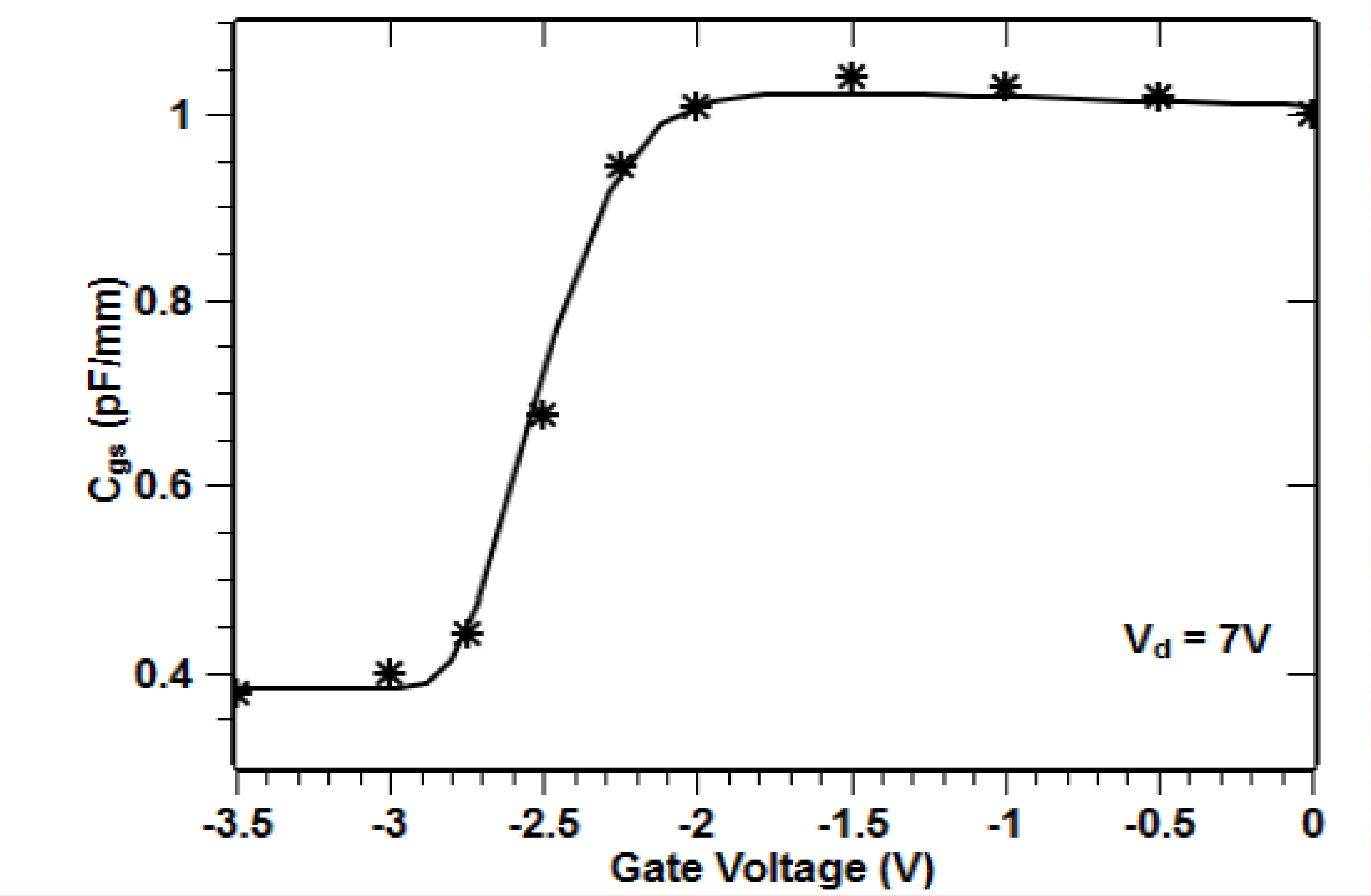




Measured and modeled I-V
for a GaN HEMT with L=0.7 μm
V_g from -3V to 1 V

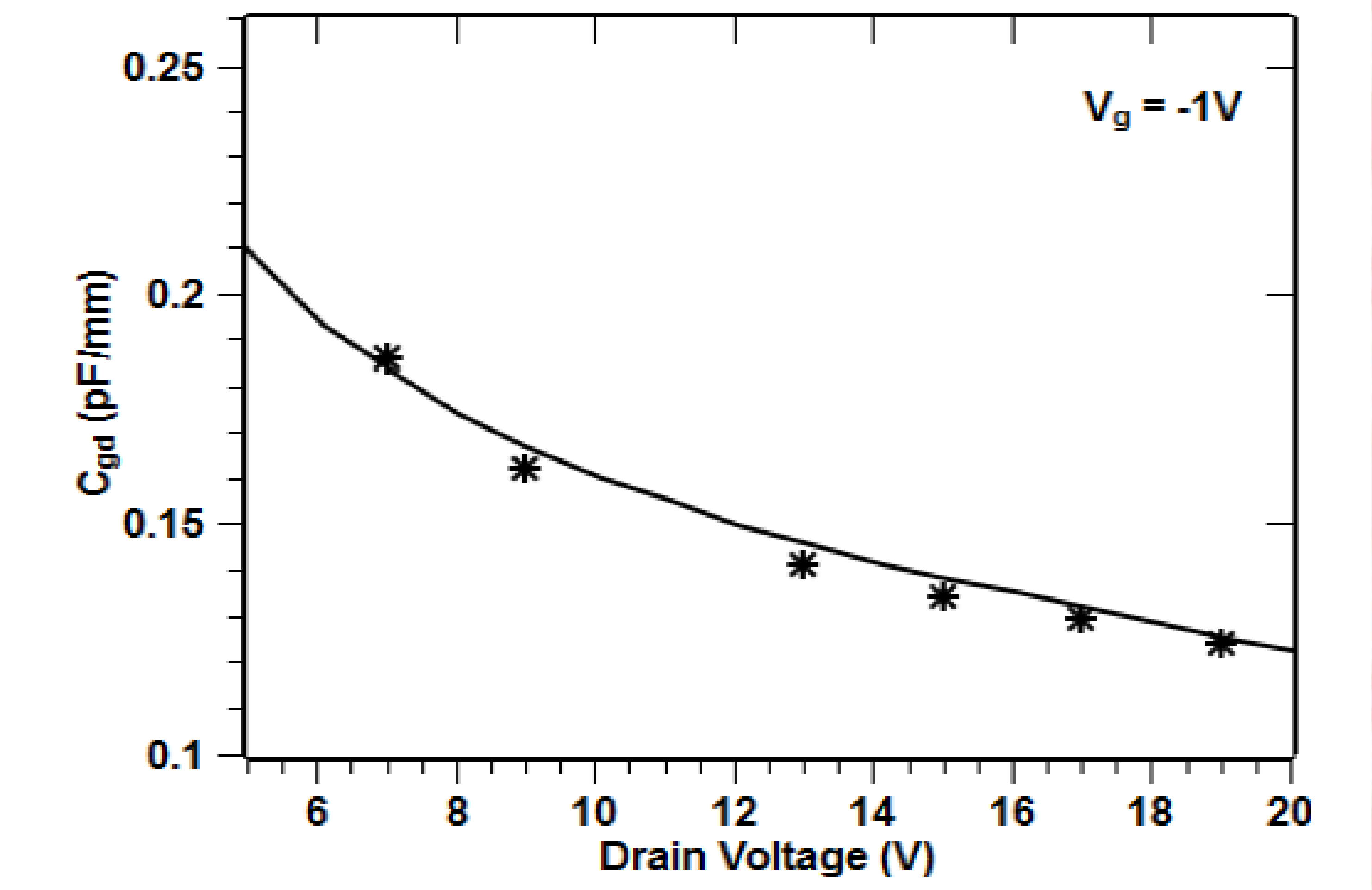
Measured and modeled I-V
for a GaN HEMT with L=0.35 μm
V_g from -3V to 0 V

Results



Measured and modeled C_{gs} for a GaN HEMT with L=0.35 μm at V_d = 7V

Results



Measured and modeled C_{gd} for a GaN HEMT with L=0.35 μm at V_g = -1V

Conclusions

- We have presented a compact model for AlGaN/GaN with analytical expressions of the small-signal parameters
- The model is developed from a unified charge control model obtained from the band structure of the potential well at the heterointerface considering the contribution of only the first level (assuming a triangular well)
- Good agreement is observed with experimental data

Acknowledgements

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