Application of the Grey-Box Modelling to Simulate GaN HEMTs

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Overview

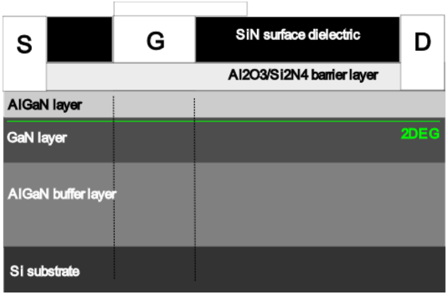
1. GaN HEMT
2. Computational Method
3. Equivalent Circuit
4. Nonlinear Current Source Model
5. Conclusions

GaN HEMT as a Pulsed Power Switch

Relevance for pulsed power switching:

- Short achievable rise time (down to 1 ns and less) (Sack et al. 2023);
- Bidirectional operation;
- Achievable output voltages of up to 600 V. (Paraliev 2022)

Typical structure of a GaN HEMT

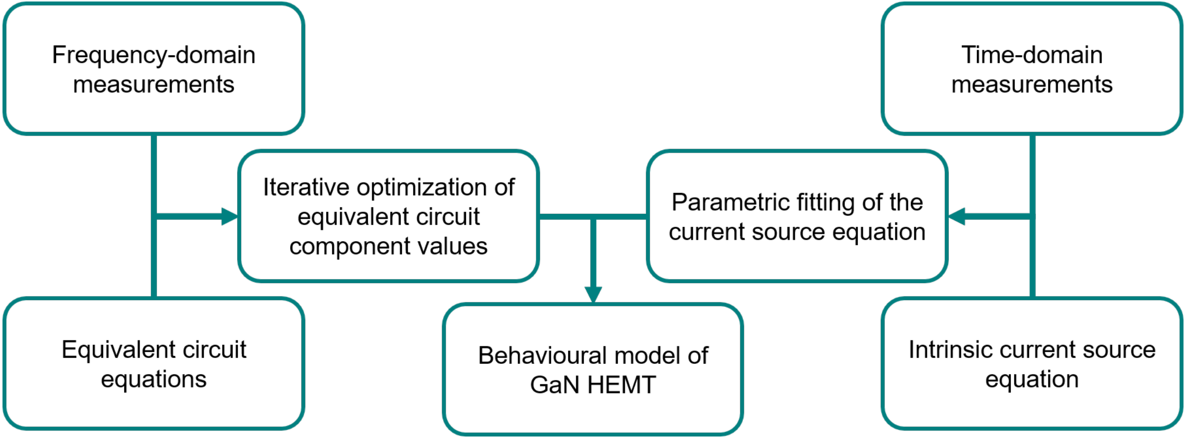


Modelling Goals

Requirements for a behavioural model of a GaN HEMT:

- Obtainable by using results of standard S-parameter and double-pulse measurements as an input.
- Captures all operation regimes important for a particular application.
- Model parameters can be traced back to quantifiable and measurable characteristics.
- Augmentable with subcircuits for trapping effects.

Modelling Method



Frequency-domain measurements

Time-domain measurements

Iterative optimization of equivalent circuit component values

Parametric fitting of the current source equation

Equivalent circuit equations

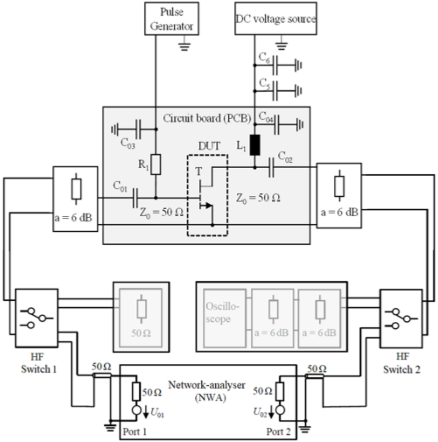
Behavioural model of GaN HEMT

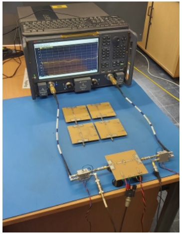
Intrinsic current source equation

Measurements

Measurements provide a set of S-parameters

- Operating point: U_{gs} and U_{ds} are set using a DC and a pulse generators;
- Frequency is set at the NVA ports;
- Operating time (used to assess self-heating in the ON-state) is accounted for.

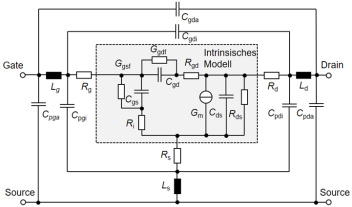




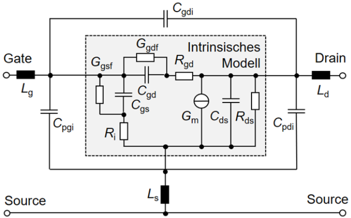
Computational process

- The method was tested using I-V curves and S-parameters
    - simulated with the manufacturer-supplied models for 3 devices,
    - obtained from the characterization of a real device.
- Computations were made using MatLab libraries.
    - Grey-box estimation to obtain equivalent circuit component values,
    - Surface Fitting to obtain bias-dependent functions for variable components.
- Output data was represented as a SPICE sub-circuit.

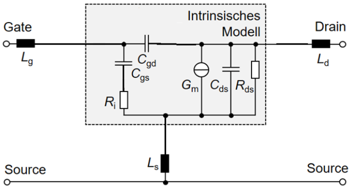
Equivalent Circuits



21 components: for frequencies up to 100 GHz.



15 components: for frequencies up to 500 MHz.

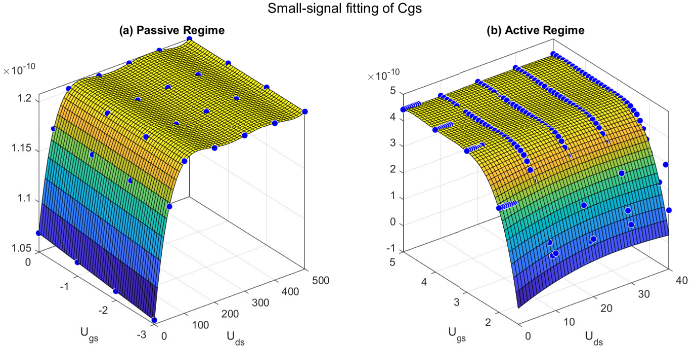


9 components: reducing degrees of freedom by removing negligible elements.

For each set OP, measured S-parameters are compared and iteratively fitted to parametric equations that describe the chosen equivalent circuit

Sources: A. H. Jarndal 2006; Hergt 2021

Circuit Components



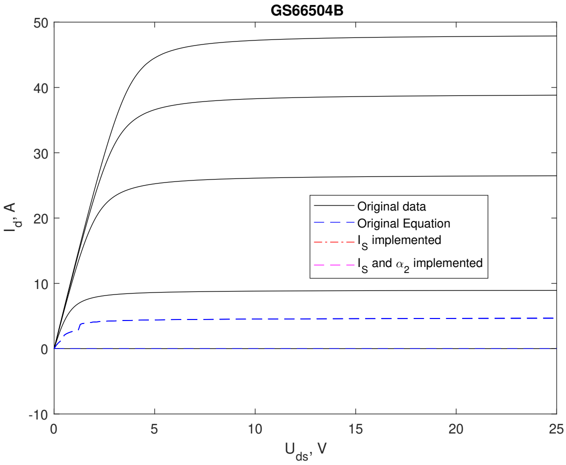
- Iterative computation yields component values corresponding to the measured set of operating points.
- Fitting to describe the corresponding components with bias-dependent functions.
- The best fit is the 5th-order polynomial, with different parameters for the passive regime and the active regime at high and low U_{gs}.

Nonlinear Current Source Model

Current-voltage characteristics can be described by the Chalmers equation (Angelov, Zirath, and Rosman 1992):

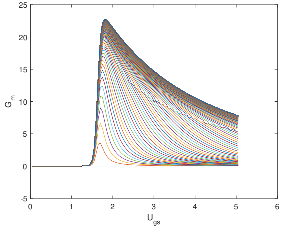
$$I_{ds} = I_{pk} \cdot \left(1 + \tanh\left(P_1 \cdot (U_{gs} - U_{pk}) + P_2 \cdot (U_{gs} - U_{pk})^2 + P_3 \cdot (U_{gs} - U_{pk})^3\right)\right) \cdot \tanh(\alpha_1 \cdot U_{ds}) \cdot (1 + \lambda U_{ds}) \cdot (1 - \Theta). \tag{1}$$

Current-Voltage Characteristics



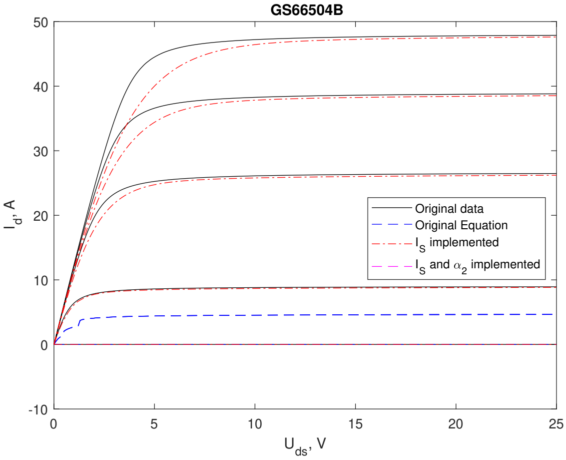
Nonlinear Current Source Model

The assumption of the bell-shaped G_m is not fulfilled for the characterized transistors.
The first coefficient should become I_S in the ON state.



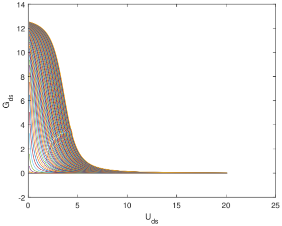
$$I_{ds} = I_{pk}\frac{I_S}{I_{pks}} \cdot \left(1 + \tanh\left(P_1 \cdot (U_{gs} - U_{pk}) + P_2 \cdot (U_{gs} - U_{pk})^2 + P_3 \cdot (U_{gs} - U_{pk})^3\right)\right) \cdot \tanh(\alpha_1 \cdot U_{ds}) \cdot (1 + \lambda U_{ds}) \cdot (1 - \Theta). \tag{2}$$

Current-Voltage Characteristics



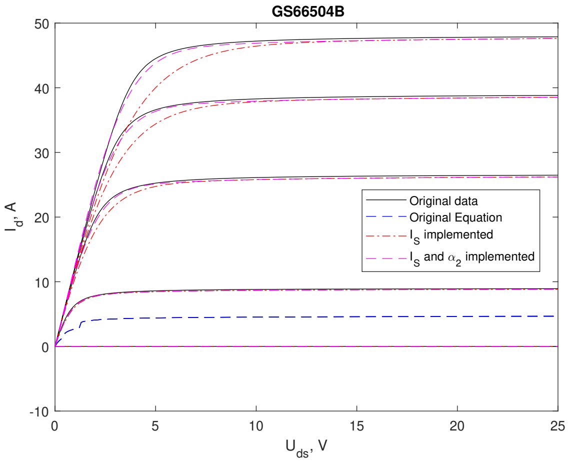
Nonlinear Current Source Model

$\alpha_1 U_{ds}$ term is not enough to describe the curve slope in the ohmic regime. Expanding this term with $\alpha_2 U_{ds}^2$ allows describing G_{ds0} behaviour in this regime.



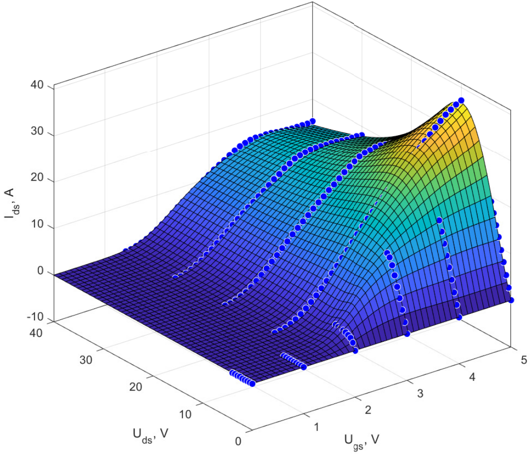
$$I_{ds} = I_{pk}\frac{I_S}{I_{pks}} \cdot \left(1 + \tanh\left(P_1 \cdot (U_{gs} - U_{pk}) + P_2 \cdot (U_{gs} - U_{pk})^2 + P_3 \cdot (U_{gs} - U_{pk})^3\right)\right) \cdot \tanh(\alpha_1 \cdot U_{ds} + \alpha_2 U_{ds}^2) \cdot (1 + \lambda U_{ds}) \cdot (1 - \Theta). \tag{3}$$

Current-Voltage Characteristics

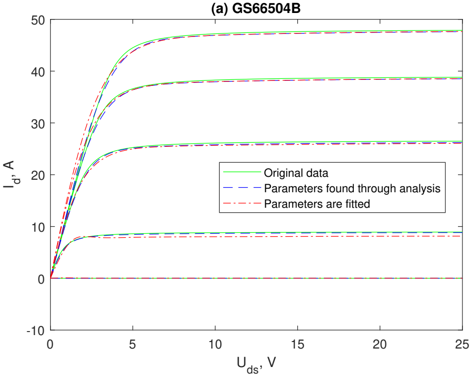


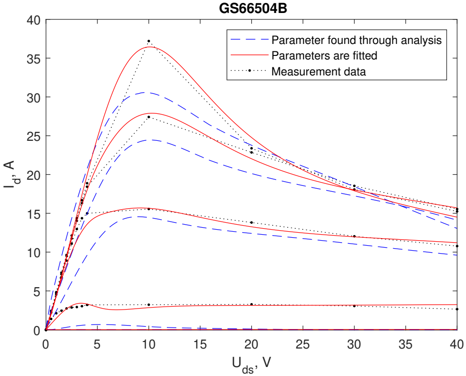
Finding Parameters Through Fitting

Instead of going through additional measurement and evaluation procedures in order to obtain the equation parameters, they can be found as fitting coefficients when using the modified Chalmers equation as a fit function for the measured IV-surface



Current-Voltage Characteristics





Fitting allows for more flexibility when the self-heating comes into play or if there are not enough measurement points to accurately find Chalmers equation parameters.

Conclusions

- The method yields a model from a frequency- and bias-dependent set of S-parameters and I-V characteristics.
- The obtained model can describe a GaN HEMT in the bias range of U_{ds} between - 0 and 500 V, and all U_{gs} allowed by a data sheet, provided enough measured points, thus covering the pinch-off, the ohmic and the saturation regimes.
- The parameter extraction process is based on widely-used equations for the equivalent circuit (e.g., A. Jarndal and Kompa 2006) and the non-linear current source (e.g., Angelov, Zirath, and Rosman 1992), modified for a specific device type.
- Modelling provides suggestions about the distribution of the measured OPs.
- Possible extensions of the model include: improving of self-heating description, expansion to the reversed-operation regime, explicit accounting for dispersive effects etc.

THANK YOU FOR YOUR ATTENTION!

Circuit Equations

Admittance matrix for the intrinsic part of the circuit at the n-th operating point:

$$Y_i^n = \begin{pmatrix} \frac{G_{gsf}^n + j\omega C_{gs}^n}{1 + R_i^n (G_{gsf}^n + j\omega C_{gs}^n)} + \frac{G_{gdf}^n + j\omega C_{gd}^n}{1 + R_{gd}^n (G_{gdf}^n + j\omega C_{gd}^n)} & -\frac{G_{gdf}^n + j\omega C_{gd}^n}{1 + R_{gd}^n (G_{gdf}^n + j\omega C_{gd}^n)} \\ \frac{G_m^n}{1 + R_i^n (G_{gsf}^n + j\omega C_{gs}^n)} - \frac{G_{gdf}^n + j\omega C_{gd}^n}{1 + R_{gd}^n (G_{gdf}^n + j\omega C_{gd}^n)} & \frac{G_{gdf}^n + j\omega C_{gd}^n}{1 + R_{gd}^n (G_{gdf}^n + j\omega C_{gd}^n)} + G_{ds}^n + j\omega C_{ds}^n \end{pmatrix} \tag{4}$$

External inductances as elements of a T-circuit are described with an impedance matrix:

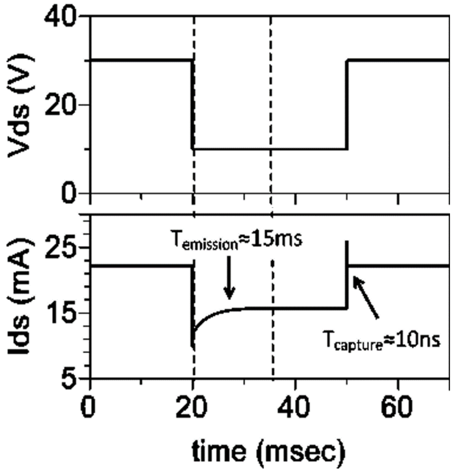
$$Z_l^n = \begin{pmatrix} Z_{i,11}^n + j\omega (L_g^n + L_s^n) & Z_{i,12}^n + j\omega L_s^n \\ Z_{i,21}^n + j\omega L_s^n & Z_{i,22}^n + j\omega (L_d^n + L_s^n) \end{pmatrix} \tag{5}$$

External capacitances as elements of a Π-circuit are described with an admittance matrix:

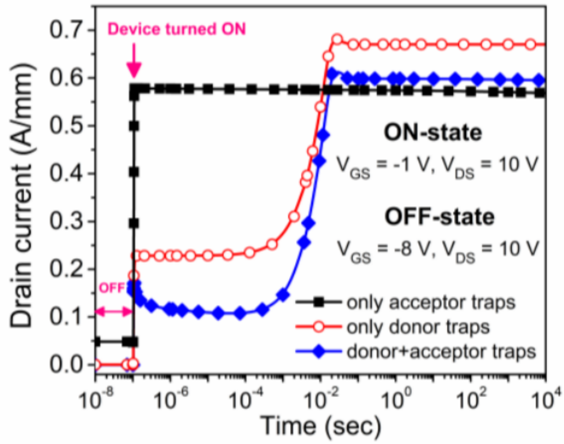
$$Y^n = \begin{pmatrix} Y_{l,11}^n + j\omega (C_{pgi}^n + C_{gdi}^n) & Y_{l,12}^n + j\omega C_{gdi}^n \\ Y_{l,21}^n + j\omega C_{gdi}^n & Y_{l,22}^n + j\omega C_{pdi}^n \end{pmatrix} \tag{6}$$

Sources: A. H. Jarndal 2006; Hergt 2021

Drain and Gate Lag



Luo, Bengtsson, and Rudolph 2017



De and Dutta 2018