Characterization and Modeling of AlGaN/GaN HEMT Trapping Transients

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Instituições Associadas

Presentation Outline

1 – Introduction and Motivation

2 – Physical Origins of GaN HEMT Trapping Effects

3 – Modeling of Trap Capture and Emission Dynamics

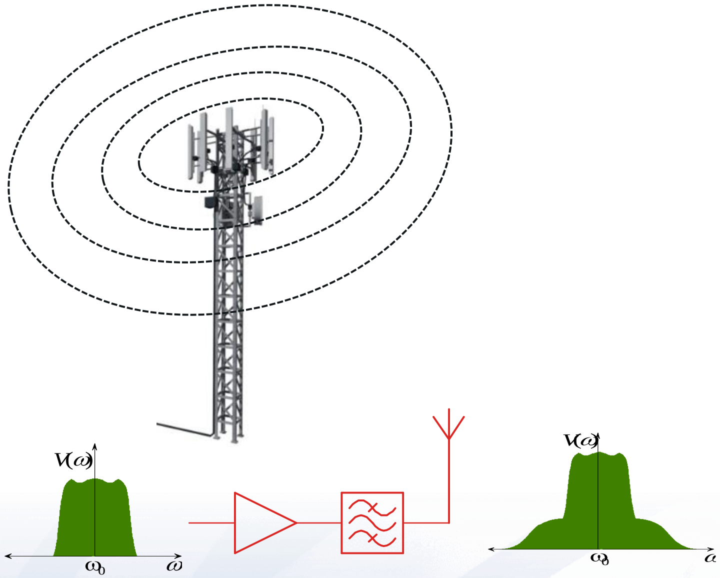
4 – GaN HEMT Nonlinear Model Validation

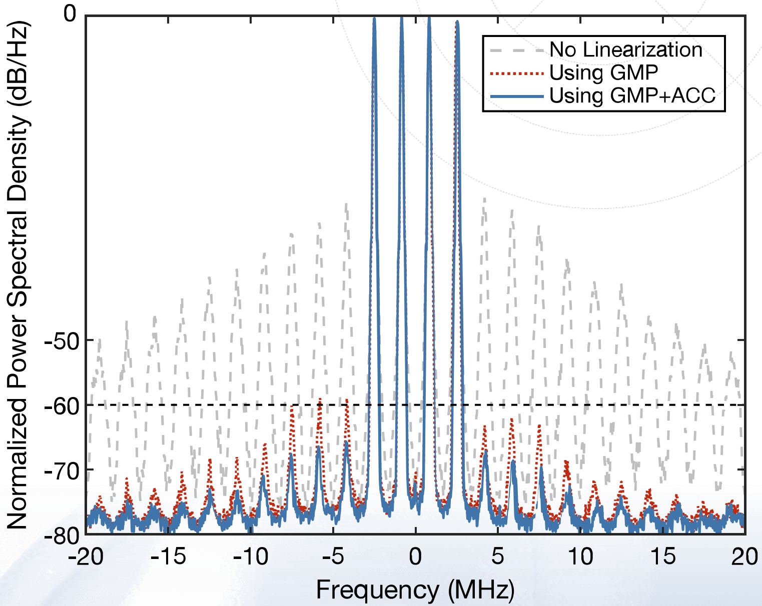
5 – Conclusions

Presentation Outline

1 – Introduction and Motivation

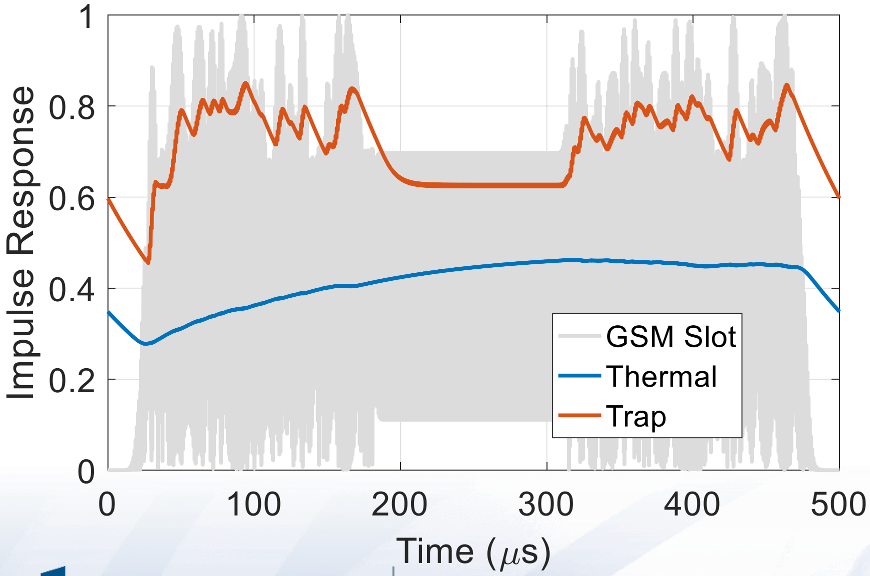
Nowadays, a substantial amount of power is lost in the RF power amplifier of a base-station because of its need to comply with spectral emission masks: the linearity-efficiency compromise.





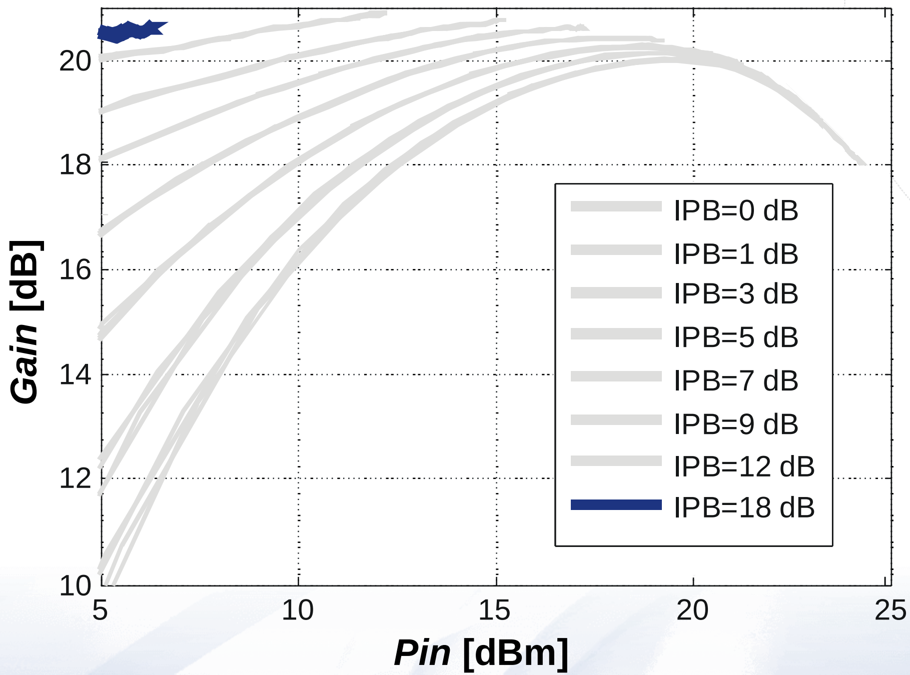
1 – Introduction and Motivation

Despite the high efficiency and output power density of AlGaN/GaN HEMT based RF power amplifiers, they suffer from long-term memory effects, which introduce significant spectral regrow and BER increase.



These are attributed to electro-thermal and trapping phenomena.

These long-term memory effects can be noticed as a severe small-signal gain drop versus peak power drive …



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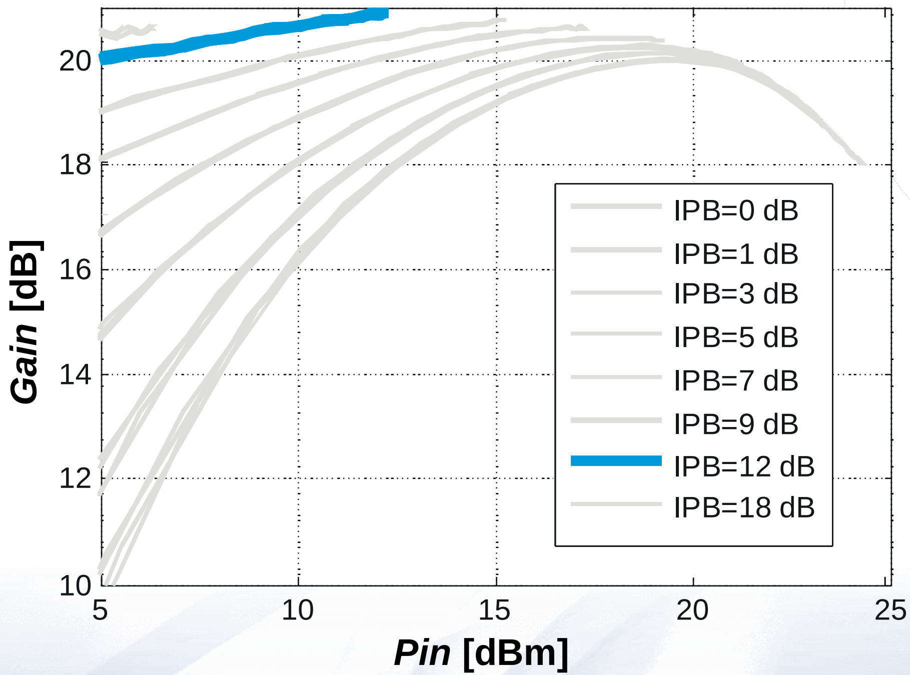

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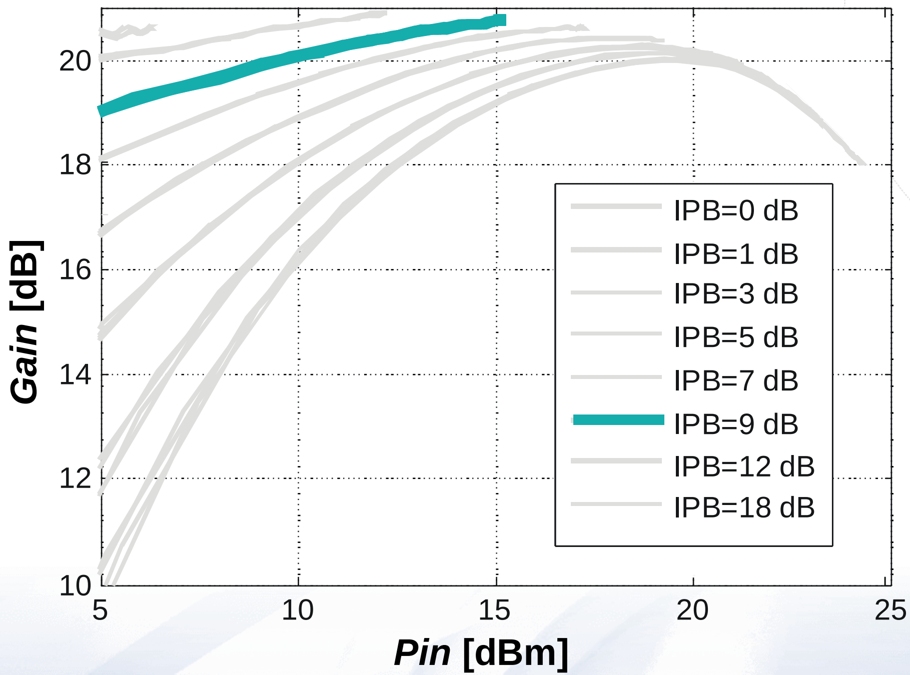

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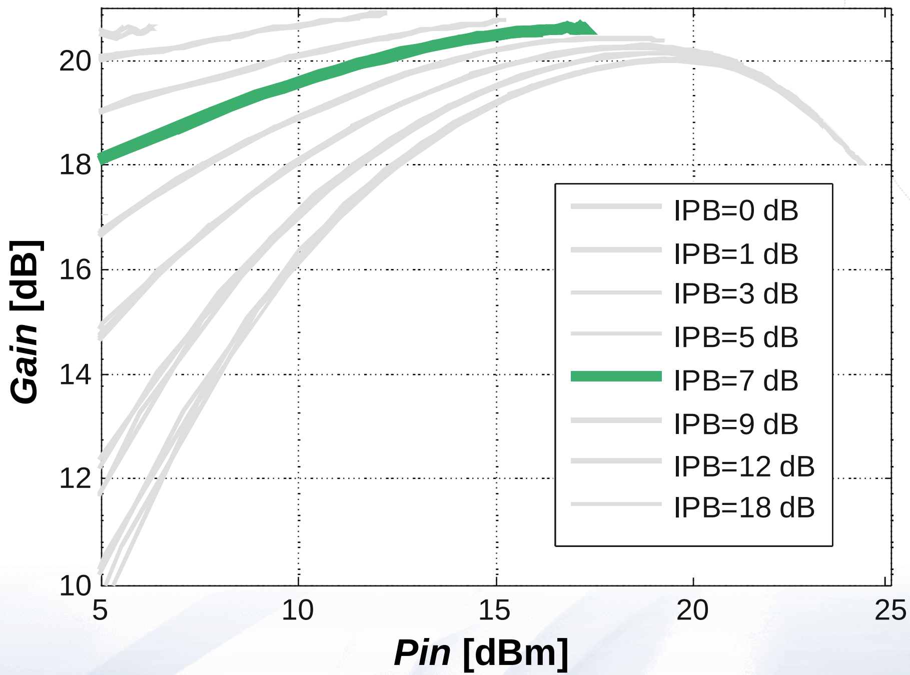

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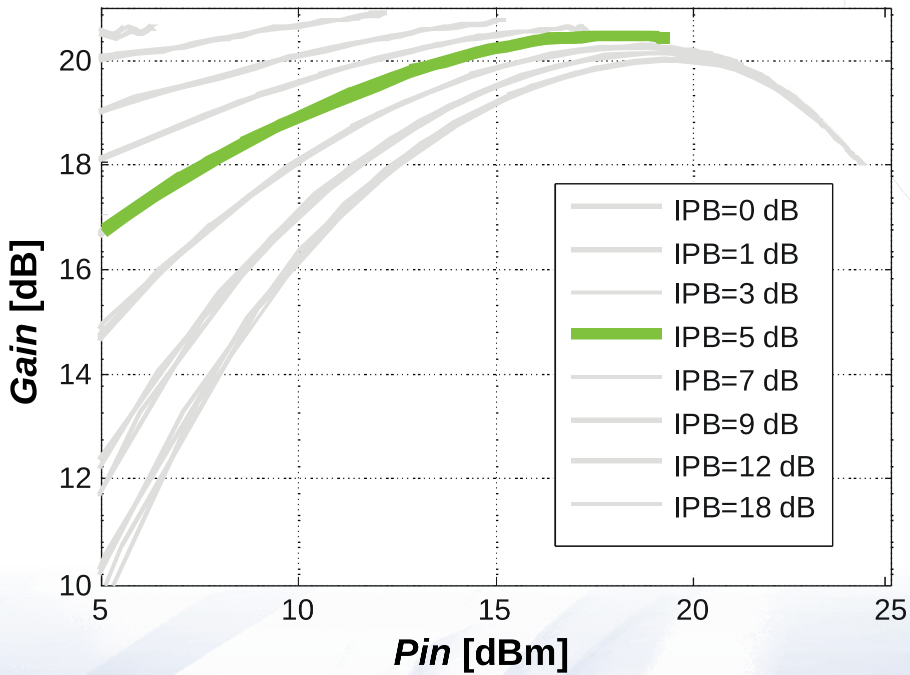

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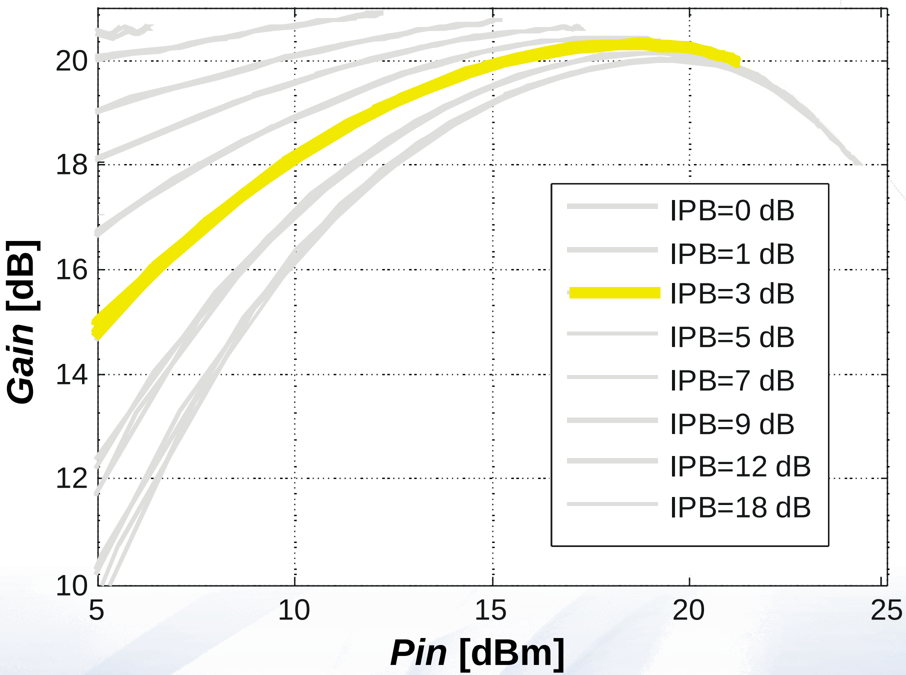

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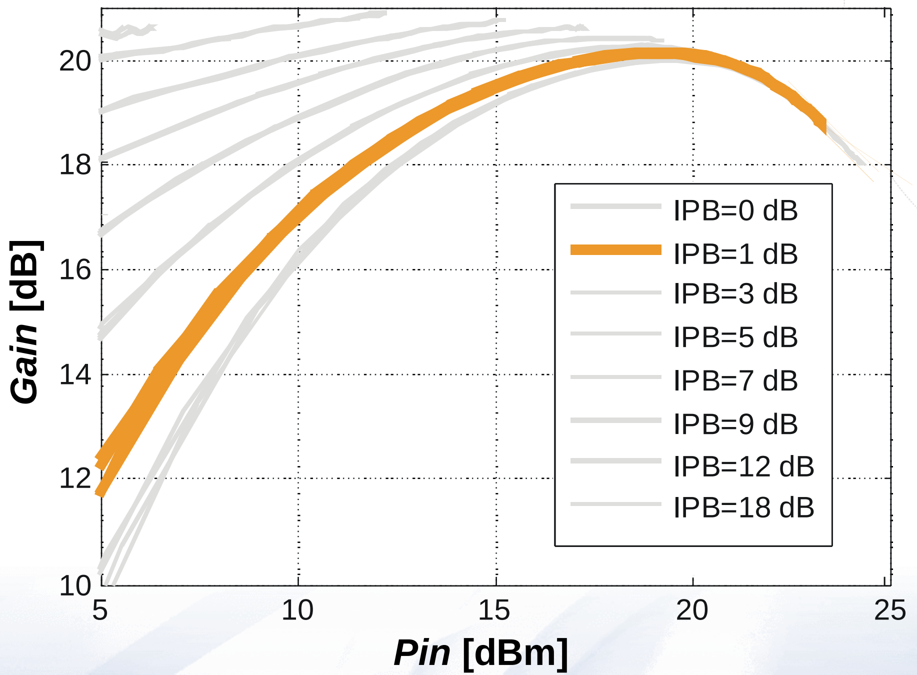

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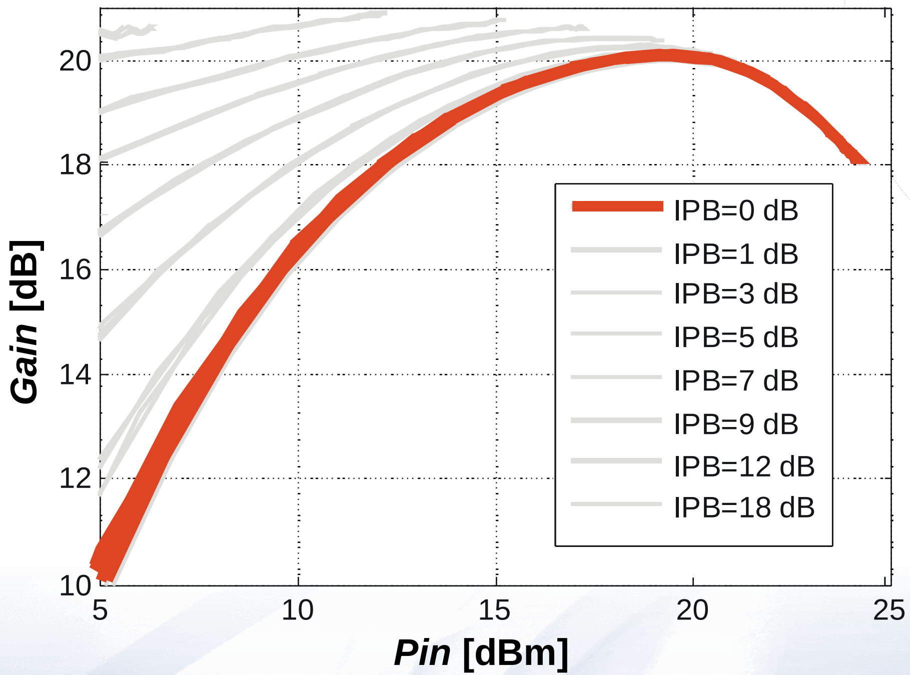
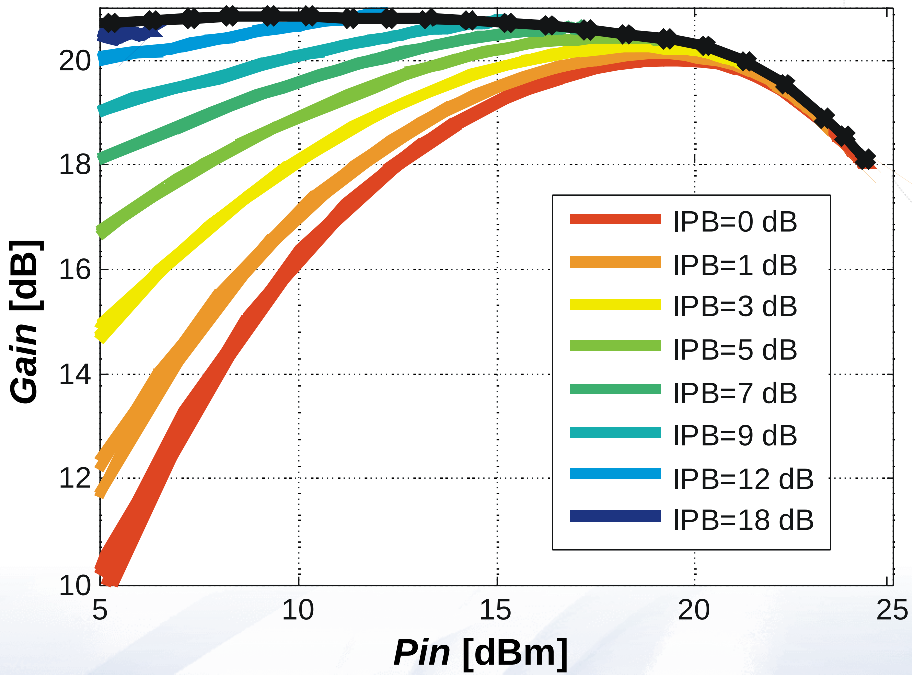


1 – Introduction and Motivation

This small-signal gain drop is also visible under varying envelope speed:



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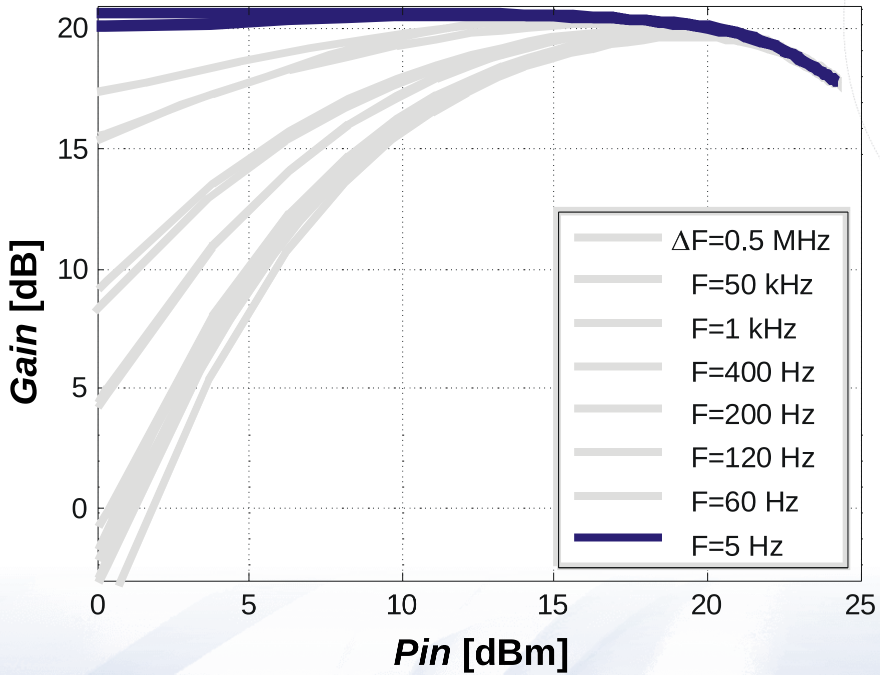

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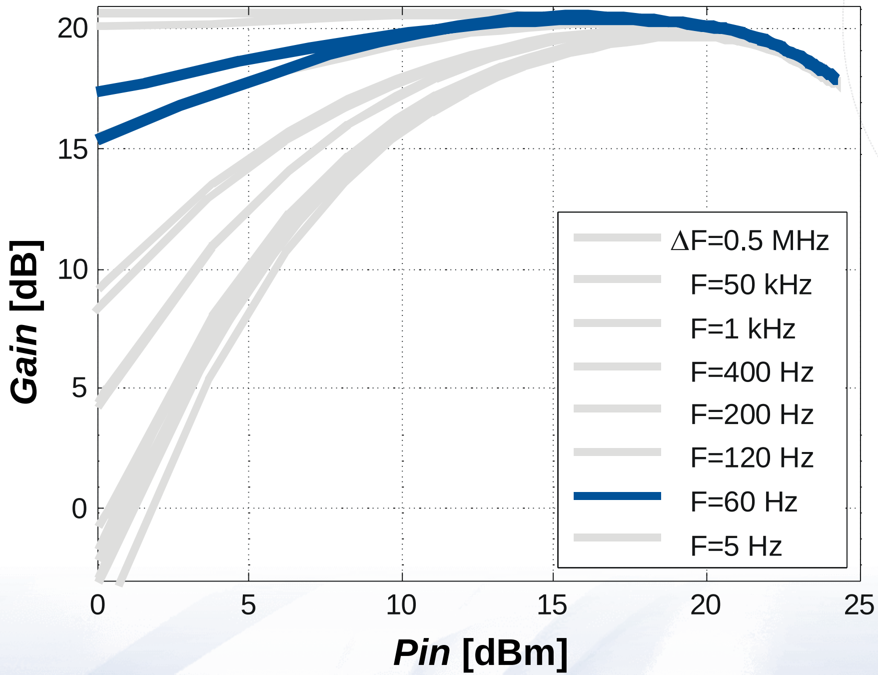

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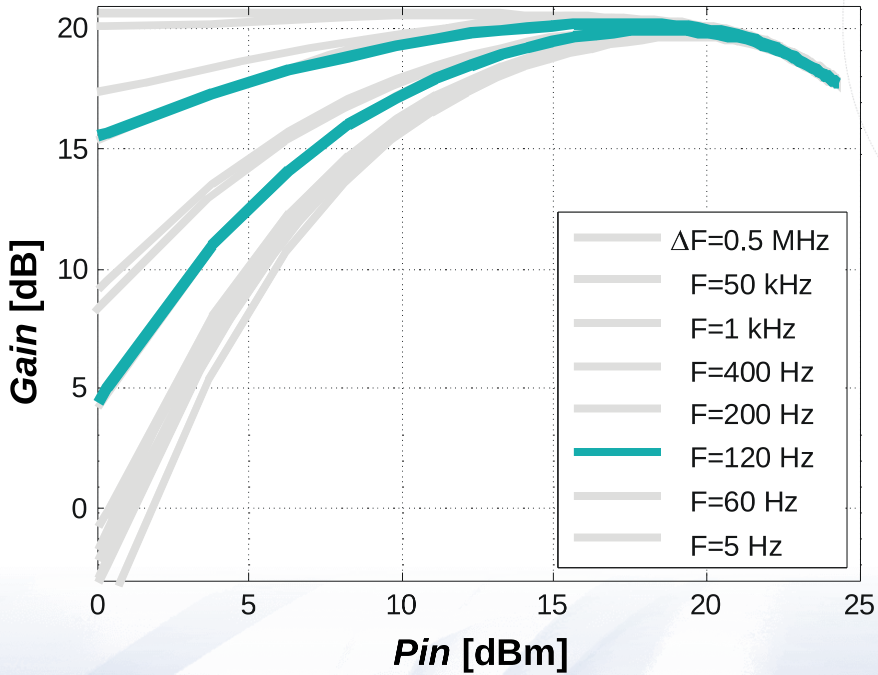

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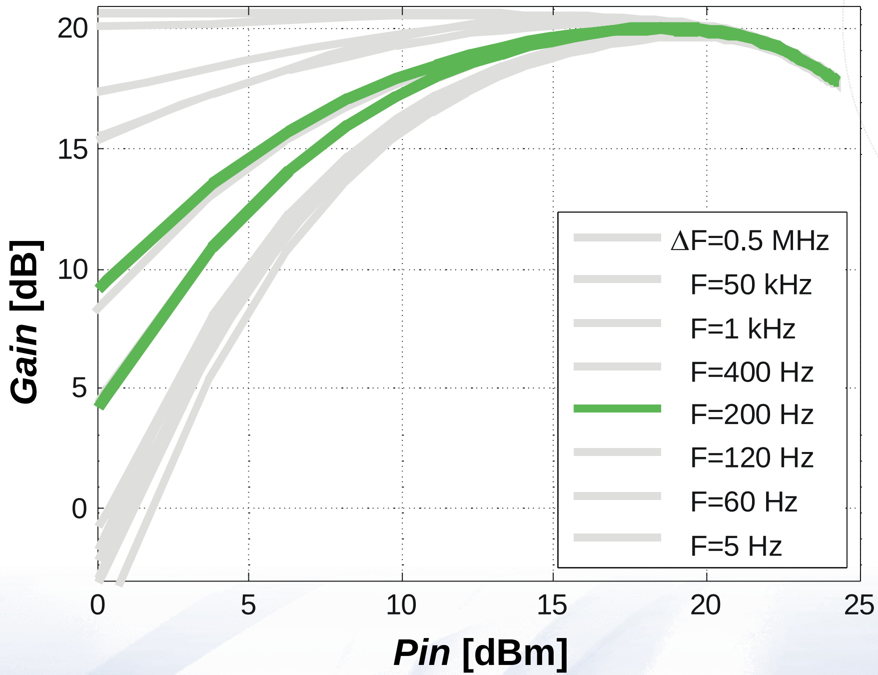

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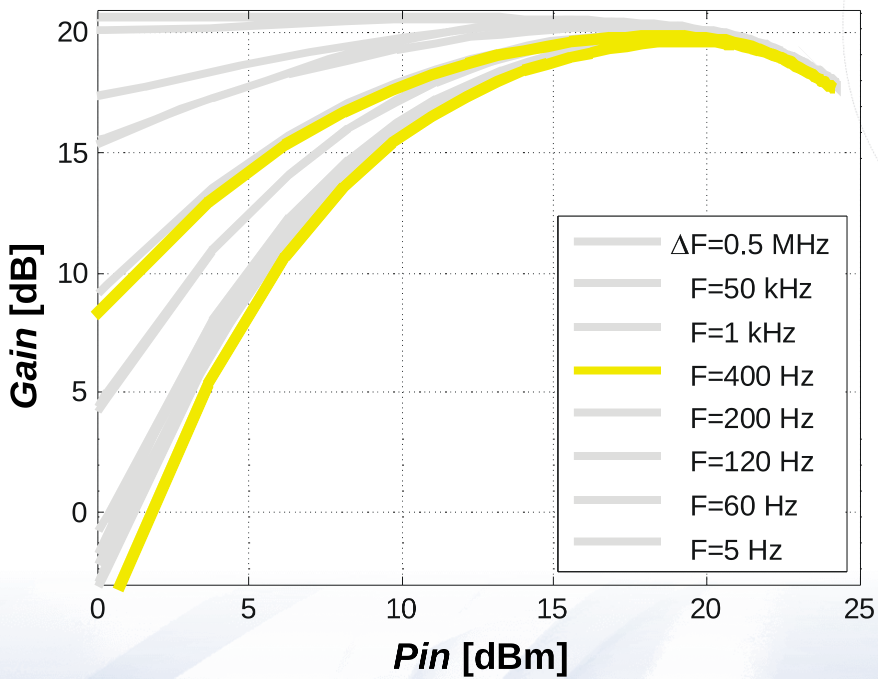

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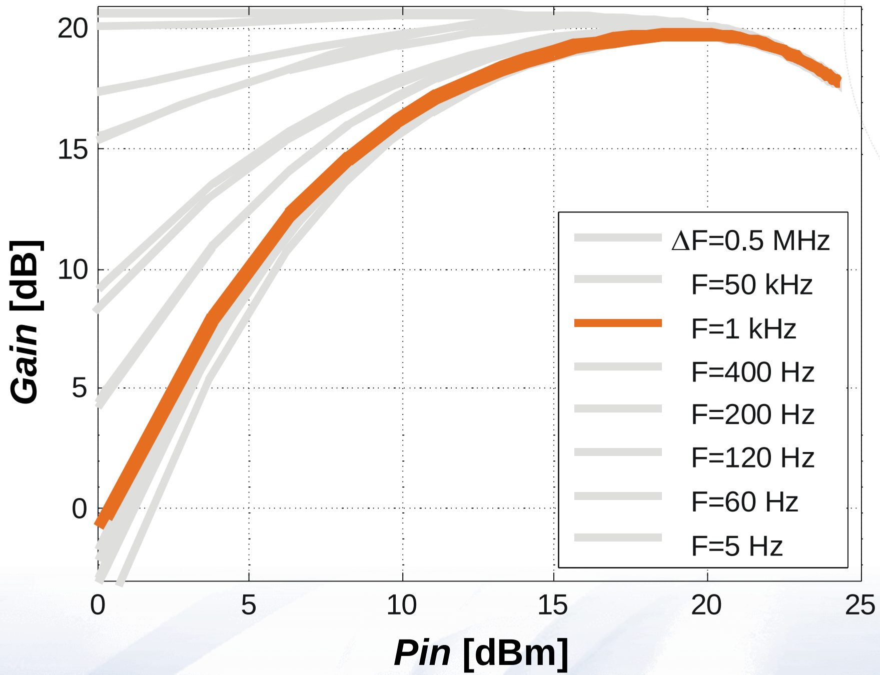

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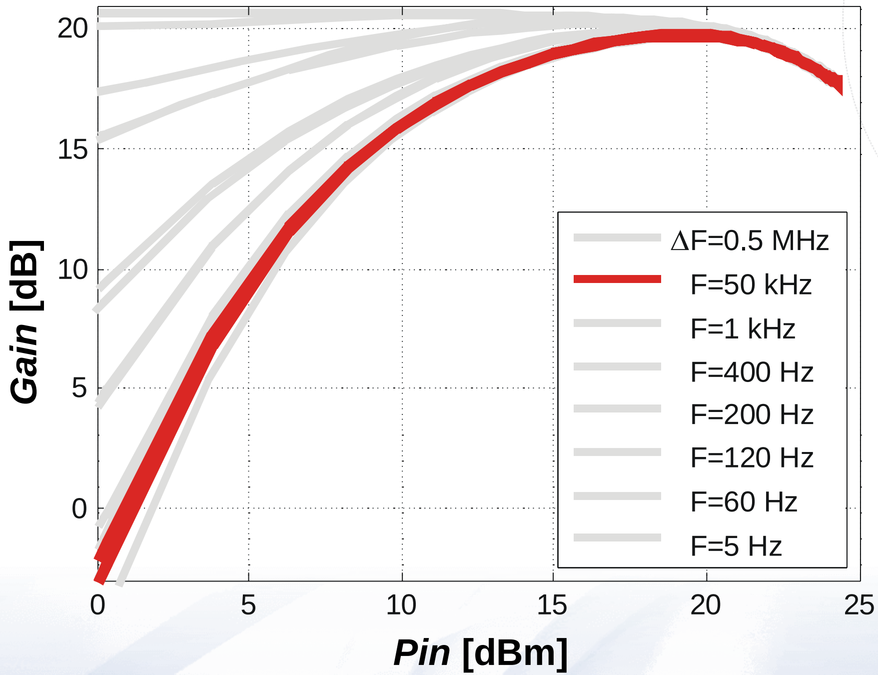

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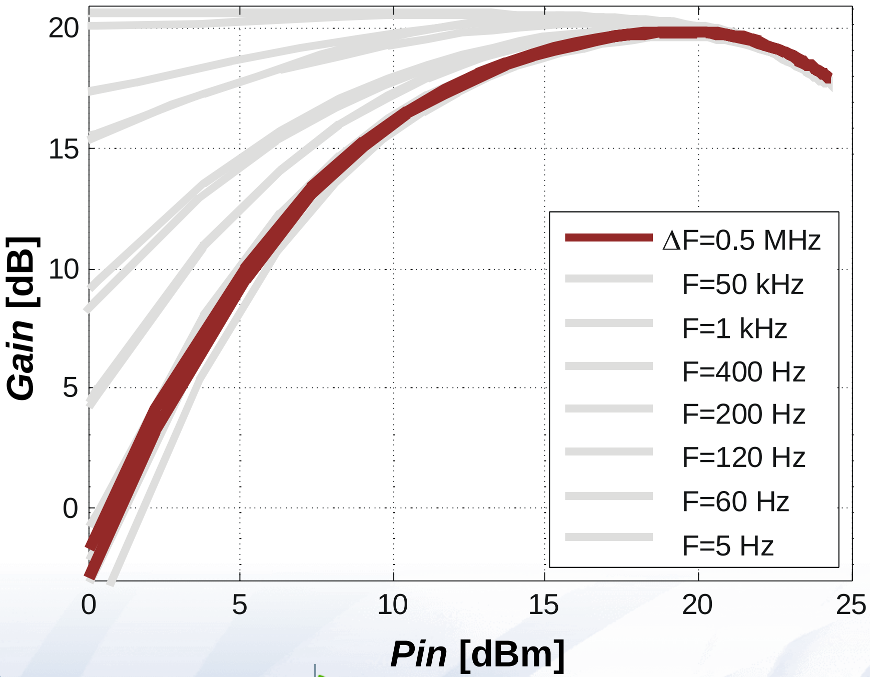
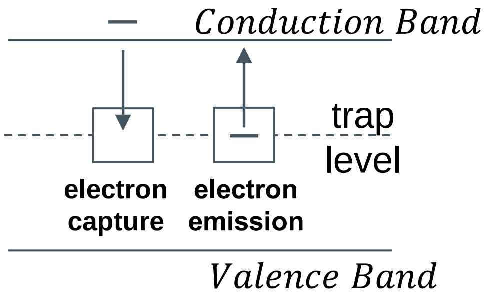


So, a thorough characterization and deep understanding of these phenomena are essential for improved RF PA design.

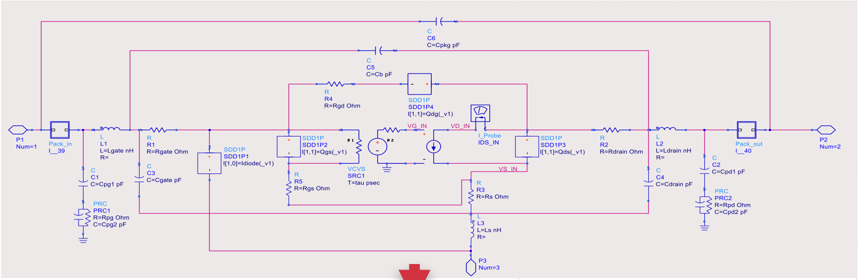
1 – Introduction and Motivation

Physics-Based Modeling

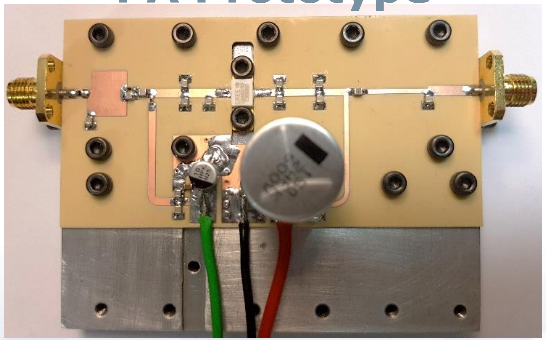


Equivalent-Circuit Modeling

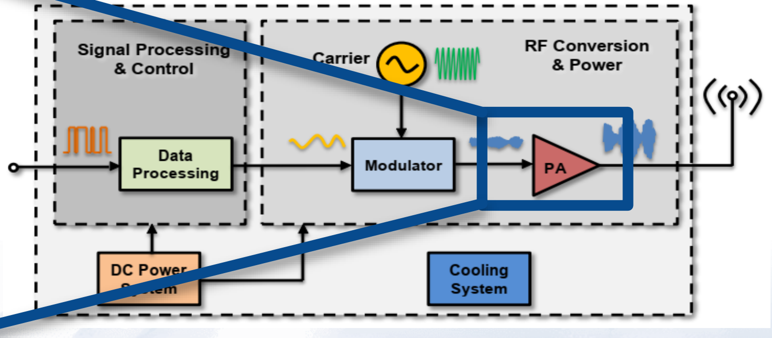
Circuit Simulation



PA Prototype



System Implementation



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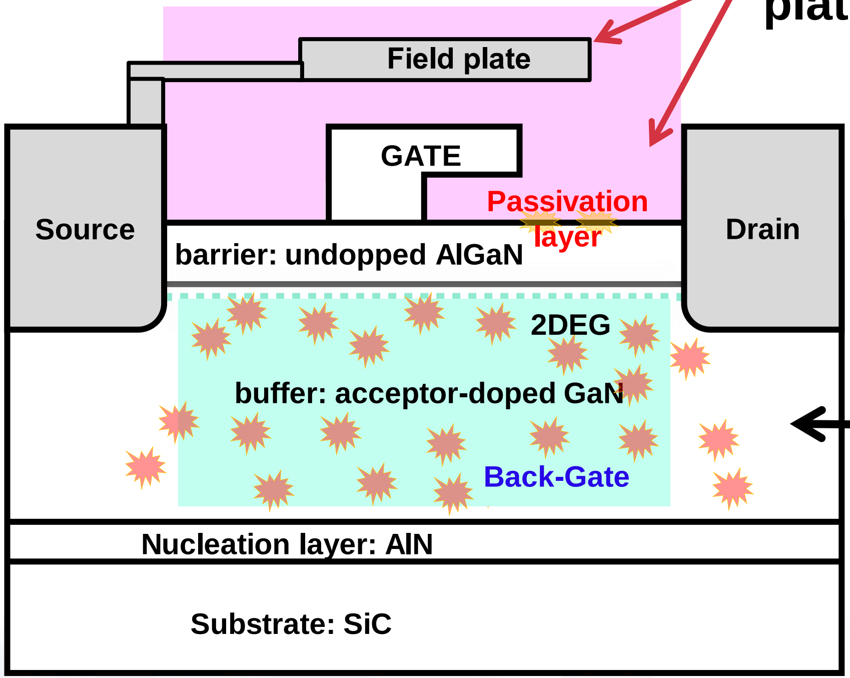
2 – Physical Origins of GaN HEMT Trapping Effects



Surface traps can be reduced using a **field plate** and an appropriate **passivation layer**.

Buffer traps result, from an **intentional doping** to prevent current leakage through the buffer.

Deep-level electron acceptors: Carbon or Iron

Back-Gate accumulated negative charge results in an equivalent increase of the HEMT's threshold voltage.

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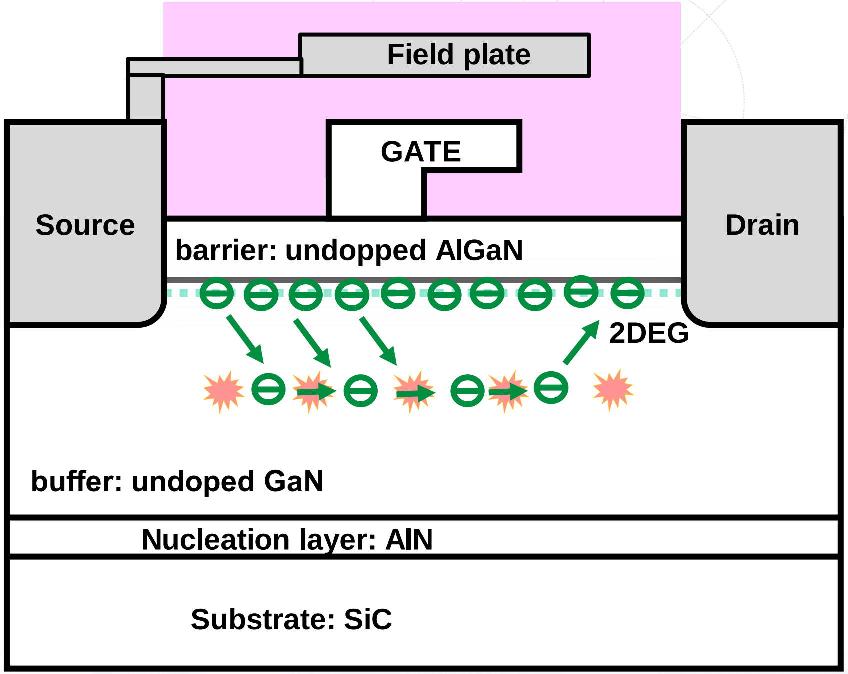
2 – Physical Origins of GaN HEMT Trapping Effects

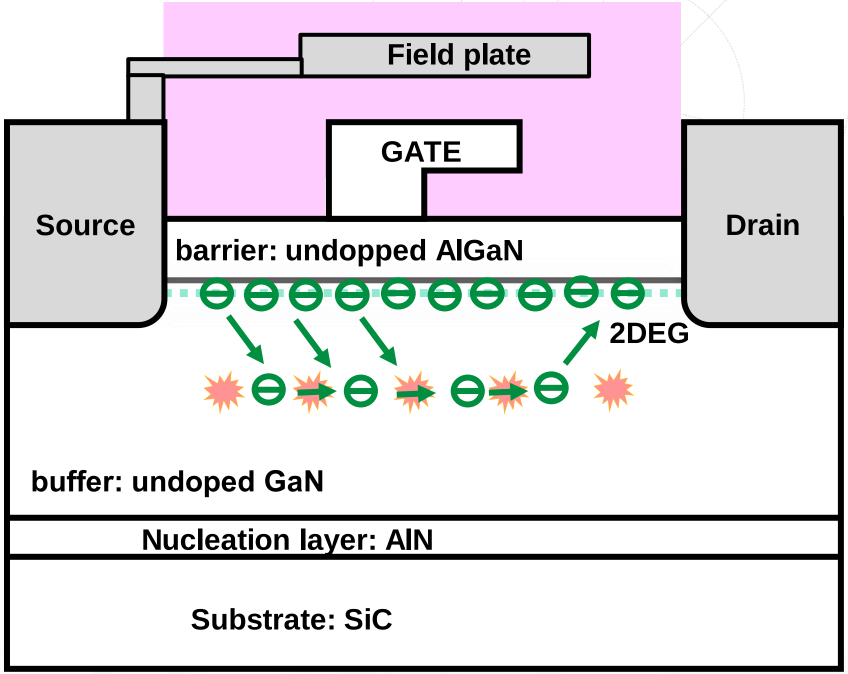
When v_{DS} is increased, electrons are injected into the buffer making it conductive (leakage current).

This disrupts the equilibrium between the concentration of free electrons in the conduction band, n_c, and trapped electrons in the ionized traps, n_A, favoring electron capture.



When v_{DS} is decreased, to its original value, electrons are returned back into the 2DEG.

This reduces the concentration of free electrons in the conduction band, n_c, favoring now electron emission.

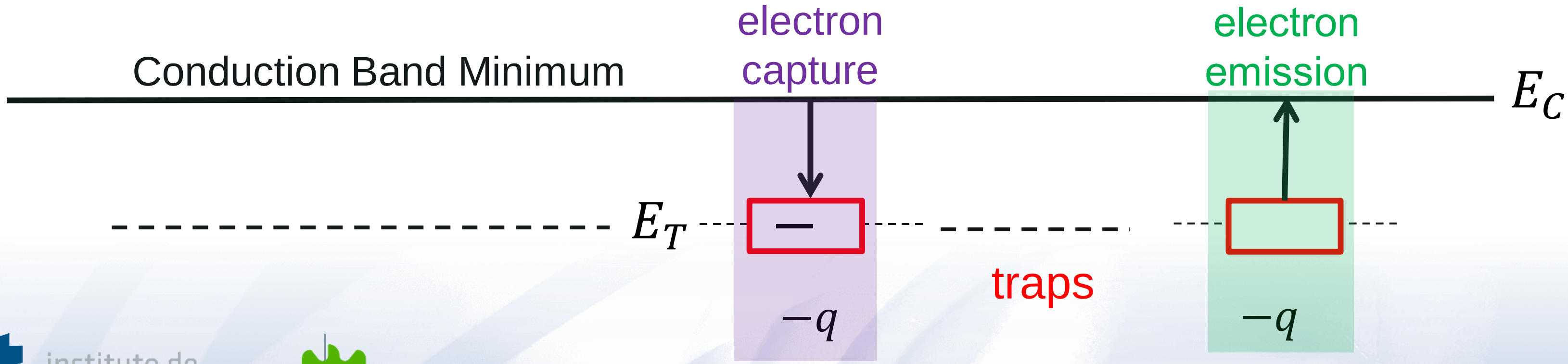


2 – Physical Origins of GaN HEMT Trapping Effects

According to the Shockley-Read-Hall model, the **concentration of trapped electrons, $\boldsymbol{n_A}$**, in, e.g., acceptor-like traps, can be given as a function of the injected electron concentration in the buffer, $\boldsymbol{n_c}$

$$\frac{dn_A(t)}{dt} = c_n n_C(t)[N_A - n_A(t)] - e_n n_A(t)[N_C - n_C(t)]$$

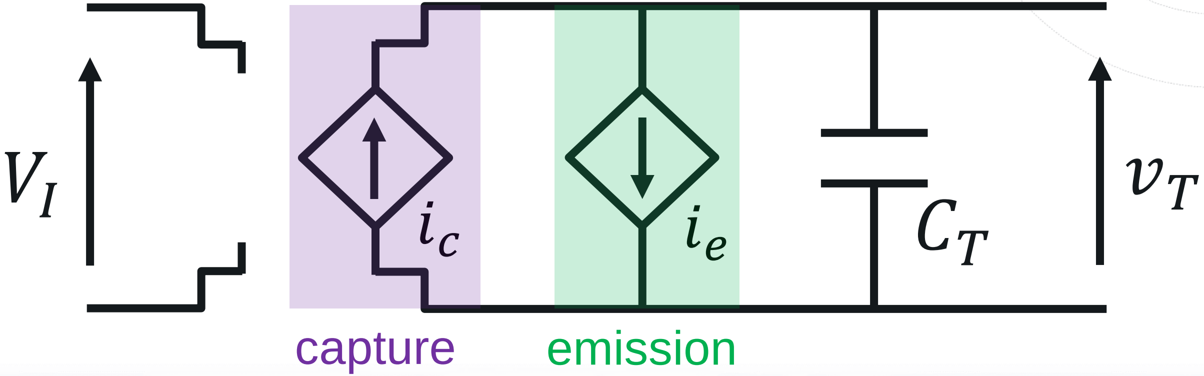
$$\frac{dn_A(t)}{dt} \approx c_n N_C \left[(N_A - n_A(t)) e^{\frac{F_I(t) - E_C}{kT}} - n_A(t) e^{\frac{E_T - E_C}{kT}} \right]$$



2 – Physical Origins of GaN HEMT Trapping Effects

We can recast the previous equation in terms of an **effective trap potential, $v_T(t)$**, and effective difference between the quasi-Fermi and conduction band, $F_I(t) - E_C$, $V_I(t)$, as

$$\frac{dv_T(t)}{dt} = \omega_0 \left[V_0 e^{\frac{qV_I(t)}{kT}} - v_T(t) \left(1 + e^{\frac{qV_I(t)}{kT}} \right) \right]$$



$$V_I(t) = \alpha\, v_{DS}(t) - \beta v_T(t) + C$$

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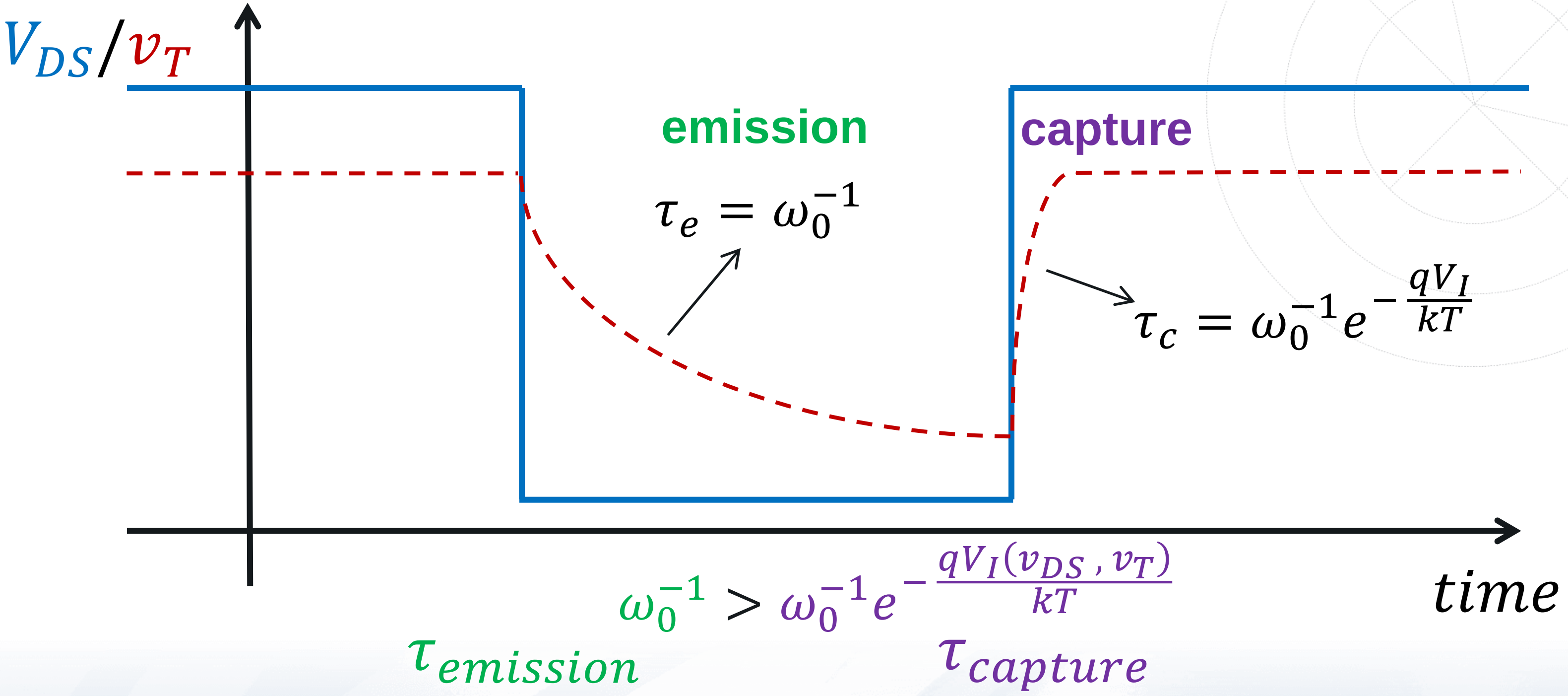
$V_I(t)$ is a representation of $F_I(t) - E_C$ depending on →

- v_{DS}
- ~~v_{GS}~~
- v_T

ω_0 is the characteristic frequency of our system

V_0 is the maximum effective trap potential – all traps filled

2 – Physical Origins of GaN HEMT Trapping Effects



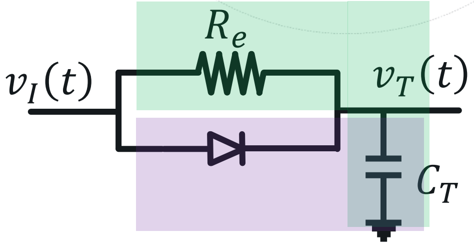
Presentation Outline

3 – Modeling of Trap Capture and Emission Dynamics

This SRH model was first used by Kunihiro and Ohno[1] for buffer trapping phenomena in GaN HEMTs, who realized that the capture process could be modeled by the charge of a capacitor driven by a diode, while the emission could be represented by the discharge of that capacitor through a linear resistor:

Kunihiro-Ohno Model

$$\frac{dv_T(t)}{dt} = \frac{1}{R_e C_T}\left[V_0 e^{\frac{qV_I(t)}{kT}} - v_T(t)\left(1 + e^{\frac{qV_I(t)}{kT}}\right)\right]$$

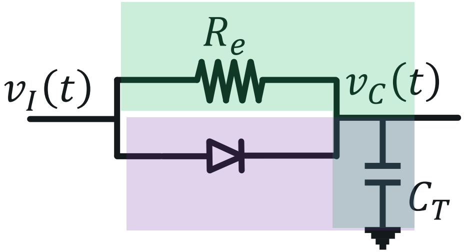


[1] K. Kunihiro, and Y. Ohno, “A large-signal equivalent circuit model for substrate-induced drain-lag phenomena in HJFETs,” *IEEE T-ED*, Sept. 1996.

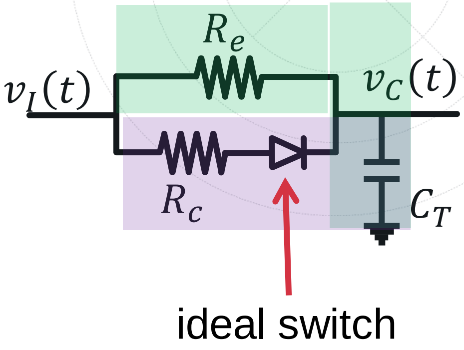
3 – Modeling of Trap Capture and Emission Dynamics

This model was then simplified by Jardel[2] and others assuming the diode is an ideal switch, this way defining two different RC time constants, for capture and emission, respectively:

Kunihiro-Ohno Model



Jardel Model



2 O. Jardel, F. De Groote, T. Reveyrand, J. C. Jacquet, C. Charbonniaud, J. P. Teyssier, D. Floriot, and R. Quere, "An Electrothermal Model for AlGaN/GaN Power HEMTs Including Trapping Effects to Improve Large-Signal Simulation Results on High VSWR," *IEEE T-MTT*, Dec. 2007.

3 – Modeling of Trap Capture and Emission Dynamics

1 – Trapping and electro-thermal effects present dynamic characteristics that share similar time-constants.

2 – Because the SRH generation-recombination model is based on the Fermi-Dirac statistics, trapping time-constants, themselves, are known to be strongly dependent on the device's temperature.

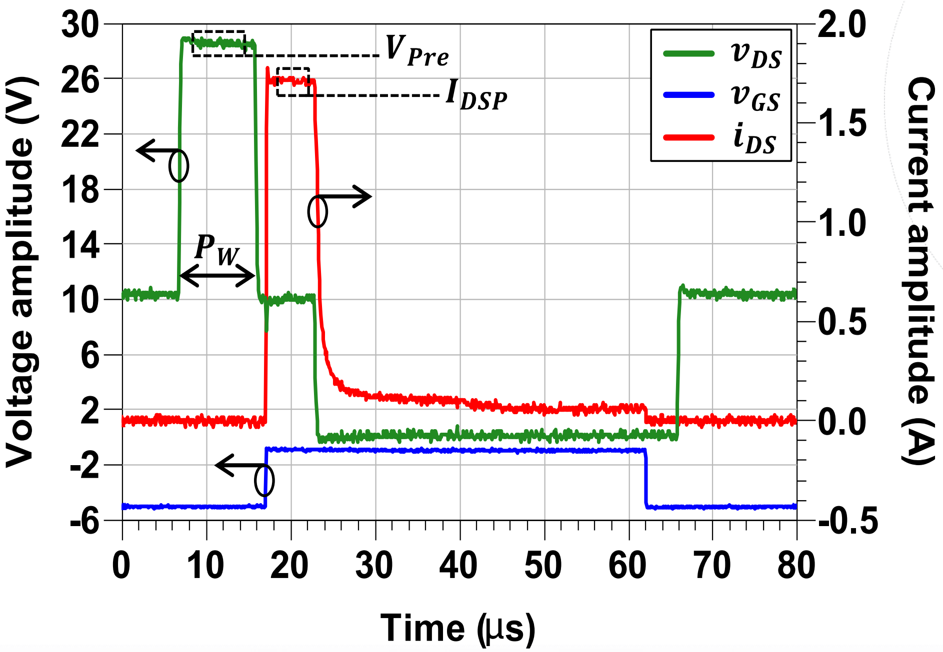
3 – So, it is essential to decouple trapping behavior from electro-thermal effects, assuring isothermal testing.

4 – For that, the device is always subjected to a trap setting state pre-pulse, in which $v_{GS}<V_T$. Therefore, during the pre-pulse, the i_{DS} current is zero and thus the device is always kept at room temperature[3].

[3] J. Gomes, L. Nunes, C. Gonçalves and J. Pedro, "An Accurate Characterization of Capture Time Constants in GaN HEMTs," *IEEE T-MTT*, Jul. 2019.

3 – Modeling of Trap Capture and Emission Dynamics

5 – **DUT's capture transients**, via double-pulse IDS-DLTS measurements.



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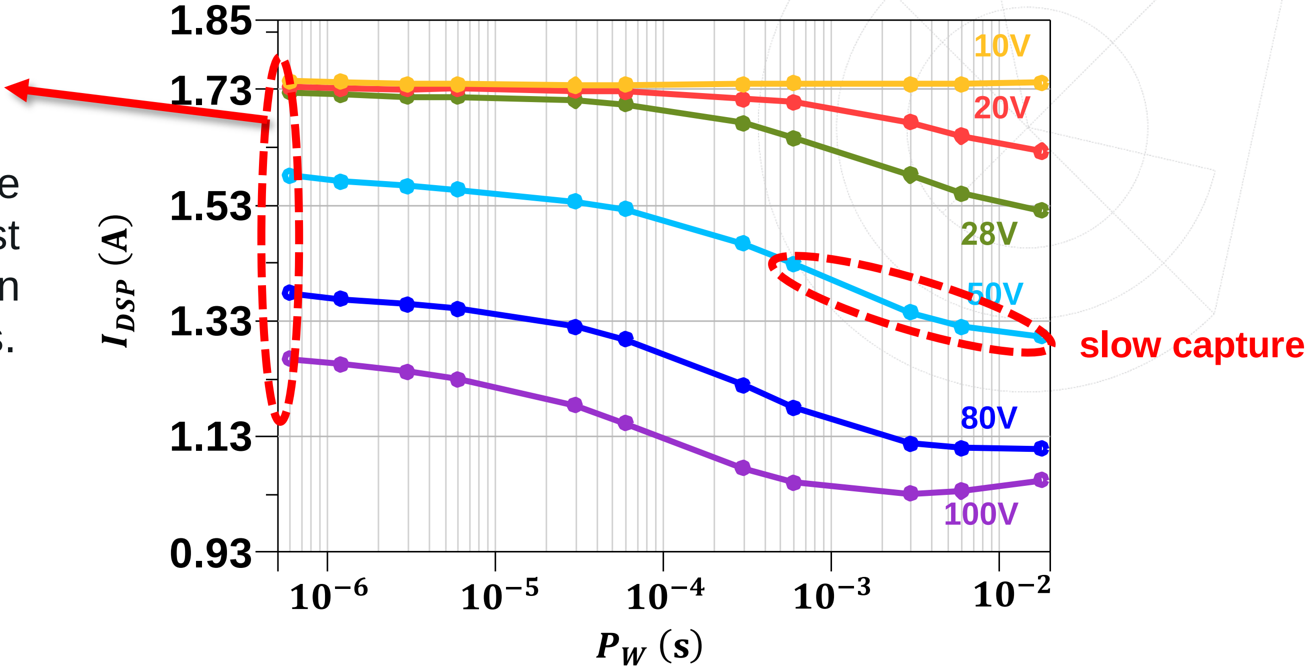
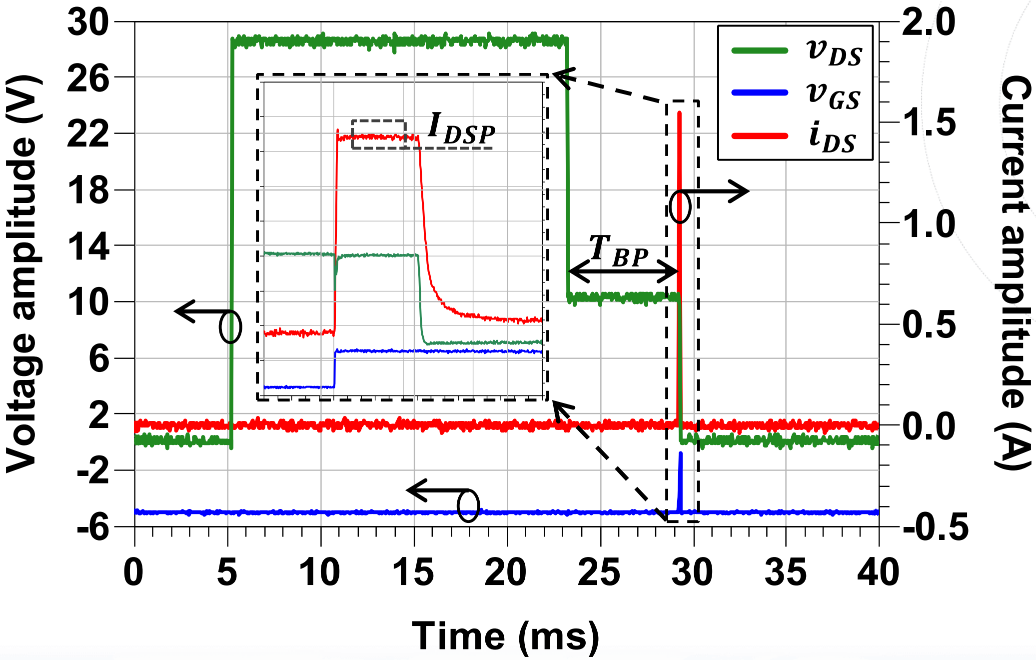


TCAD simulations have shown that these fast capture transients are on the order of ns or tens of ns.

[3] J. Gomes, L. Nunes, C. Gonçalves and J. Pedro, "An Accurate Characterization of Capture Time Constants in GaN HEMTs," *IEEE T-MTT*, Jul. 2019.

6 – **DUT's emission transients**, via double-pulse IDS-DLTS measurements.



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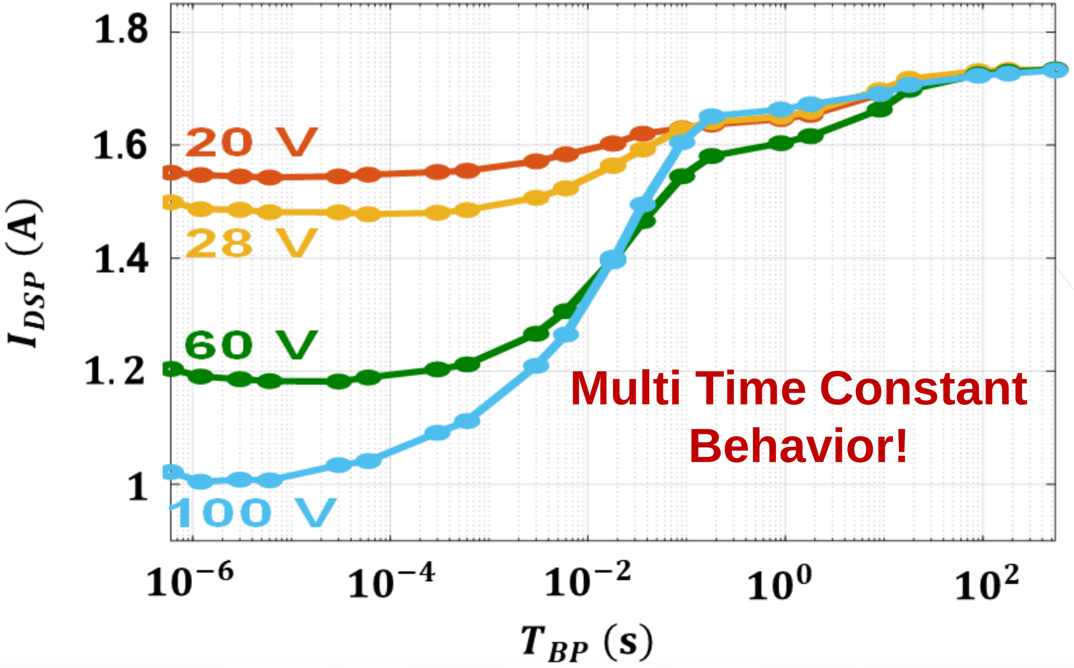

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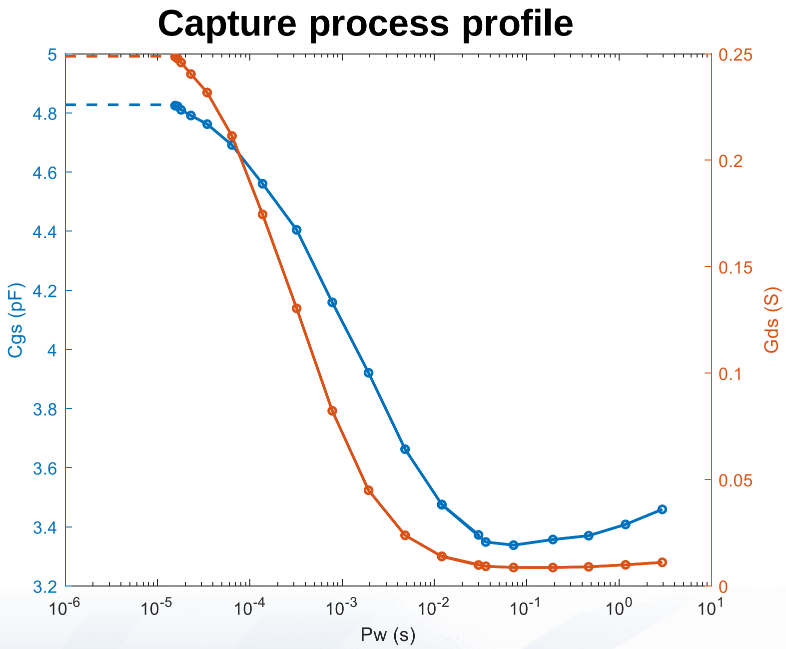
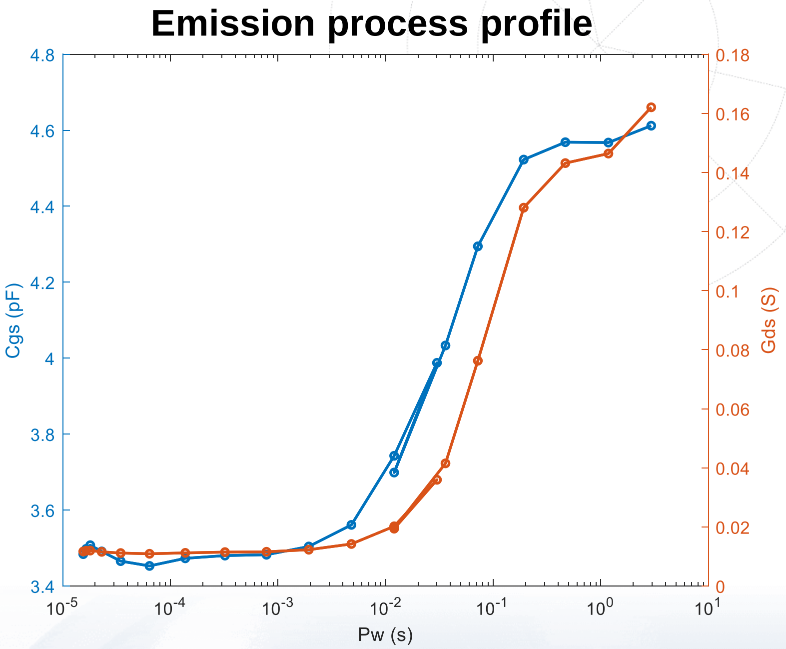
3 – Modeling of Trap Capture and Emission Dynamics

Cgs,Gds – DLTS (for room temperature) – Capture and Emission Transients





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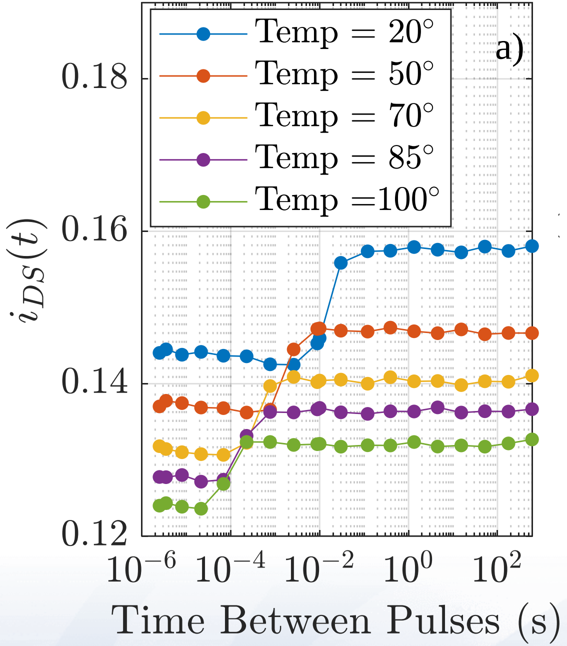
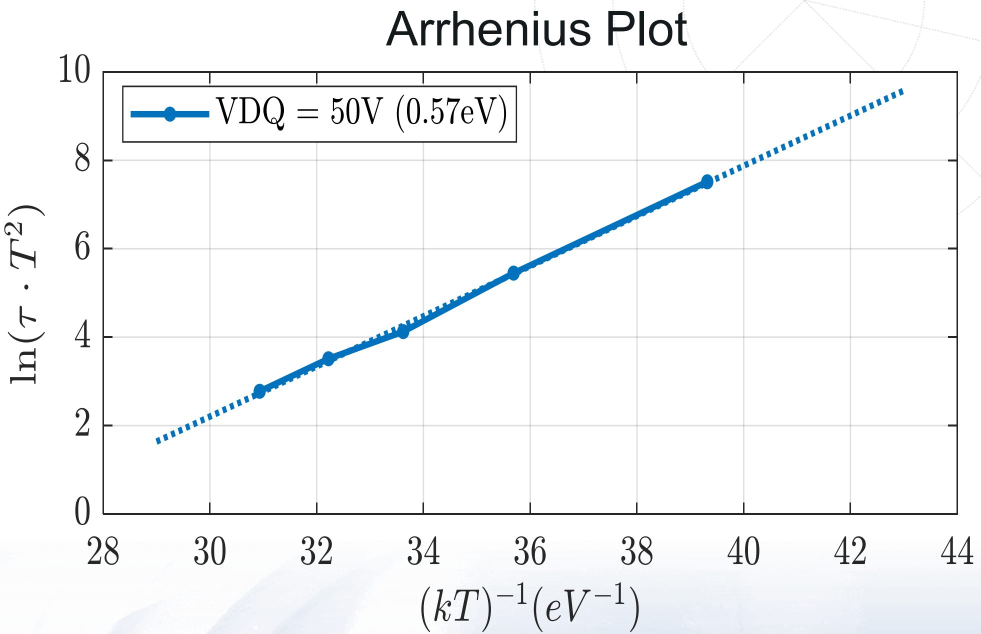
3 – Modeling of Trap Capture and Emission Dynamics

Guaranteeing constant temperature in IDS-DTLS measurements is essential since the SRH $\omega_0 \propto T^2 e^{-\frac{E_A}{kT}}$ can vary about 2 orders of magnitude in just 80°C.





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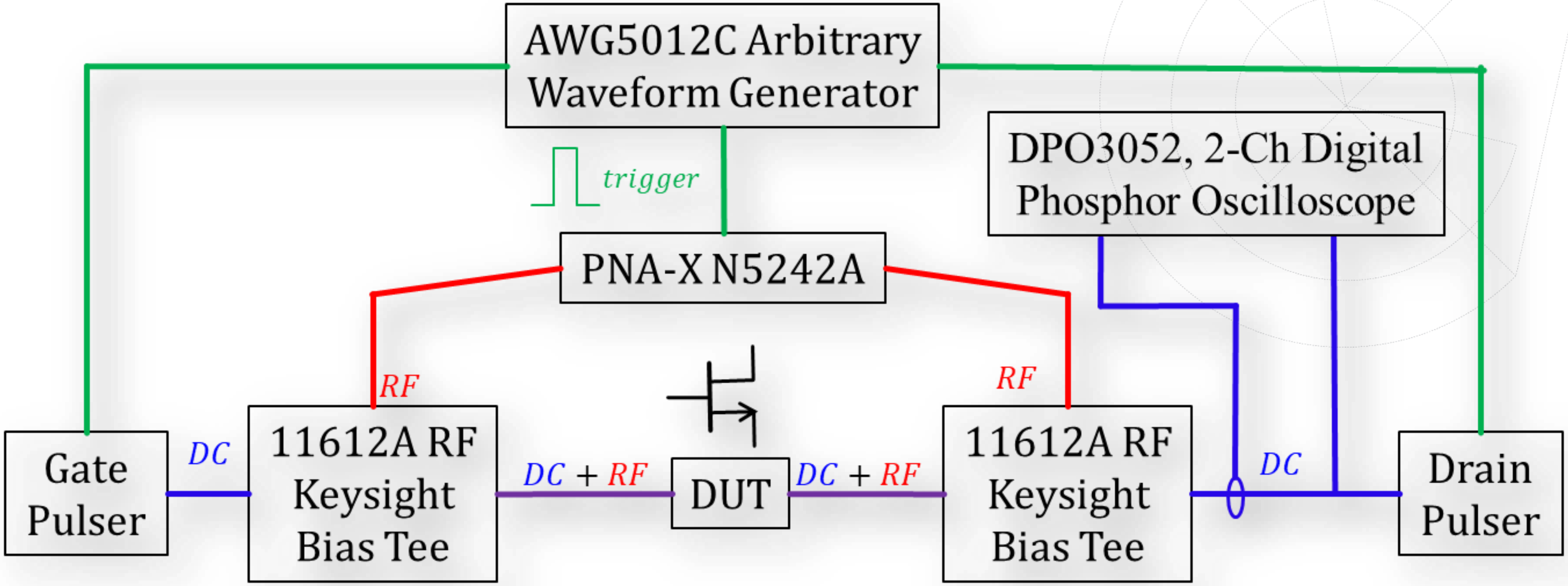

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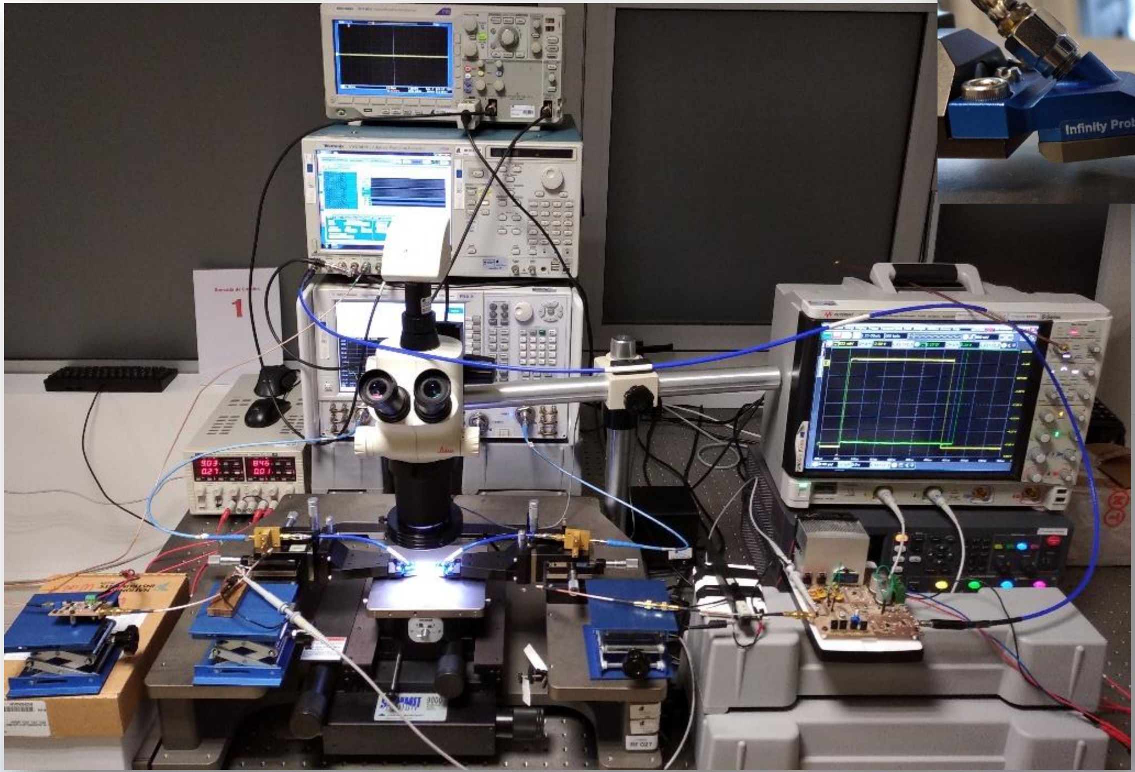
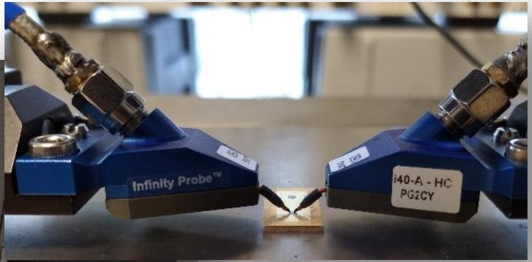
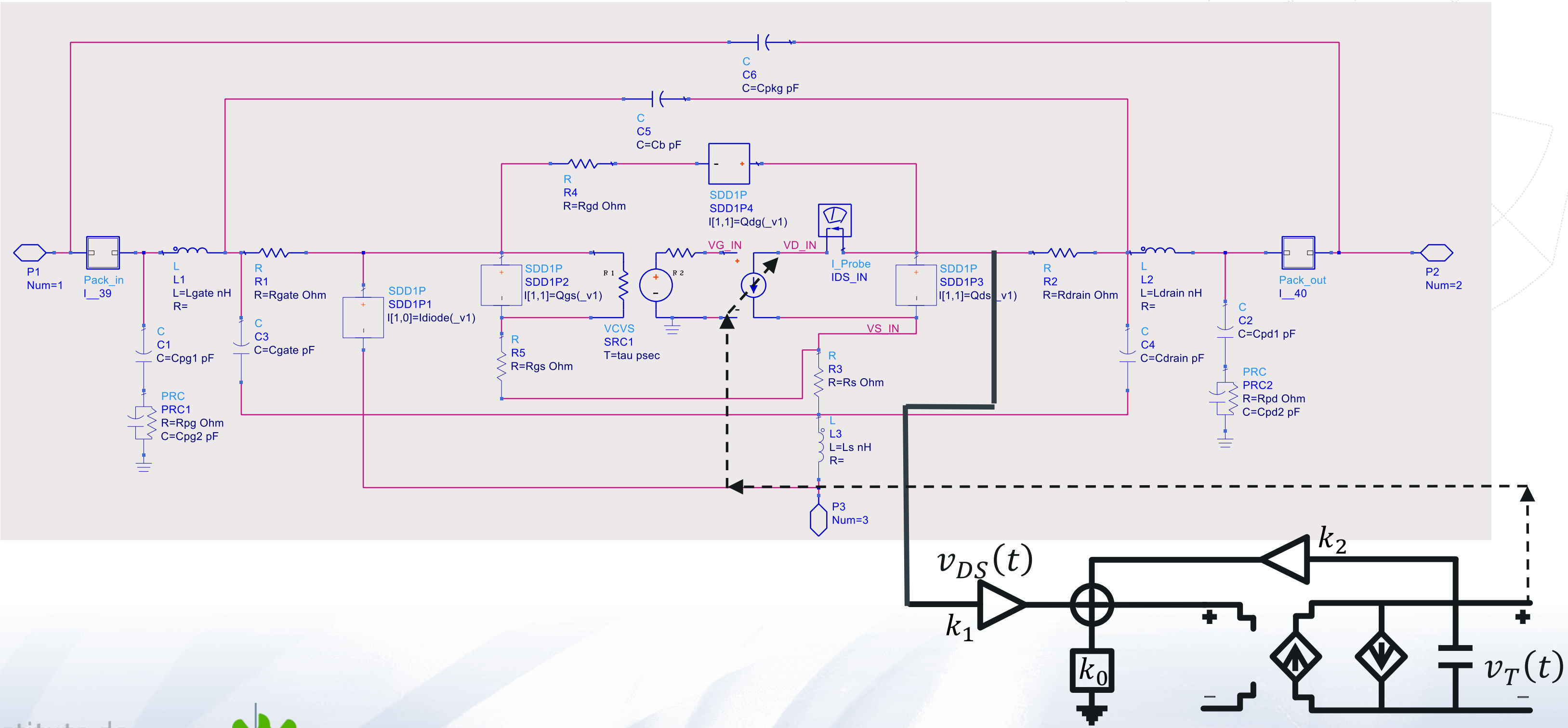


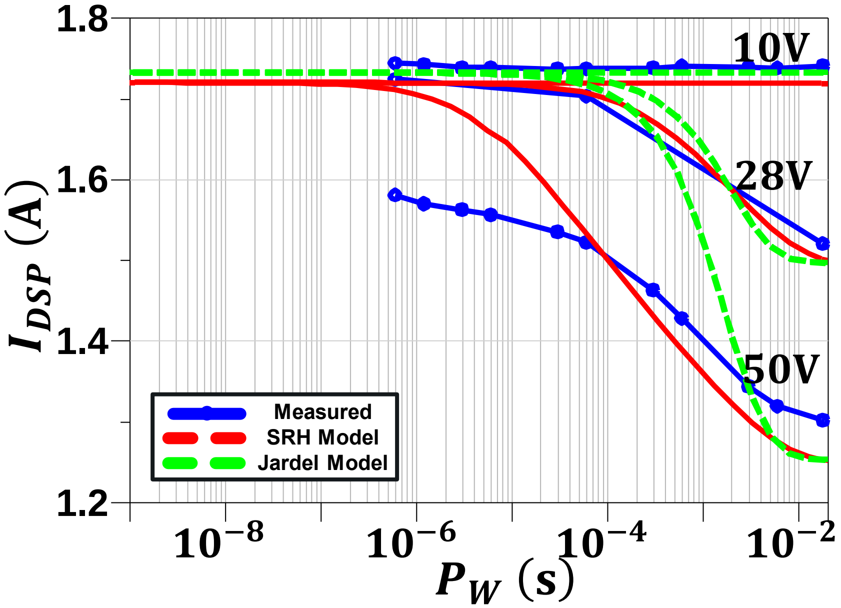


Nonlinear Equivalent-Circuit GaN HEMT Modeling



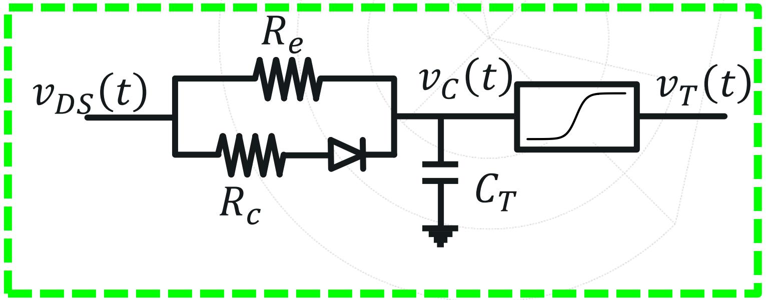
3 – Modeling of Trap Capture and Emission Dynamics

Prediction of GaN HEMT Capture Transients

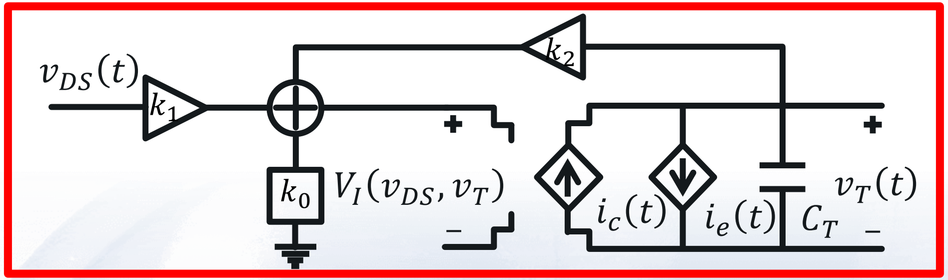


Much better prediction, but there is still a wide room for improvement!

Fixed Time Constant



Varying Time Constant



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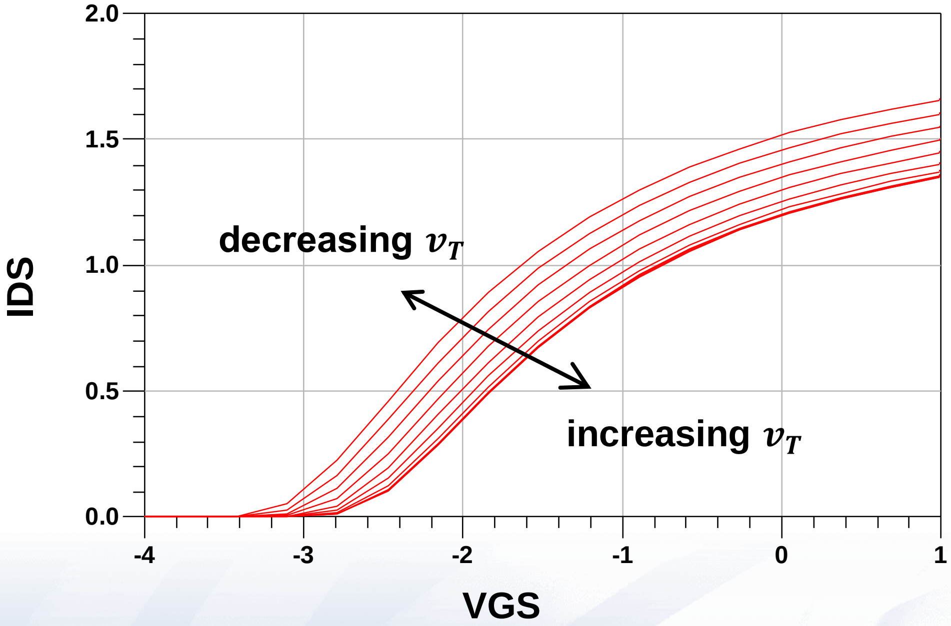
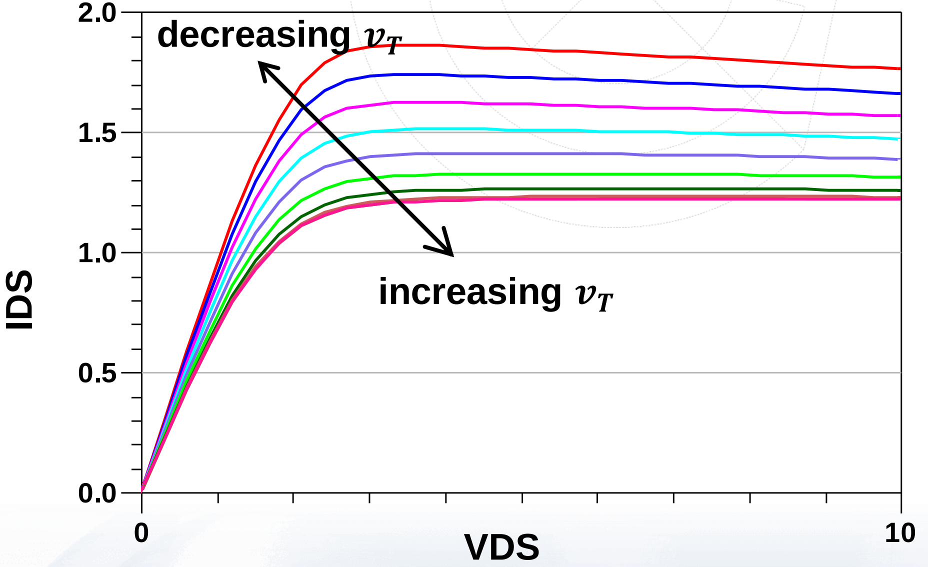
Inclusion of trapping effects in an equivalent-circuit Model





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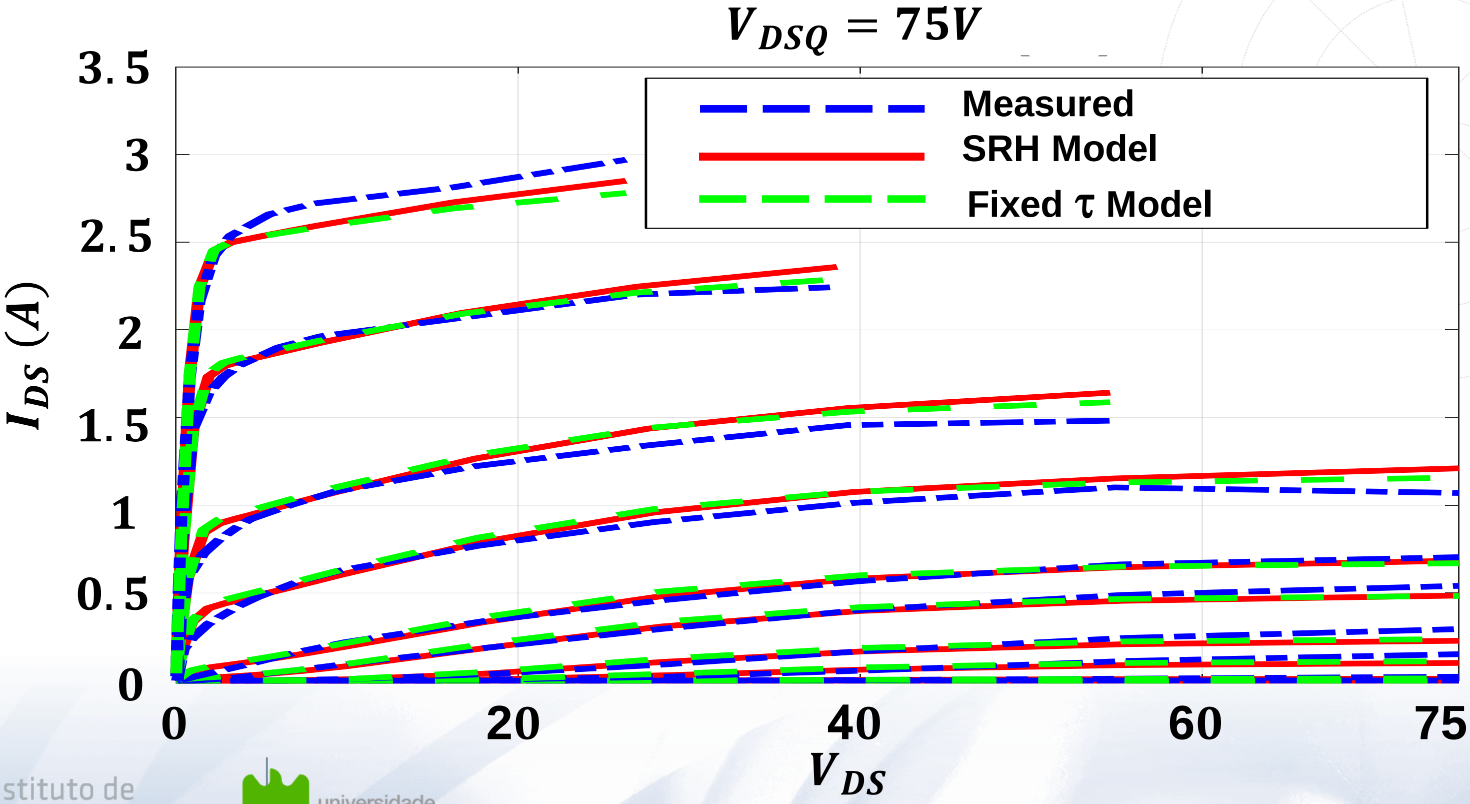

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1 – Introduction and Motivation

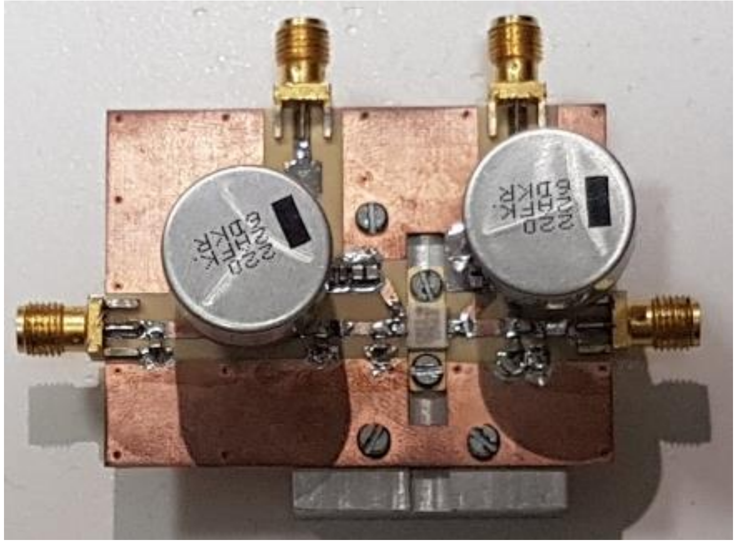
2 – Physical Origins of GaN HEMT Trapping Effects

3 – Modeling of Trap Capture and Emission Dynamics

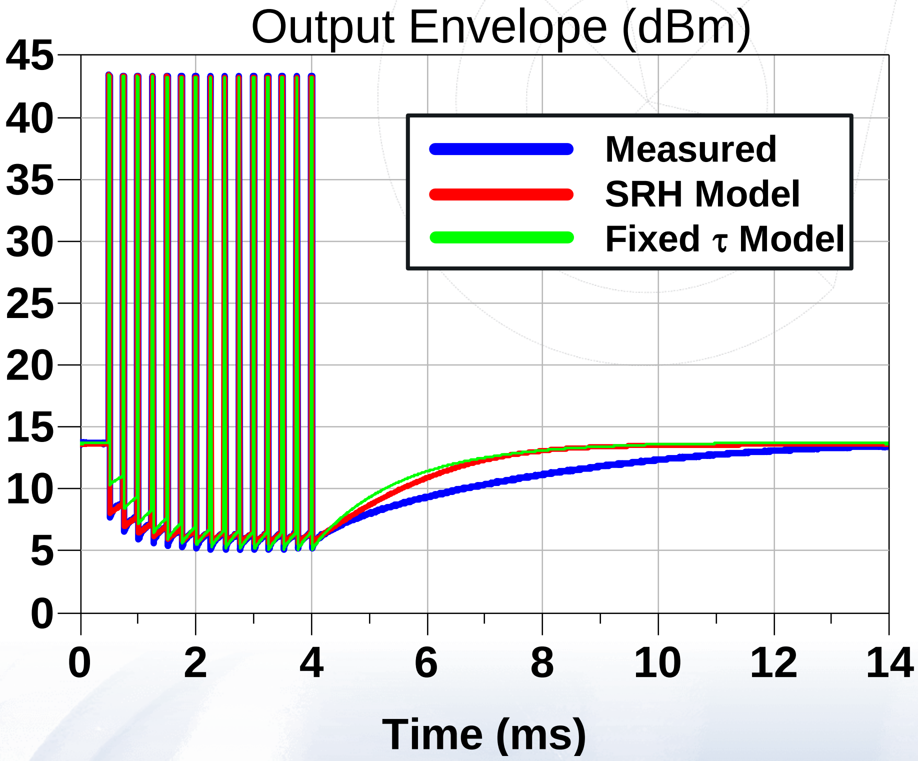
4 – GaN HEMT Nonlinear Model Validation

5 – Conclusions

Validation of the Proposed Model in Radar Applications

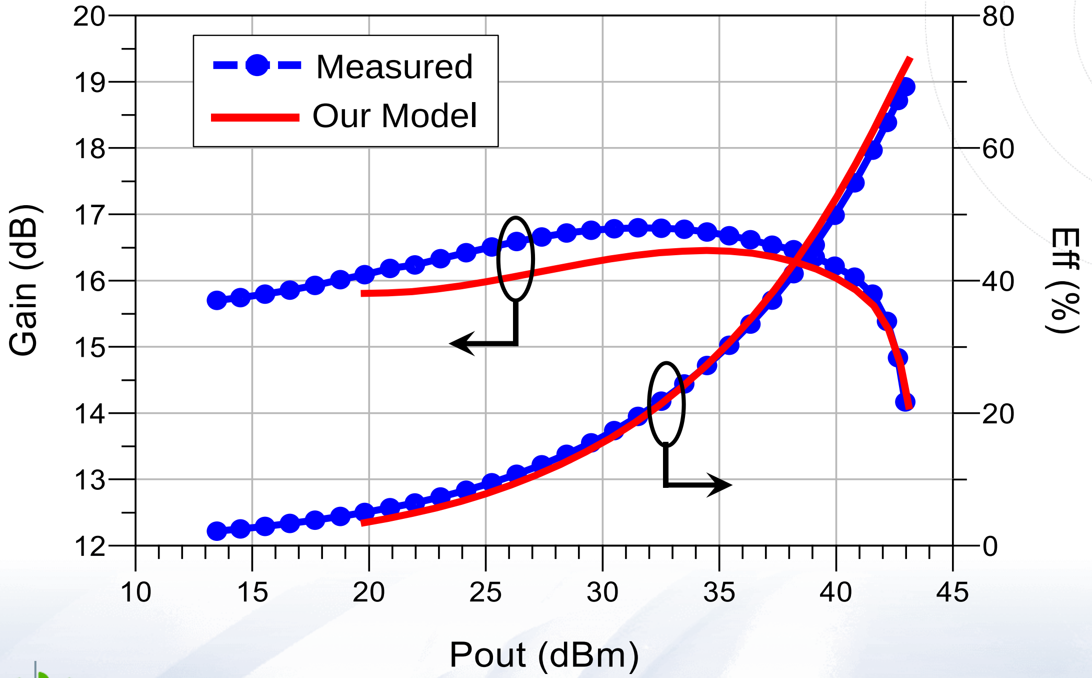


Implemented GaN HEMT based class AB PA



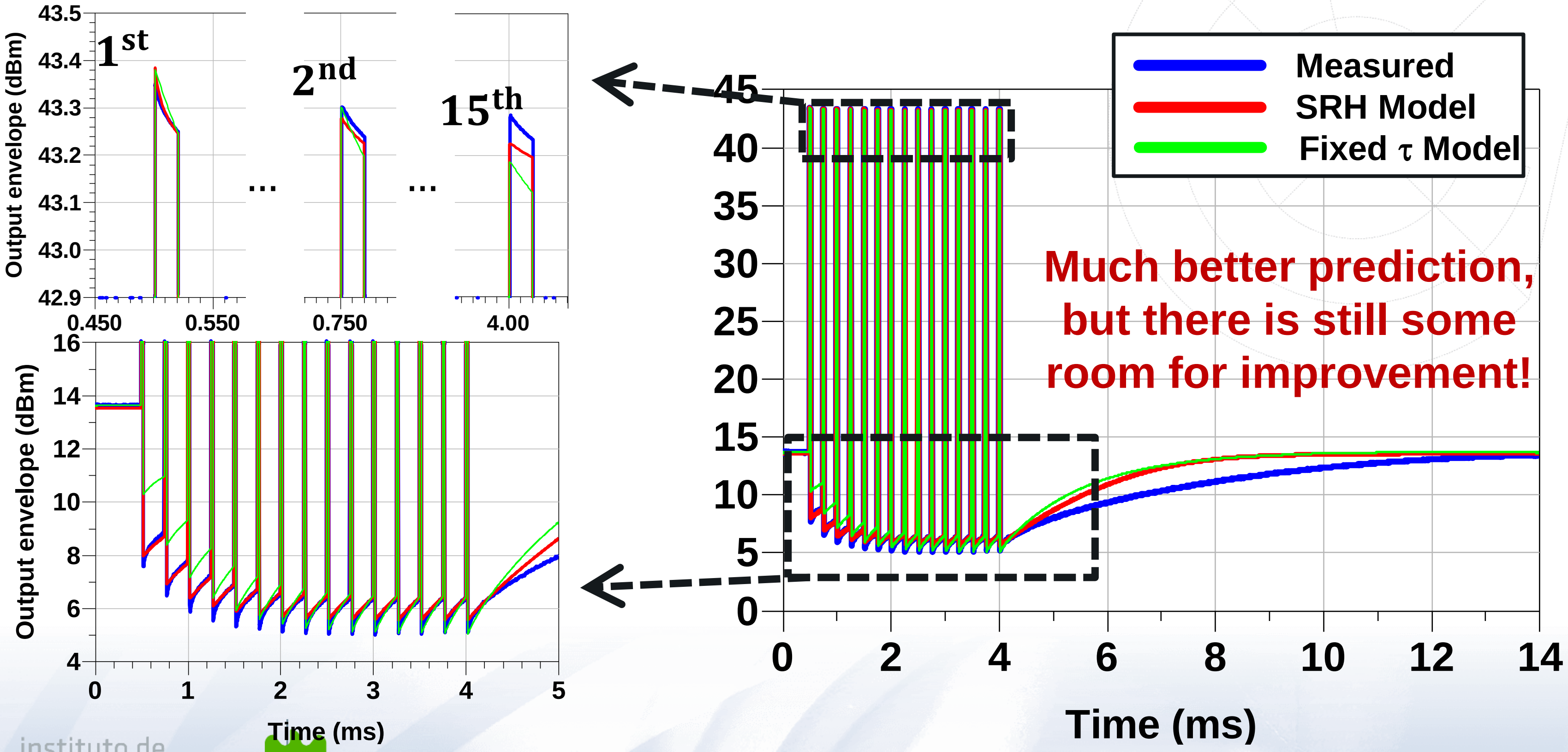
Validation of the Proposed Model in Radar Applications

Output Power and Efficiency Characteristics under CW Excitation



4 – GaN HEMT Nonlinear Model Validation

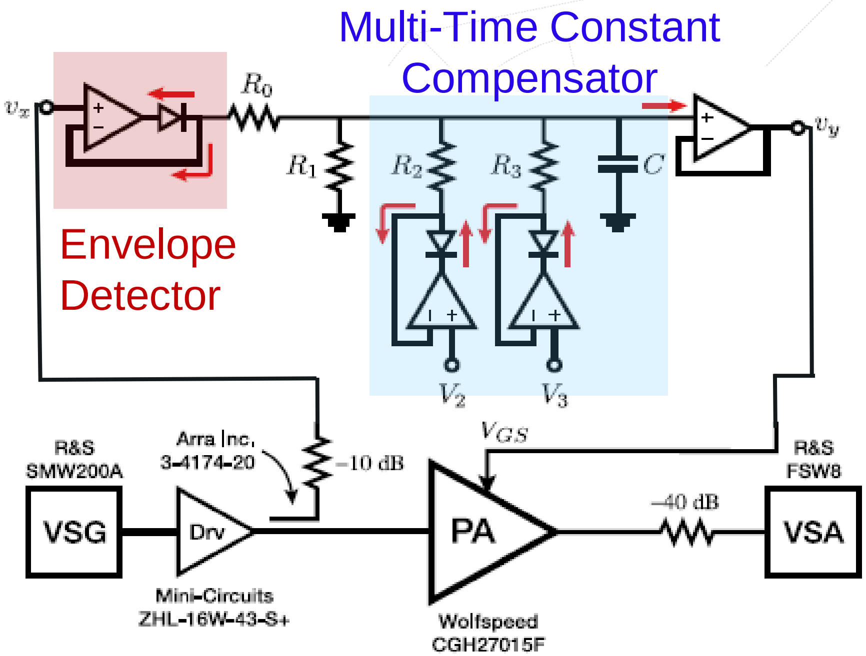
Validation of the Proposed Model in Radar Applications



Much better prediction, but there is still some room for improvement!

4 – GaN HEMT Nonlinear Model Validation

Since trapping effects can be approximately modeled as a variation of the HEMT's threshold voltage, imposed by the back-gate, they should be possible to compensated by a corresponding slow variation of the gate voltage[4,5]:

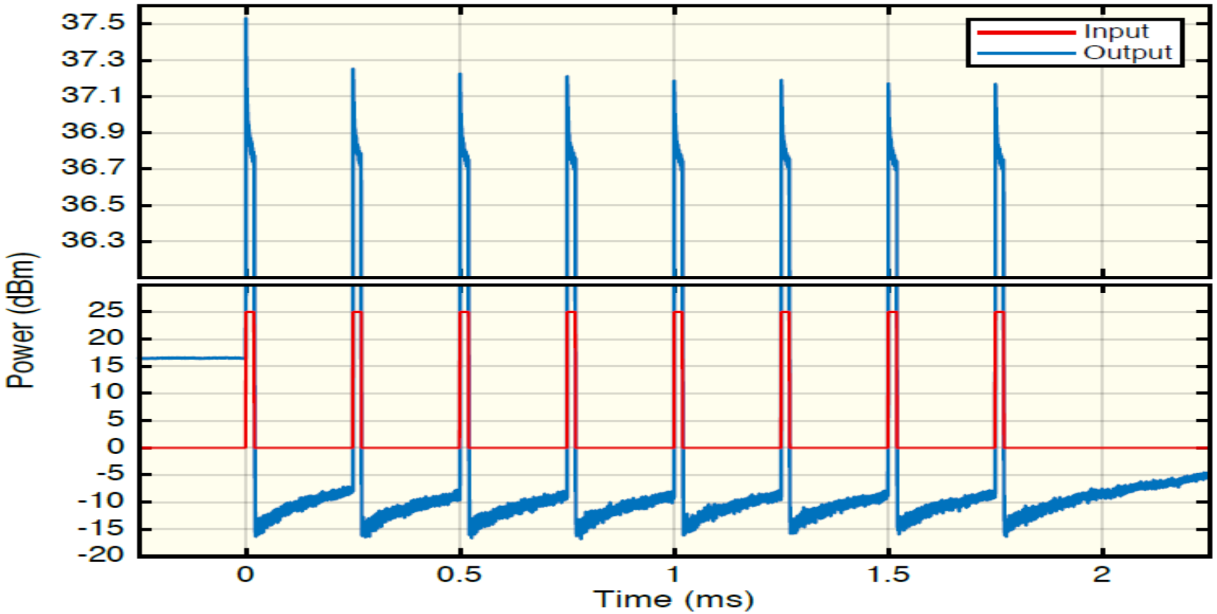


[4] P. Tomé ; F. Barradas ; T. Cunha and J. Pedro, "Hybrid Analog/Digital Linearization of GaN HEMT-Based Power Amplifiers," *IEEE T-MTT*, Jan. 2019.

[5] ----, "A Multiple-Time-Scale Analog Circuit for the Compensation of Long-Term Memory Effects in GaN HEMT-Based Power Amplifiers," *IEEE T-MTT*, early access 2020.

4 – GaN HEMT Nonlinear Model Validation

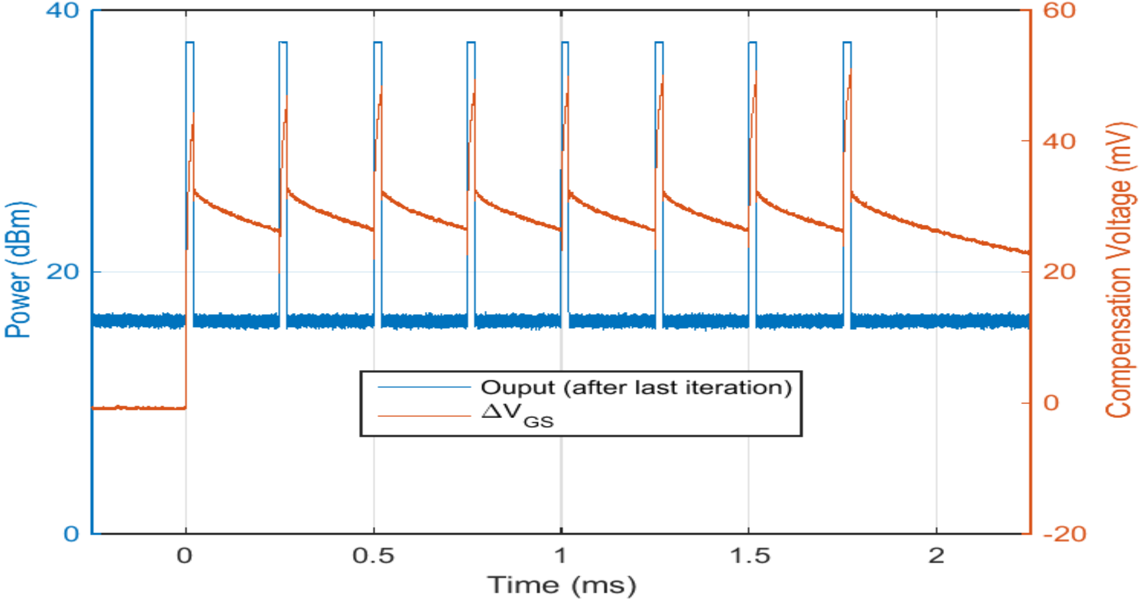
Input and uncompensated output[6]:



[6] F. Barradas ; P. Tomé ; T. Cunha and J. Pedro, "Hybrid Analog/Digital Linearization of GaN HEMT-Based Power Amplifiers," *IEEE T-MTT*, Dec. 2019.

4 – GaN HEMT Nonlinear Model Validation

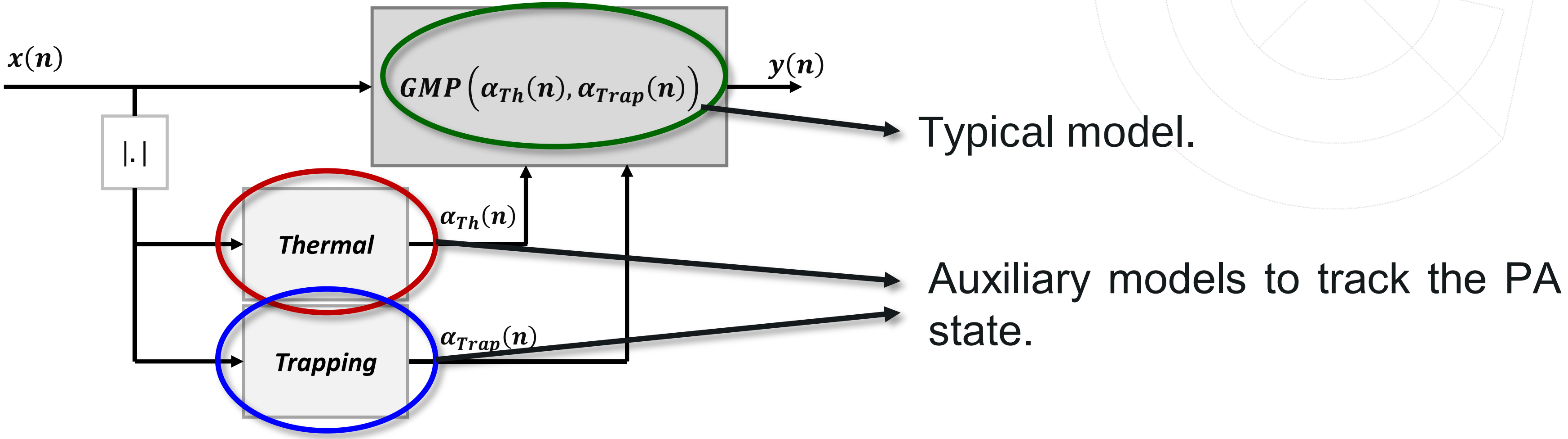
Compensated output and $v_{GS}(\tau)$ correction[6]:



[6] F. Barradas ; P. Tomé ; T. Cunha and J. Pedro, "Hybrid Analog/Digital Linearization of GaN HEMT-Based Power Amplifiers," *IEEE T-MTT*, Dec. 2019.

4 – GaN HEMT Nonlinear Model Validation

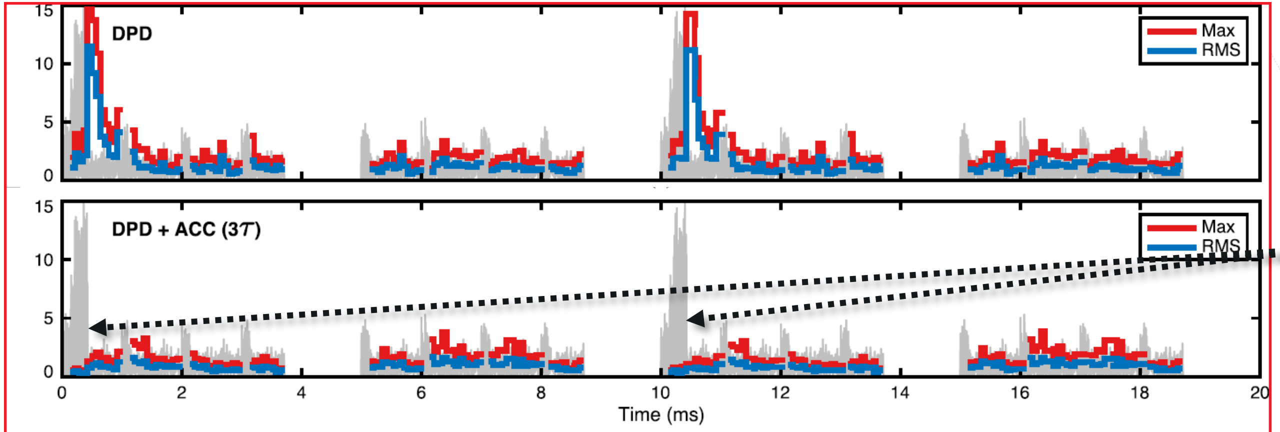
These memory effects could have also been compensated in the digital domain adapting the coefficients of a conventional DPD according to the slowly varying electro-thermal and trapping signals.



[7] F. M. Barradas, L. C. Nunes, T. R. Cunha, P. M. Lavrador, P. M. Cabral and J. C. Pedro, "Compensation of GaN Long-Term Memory Effects on GaN HEMT Based Power Amplifiers," *IEEE TMTT,* Mar. 2017.

4 – GaN HEMT Nonlinear Model Validation

The application of these nonlinear memory compensation techniques to a PA processing 5G NR signals, showed a remarkable improvement on the EVM.



(c)

With slow gate bias control.

Presentation Outline

5 – Conclusions

1 – Trapping effects are still a major shortcoming of GaN HEMT devices that is impeding a more rapid deployment of this promising RF power device technology.

2 – Careful characterization of trapping transients plays a major role in GaN HEMT modeling, but also on device optimization at the fab level. This requires a fruitful interaction between RF designers and device physicists.

3 – Multiple time constant behavior of these transients at both the electron capture and emission states is still an open problem.

4 – Precise understanding of these complex phenomena and corresponding modeling efforts, pays back in practical applications where time from design to product is a must.

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Luis C. Nunes – Assistant Researcher
Filipe E. Barradas – Assistant Researcher

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HUAWEI

AMPLEON Amplify the future (former: NXP)

instituto de telecomunicações
universidade de aveiro

Characterization and Modeling of AlGaN/GaN HEMT Trapping Transients

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Instituições Associadas

Thank you !