

Workshop
WMB

2009 International Microwave Symposium



Nonlinear characterization and modeling of low frequency dispersive effects in power transistors

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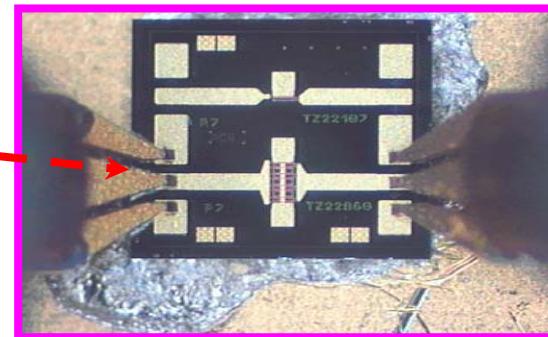
- Characterization methods
- Thermal Issues
- Trapping effects
- Impact Ionization effects
- Conclusion

- Design of High Power Amplifiers requires accurate Non linear models that take into account:
 - Strong Thermal constraints
 - Parasitics effects such as Traps in HEMTs
 - Impact Ionization limits in GaAs PHEMTs
- To cope with
 - Reliability issues
 - Degradation of Large signal characteristics
- Rely on specialized characterizations tools

Characterization Tools

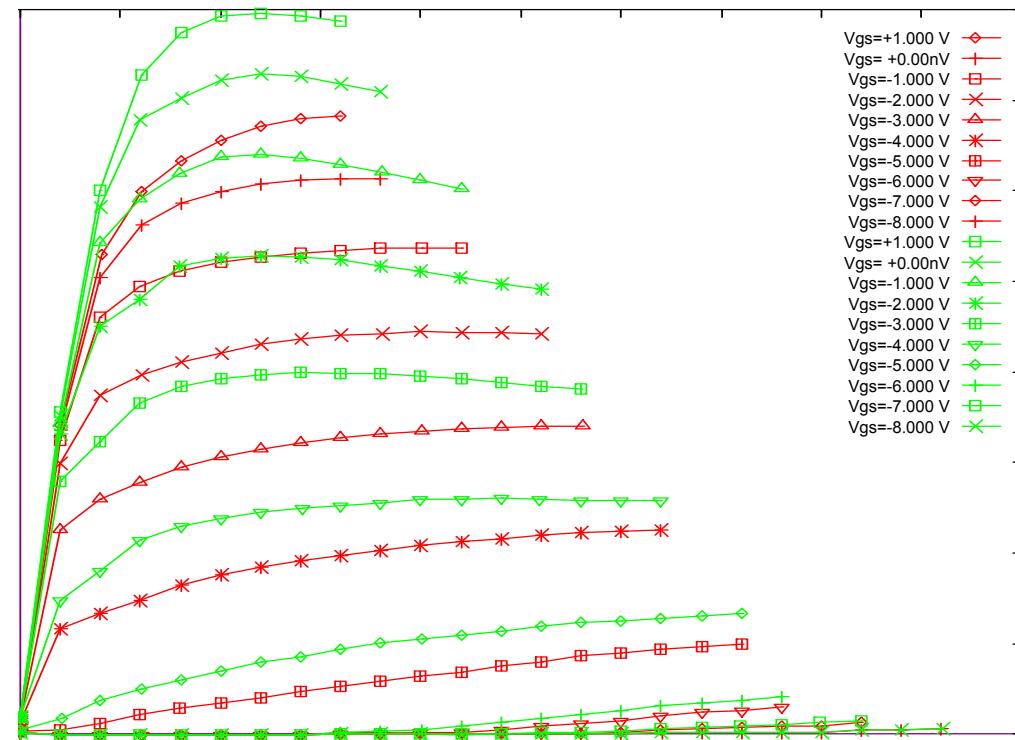
In the modelling process, the characterization phase is preeminent, as some effects can only be put into evidence using specialized measurements techniques.

- DC and Pulsed I-V measurements
- CW and pulsed S-parameters measurements
- CW and pulsed Load-Pull frequency measurements
- CW and pulsed Load-Pull time domain measurements (LSNA)
- Low Frequency Z and S parameters measurements
- Two tone IM measurements.

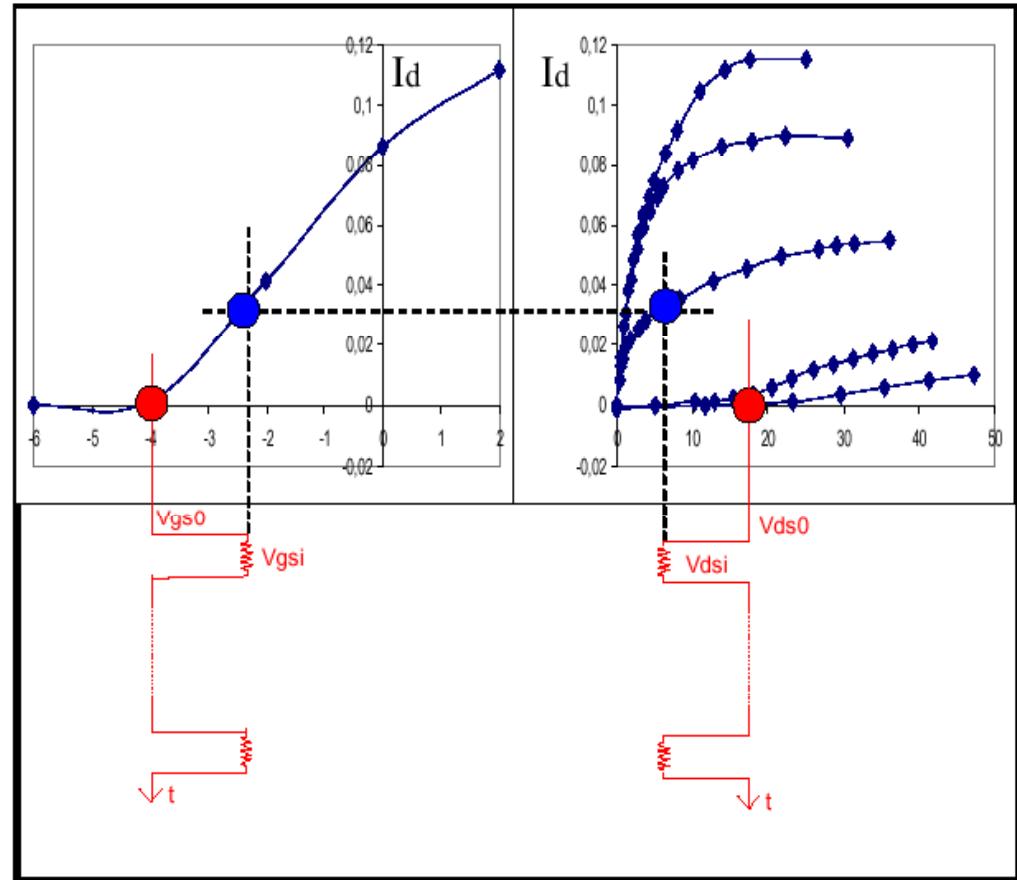


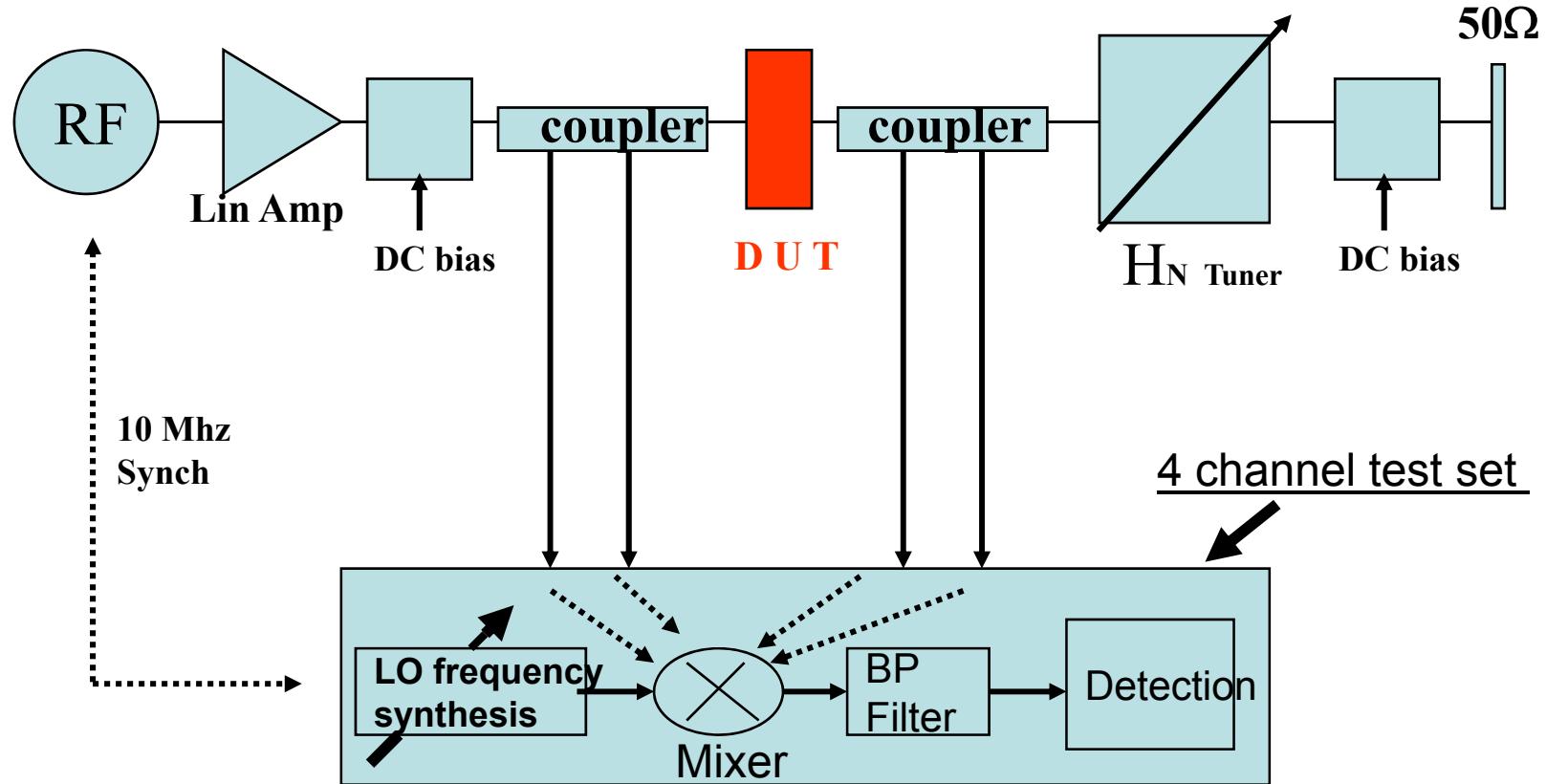
On Wafer performances

- Max current 5A
- Min current 1 μ A
- Max Voltage 120V
- S-parameters 1- 40 GHz
- Température -65°C / 200°C
- Pulse duration > 300ns
- duty cycle > 0.5 %



- short pulses 400ns : quasi – isothermal state
- period : 6μs
- starting point of the pulses is the quiescent bias point (V_{gs0}, V_{ds0}) that defines the thermal and trapping state of the device
- small-signal RF during the steady state of the pulses
- I(V) and S-Parameters are taken during the pulses



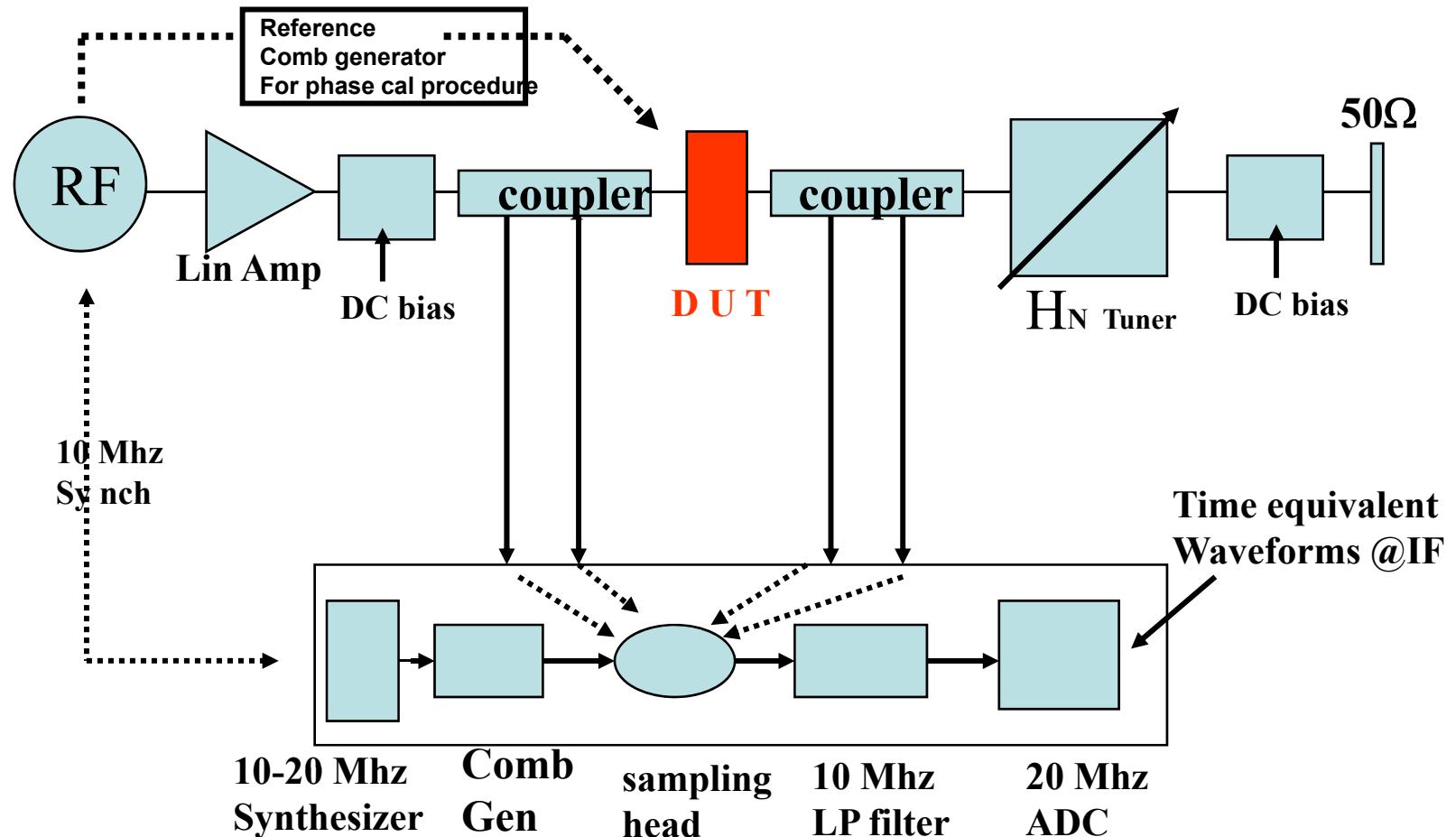


VNA receiver operation mode : Heterodyne Principle + narrow BP IF filter

Sequential Measurements of Harmonic components H_n

No phase relationship measurements between H_n and H_{n+1}

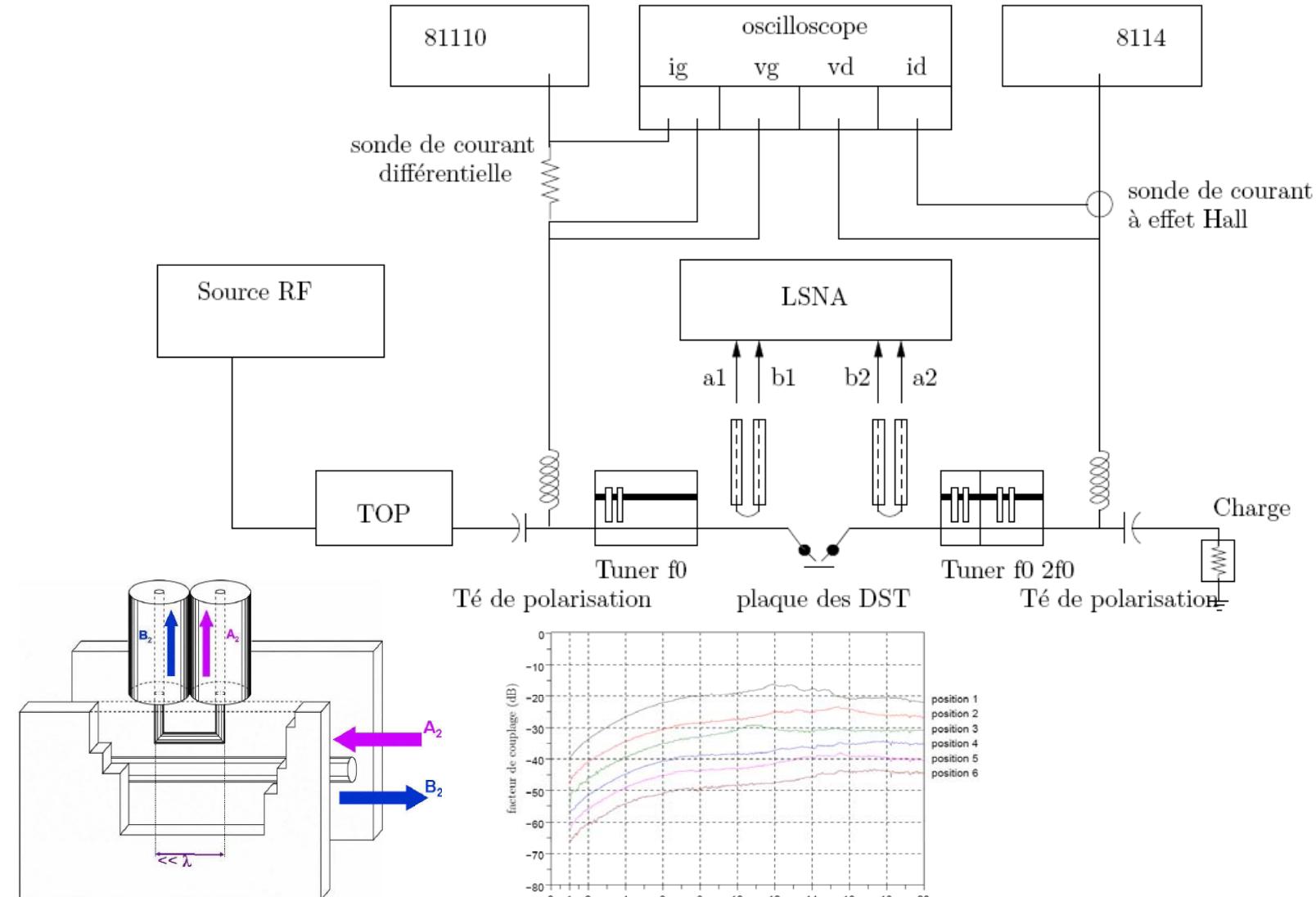
Absolute power and power wave ratios measurements @ H_n

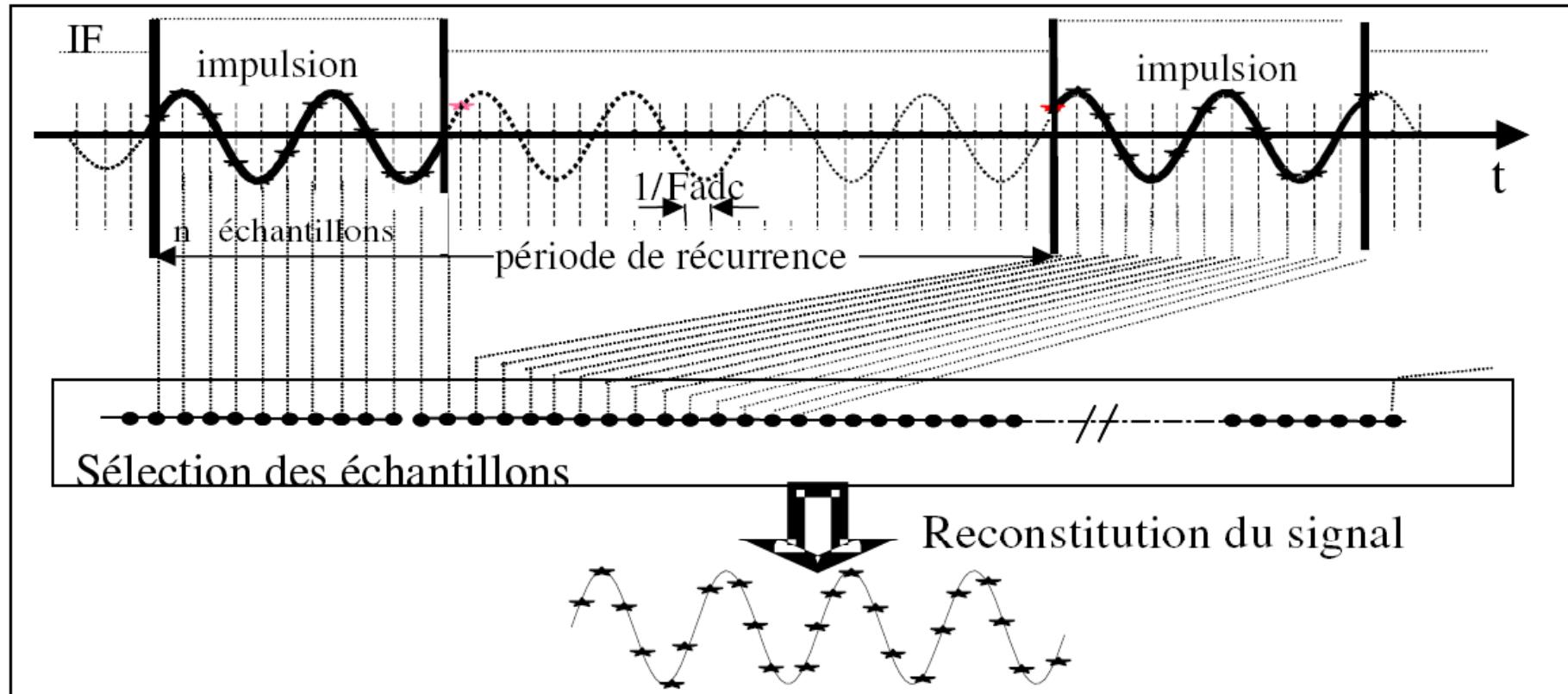


Harmonic Sub Sampling @ 20 MHz

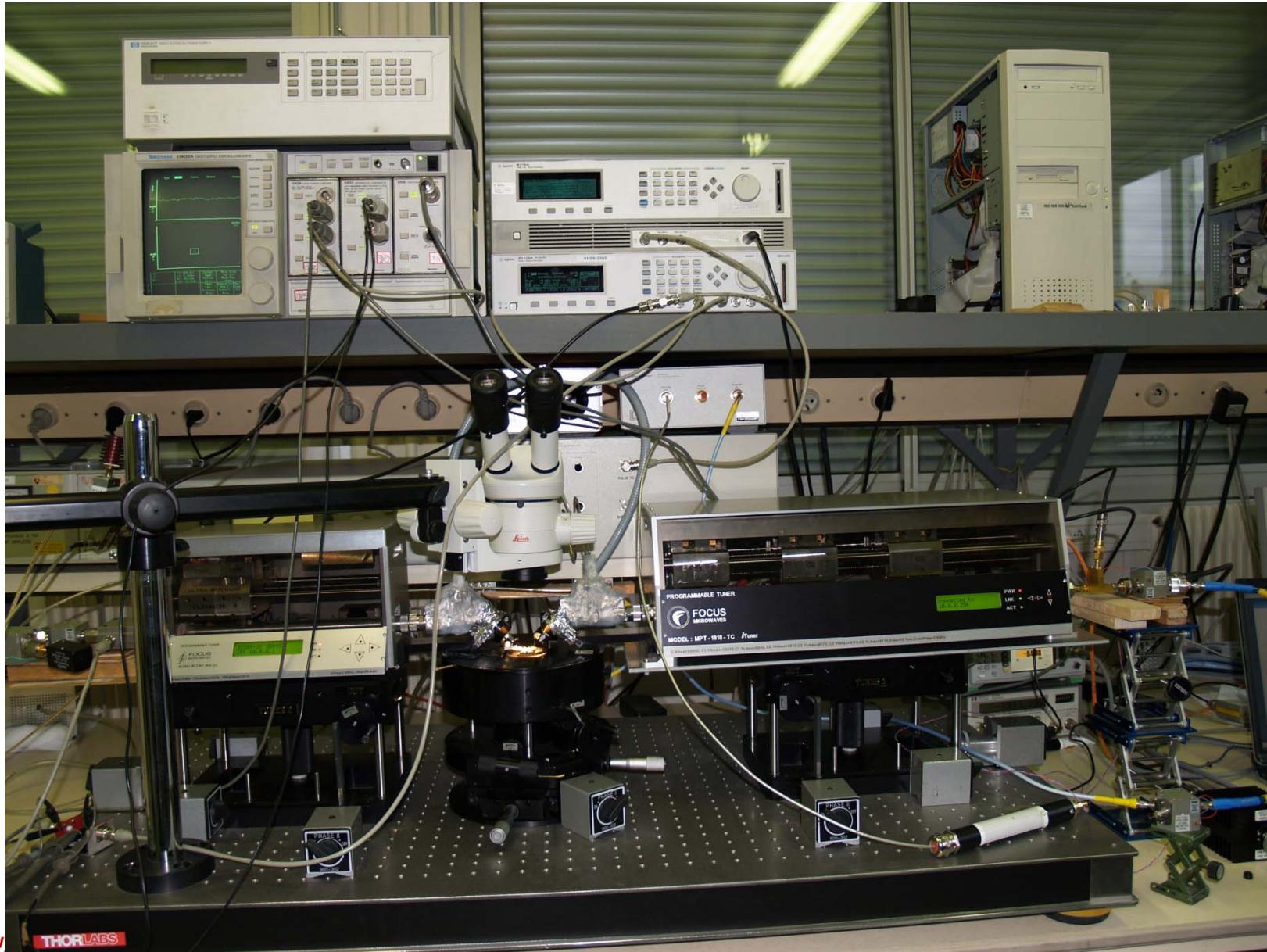
Frequency Translation and compression into a 10 Mhz IF Bandwidth

Pulsed LSNA-organisation

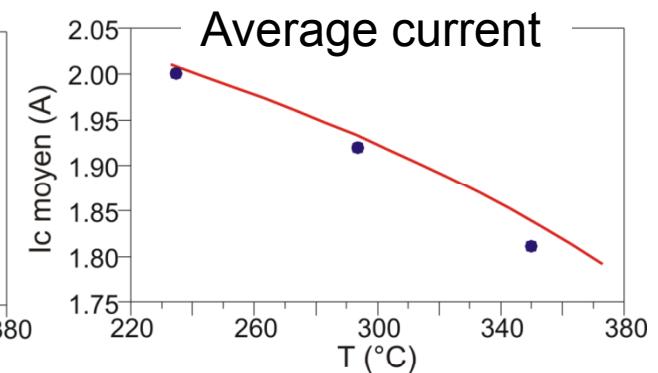
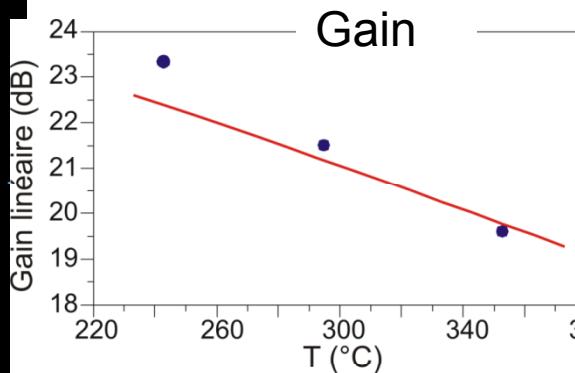
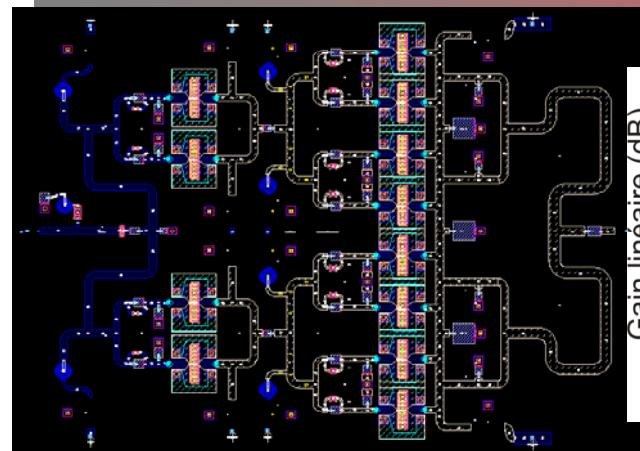




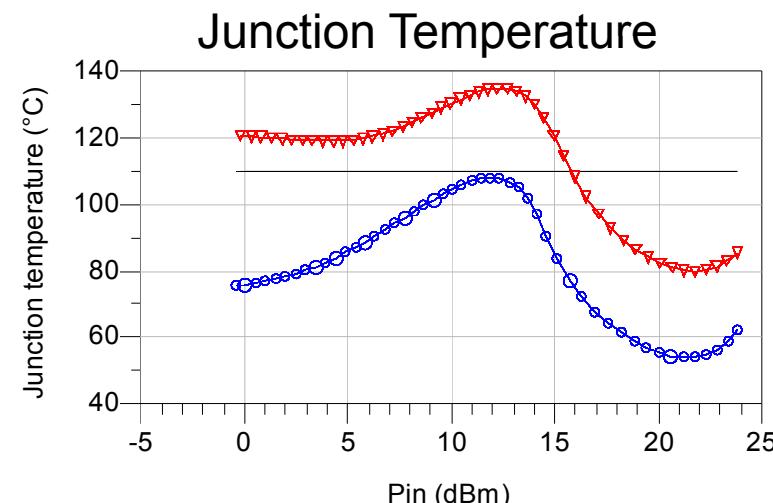
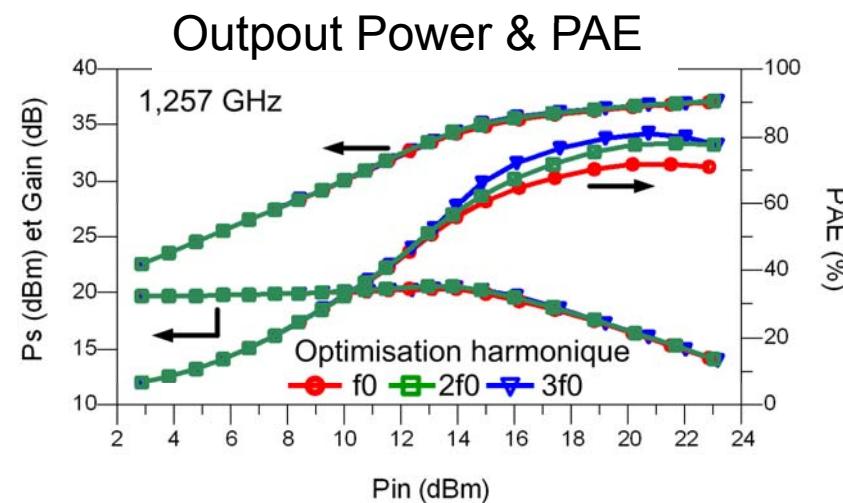
Pulsed LSNA- The set-up



Thermal issues

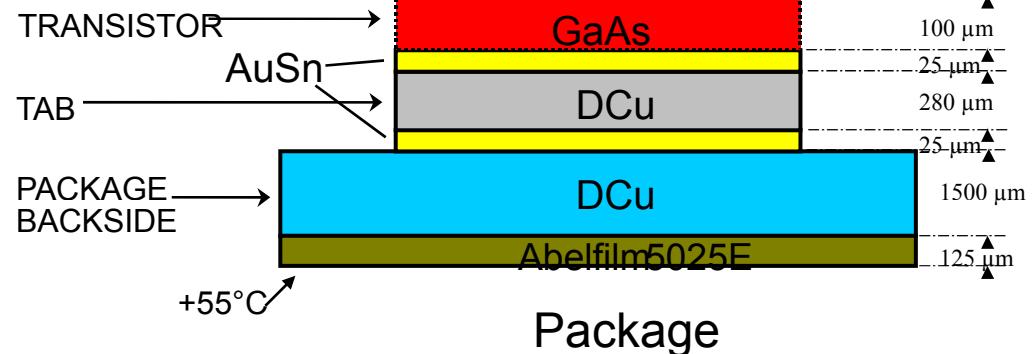
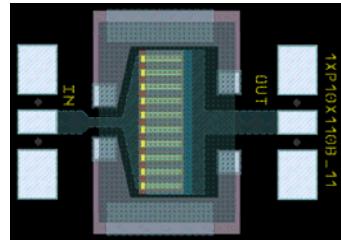


Degradation of performances for a 10W X band PA

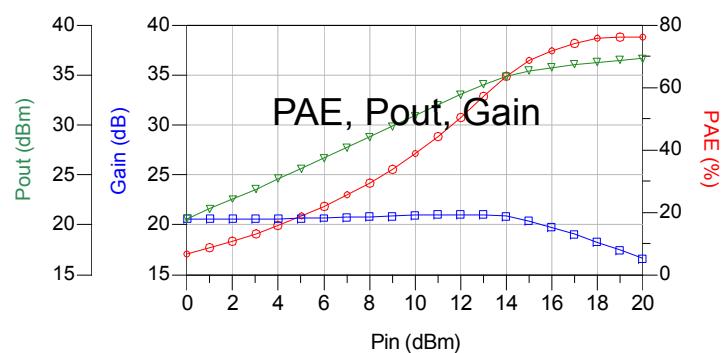
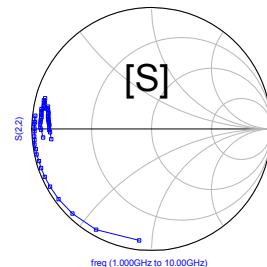
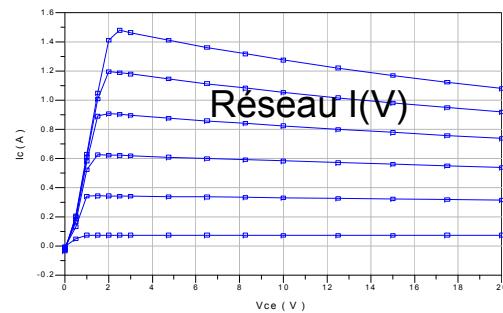


Optimization of PAE allows to reach the reliability constraints for space applications

Electrothermal modeling of HBTs



$$\begin{cases} I_B = f_1(V_{BE}, V_{BC}, T) \\ I_C = f_2(V_{BE}, V_{BC}, T) \end{cases}$$



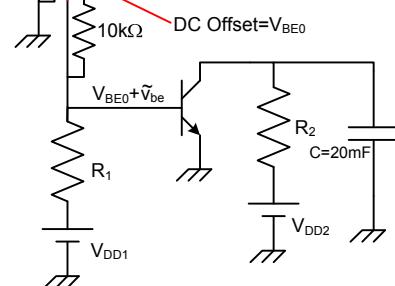
$$\begin{cases} \tilde{P} = V_{CE} \cdot I_C + V_{BE} \cdot I_B \\ \tilde{T}(j\omega) = \tilde{Z}_{TH}(j\omega) \cdot \tilde{P} \end{cases}$$

Full electrothermal model requires the knowledge of

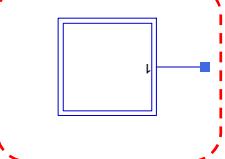
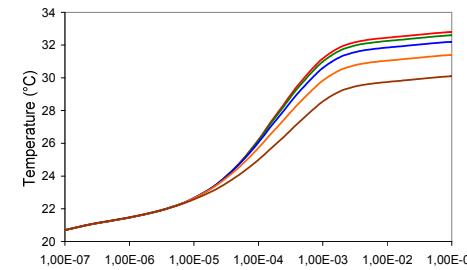
$$\tilde{Z}_{TH}(\omega)$$

Experimental set up

Electrical measurement of the thermal impedance

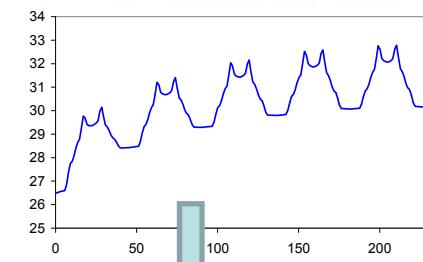
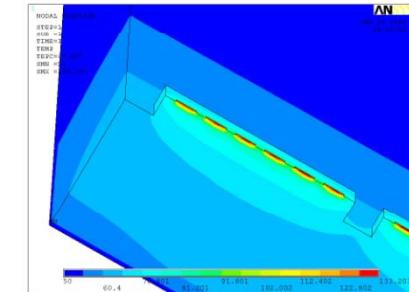


Thermal Model



SIMULATION

3D finite element simulation

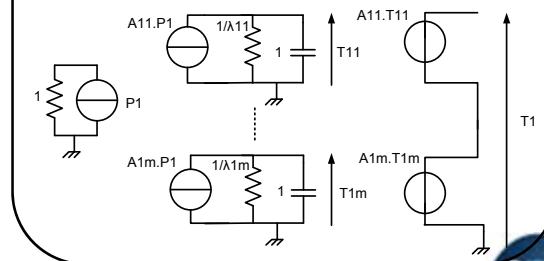


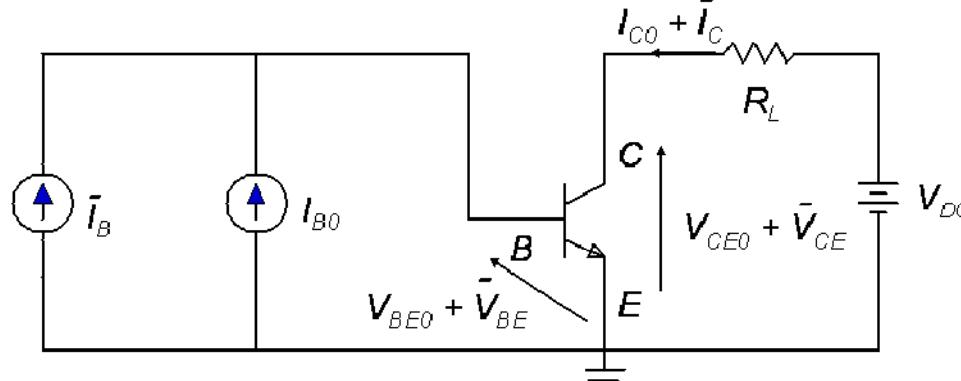
Model Comparison

Model Order Reduction

$$C_R \cdot \dot{X}_R = -K_R \cdot X_R + F_R u$$

$$T_R = E^T \cdot X_R$$





Principle of the measurement of the input impedance

$$V_{BE} = f(I_B, T)$$

$$\frac{\partial \tilde{V}_{BE}}{\partial \tilde{I}_B} = \left. \frac{\partial f}{\partial I_B} \right|_{T_0} + \underbrace{\left. \frac{\partial f}{\partial T} \right|_{I_{B0}}}_{\text{green circle}} \cdot \frac{\partial \tilde{T}}{\partial \tilde{I}_B}$$

$$\tilde{Z}_{in} = Z_{inISO} + \varphi \cdot \frac{\partial \tilde{T}}{\partial \tilde{I}_B}$$

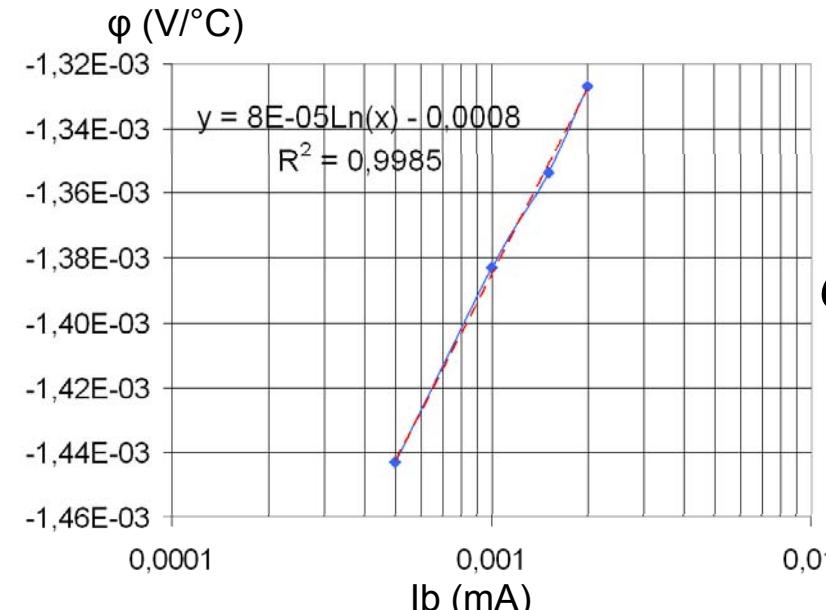
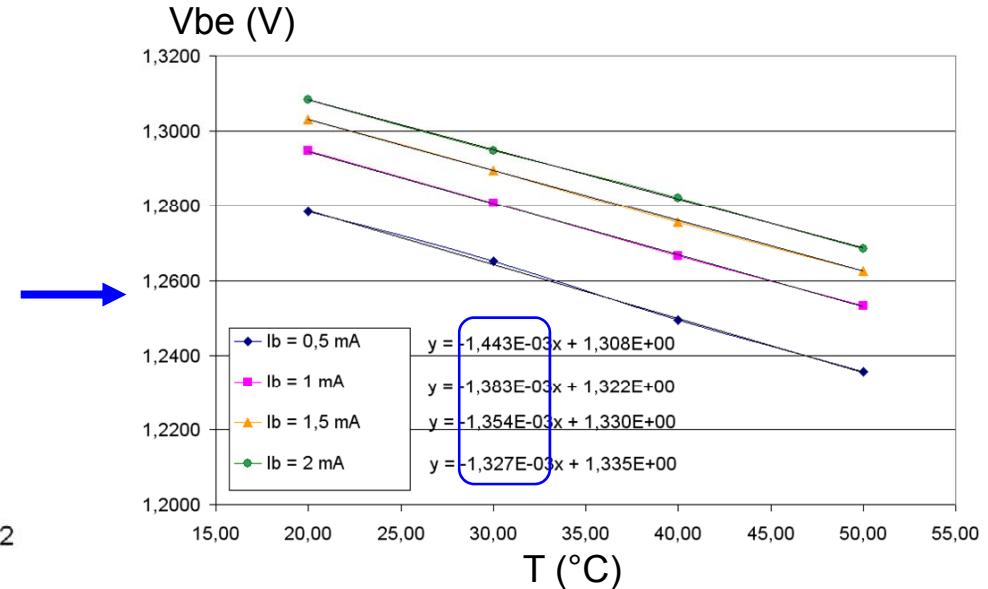
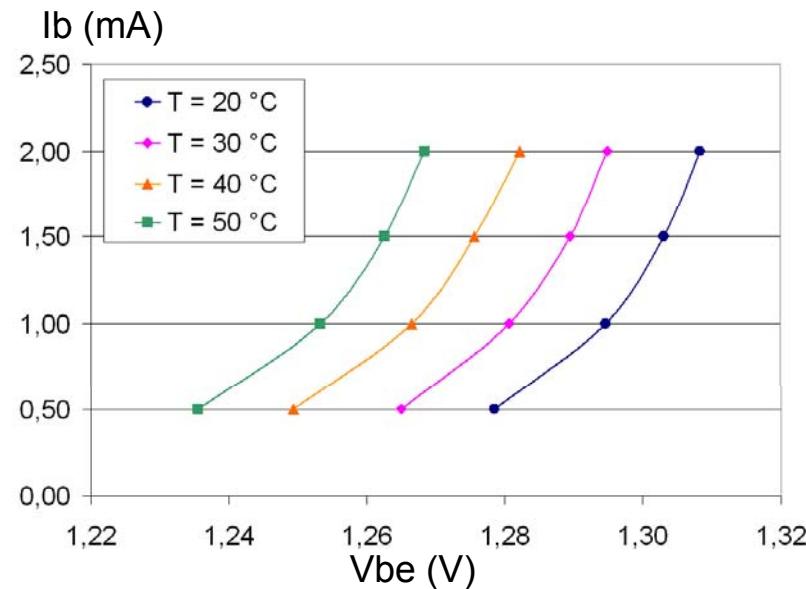
$$\partial \tilde{T} = Z_{th}(\omega) \cdot \partial \tilde{P}$$

$$\tilde{P} = V_{CE0} \cdot \tilde{I}_C + \tilde{V}_{CE} \cdot I_{C0}$$

$$\frac{\partial \tilde{P}}{\partial \tilde{I}_B} = h_{fe} \cdot (V_{CE0} - R_L \cdot I_{C0})$$

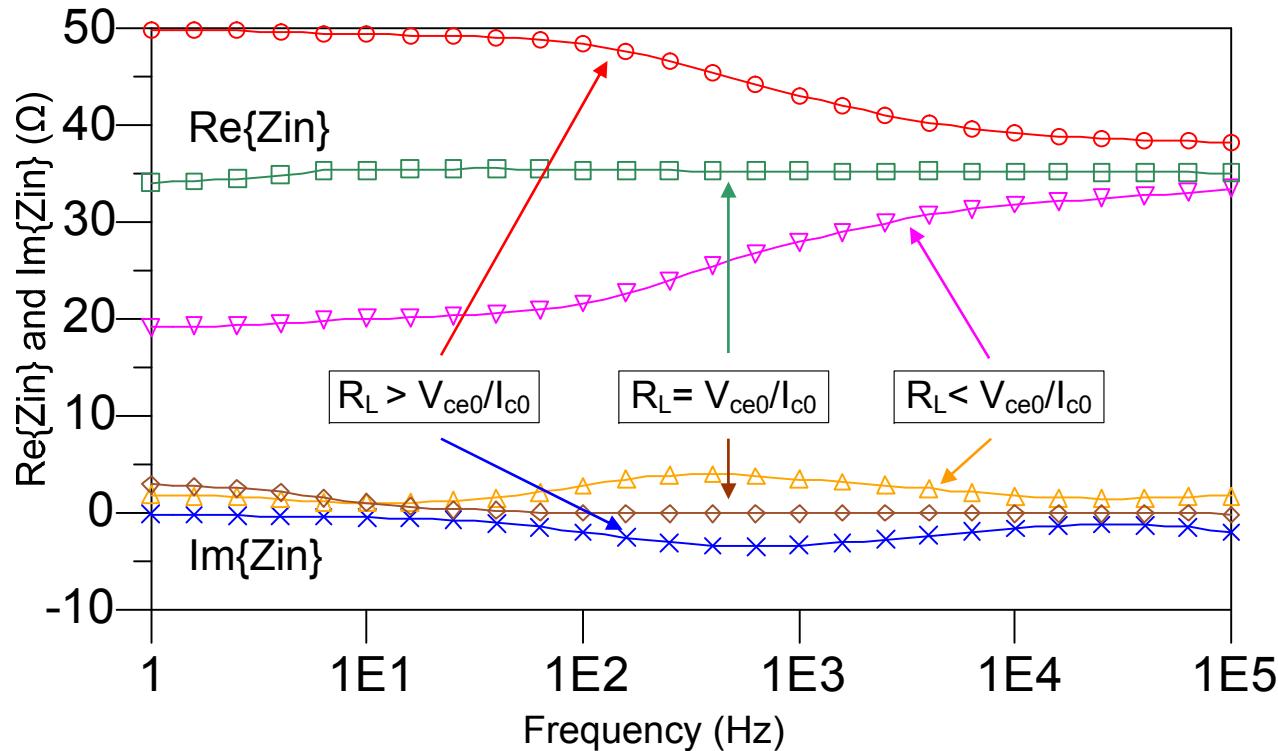
$$\tilde{Z}_{in} = Z_{inISO} + \varphi \cdot Z_{th}(\omega) \cdot h_{fe} \cdot (V_{CE0} - R_L \cdot I_{C0})$$

Extraction of φ



$$\varphi(I_B) = \left. \frac{\partial V_{BE}}{\partial T} \right|_{I_{Bo}}$$

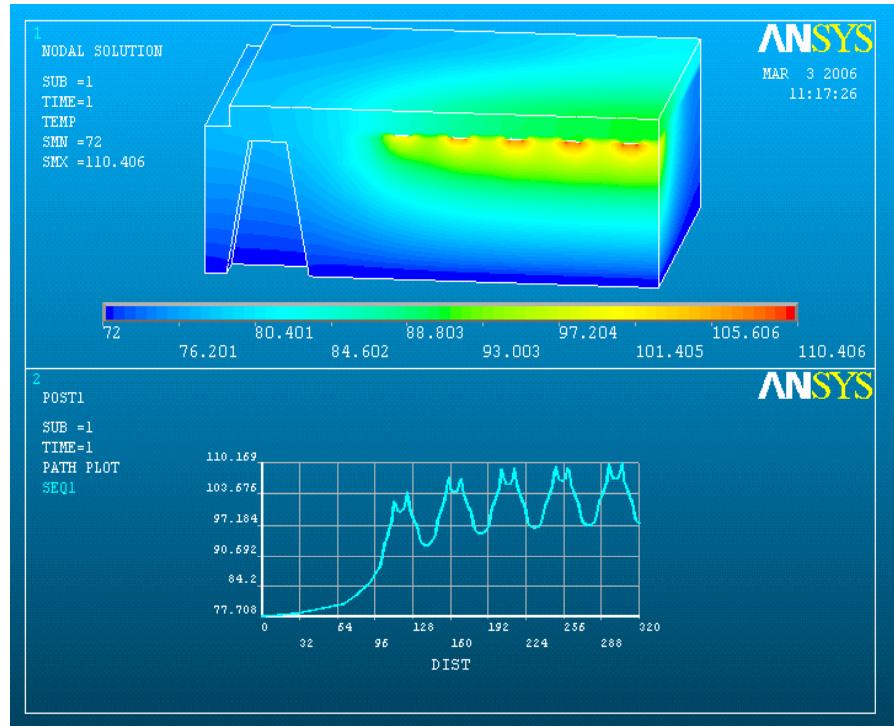
Input impedance variation



$$\tilde{Z}_{in} = Z_{inISO} + \underline{\varphi} \cdot \underline{Z_{th}}(\omega) \cdot \underline{h_{fe}} \cdot \underline{(V_{CE0} - R_L \cdot I_{C0})}$$

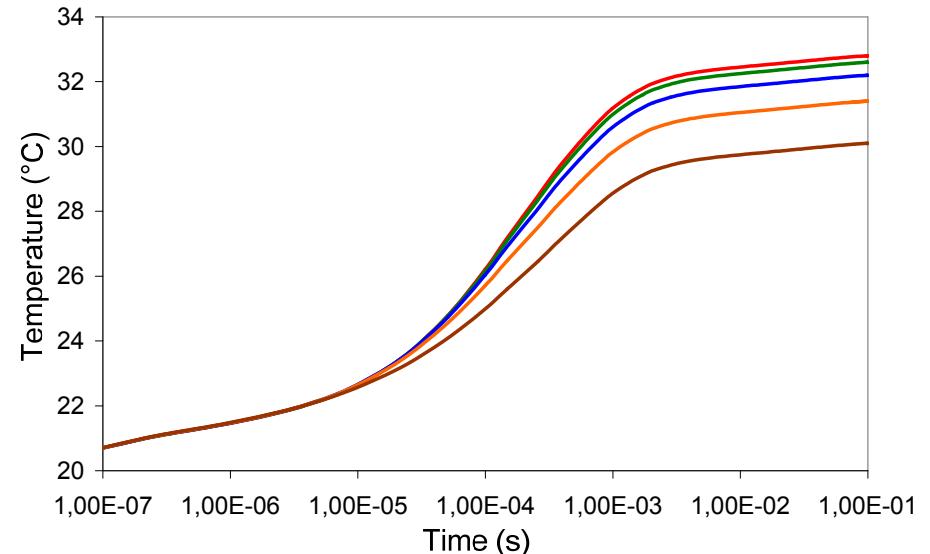
→ Z_{in} purely real if the condition $(V_{CE0} - R_L \cdot I_{C0}) = 0$ is verified

3D FE Simulation Static & Dynamic



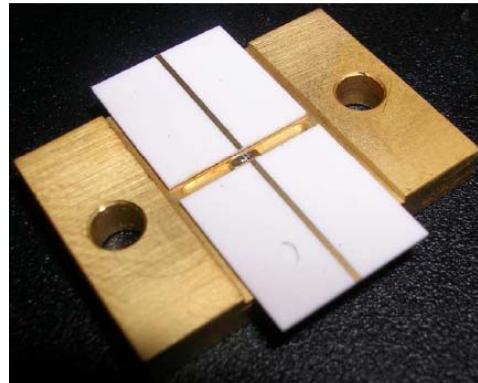
Hot points, temperature profile

Transient regime at the selected points



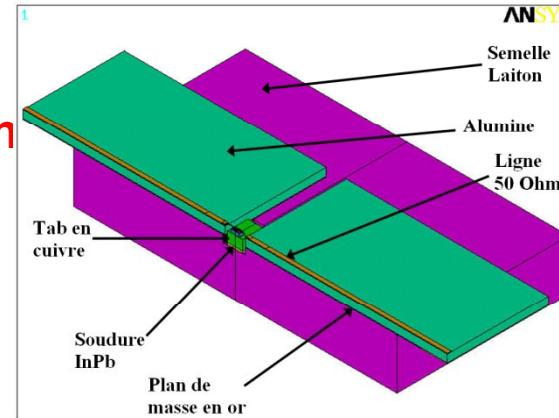
- Homogeneous repartition of the power
- Useful tool for the design of microwave power transistors
- But huge calculation time and heavy computing ressources

Model Order Reduction



Real system

Representation



FEM

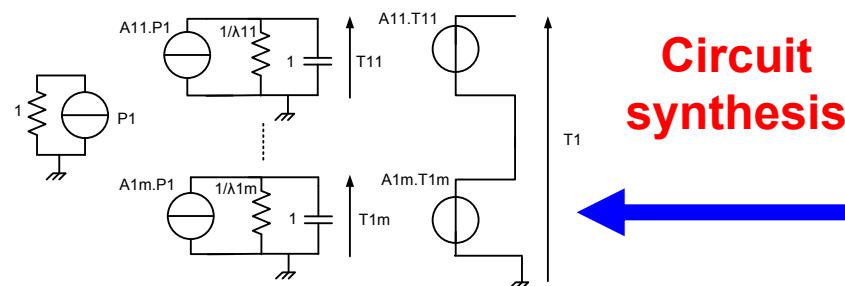
Linear conductivity

3D Modeling

Numerical system

$$C \cdot T + K \cdot T = F$$

Thermal subcircuit

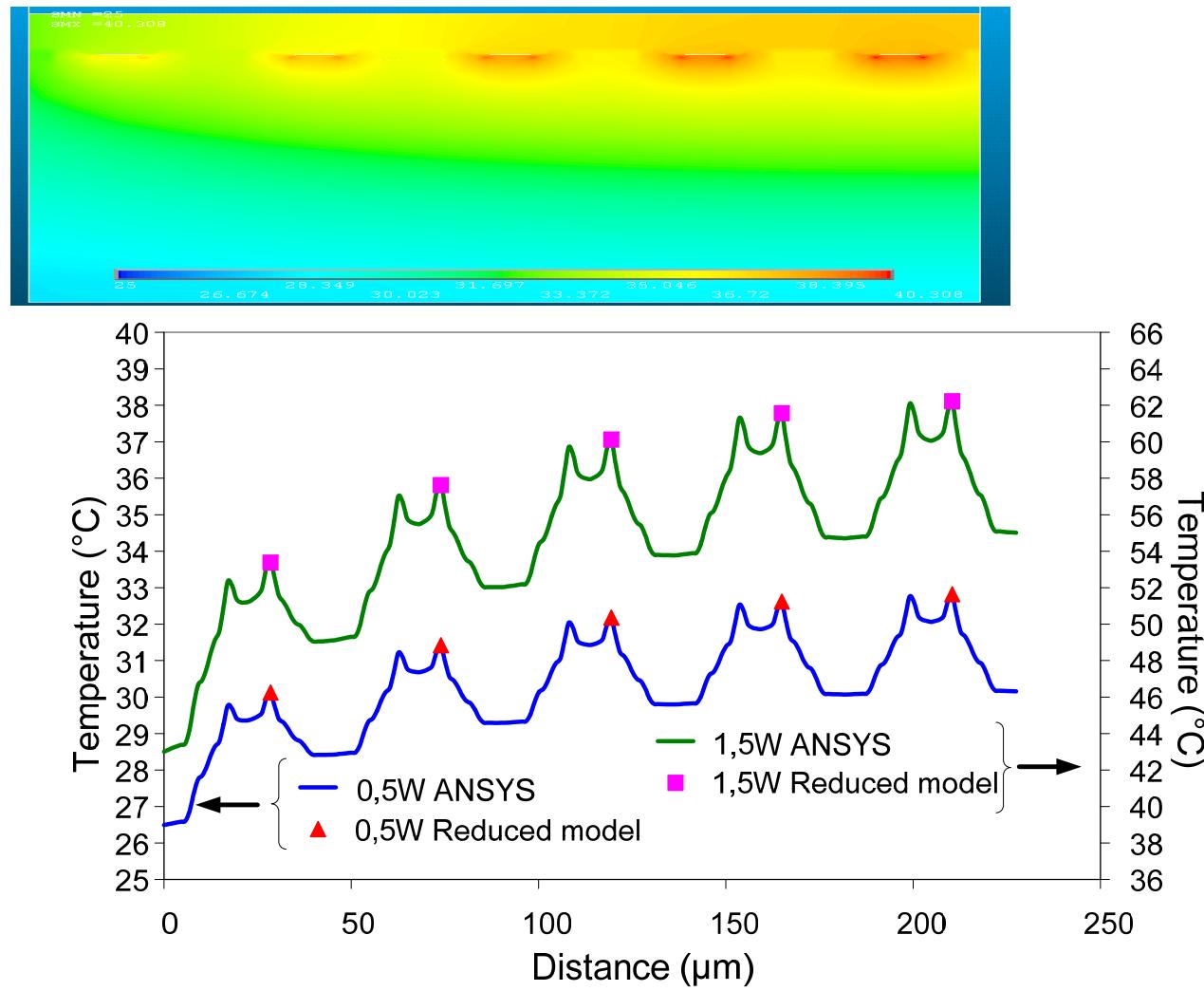


Circuit synthesis

Reduced Order Model

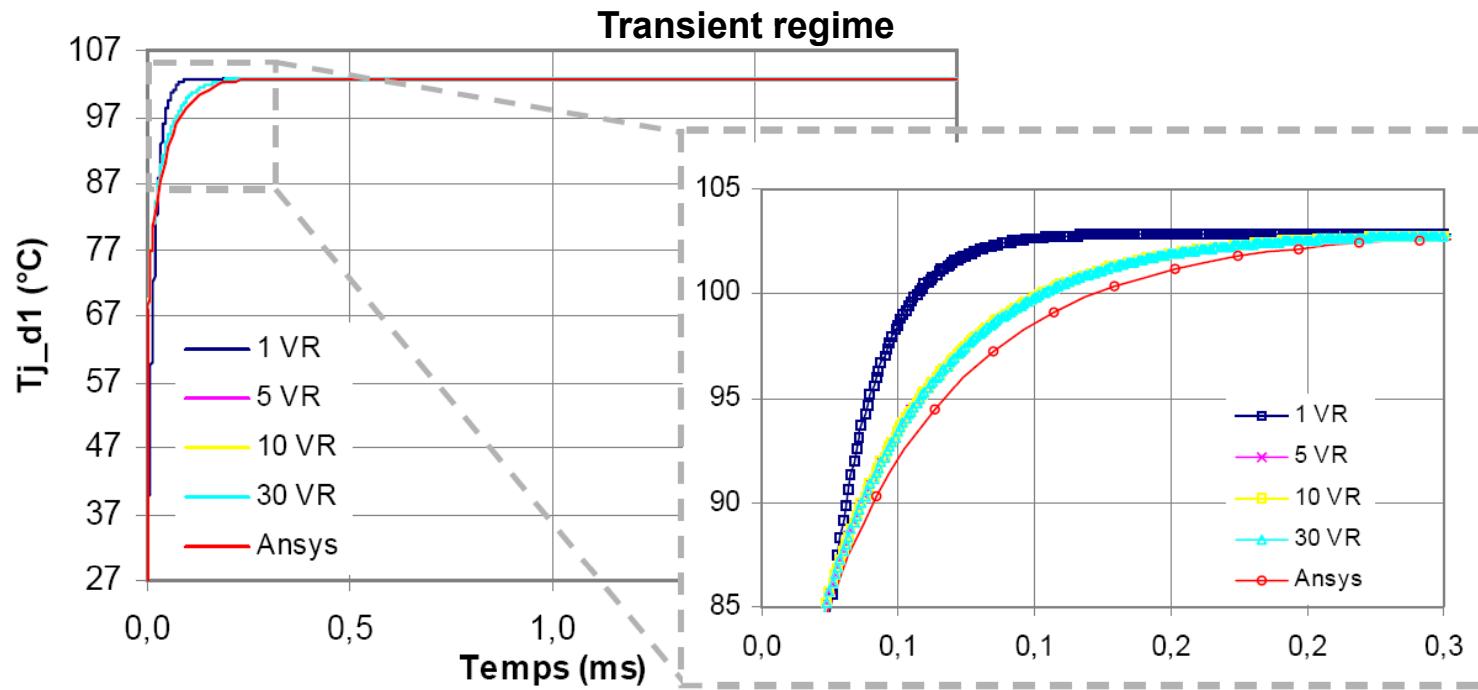
MOR

Comparison ANSYS vs MOR (static)

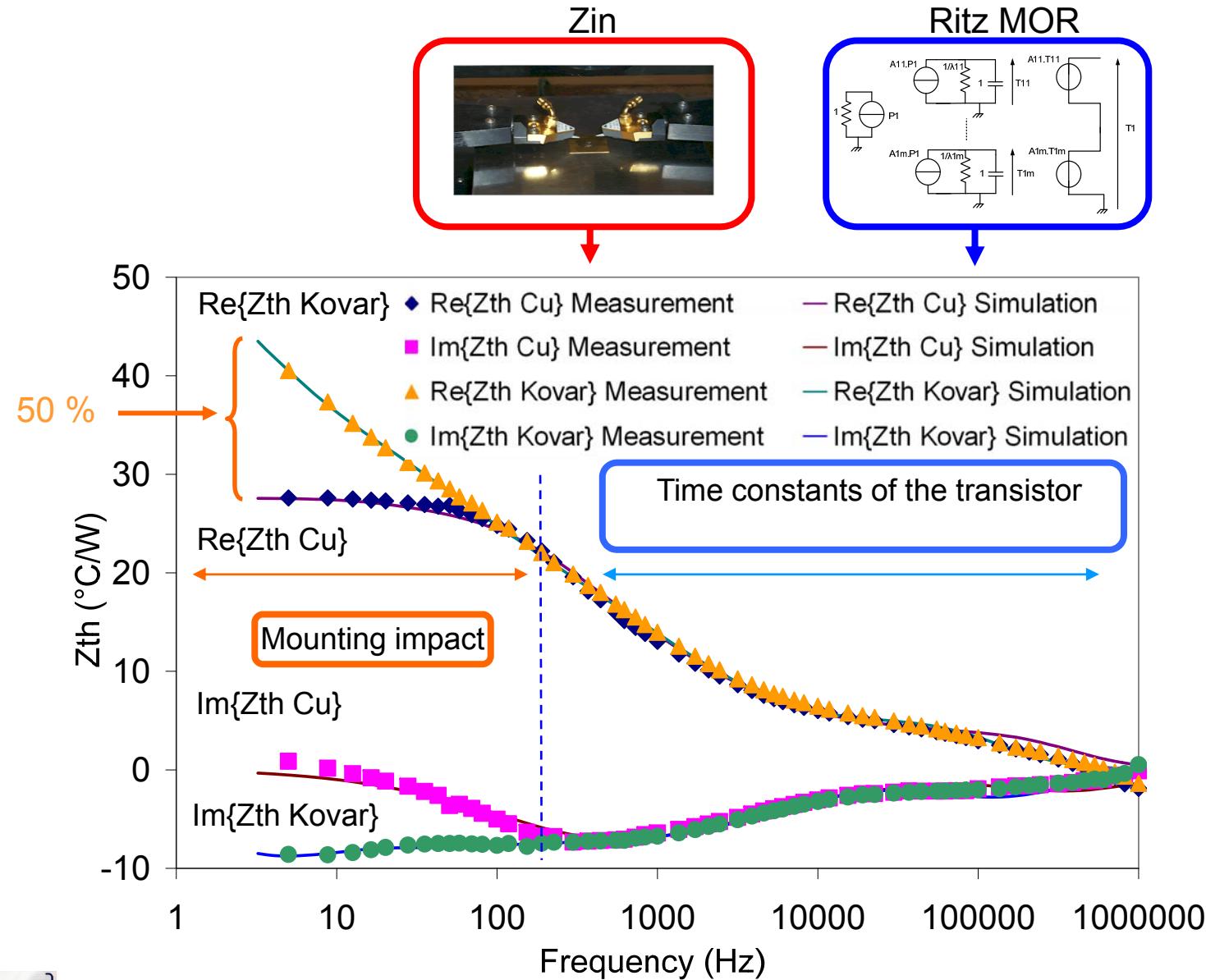


→ The Ritz method for MOR guarantees that steady state temperature is reached

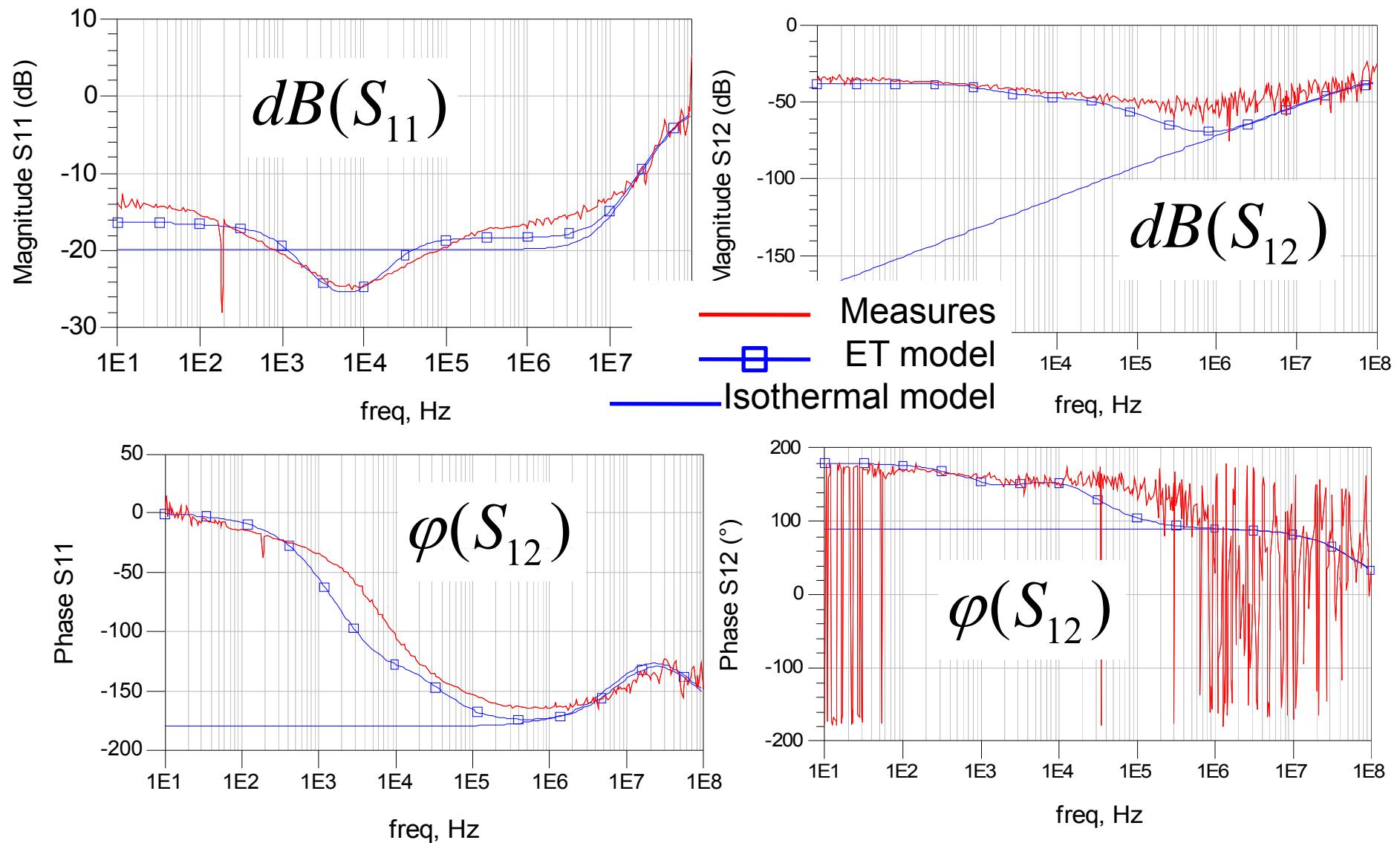
Comparison ANSYS vs MOR (dynamic)



- The number of Ritz vectors determine the precision of the transient regime
- Computing time (30 000 nodes) ANSYS : 10 minutes (30 V) Ritz : immediate
- MOR provides a significant gain of computing time without loss of precision and allows the integration of the model in CAD softwares



Low Frequency S-parameters for a HBT



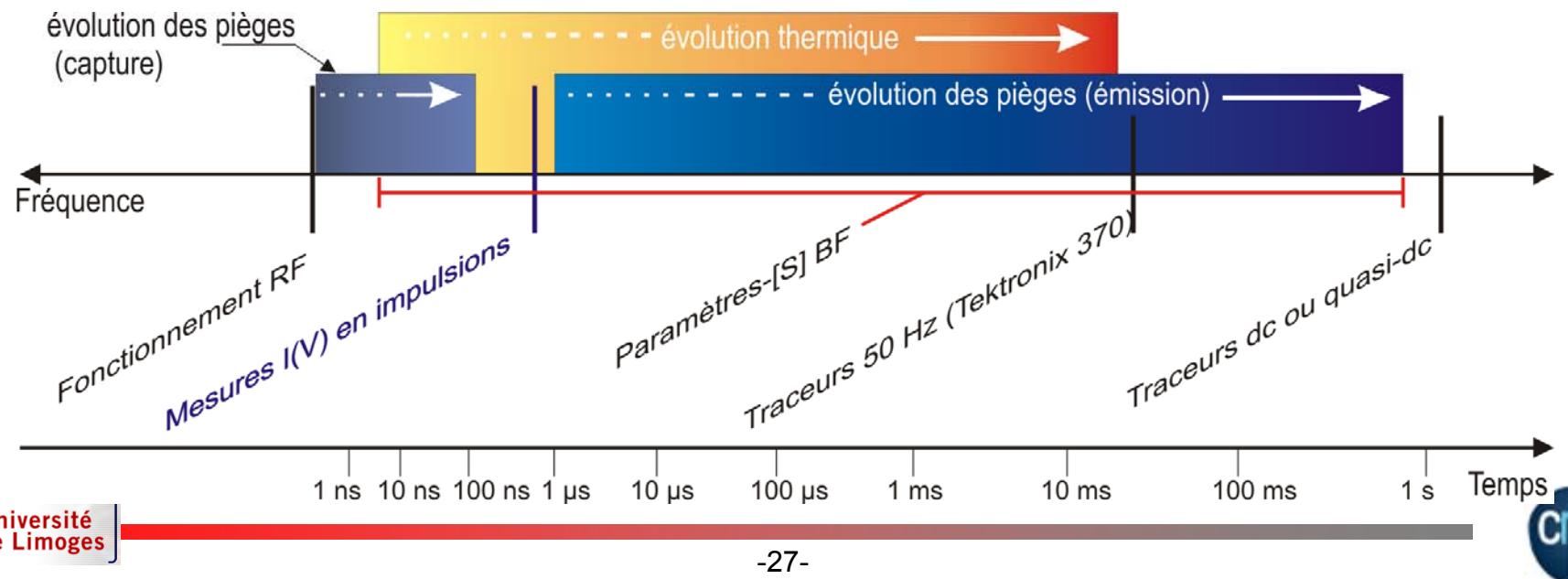
Trapping Effects

Some issues of GaN HEMTs

- Various electrical effects (traps, thermal) which cover a large frequency band from BF to RF
- Seriously impact the power behavior

Useful characterization tools:

- Pulsed I-V and S-parameters
- Load Pull frequency domain measurements
- Load Pull time domain measurements (LSNA)



Trapping Effects (1/3)

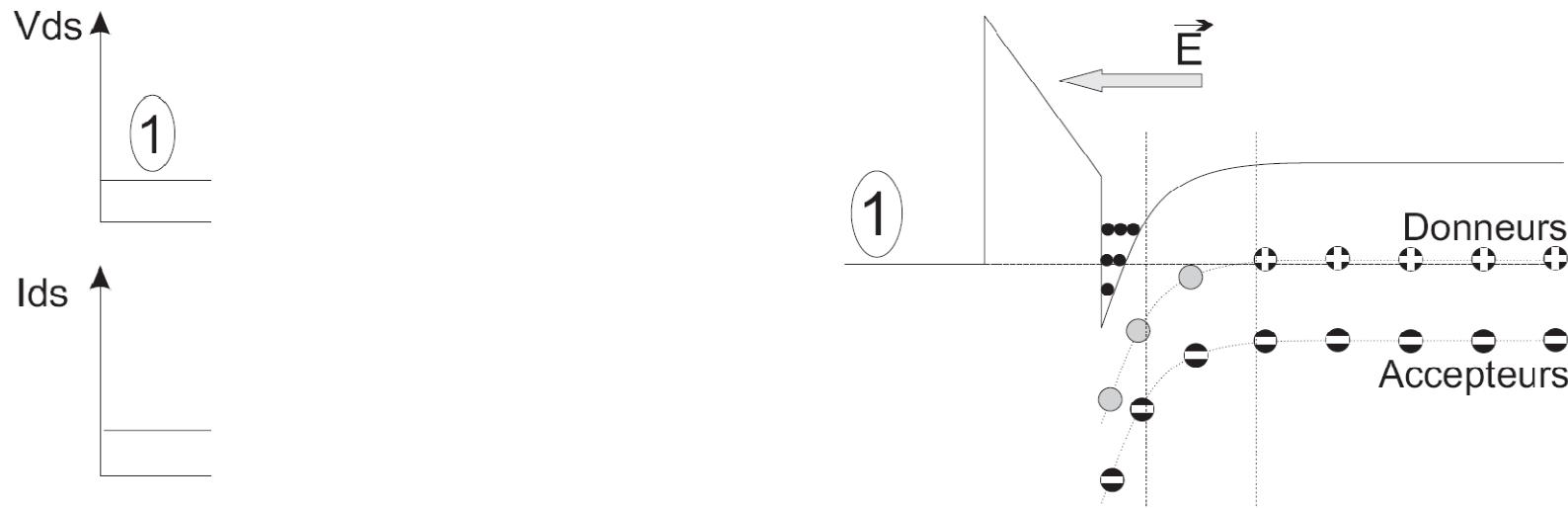
Origin: Chemical defects which induce electrical defects.

Impact: Slow current transient

$$\cancel{I_{ds} = f(V_{gs}, V_{ds})}$$

↓

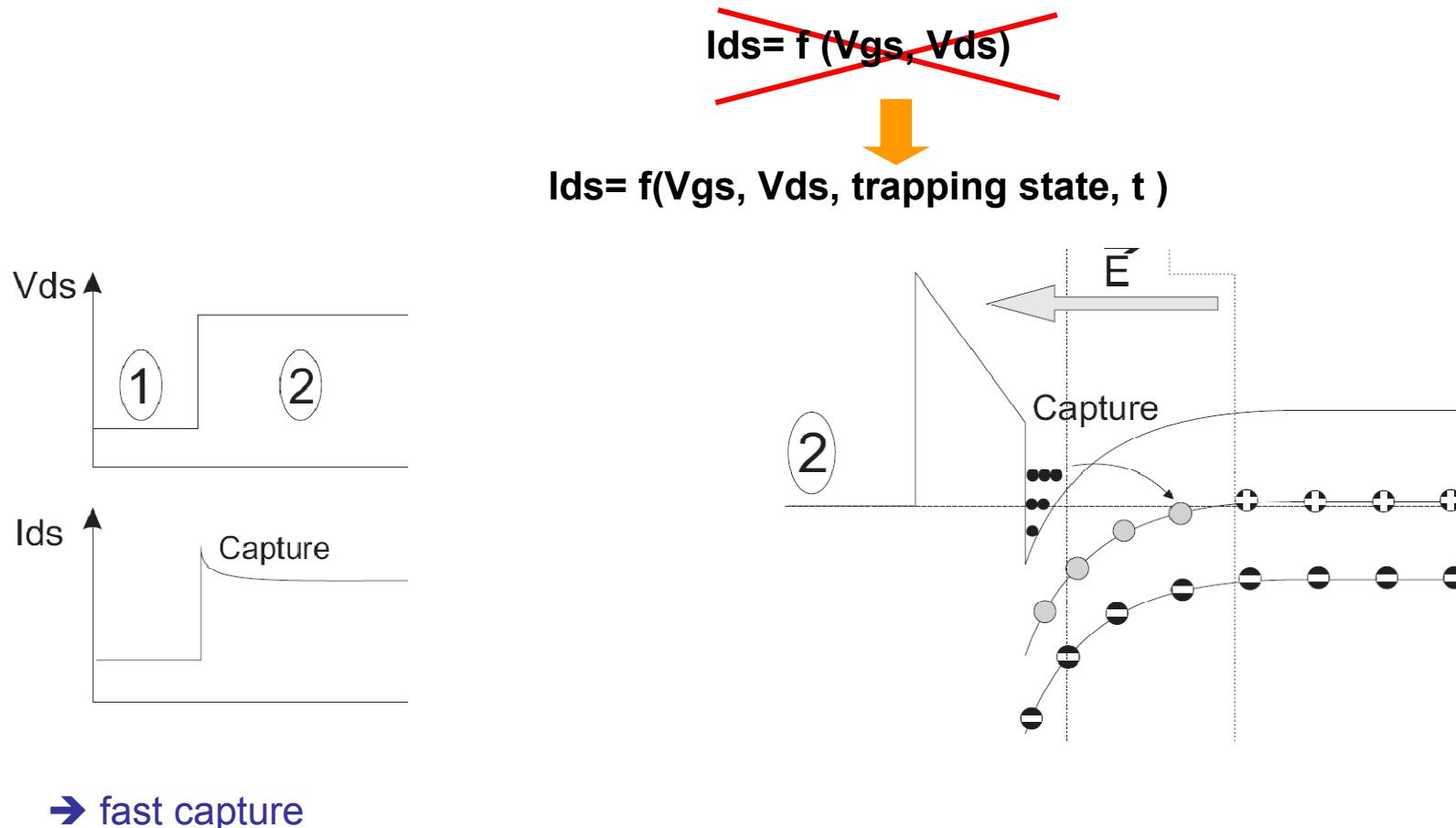
$$I_{ds} = f(V_{gs}, V_{ds}, \text{trapping state}, t)$$



Trapping Effects (2/3)

Origin: Chemical defects which induce electrical defects.

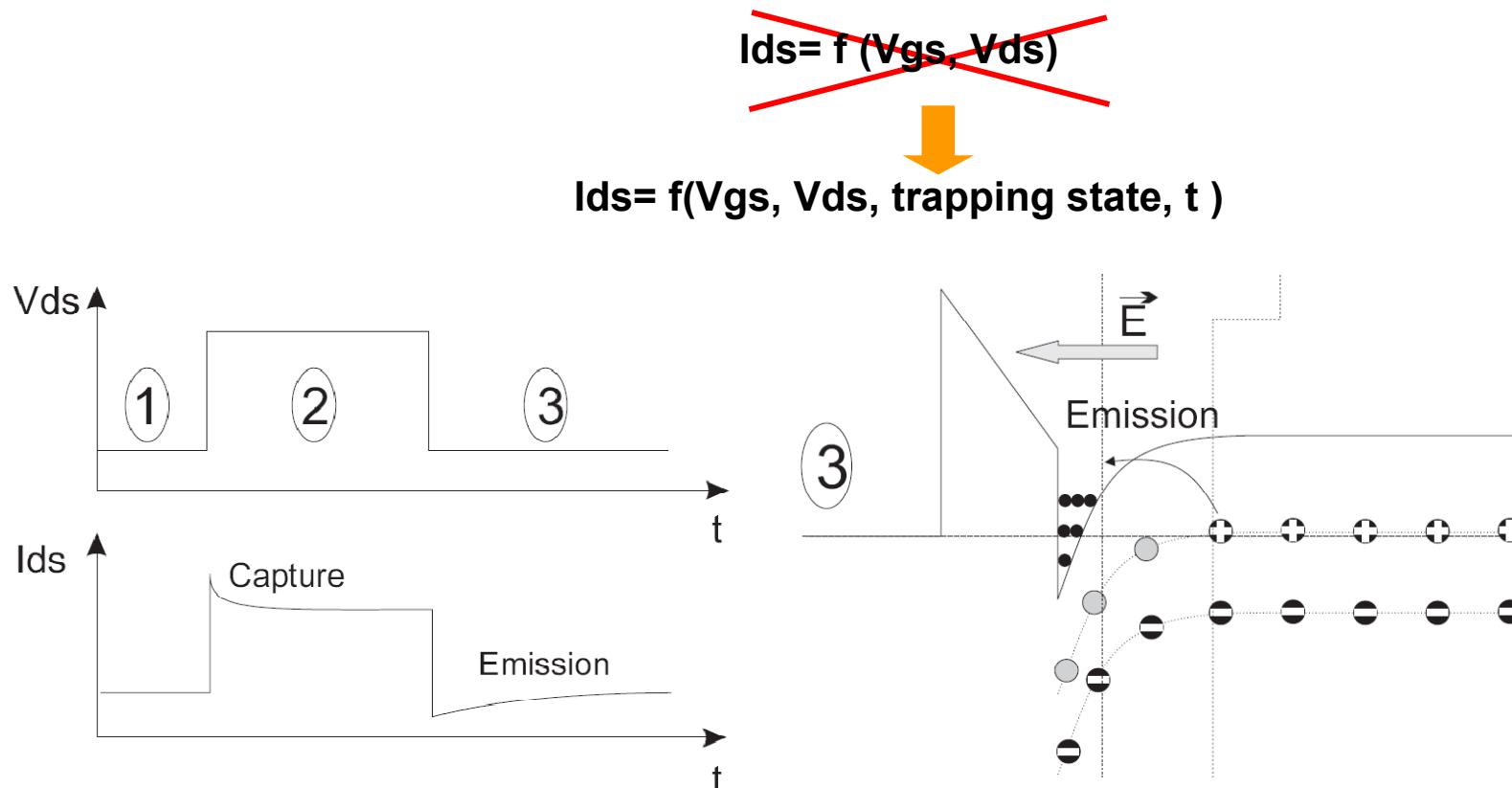
Impact: Slow current transient



Trapping Effects (3/3)

Origin: Chemical defects which induce electrical defects.

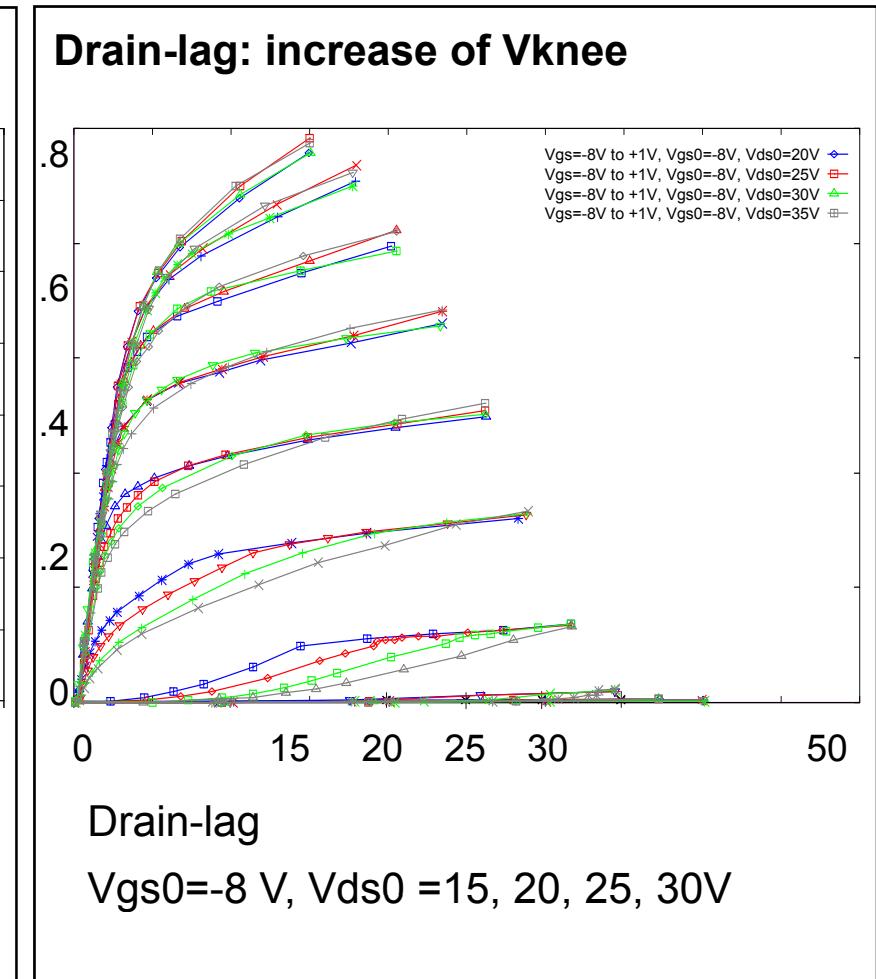
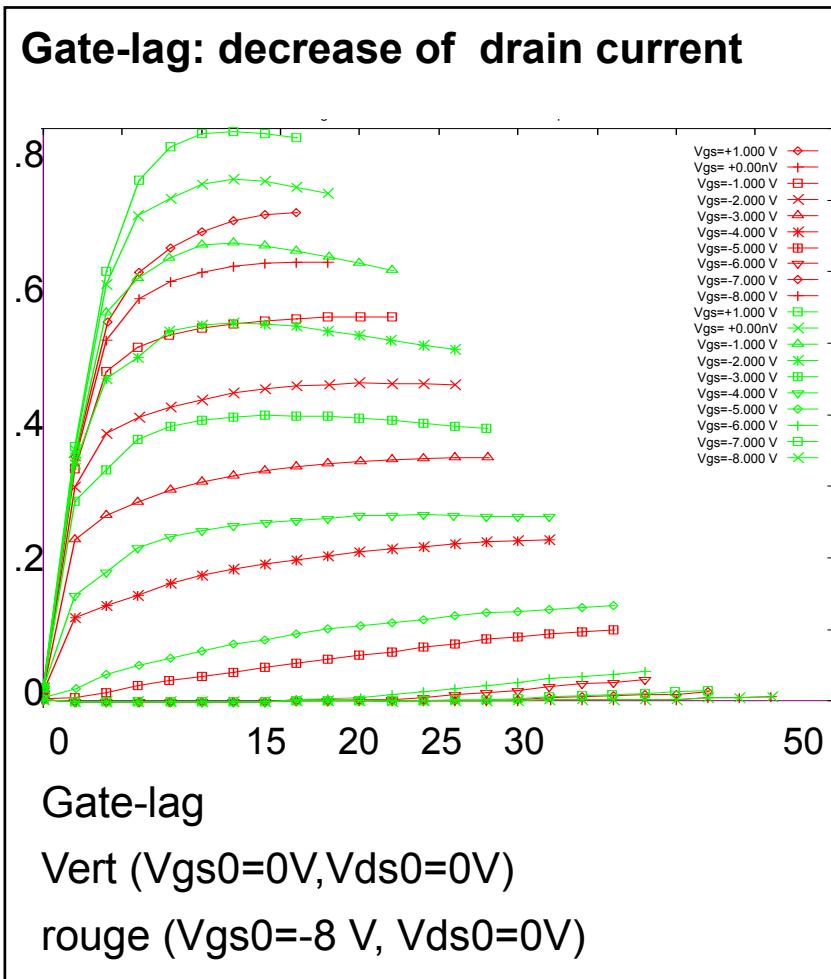
Impact: Slow current transient



→ Fast capture (~ ns)

→ Slow emission (up to second)

Evidence of trapping effects

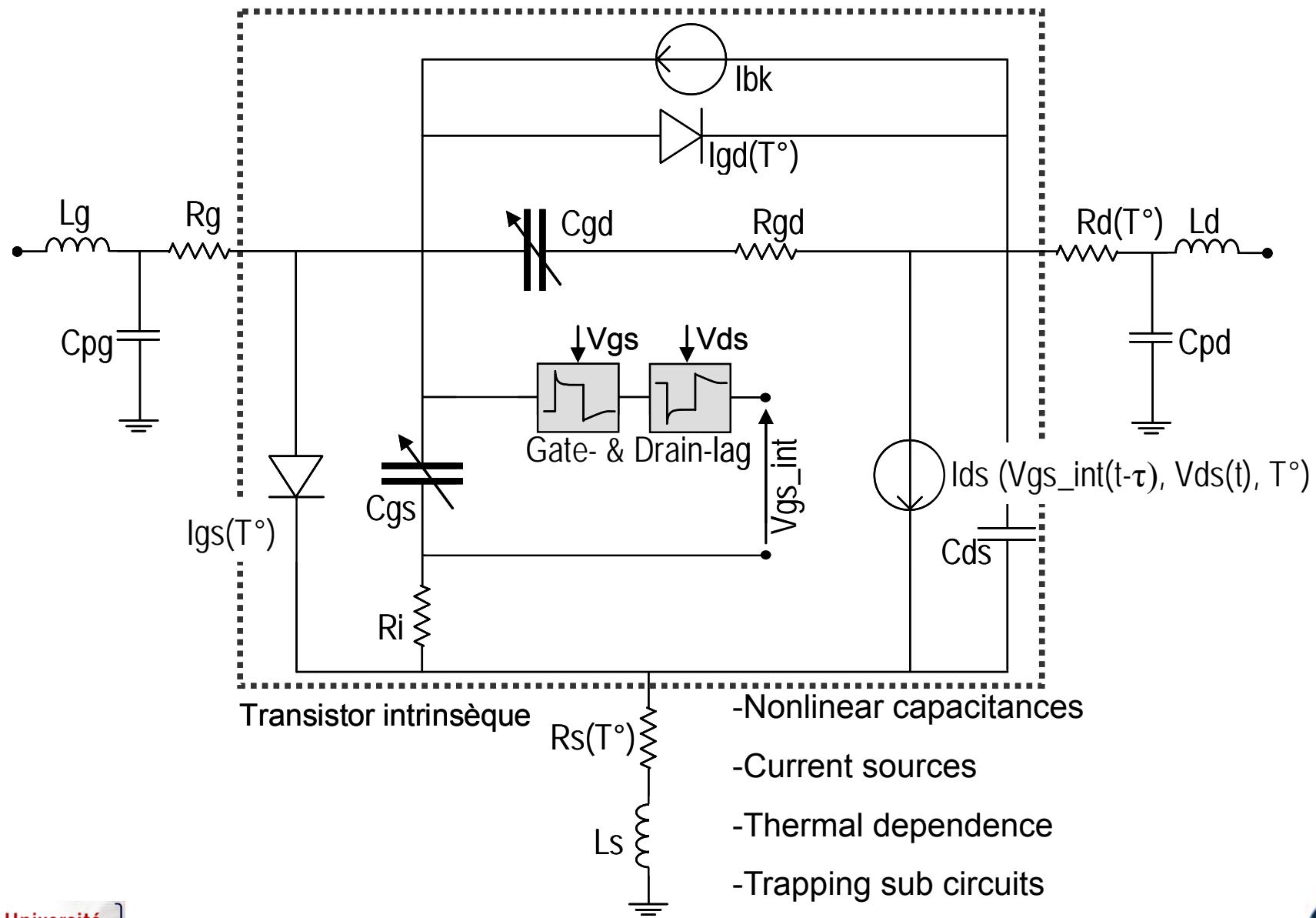


Mise en évidence des pièges

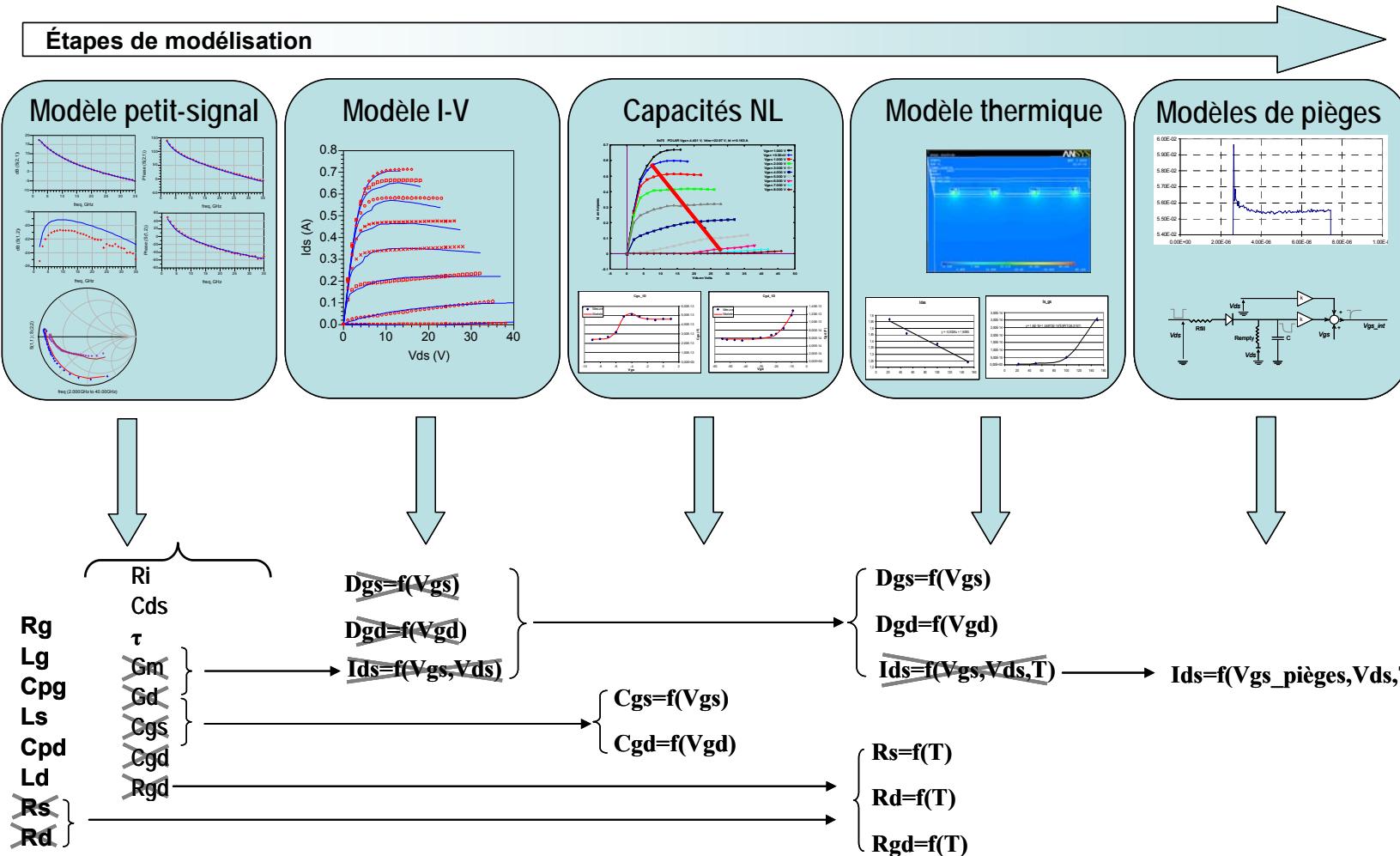
$\tau_{\text{capture}} \ll t_{\text{IMPULSION}} \ll \tau_{\text{émission}}$

During the pulses capture takes place, emission freezed

Nonlinear electrothermal model with trapping effects

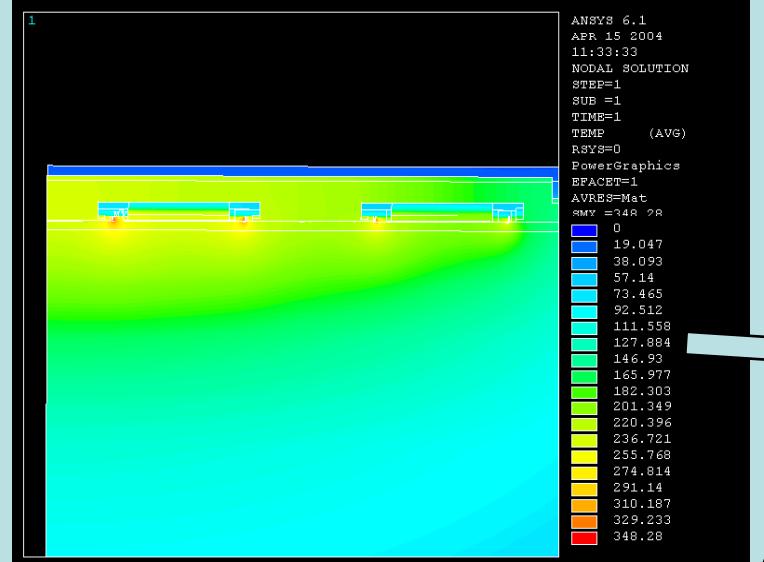


Steps of the modeling process

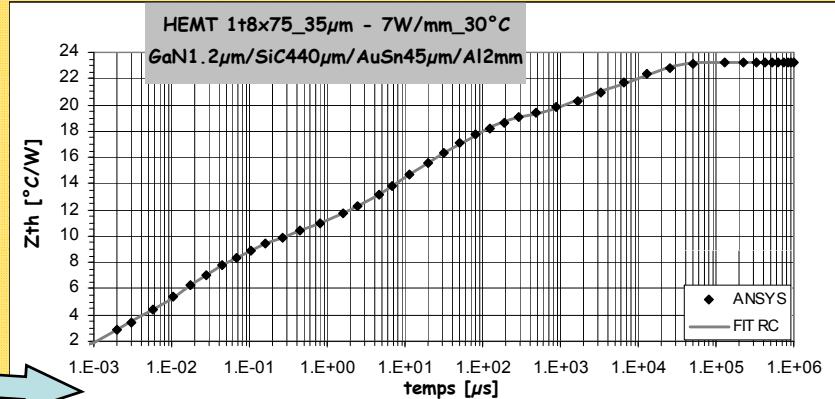


Various parasitics effects are successively added

Thermal simulations (3-5 lab)



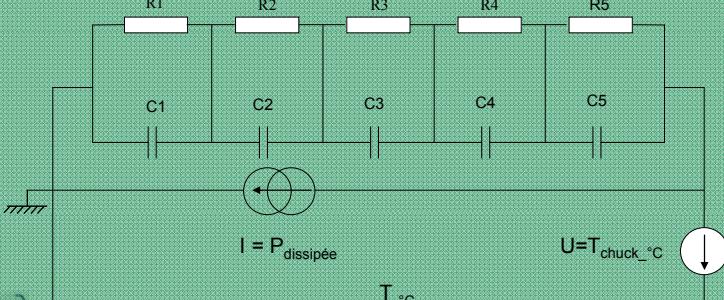
Heating as a function of time



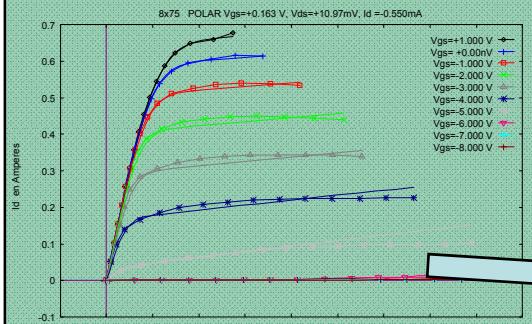
Mise en équation avec des formes exponentielles

$$\begin{aligned} \text{TEMP} = & 22.8 \cdot (1 - e^{-t/\tau_1}) \\ & + 21.7 \cdot (1 - e^{-t/\tau_2}) \\ & + 7 \cdot (1 - e^{-t/\tau_3}) \\ & + \dots \end{aligned}$$

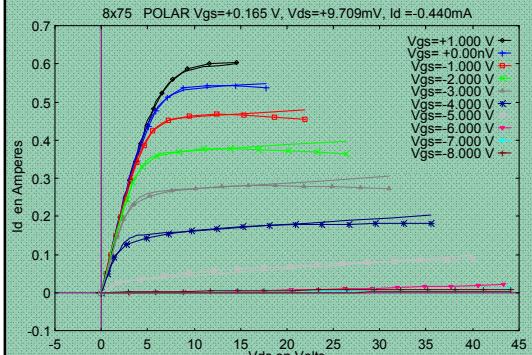
Thermal subcircuit



I-V @ various temperatures

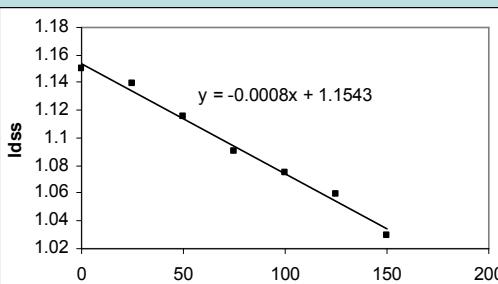
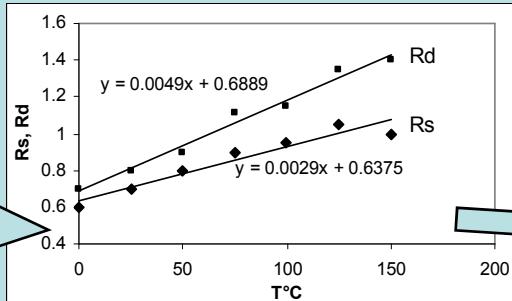


IV @ 25°C



IV @ 150°C

Thermal laws



Equations

Thermal parameters

- Access resistances
- Current sources
- Diodes

$$R_s = R_{s0} + \alpha_{Rs} T$$

$$R_d = R_{d0} + \alpha_{Rd} T$$

$$Idss = Idss_0 + Idss_t T$$

$$P = P_0 + P_t T$$

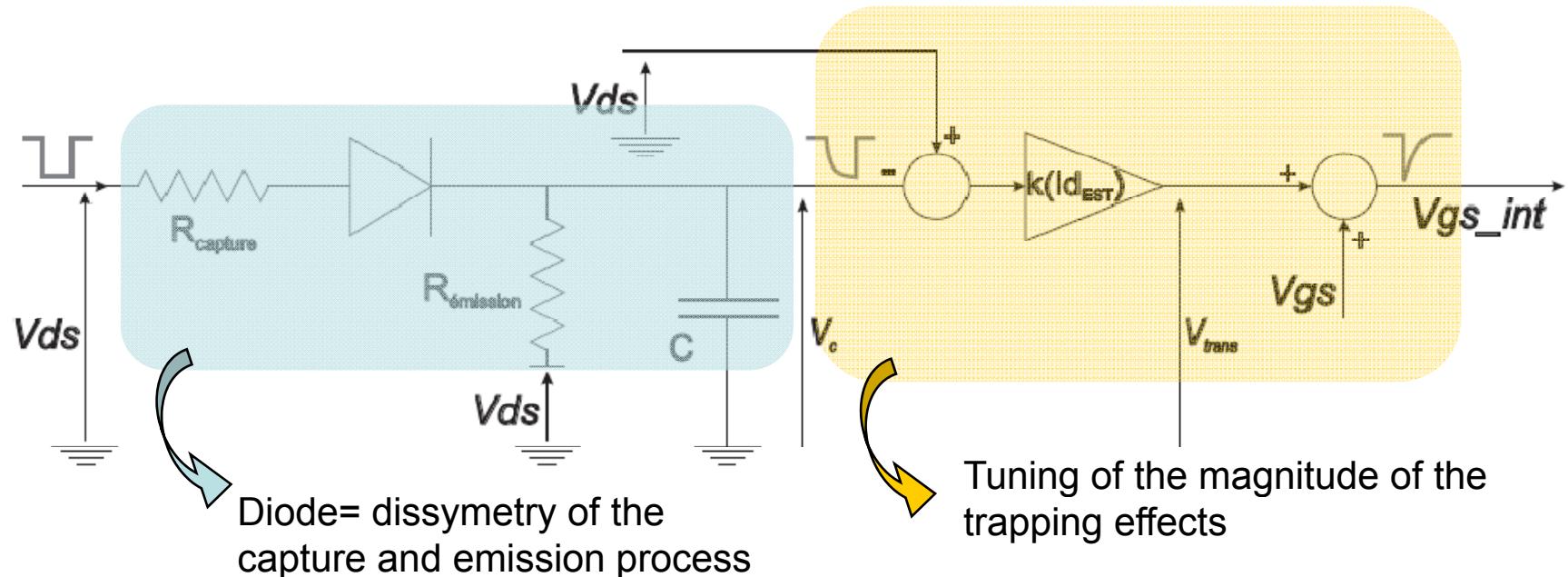
$$N_{gs} = N_{gs0} + N_{gs_t} T$$

$$N_{gd} = N_{gd0} + N_{gd_t} T$$

$$I_{sgs} = I_{sgs0} + I_{sgs_t} e^{(T/T_{sgs})}$$

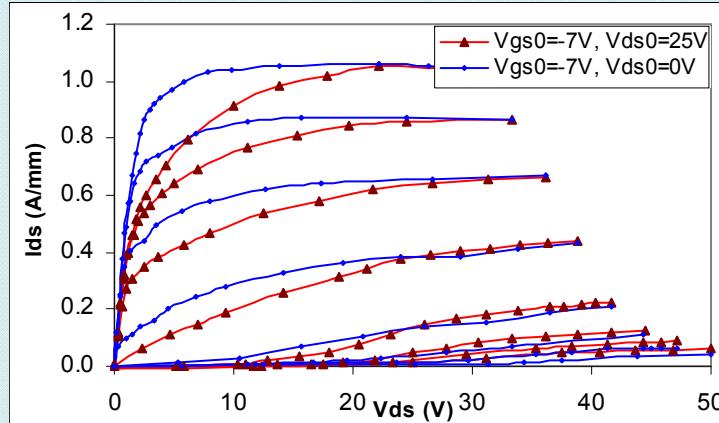
$$I_{sgd} = I_{sgd0} + I_{sgd_t} e^{(T/T_{sgd})}$$

- Trapping effects modify the gate command (back gating)
- ➔ transients on V_{gs} Transients of the drain current
- Charge of the capacitance= Ionized traps
- Charge through $R_{capture}$, Emission through Rémission



Fundamental assumption : dissymmetry of the capture and emission process

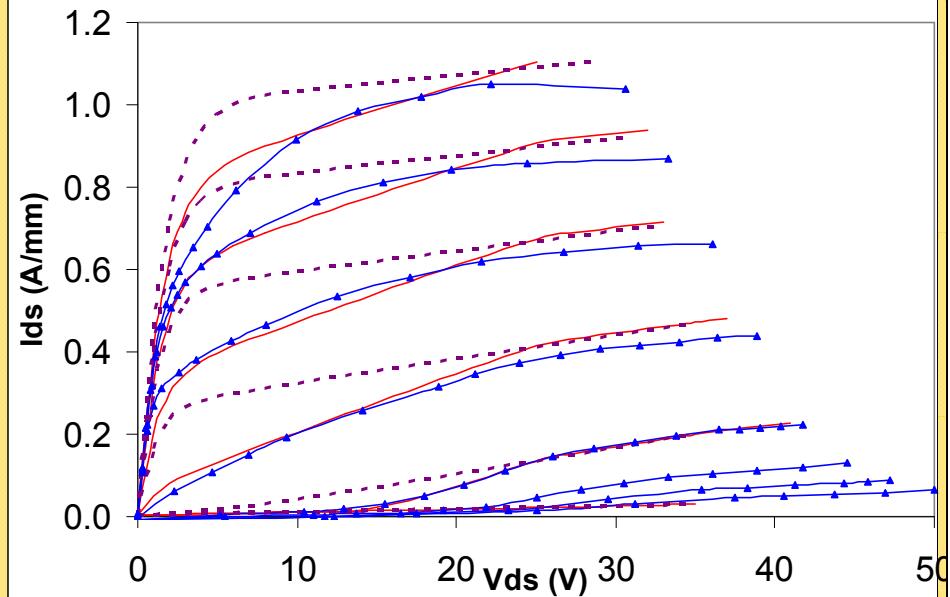
Measured Drain Lag



Pulsed Measurements

- $Vgs0 = -7V, Vds0 = 0V$ (bleu)
- $Vgs0 = -7V, Vds0 = 25V$ (rouge)

Simulations drain-lag ON/OFF

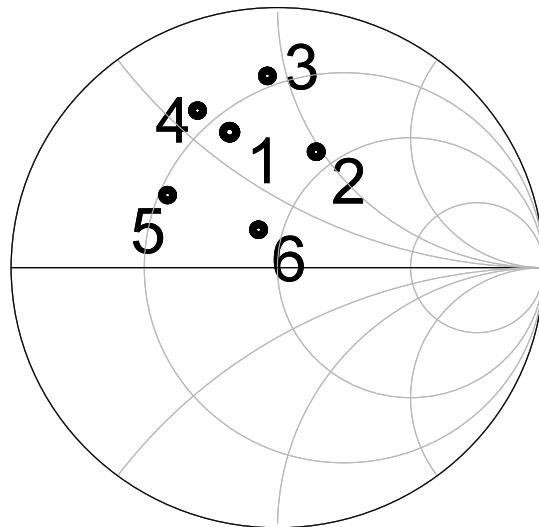


Simulated I-V Characteristics

- @ $Vgs0 = -7V, Vds0 = 0V$ (pointillés)
- @ $Vgs0 = -7V, Vds0 = 25V$ (rouge)
- Measure @ $Vgs0 = -7V, Vds0 = 25V$ (bleu)

Large signal impact of traps (1)

Load pull measurements at various loads



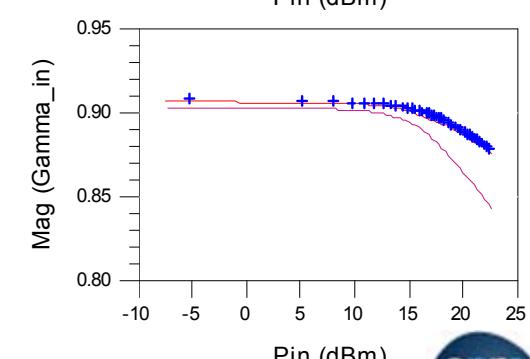
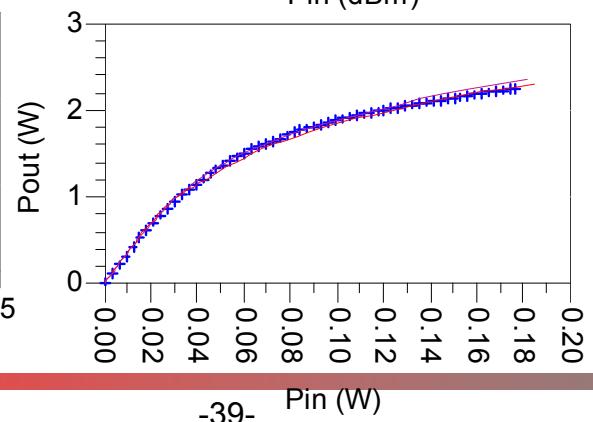
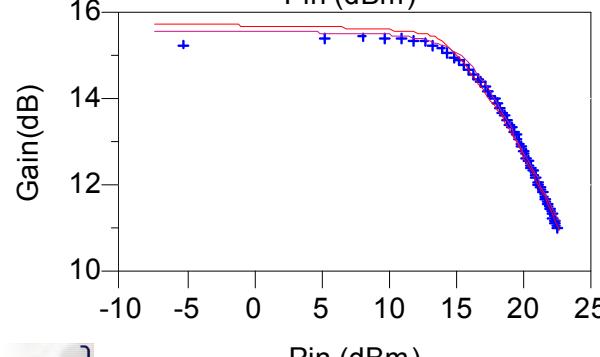
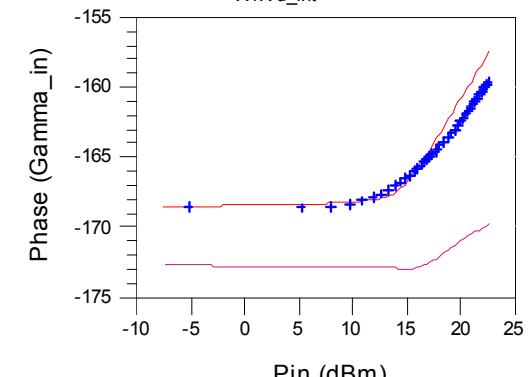
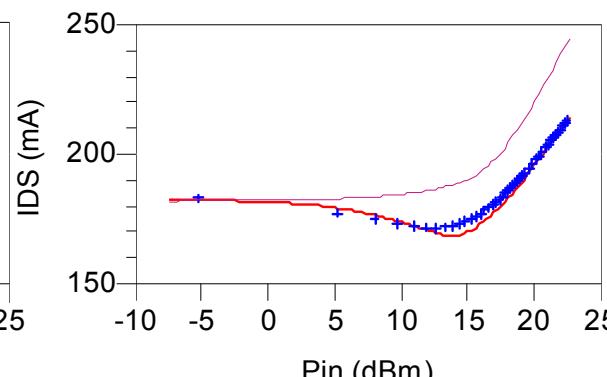
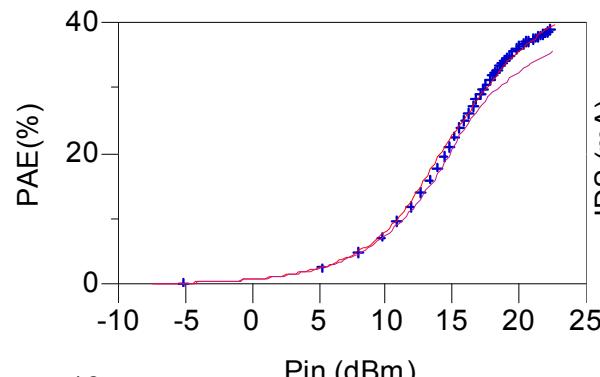
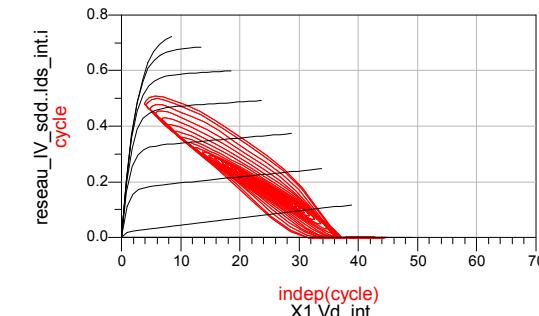
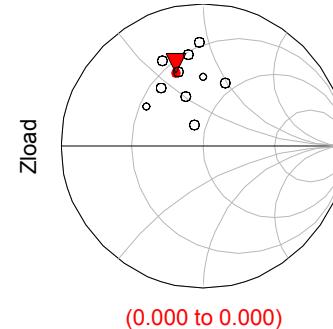
- 1 : Z_{OPT}
- 2 : Z_2 VSWR=2.5
- 3 : Z_3 VSWR=2.5
- 4 : Z_4 VSWR=1.6
- 5 : Z_5 VSWR=2.5
- 6 : Z_6 VSWR=2.5

Class AB, Vds=25 V , DC Bias , RF CW, 10 GHz

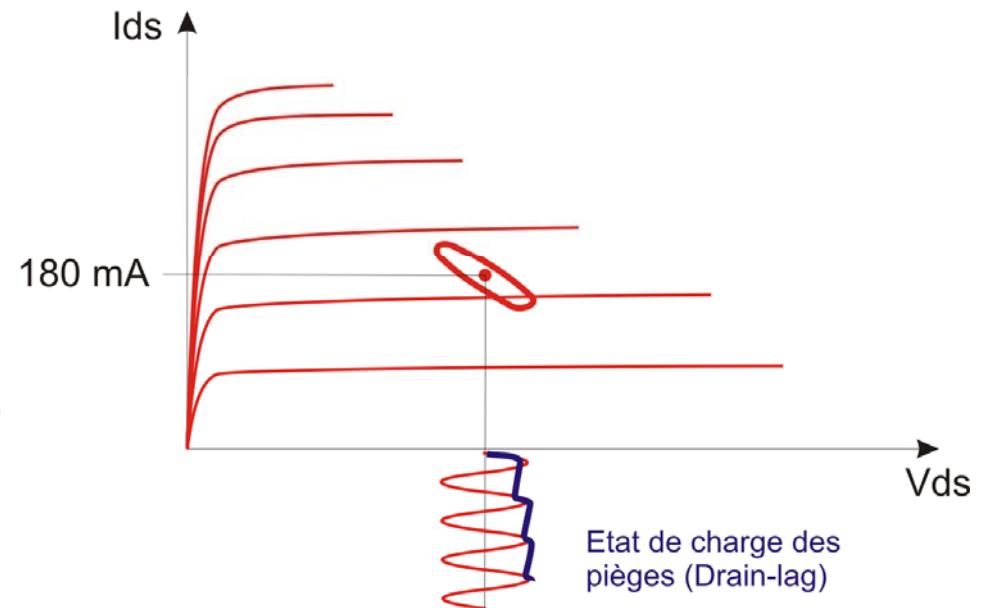
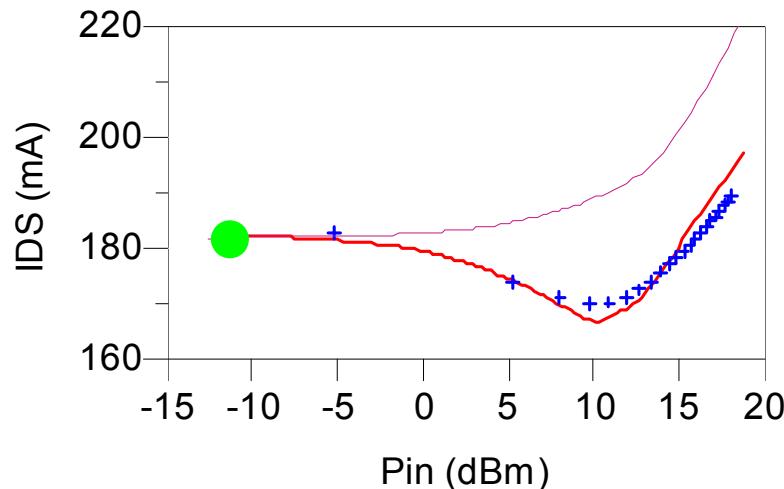
Large signal impact of traps (2)

Load tuned for optimum power

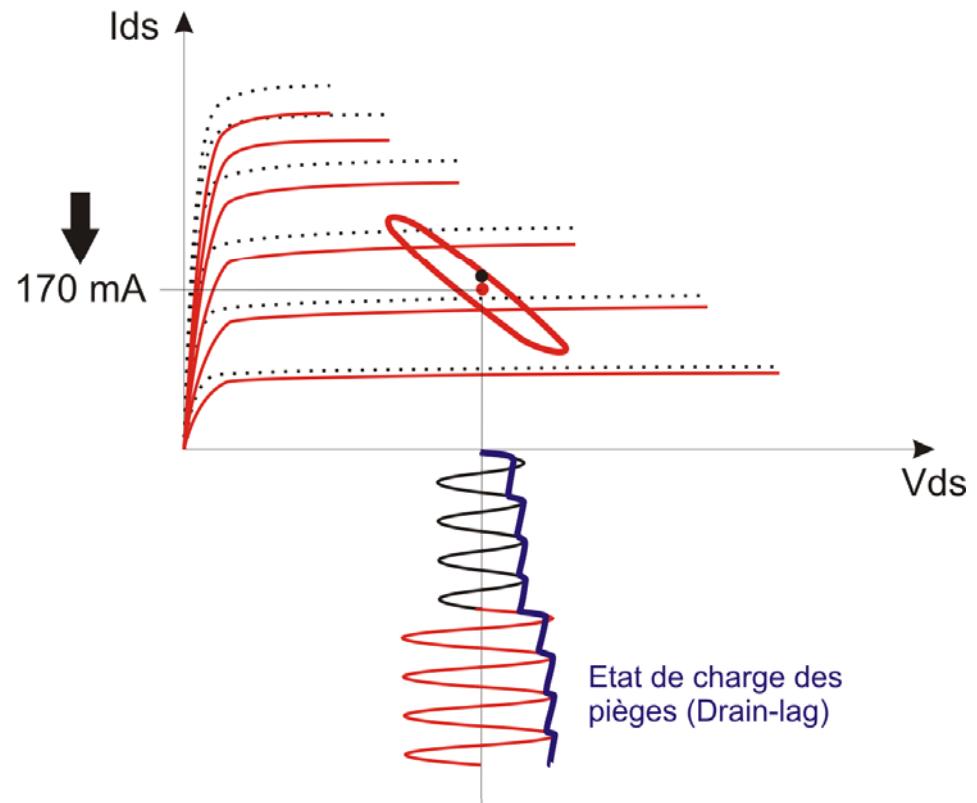
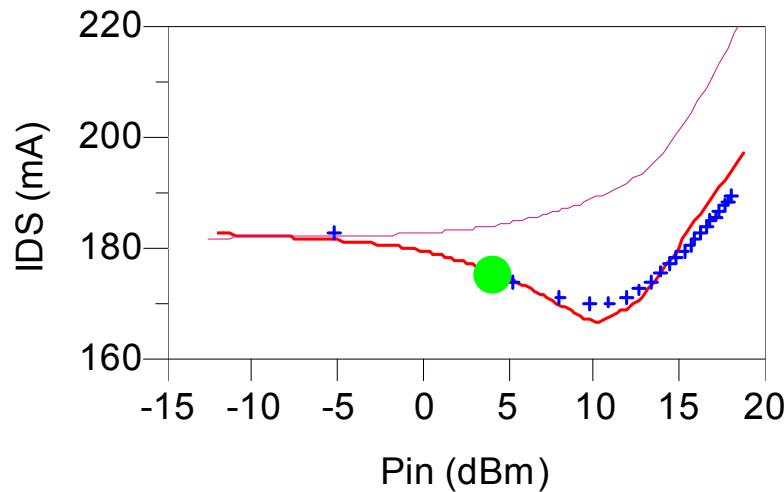
- Pièges ON
- Pièges OFF
- + Mesure



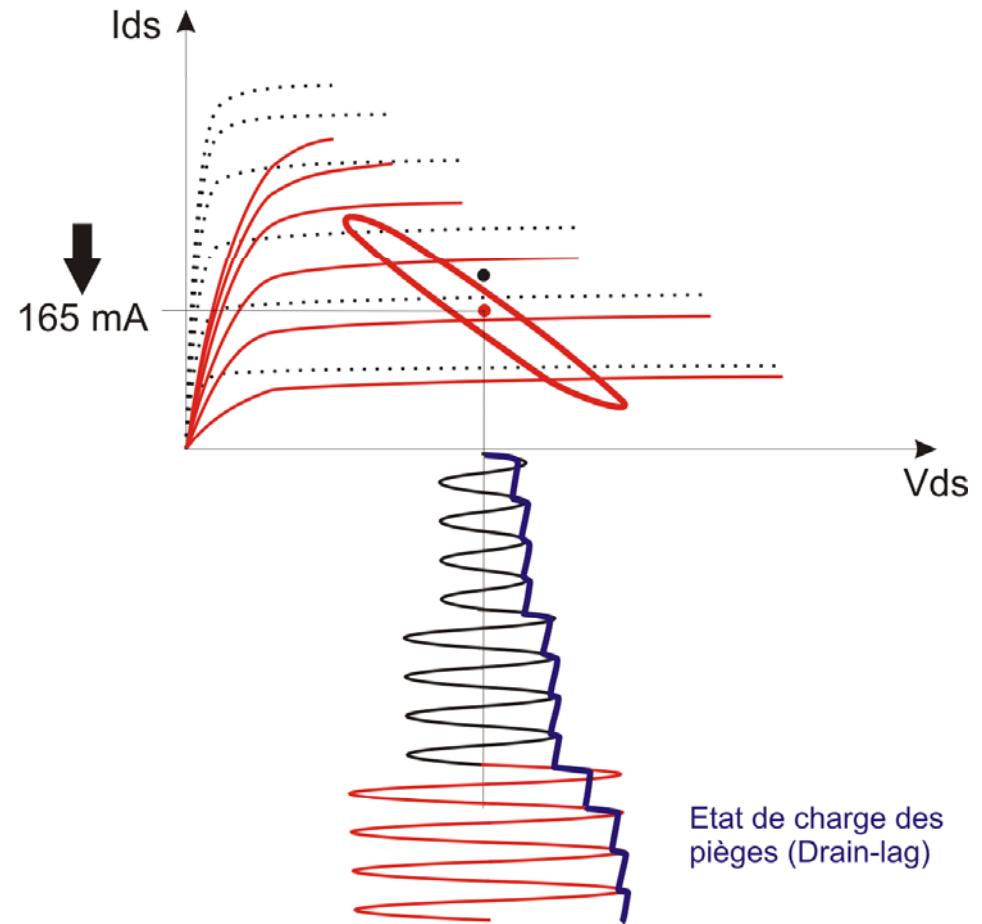
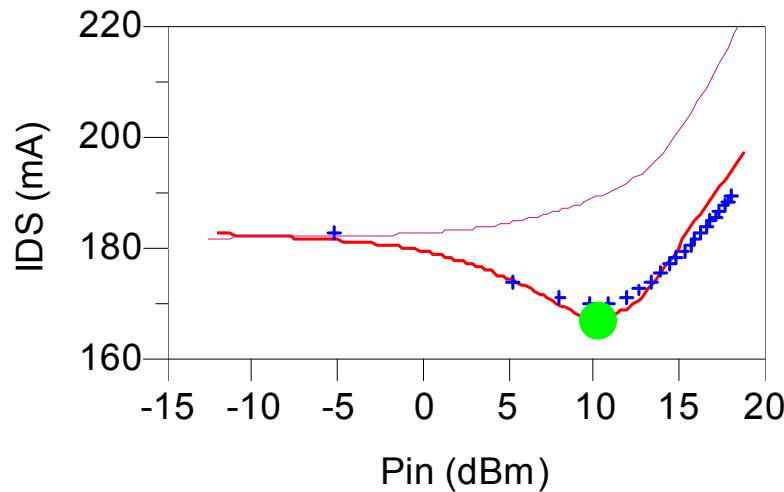
Explanation of the decrease of the average current



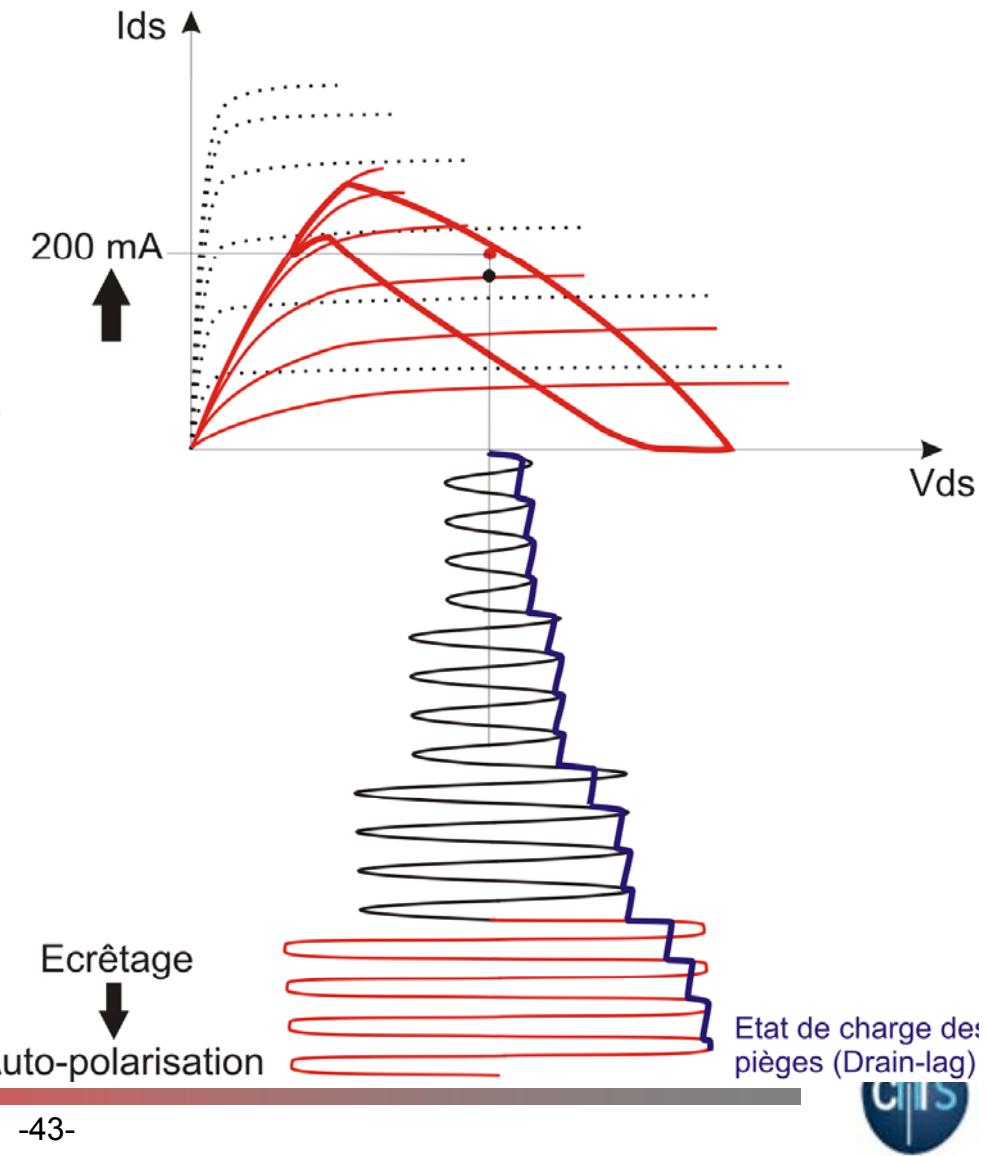
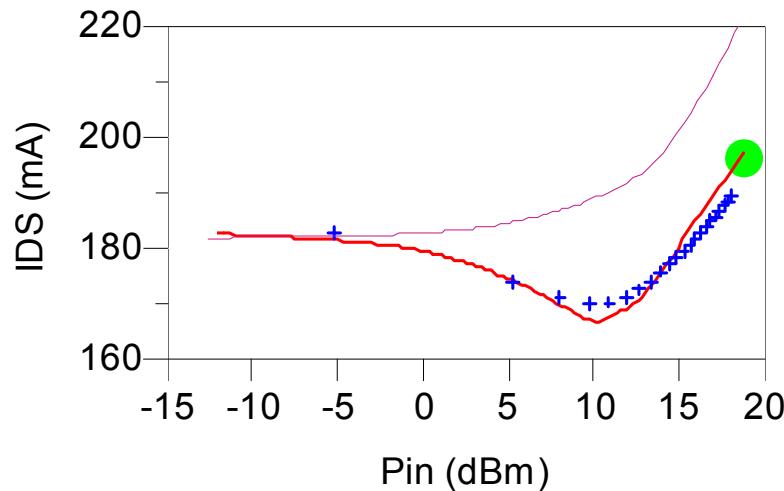
Explanation of the decrease of the average current



Explanation of the decrease of the average current



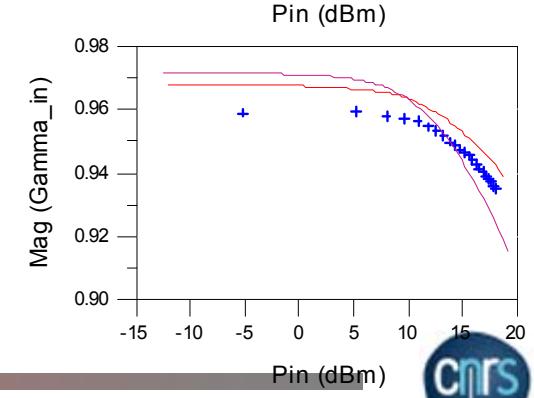
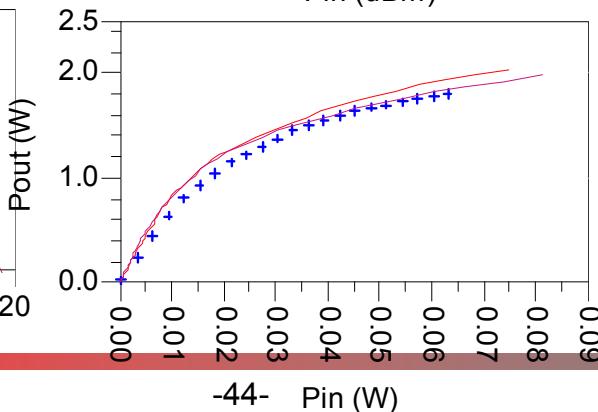
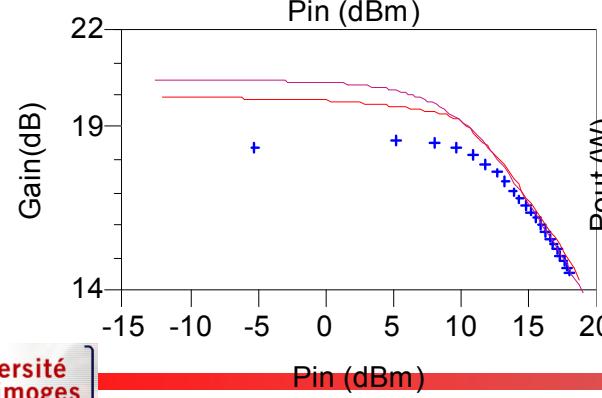
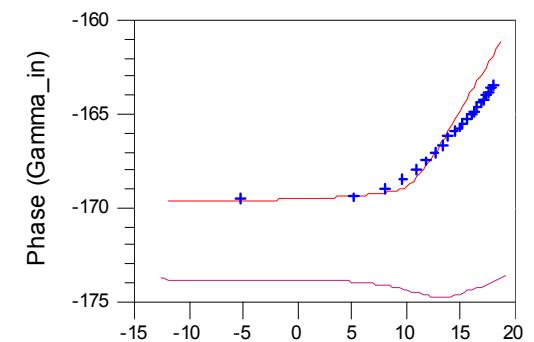
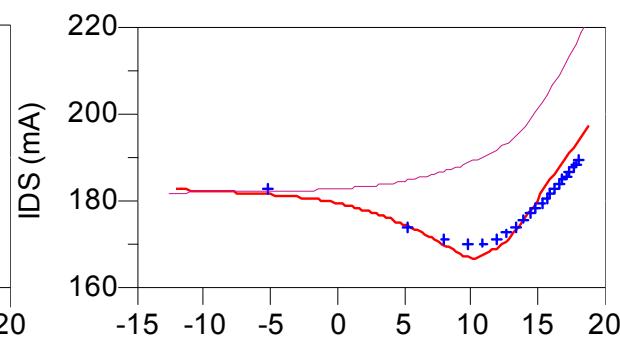
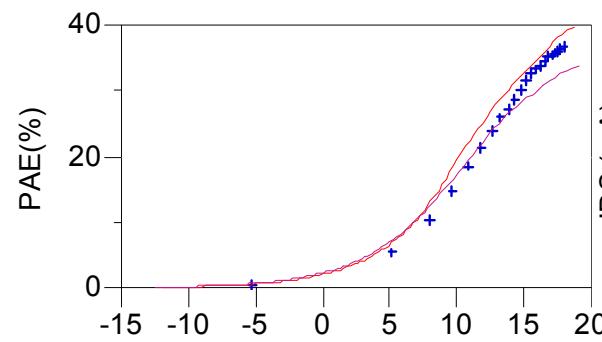
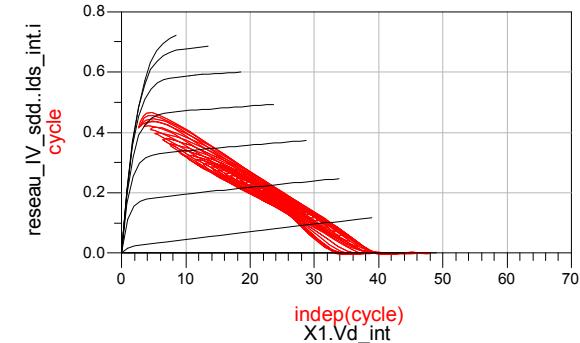
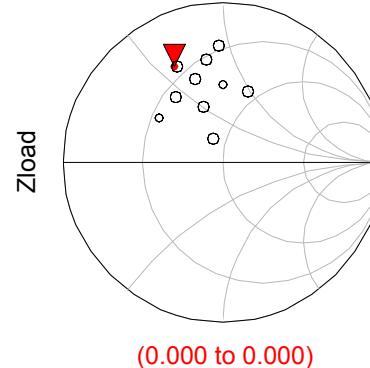
Explanation of the decrease of the average current



Validation of the model with mismatched loads

TOS=1,6

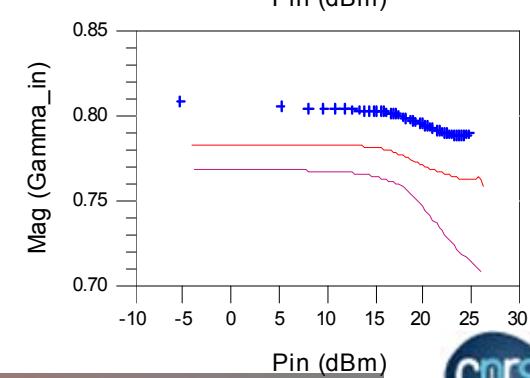
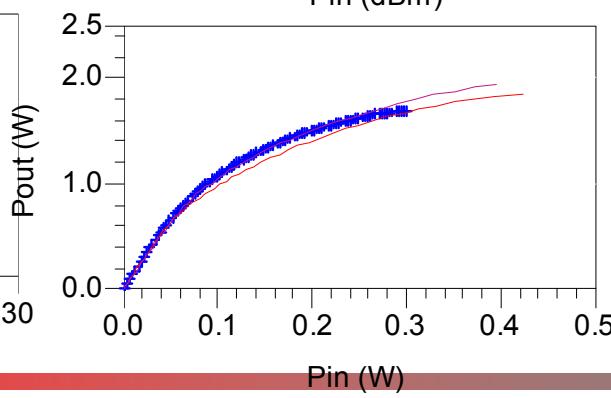
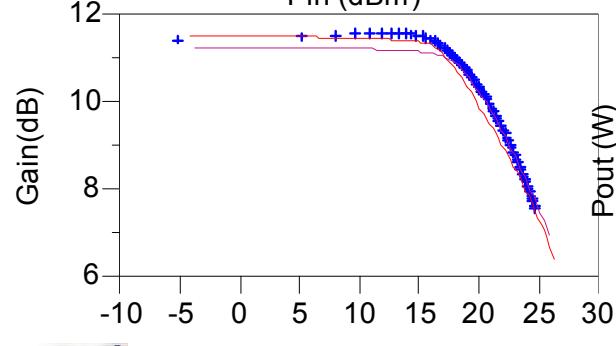
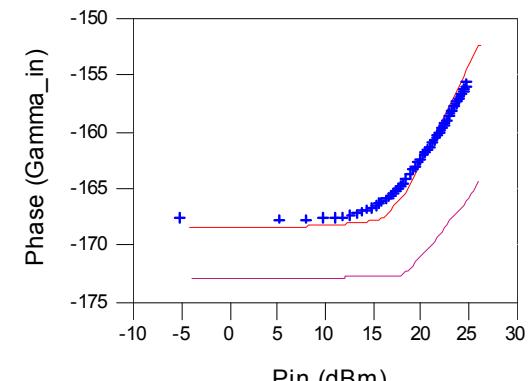
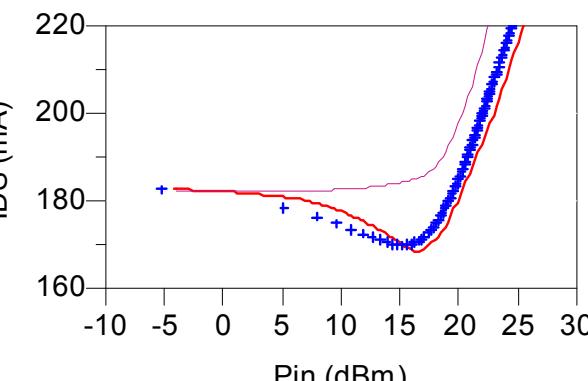
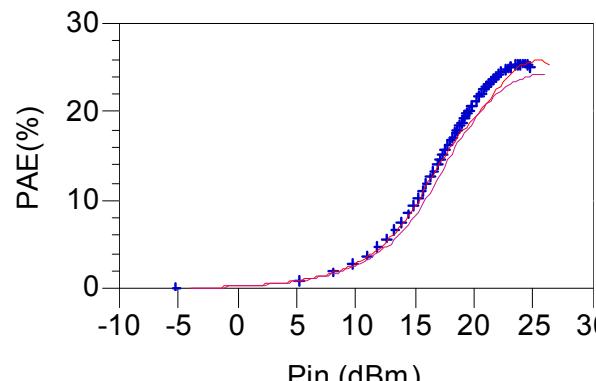
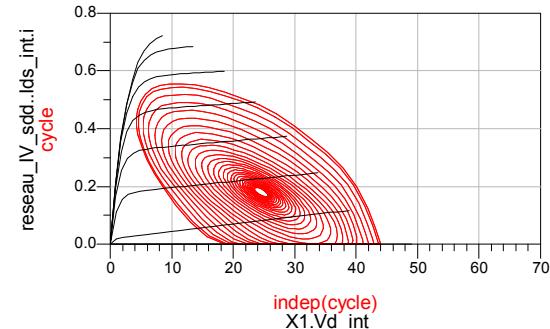
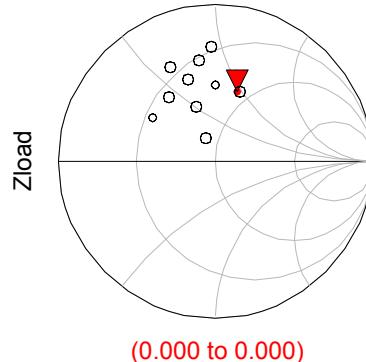
- Pièges ON
- Pièges OFF
- + Mesure



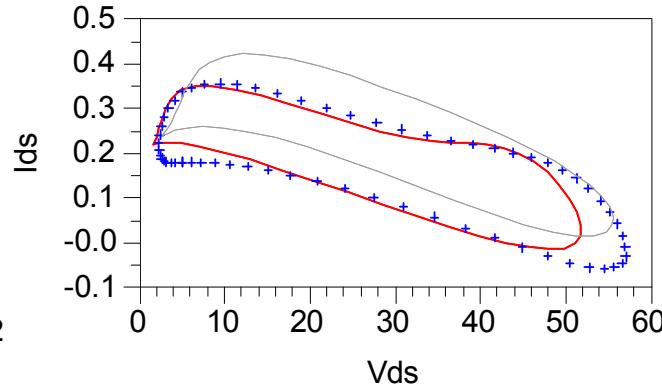
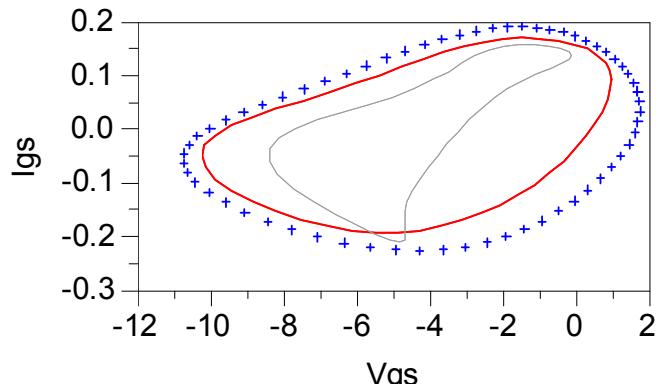
Validation of the model with mismatched loads

TOS=2,5

- Pièges ON
- Pièges OFF
- + Mesure

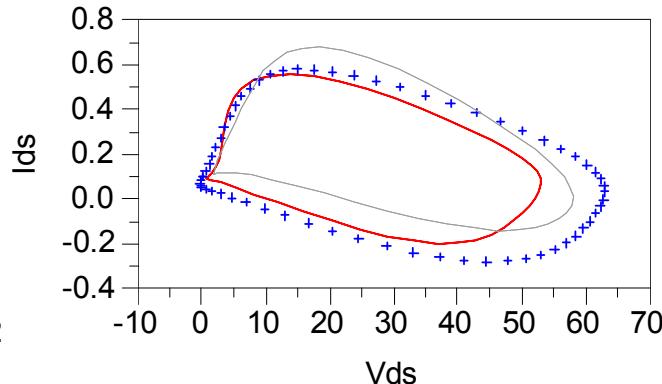
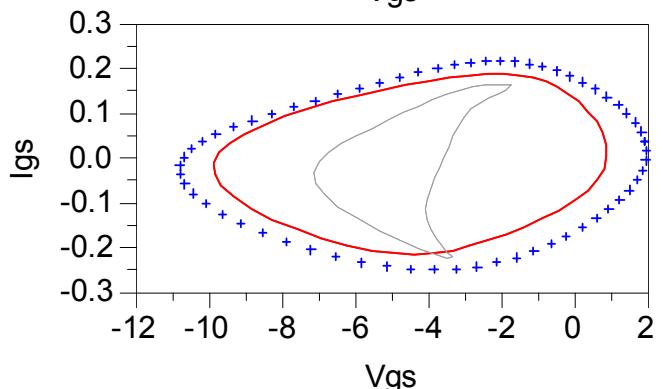


Measurements @ 5 GHz, 25V, dc/cw

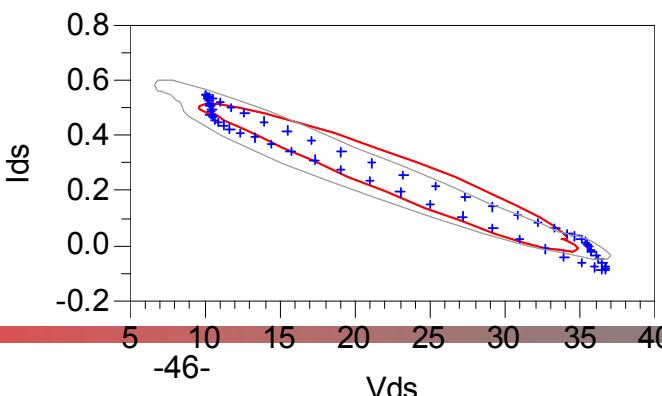
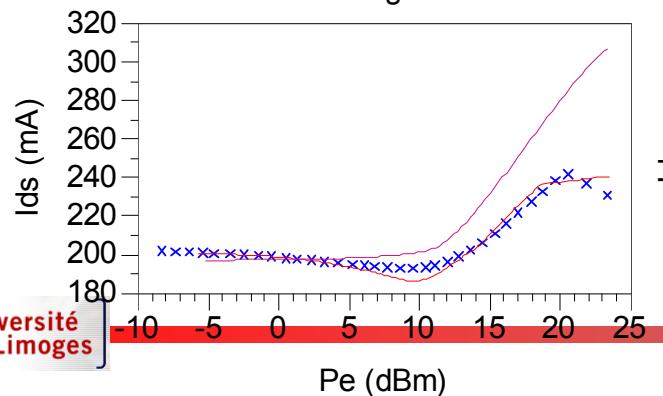


— Pièges ON
— Pièges OFF
+ Mesure

TOS 4
5dB compression

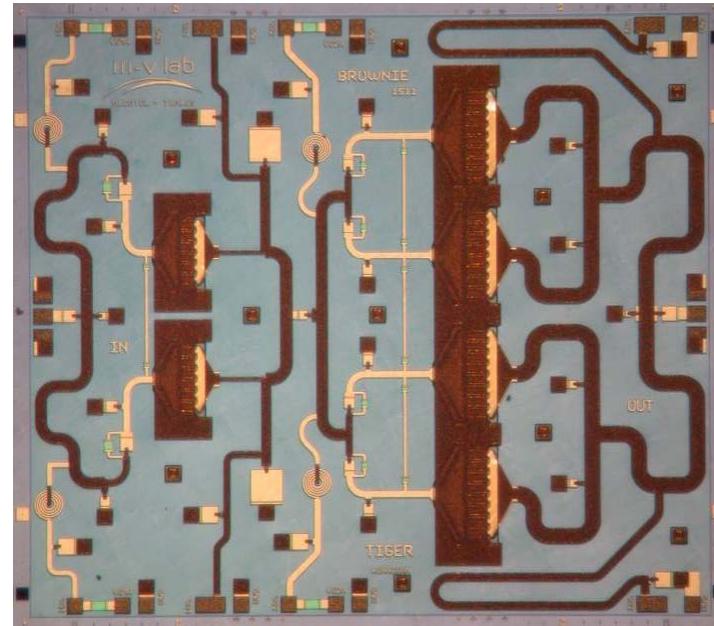
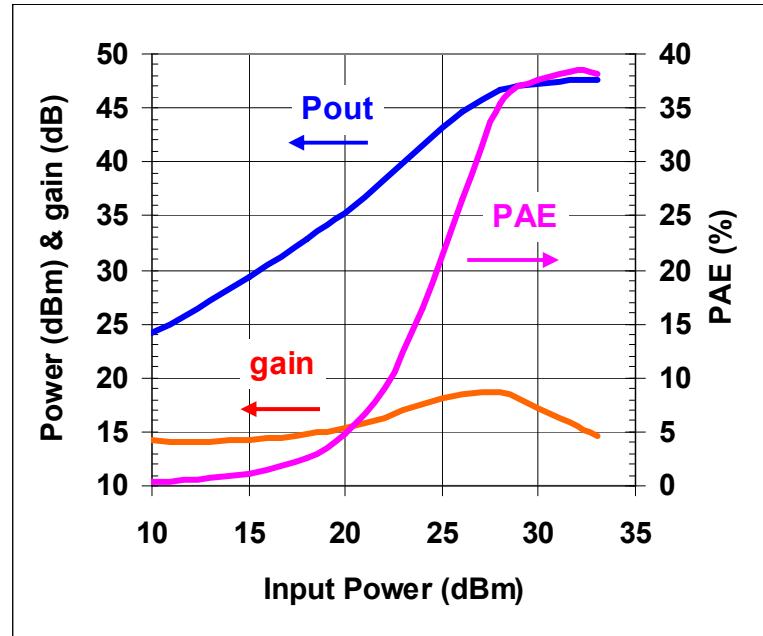


TOS 3,3
7dB compression



TOS 2
8dB compression

Output power, PAE & Gain at 9 GHz
Drain Bias 32V



- Pout = 47.7 dBm (58 W)
- PAE = 38 %
- 6.5 W/mm
- Gain = 14.6 dB
- Vds₀ = 32V, Ids₀ = 2.3A

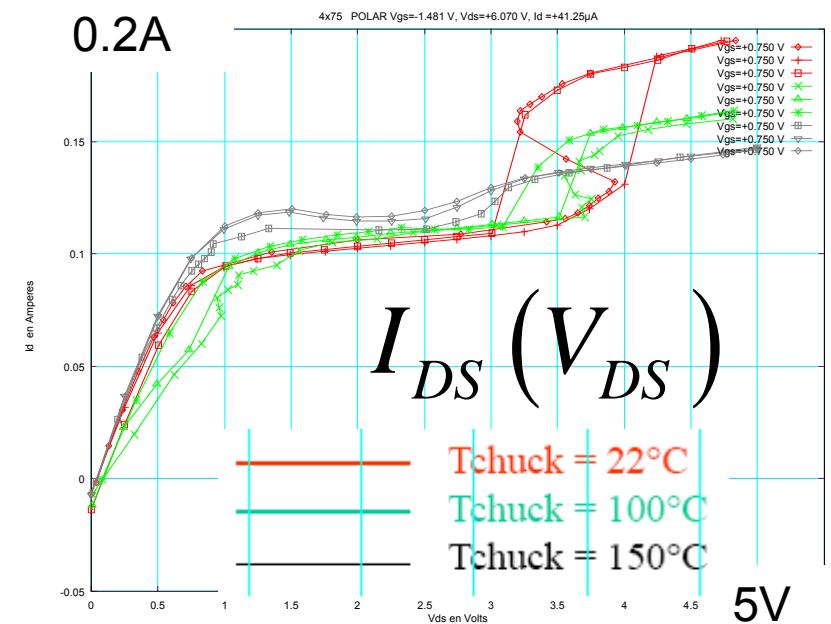
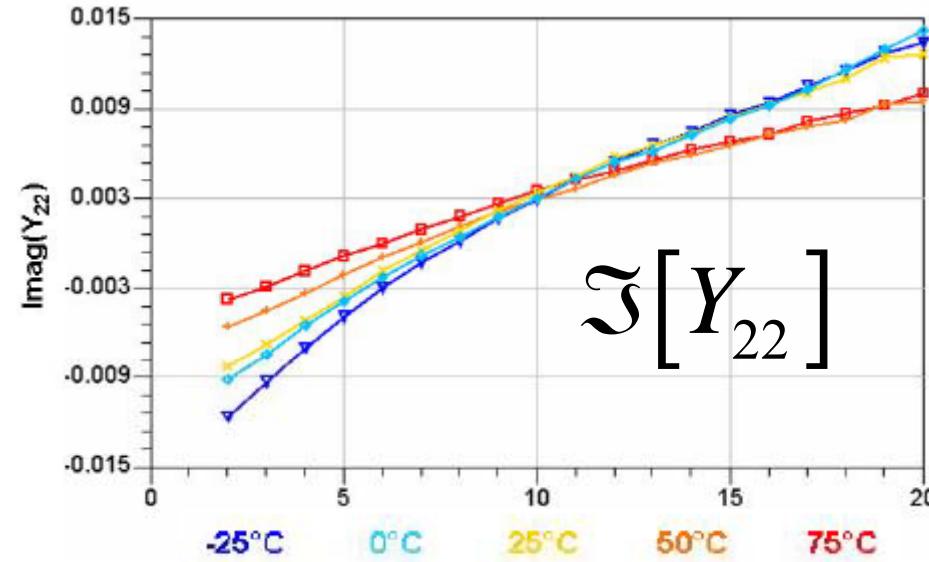
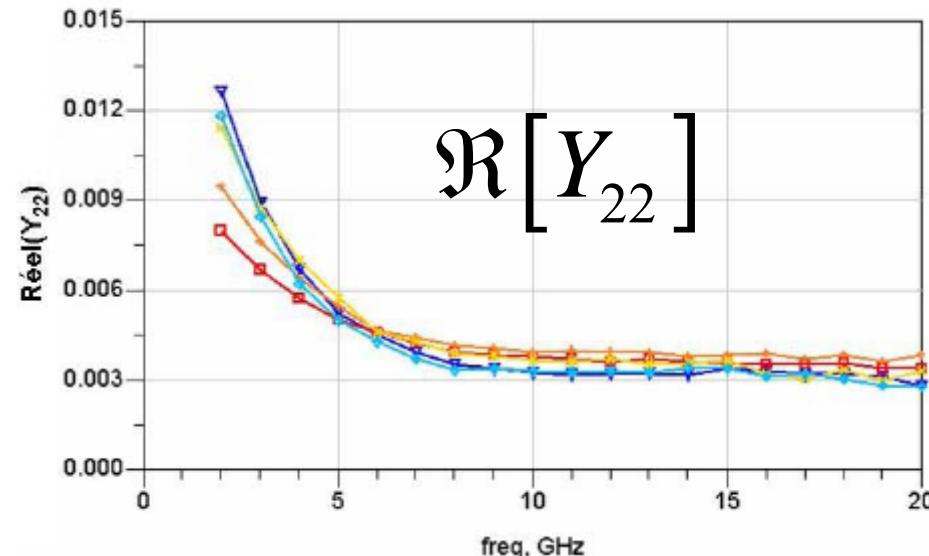


Chip size : 16.5 mm²
4300x3800 μm²
1st stage : 2.4 mm
2nd stage : 8.96 mm

**State-of-the-Art Output Power with
AlGaN/GaN MMIC HPA at X Band**

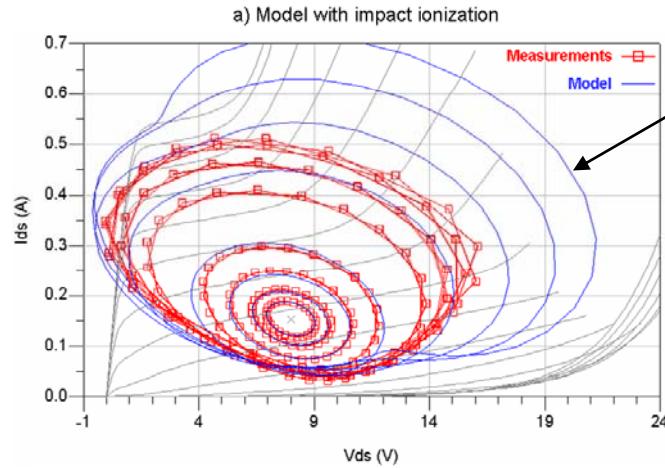
Impact Ionization

Impact Ionization in GaAs HEMTs

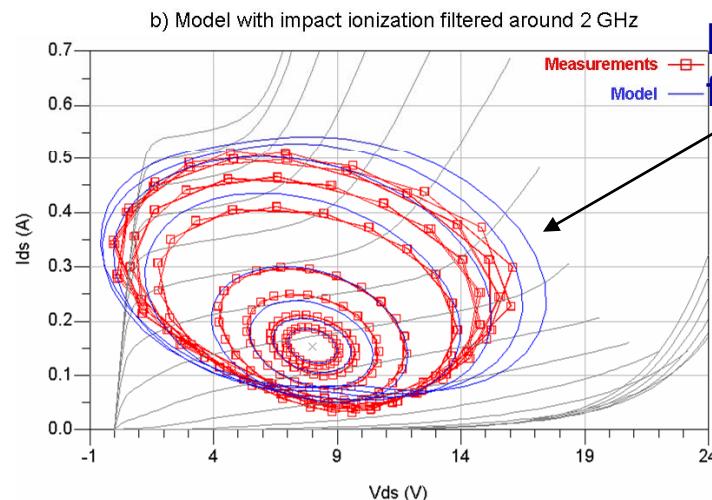
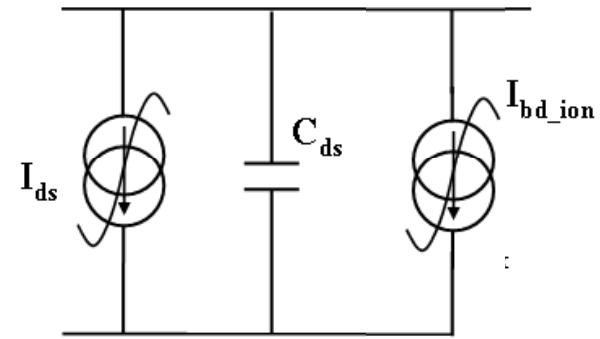


- Interaction between II and Traps
- Temperature dependence
- Frequency dispersion of output conductance

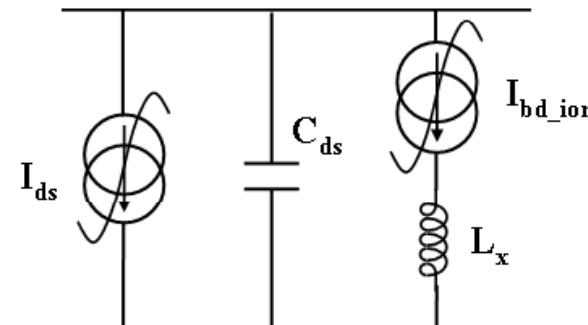
Impact ionization is frequency dependent



Model with impact ionization source



Model with impact ionization filtered around 2 GHz



Lowpass filter with a cut-off frequency of 2 GHz

- Dispersive effects have a strong impact on transistors performances
 - ✓ Thermal Effects in all devices
 - ✓ Trapping effects in HEMTs (GaN and GaAs)
 - ✓ Impact ionization effects coupled with trapping effects
- Require specialized characterization tools
 - ✓ Pulsed I-V and S-parameters measurements
 - ✓ Load Pull Frequency and Time Domains
 - ✓ Low Frequency Characterization
 - ✓ Physical and thermal simulation
- Need further investigations for checking the consistency of different kinds of characterization and modeling.
- To provide useful tools for the technology assessment and improvement as well as optimization of PA performances