Platform of Reliability tOOls for Failure analysis
dedicated to wide bandgap devices

COS PROOF

jeudi 4 février 2021

Méthode d'analyse électrique et en bruit BF pour un diagnostic précis des défauts dans les technologies III-N

J.G. TARTARIN – GT2

PLAN DE LA PRÉSENTATION

LES OUTILS DU LAAS, L'EXPERIENCE et LE POSITIONNEMENT NATIONAL/INTERNATIONAL

LES PROJETS DEPUIS 2002 + SUIVI DES ÉVOLUTIONS TECHNOLOGIQUES GaN
(substrats SiC, Si, GaN, Diamant)

QUELQUES CAS D'ÉTUDES

LES PROSPECTIVES ET LES OPPORTUNITÉS VIA PROOF

SYNTHÈSE et DISCUSSIONS

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Electrical noise : from single device to complex system EUROPEAN KNOW-HOW – labelled by Keysight

Main scientific fields :

> **New devices :**
- *Modelling and noise sources identification - process improvement*

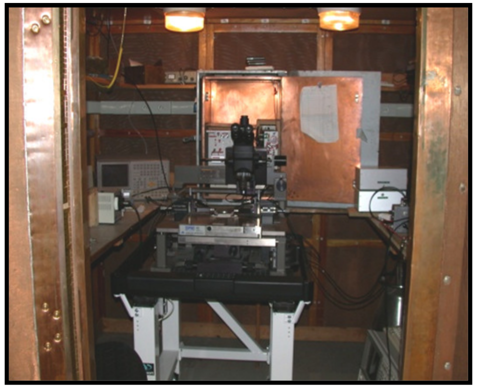
> **Reliability :**
- *Reliability through noise measurement, at device and circuit level – process improvement*

> **Linear & Nonlinear circuits and noise :**
- *Noise sources modelling under nonlinear conditions*
- *Low Noise Amplifier design – harshness vs jamming (+ nonlinear noise figure)*
- *Phase noise modelling (oscillator, amplifier…)*

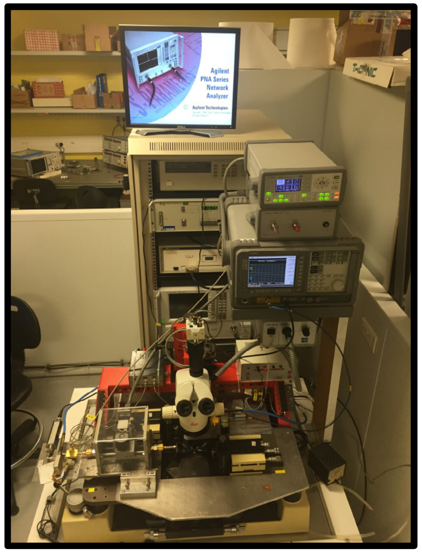
> **Noise in complex systems :**
- *Noise in frequency synthesis,*
- *Noise in Tx/Rx RF links…*

> **Noise metrology :**
- *Low frequency noise (1/f – GR - RTN)*
- *Microwave linear noise (NF50, 4 parameters)*
- *Nonlinear HF noise*
- *Phase noise (RF and microwave sources)*
- *additive phase noise*
- *Optical noise (ex : laser RIN, $\Delta\nu$)*

Only 1 to 3 active dedicated researchers! Need to strengthen the activity (**PROOF** !)



LF noise measurement



HF noise parameters measurement 1-40 GHz

NOISE @ LAAS:
NATIONAL - INTERNATIONAL POSITION

Positioned at a European excellence level:

- Cited in European Microwave Journal 2012
- Referenced by Keysight as European Reference Center for LFN in 2016
- Unique experimental setup for LF and HF linear and non linear noise measurement facilities (in Europe at least !)

Cooperation with academic laboratories has often specialized in specific topics (for instance, **IEMN** on device processing, simulation, and characterization; **XLIM** on microwave components and systems modelling and simulation; **<u>LAAS on noise</u>**; **IMS** on silicon devices and reliability; **LabSTICC** on filtering; and **IETR** on antenna design and characterization

From IEEE Microwave Magazine, "European Microwaves", Sept-Oct 2012

NOISE @ LAAS:
NATIONAL - INTERNATIONAL POSITION

Noise in France:

How is LAAS is positioned in this area ?
→IEMN Lille (HF noise)
→IMS Bordeaux (LF Noise & reliability)
→IES montpellier (LF noise-Silicon)
→XLIM Limoges (LF Noise and N.L. circuits)

Noise in Europe & Worldwide ?

A small but active community (almost 500 active researchers mainly in Europe, USA, Japan)
-ICNF conference (every 2 years), ESREF, …
-IEEE Trans. Microwave Theory and Technique, Microelectronics Journal, IEEE Elec. Device Letters, IEEE Trans. Elec. Device

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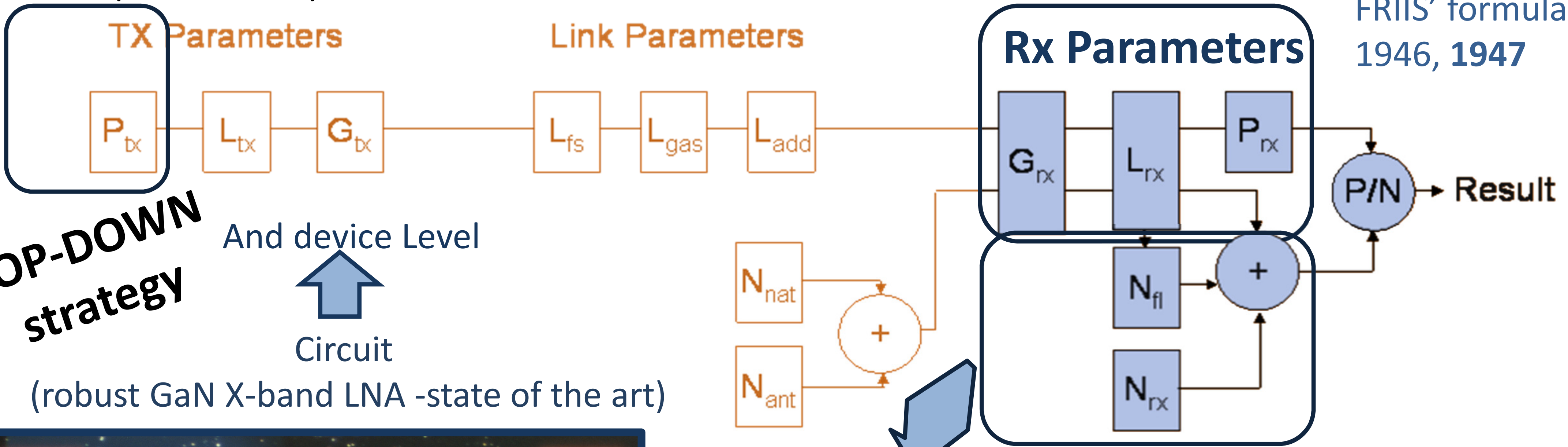
From IEEE Microwave Magazine, "European Microwaves", Sept-Oct 2012

NOISE: a story of Radiolink budget – …. to internal

$$P_{RX} = P_{TX} - L_{TX} + G_{TX} - L_{FS} - L_{gas} - L_{add} + G_{RX} - L_{RX}$$

Power Amp. – reliability



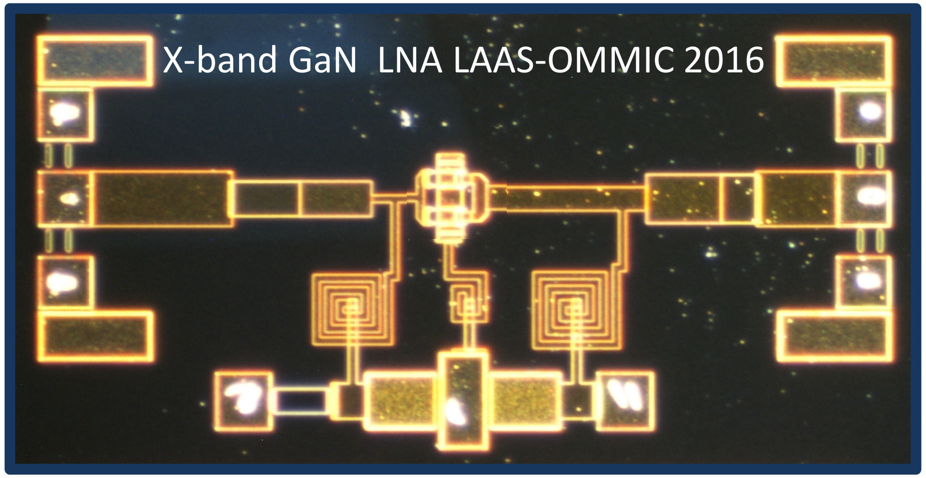
FRIIS' formulas
1946, **1947**

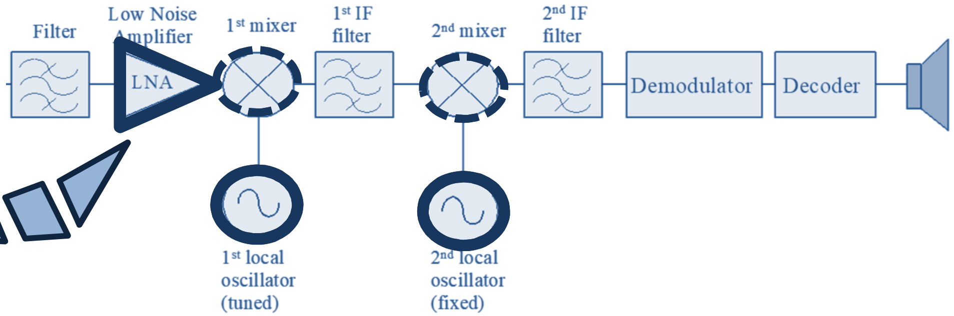
TOP-DOWN strategy

And device Level

Circuit

(robust GaN X-band LNA -state of the art)


X-band GaN LNA LAAS-OMMIC 2016



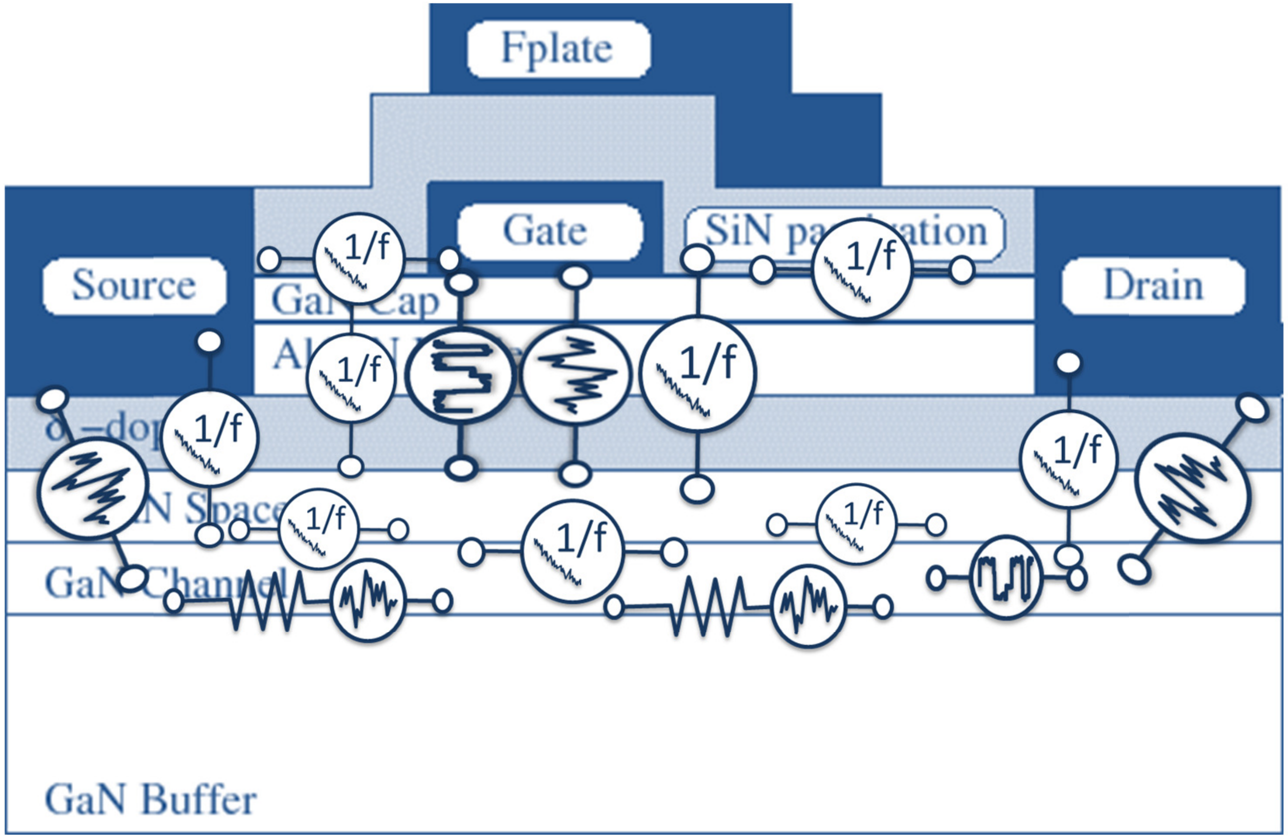
Noise is considered at the receiver's side as it is the place where the signal is at its lowest level

ANYTHING NEW SINCE the 1900s ? OF COURSE (WHAT DID YOU EXPECT ?)

Electrical improvement by frequency & power increase

→various technologies (III-V, SiGe, GaN, ...)

→various active devices (HBT, LDMOS, MESFET, HEMT, m/pHEMT, FinFET, nanoFET…)



NOISE REVEALS EVENTS (DEFECTS) THAT :

-SET THE LIMIT OF ELECTRICAL PERF.

-REVEAL WEAKNESSES OF A DEVICE

MEASUREMENTS TOOLS

NON-INVASIVE DETECTION TOOLS OF MICROSCOPIC DEFECTS

STARTING POINT OF OUR STUDIES !

… and opportunities to play with the latest technologies !

ANYTHING NEW SINCE the 1900s ? OF COURSE (WHAT DID YOU EXPECT ?)

Electrical improvement by frequency & power increase

→various technologies (III-V, SiGe, GaN, ...)

→various active devices (HBT, LDMOS, MESFET, HEMT, m/pHEMT, FinFET, nanoFET…)

BLIND TEST ON TECHNOLOGY

NOISE REVEALS EVENTS (DEFECTS) THAT :

-SET THE LIMIT OF ELECTRICAL PERF.
-REVEAL WEAKNESSES OF A DEVICE

MEASUREMENTS TOOLS

NON-INVASIVE DETECTION TOOLS OF MICROSCOPIC DEFECTS

⇩

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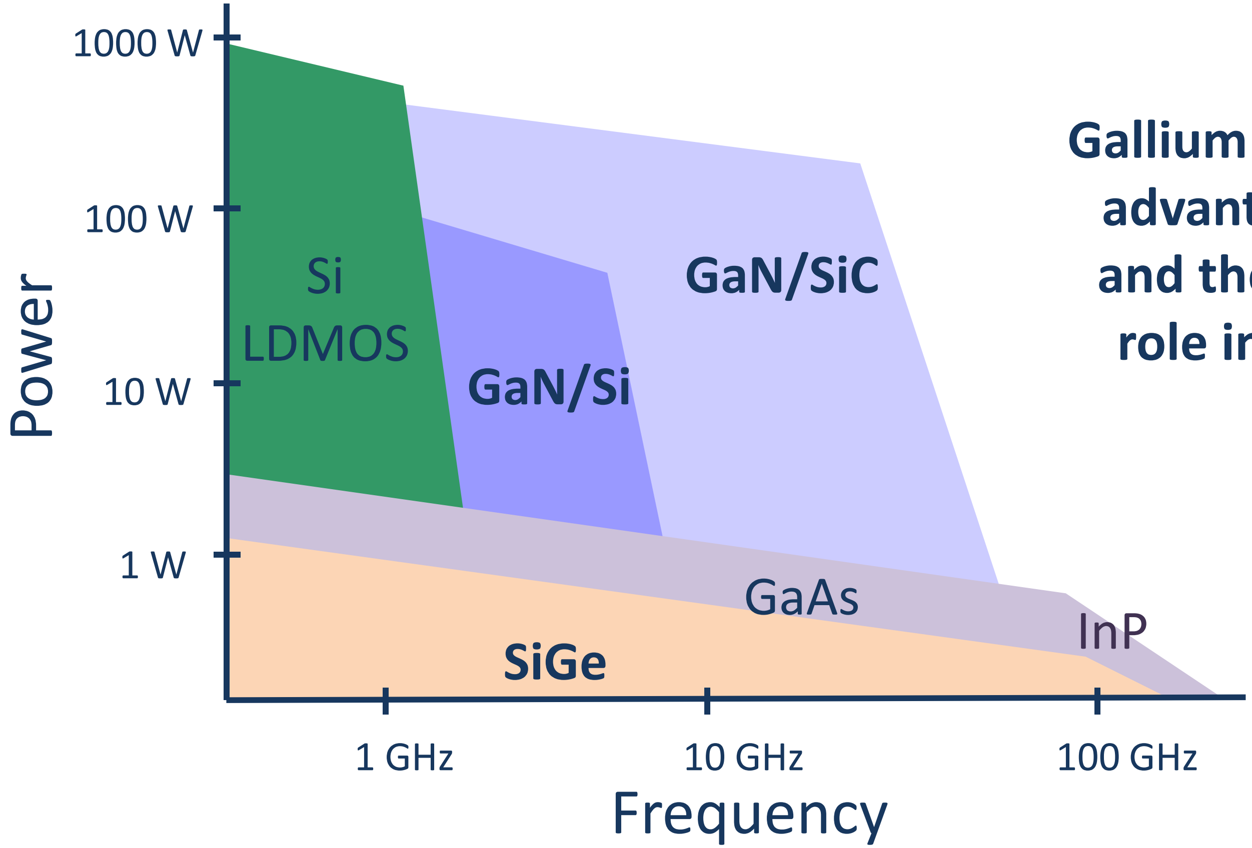
SYNTHÈSE et DISCUSSIONS

GaN for HF market



Gallium Nitride and SiGe devices have legitimate advantages in (specific) performances metrics and they will play a more and more important role in defense and radiation-hardened-type devices.

GaAs is in between GaN and SiGe

RF applications will benefit from GaN and SiGe technologies

"In the end, power is voltage times current, and a higher operating voltage makes high power easier. In regard to comparing **GaN versus silicon**, in general, that's a **complicated answer as they are very different**. **GaN is still expensive from a wafer cost, but the mask cost is far less than cutting-edge CMOS (28nm CMOS)**"

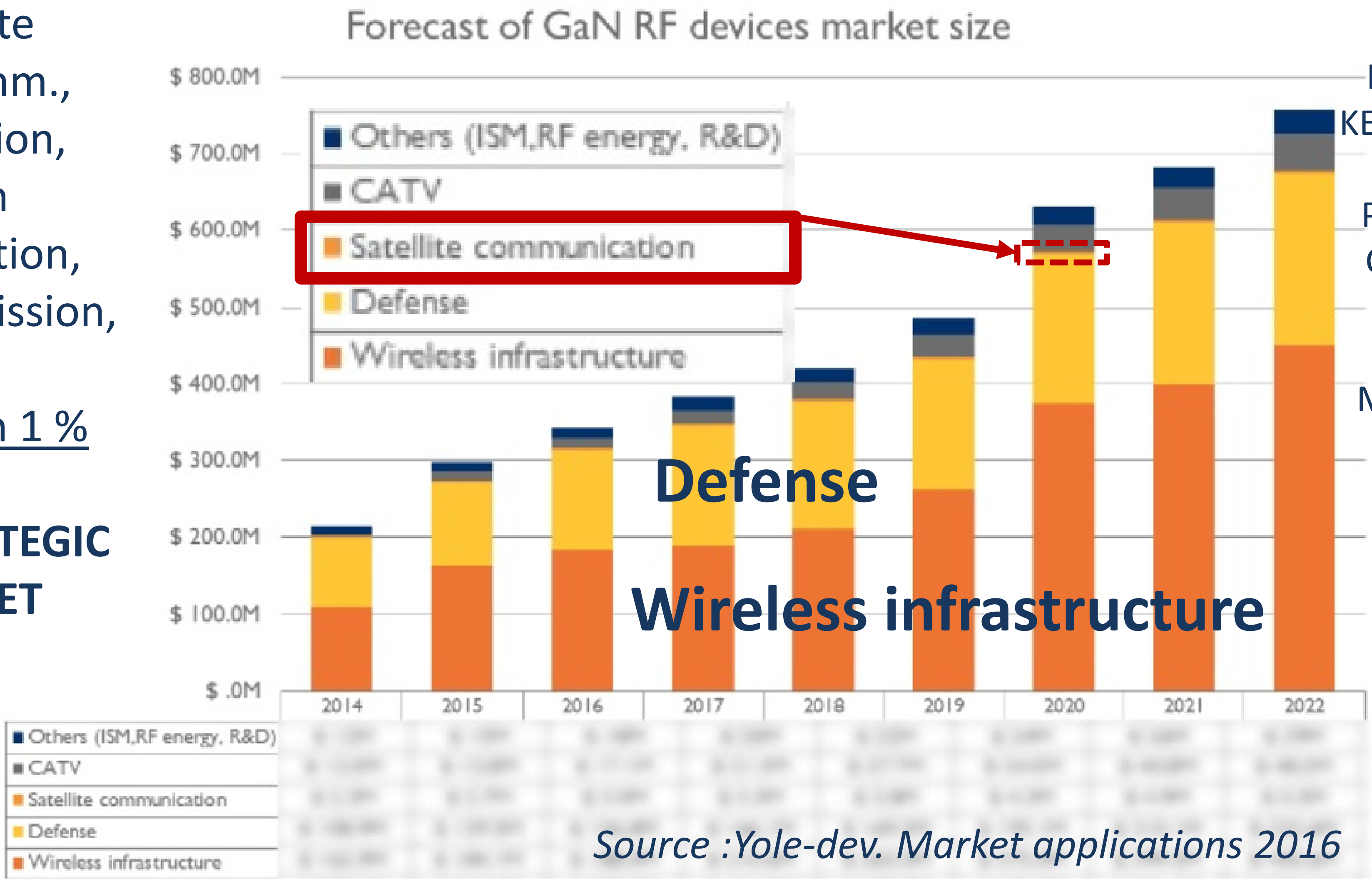
K. Benson, Analog Devices

GaN for HF markets – EVOLUTION & TRENDS

Satellite TeleComm., Navigation, Earth Observation, Science Mission,

<u>Less than 1 %</u>

BUT STRATEGIC MARKET



Defense

Wireless infrastructure

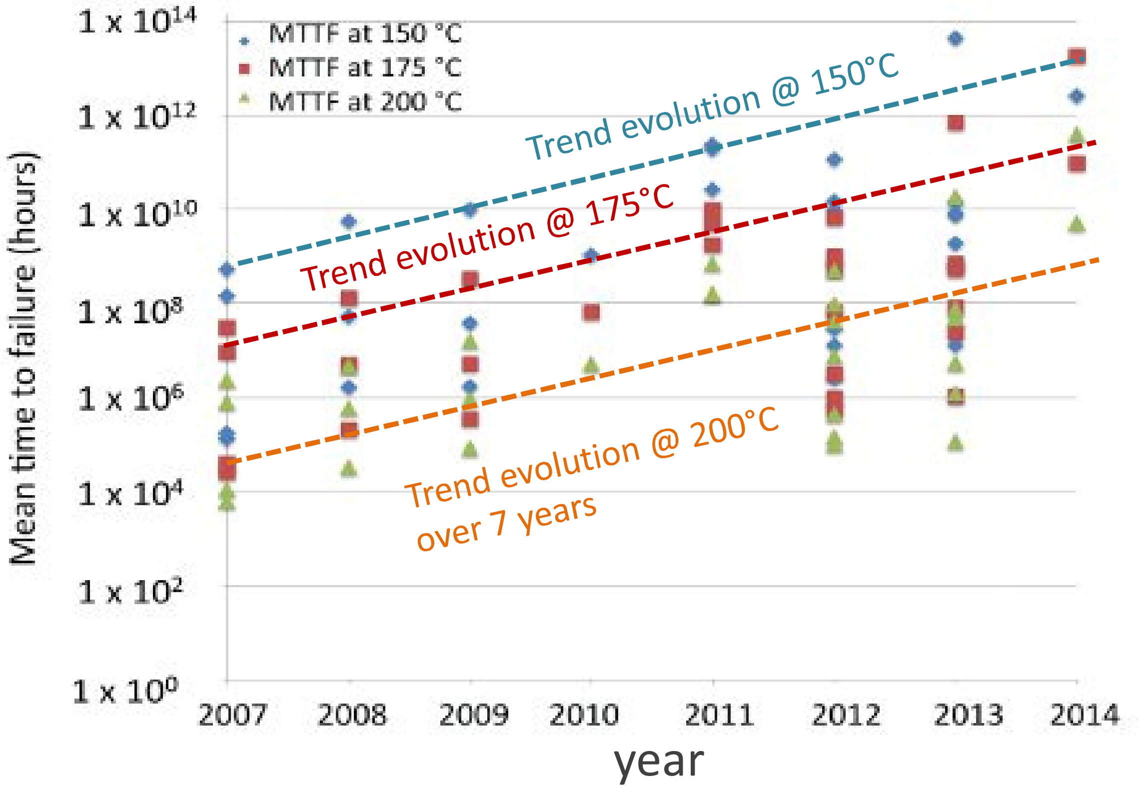
Source :Yole-dev. Market applications 2016

RELIABILITY IS A KEYPOINT TO PUSH THE PERFORMANCES CLOSE TO THEIR LIMITS (mainly THERMAL MANAGEMENT + TRAPS)

NEED SECURED FEEDBACK ON RELIABILITY OF HEMT

MTTF: a survey for GaN devices

Reliability, defect analysis → pushing the time-temperature limits



Inspired form a survey of the literature by Glen David Via from the US Air Force Research Laboratory; this figure indicates a steady increase in the mean-time-to-failure of GaN HEMTs.

Performances are not necessarily better, but Security Operating Area improves (junction temperature increase for a given MTTF)

Then it is possible to push the x3 x4 power ratio vs GaAs towards the theoretical limit (x8 to x10)

PROJETS ET COLLABORATIONS INDUSTRIELLES DEPUIS 2002 et 11 thèses GaN sous la (co)direction de JG Tartarin)

Programmes Européens

▷ Projet européen TARGET (Top Amplifier Research Groups in a European Team) (2004-2005) :
-(**R**) étude sur ‘‘Transmitter impact by non-linear and linear effects on Receiver Noise Figure degradation’’.
-(**P**) mesures du bruit BF et modélisation large-signal des transistors HEMT AlGaN/GaN : ‘‘Metric criterion comparisons for LS and noise models assessments’’

▷ Contrat ESA AO/1-3916/01/NL/CK (**P & R** de WorkPackages)(2002-2005) : étude des défauts structurels des transistors HEMT AlGaN/GaN développés sur substrats Si, SiC et saphir.

Programmes Nationaux

▷ Projet OMMIC (2015-2019 et 2020-2023): développement de structures MMIC GaN bandes X-Ku-Ka (thèses CIFRE et collaboration Afrique du Sud)

▷ Projet GaNEX (2017) **(P)** : robustesse de nouvelles structures HF GaN (avec CHREA et IEMN)

▷ Projet GaNEX (2016) **(R)** : développement d’une plateforme d’évaluation des contraintes RF-Thermiques sur les transistors GaN en bande X et bande Ka

▷ Projet ANR GENGHIS KhAN (2011-*2014*) **(P&R)** : conception de *Transceivers* GaN MMIC en bande K et bande Ka.

▷ Projet ANR REAGAN (2011-*2014*) **(P&R)** : étude et modélisation des mécanismes de défaillance des transistors HEMT AlGaN/GaN, filière industrielle UMS.

▷ Projet ANR blanc ‘MOREGAN’ (2007-2010) **(P)** : caractérisation de structures MOSFET GaN de commutation de puissance rapide.

▷ Contrat ‘ANDRO’ (RNRT) (2004-2007) **(P&R)** : identification des défauts corpusculaires intrinsèques des transistors HEMT, (filière GaN sur substrats Si et SiC), élaboration d’un modèle électrique fort-signal et réalisation d’un oscillateur 10 GHz.

▷ Action Spécifique ‘Bruit’ (2002-2004) **(P)** : outils et techniques de mesure et de modélisation du bruit linéaire et non-linéaire/ bruit des dispositifs avancés.

Collaborations directes Universités: Canada (LN2- 2 thèses), et France (IEMN- 2 thèses), Suède (Chalmers), Allemagne (Cottbus)
Collaborations bi-tri-partites : DGA (2 thèses + projets), CNES, RFHIC, OMMIC, UMS, III-V Lab etc.

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SYNTHÈSE et DISCUSSIONS

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

► First (low TRLs) – process improvement

Iterative and empirical

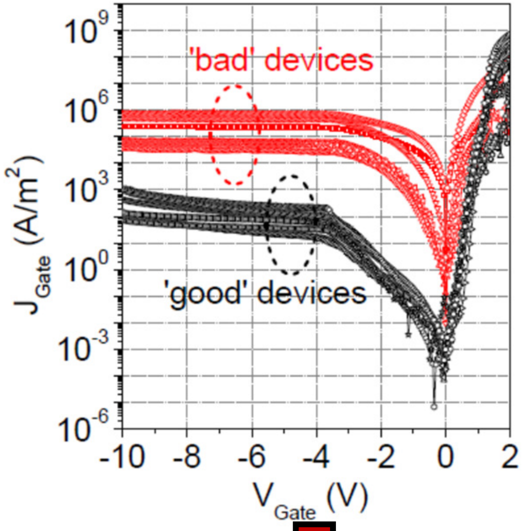
Find the weakest parts of the device

QUESTIONS : WHAT, WHERE, WHEN ?

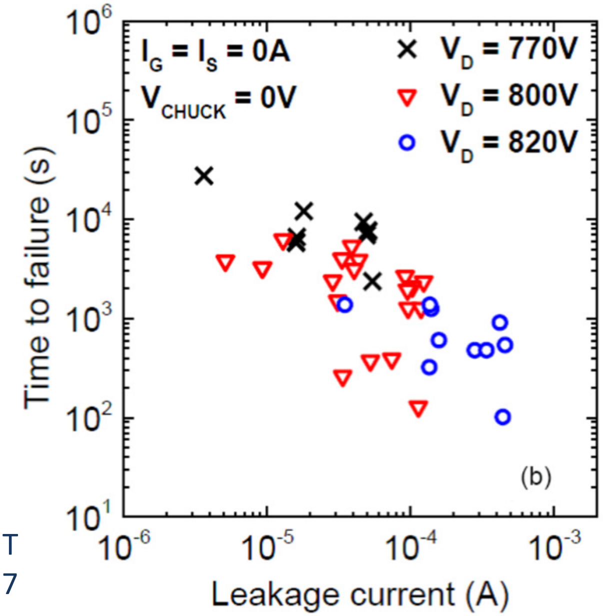
COARSE

Industry : process qualification

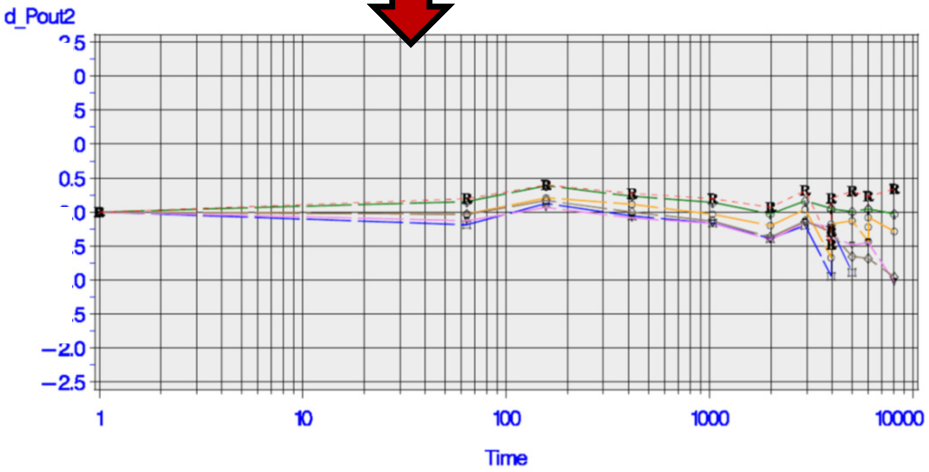
Find correlations and qualify



Gate leakage reduced → runaway reduced



Normally-off HEMT
Ref : Borga et al. IEEE TED 2017



Normally-on HEMT
Ref : UMS ECI presentation days 2016

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

► First (low TRLs) – process improvement

Iterative and empirical

Deterministic and physical

QUESTIONS : WHAT, WHERE, WHEN ? (WHY and HOW ???)

FINE

Research Labs :
Mechanisms & models

COARSE

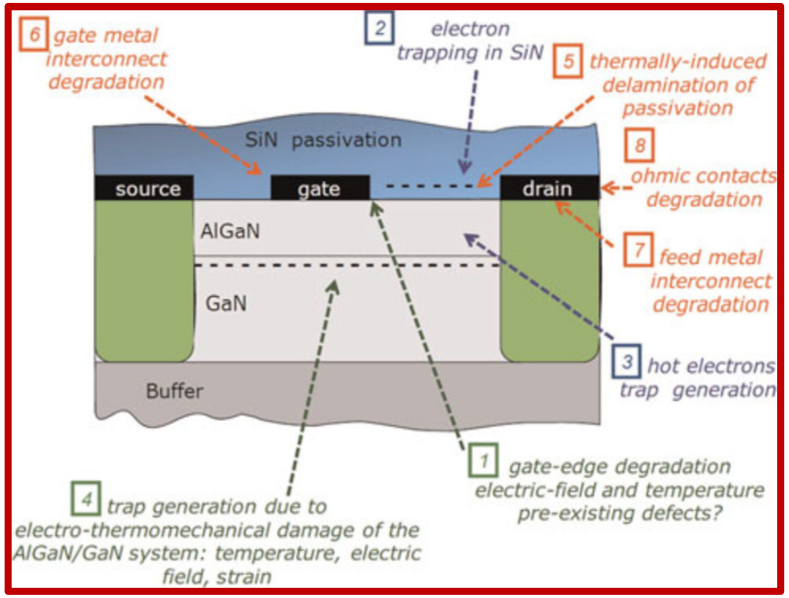
Industry : process qualification

What is (almost) known

Thermally activated
5, 6, 7 & 8

Trapping effects
2 & 3

Piezoelectric effect
1 & 4



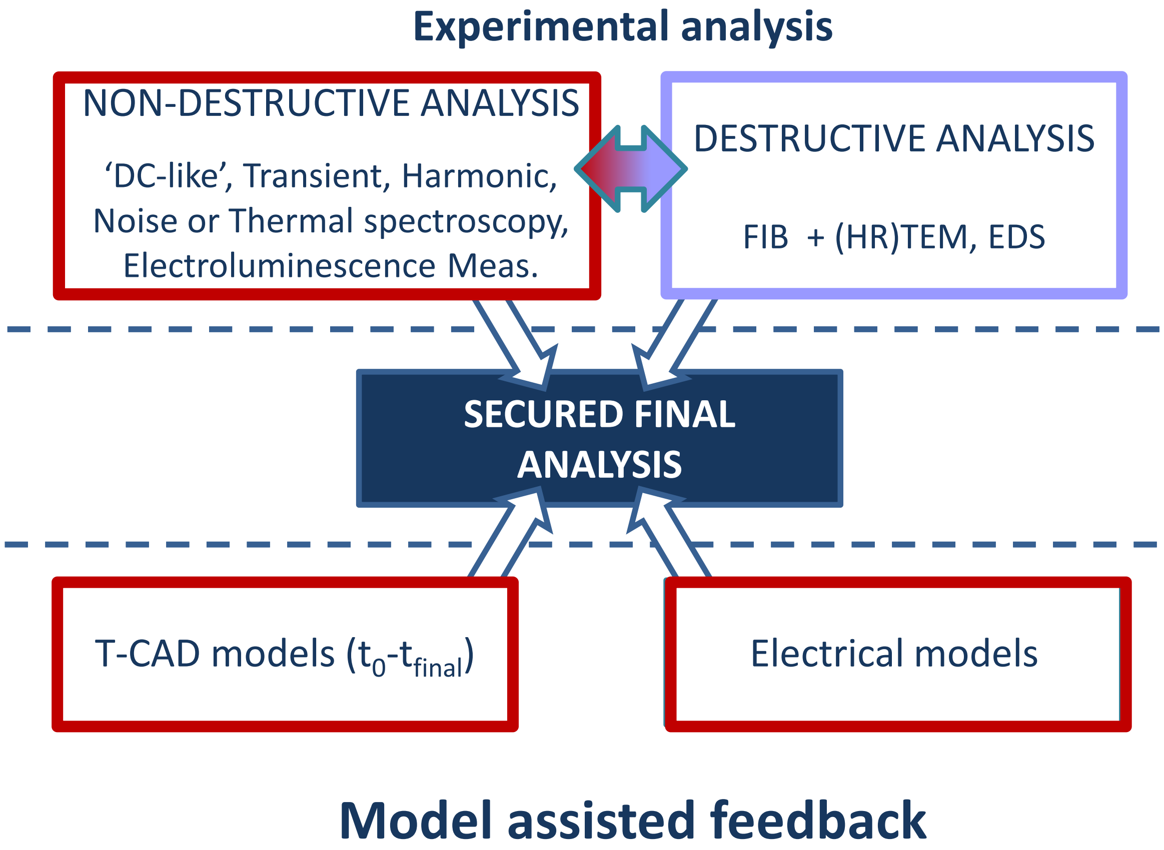
Ref :
Meneghesso
2010 :
reliability issue
GaN HEMT
MWT
cambridge
Press

► Final (high TRL) – process qualification

(process is mastered even if not necessarily understood)

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

- ▶ CASE STUDIES: PROCEDURE FOR RELIABLE DATA ANALYSIS
- ▶ Analyses and Qualification Tools & techniques for low TRL studies



Experimental analysis

NON-DESTRUCTIVE ANALYSIS

'DC-like', Transient, Harmonic, Noise or Thermal spectroscopy, Electroluminescence Meas.

DESTRUCTIVE ANALYSIS

FIB + (HR)TEM, EDS

SECURED FINAL ANALYSIS

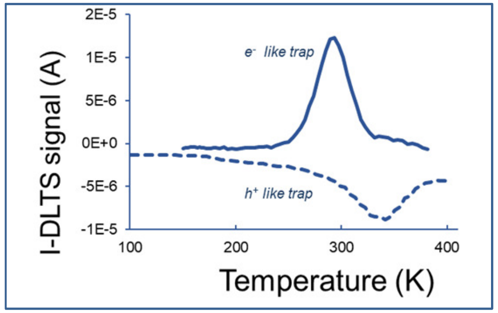
T-CAD models (t_0-t_{final})

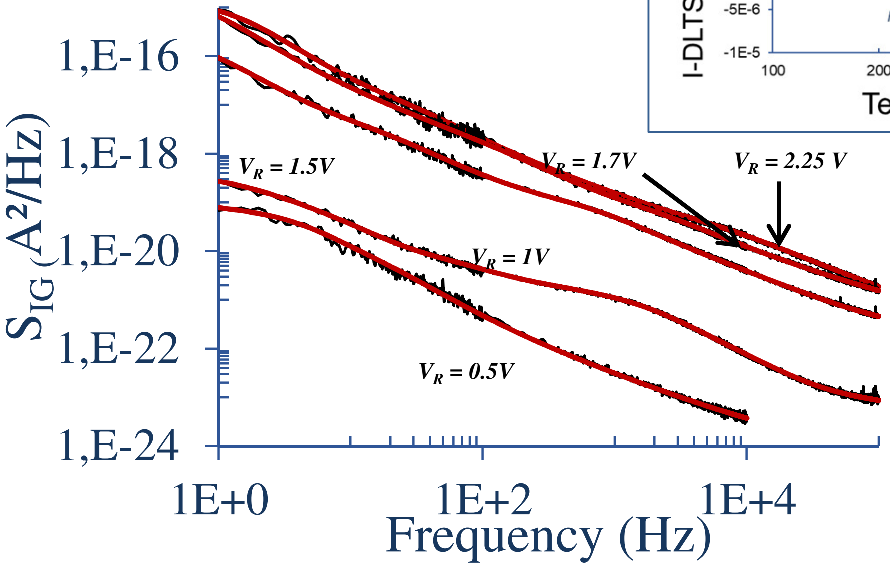
Electrical models

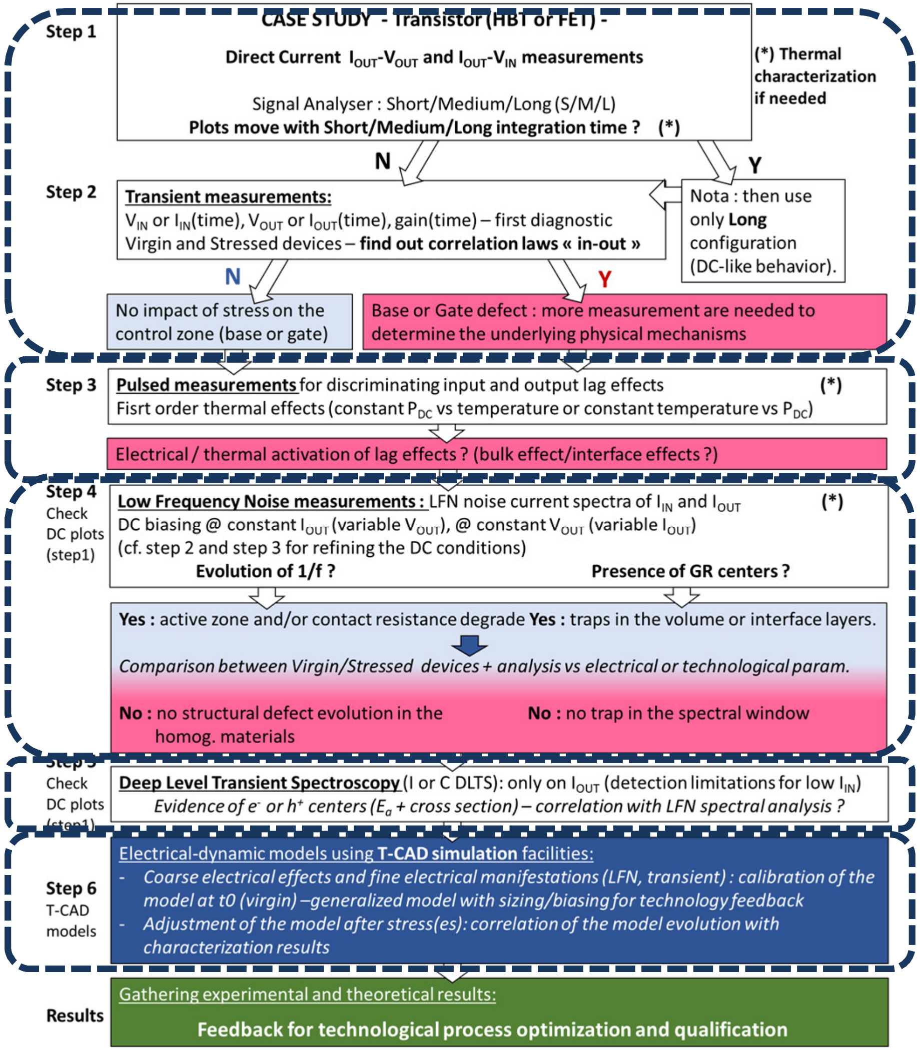
Model assisted feedback

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

- ▶ CASE STUDIES: PROCEDURE FOR RELIABLE DATA ANALYSIS
- ▶ Analyses and Qualification Tools & techniques for low TRL studies
- ▶ TCAD







CASE STUDY - Transistor (HBT or FET) -

Step 1

Direct Current I_{OUT}-V_{OUT} and I_{OUT}-V_{IN} measurements

Signal Analyser : Short/Medium/Long (S/M/L)
Plots move with Short/Medium/Long integration time ? (*)

(*) Thermal characterization if needed

N / **Y**

Nota : then use only **Long** configuration (DC-like behavior).

Step 2

Transient measurements:
V_{IN} or I_{IN}(time), V_{OUT} or I_{OUT}(time), gain(time) – first diagnostic
Virgin and Stressed devices – **find out correlation laws « in-out »**

N: No impact of stress on the control zone (base or gate)

Y: Base or Gate defect : more measurement are needed to determine the underlying physical mechanisms

Step 3

Pulsed measurements for discriminating input and output lag effects (*)
Fisrt order thermal effects (constant P_{DC} vs temperature or constant temperature vs P_{DC})

Electrical / thermal activation of lag effects ? (bulk effect/interface effects ?)

Step 4
Check
DC plots
(step1)

Low Frequency Noise measurements : LFN noise current spectra of I_{IN} and I_{OUT} (*)
DC biasing @ constant I_{OUT} (variable V_{OUT}), @ constant V_{OUT} (variable I_{OUT})
(cf. step 2 and step 3 for refining the DC conditions)

Evolution of 1/f ? **Presence of GR centers ?**

Yes : active zone and/or contact resistance degrade **Yes :** traps in the volume or interface layers.

Comparison between Virgin/Stressed devices + analysis vs electrical or technological param.

No : no structural defect evolution in the homog. materials **No :** no trap in the spectral window

Step 5
Check
DC plots
(step1)

Deep Level Transient Spectroscopy (I or C DLTS): only on I_{OUT} (detection limitations for low I_{IN})
Evidence of e^- or h^+ centers (E_a + cross section) – correlation with LFN spectral analysis ?

Step 6
T-CAD
models

Electrical-dynamic models using **T-CAD simulation** facilities:

- *Coarse electrical effects and fine electrical manifestations (LFN, transient) : calibration of the model at t0 (virgin) –generalized model with sizing/biasing for technology feedback*
- *Adjustment of the model after stress(es): correlation of the model evolution with characterization results*

Results

Gathering experimental and theoretical results:

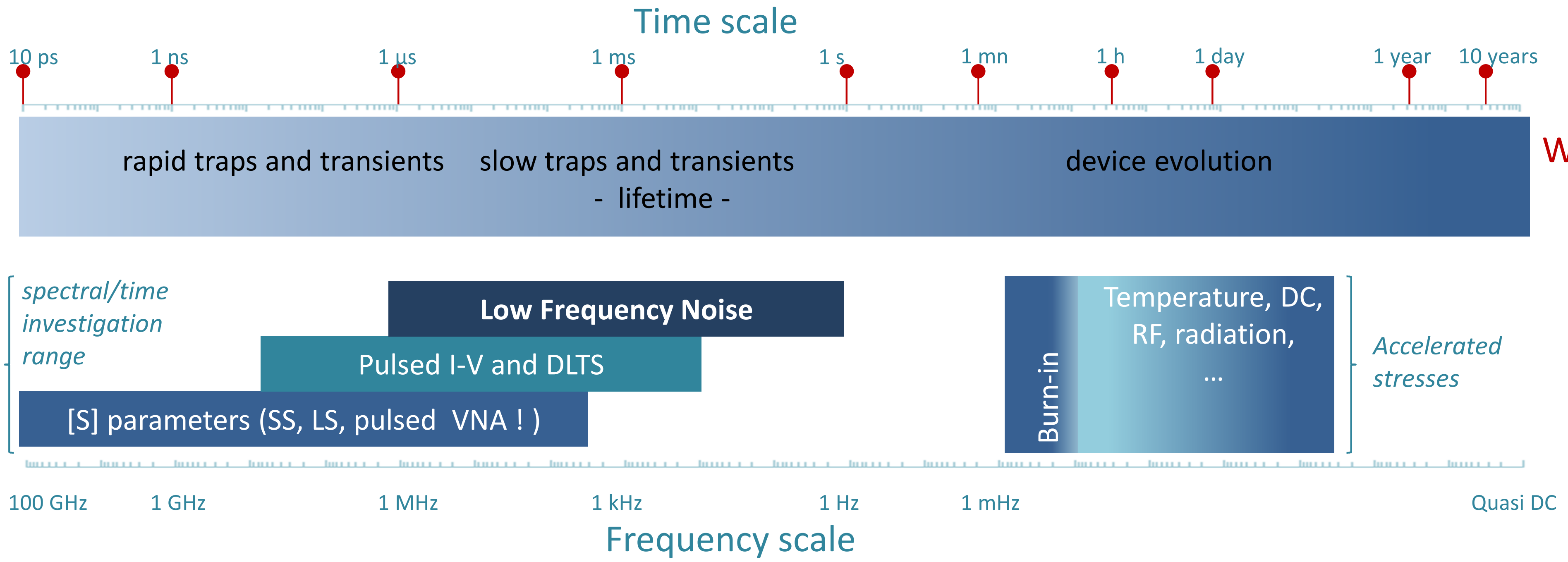
Feedback for technological process optimization and qualification

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

- ▶ Electrical characterization: mastering the tools and concepts ✓
- ▶ TCAD modeling: based on measured data ✓
  but open the ways fot the development of next generations of devices
- ▶ LFN measurement (next, few reminders) ✓

✓

Expected behaviors more or less easy to model



Time scale

10 ps | 1 ns | 1 µs | 1 ms | 1 s | 1 mn | 1 h | 1 day | 1 year | 10 years

rapid traps and transients

slow traps and transients

- lifetime -

device evolution

spectral/time investigation range

Low Frequency Noise

Pulsed I-V and DLTS

[S] parameters (SS, LS, pulsed VNA !)

Burn-in

Temperature, DC, RF, radiation, …

Accelerated stresses

100 GHz | 1 GHz | 1 MHz | 1 kHz | 1 Hz | 1 mHz | Quasi DC

Frequency scale

✗

What about new (unexpected) mechanisms (new Xperimental setups ?)

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

Generally, **electrical behaviors** feature‘**monotonic**’ electrical laws

*BUT **defects*** (or anomalies) can be:

-***distributed***

-***located***

in 3D (depends on dimension) and in their thermal or electrical dependence (V_{in}, I_{in}, V_{out}, I_{out})

And will impact electrical behaviors

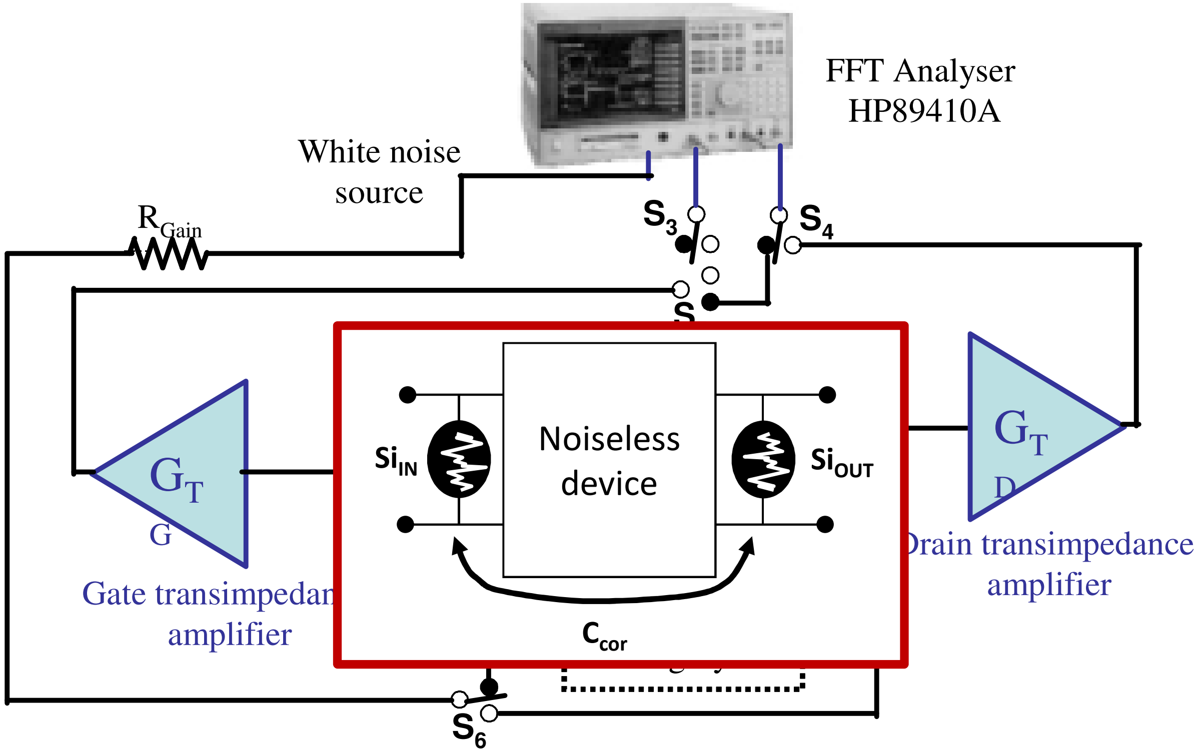
Datasheet / technology maturity

Realistic mapping of the devices, i.e. finding clues about their electrical behavior and weaknesses

Could also be I_{out}-V_{out}, I_{out}-V_{in}… according to the electrical model and physics you intend to define

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

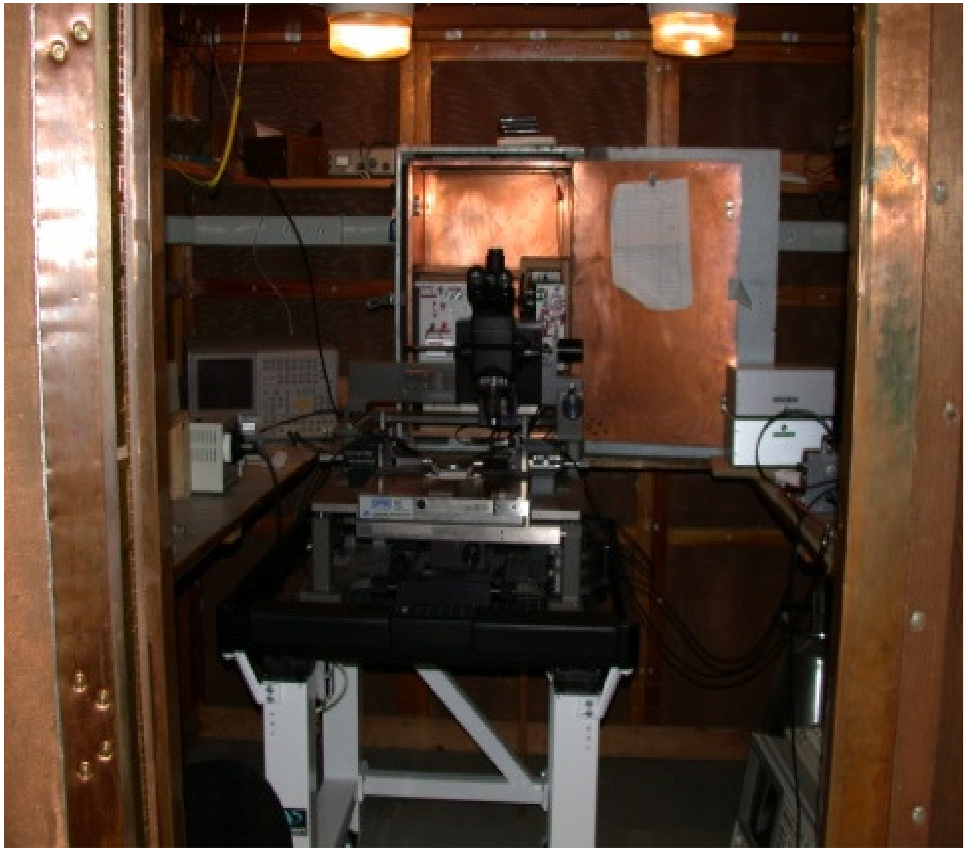
▶ LFN measurement: few reminders



Non-Linear LF noise (1Hz-1MHz, 2 exp. tools) :

→Si_{in} – Si_{out} & correlation

▶GaN technologies –studies on AlGaN/GaN and InAlN/GaN technologies from III-V Lab, UMS (GH50 and GH25-10), IEMN lab, RFHIC, OMMIC, (Eudyna)



Faraday shielded room (LF noise)

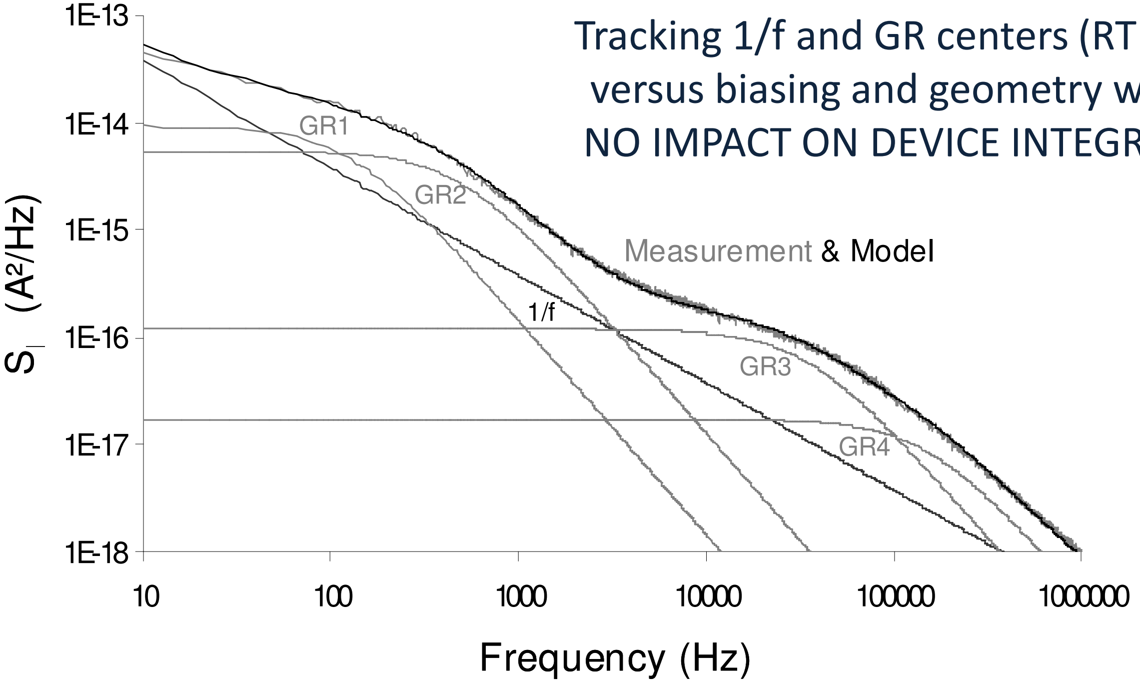
Since 2017, LAAS-CNRS has been selected **.** *by Keysight as a* ***European Platform for LFN and RTN characterization***

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

▶ LFN measurement: few reminders

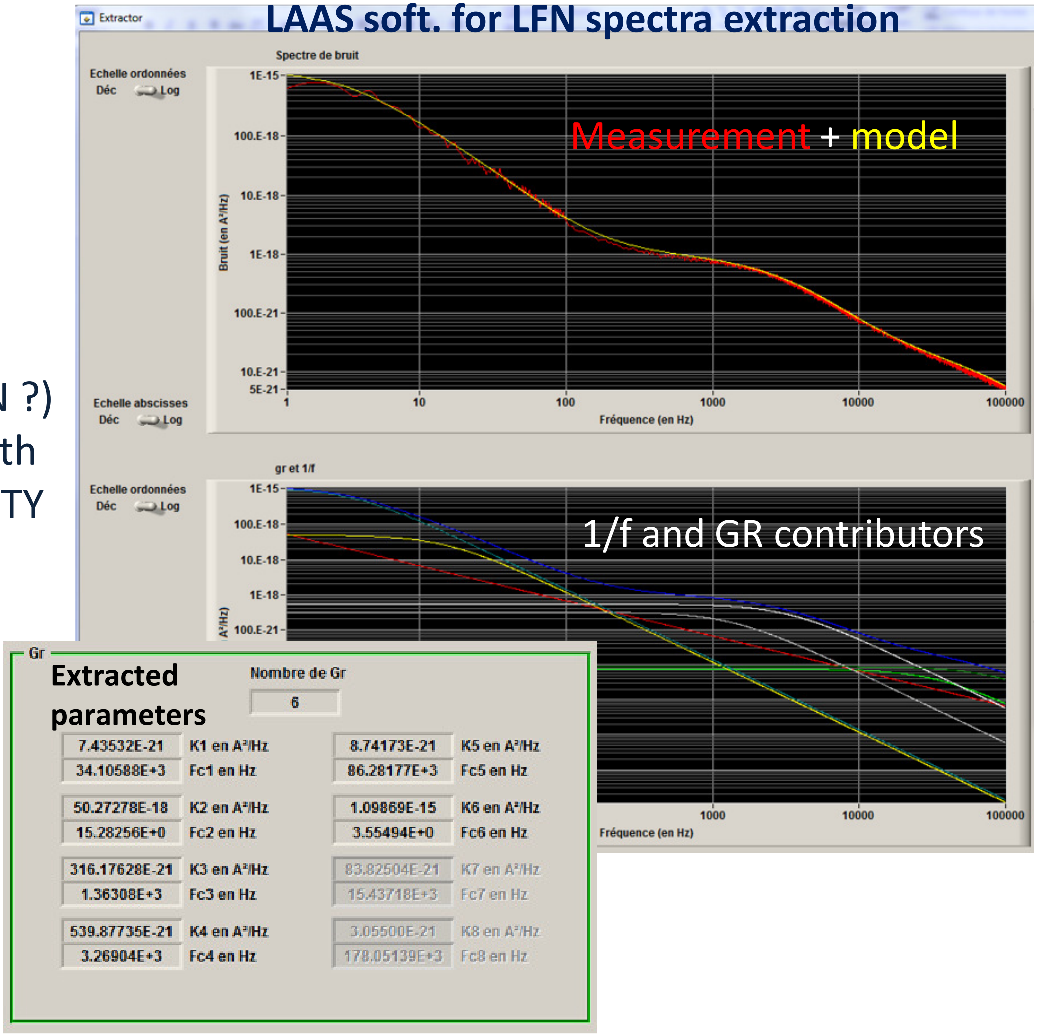
(Ohmic biasing zone)

$$S_{ID}(f) = B\frac{I_D^2}{f^{\gamma}} + \sum_i K_i^2 \frac{I_D^2 \times \tau_i}{1+(2\pi f)^2 \tau_i^2} \quad [A^2/Hz]$$



Tracking 1/f and GR centers (RTN ?) versus biasing and geometry with NO IMPACT ON DEVICE INTEGRITY

LAAS soft. for LFN spectra extraction



Extracted parameters

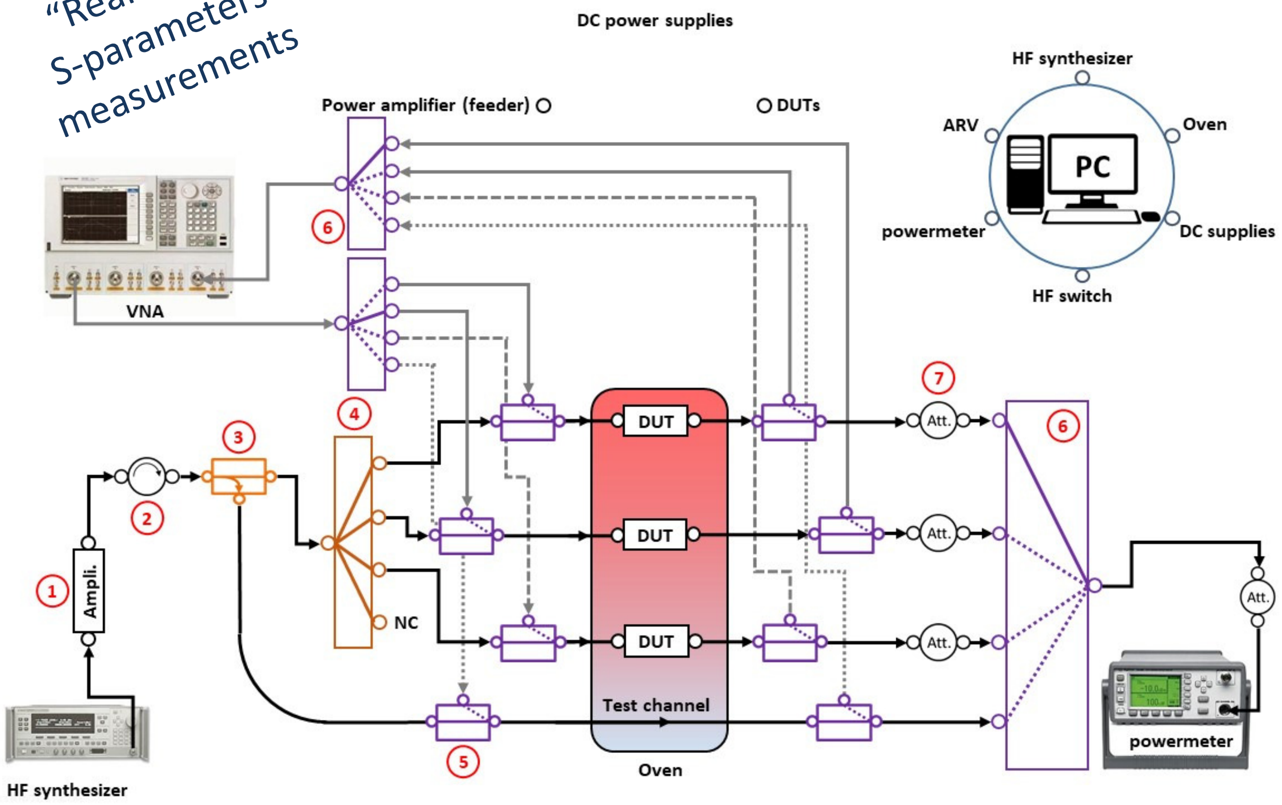
Nombre de Gr: 6

7.43532E-21	K1 en A²/Hz	8.74173E-21	K5 en A²/Hz
34.10588E+3	Fc1 en Hz	86.28177E+3	Fc5 en Hz
50.27278E-18	K2 en A²/Hz	1.09869E-15	K6 en A²/Hz
15.28256E+0	Fc2 en Hz	3.55494E+0	Fc6 en Hz
316.17628E-21	K3 en A²/Hz	83.82504E-21	K7 en A²/Hz
1.36308E+3	Fc3 en Hz	15.43718E+3	Fc7 en Hz
539.87735E-21	K4 en A²/Hz	3.05500E-21	K8 en A²/Hz
3.26904E+3	Fc4 en Hz	178.05139E+3	Fc8 en Hz

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

▶ DC-RF-thermal stresses performed at LAAS (TRL 2-3-5)

"Real-time" S-parameters measurements

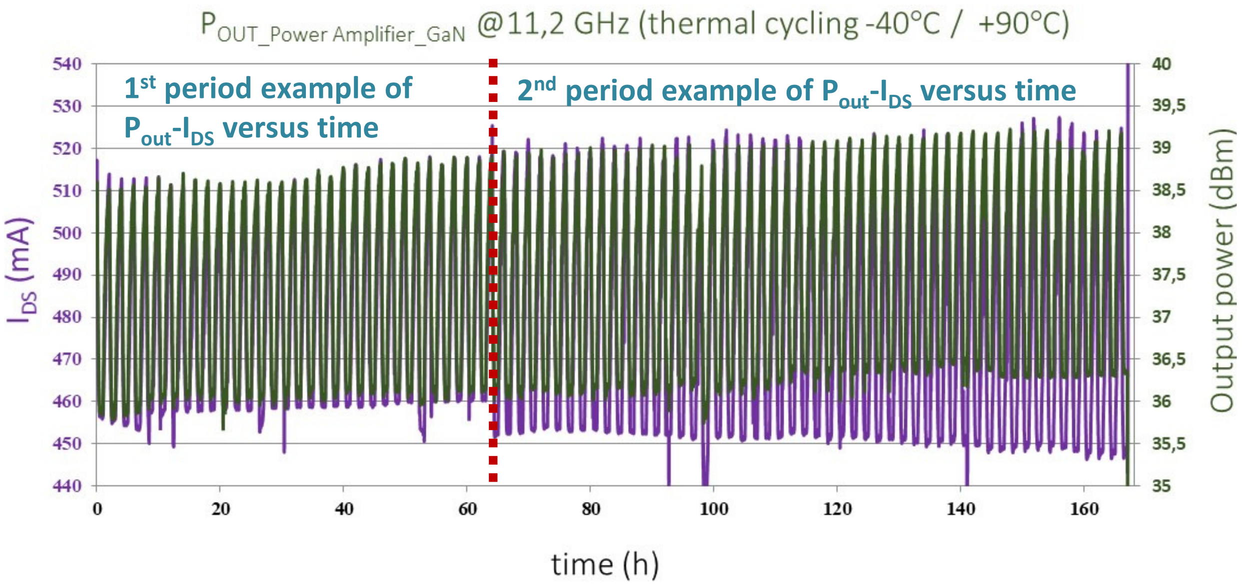


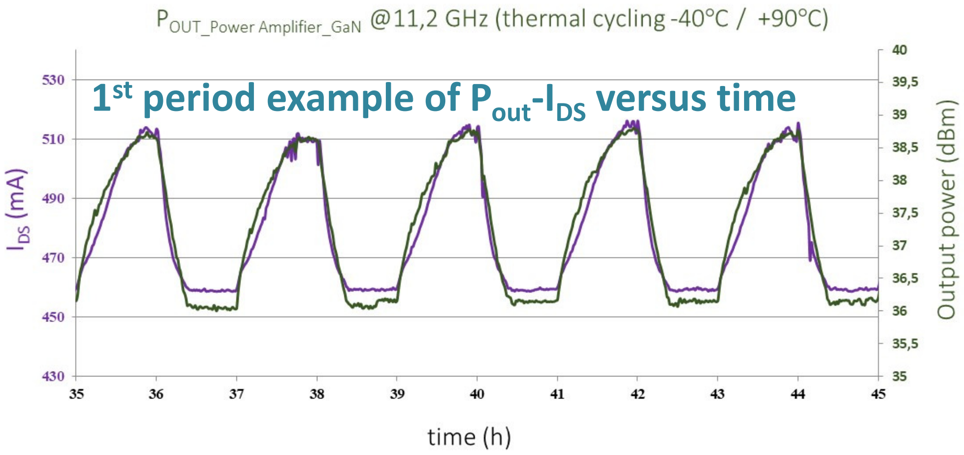
Ref : D. Saugnon, IEEE EuMW 2018

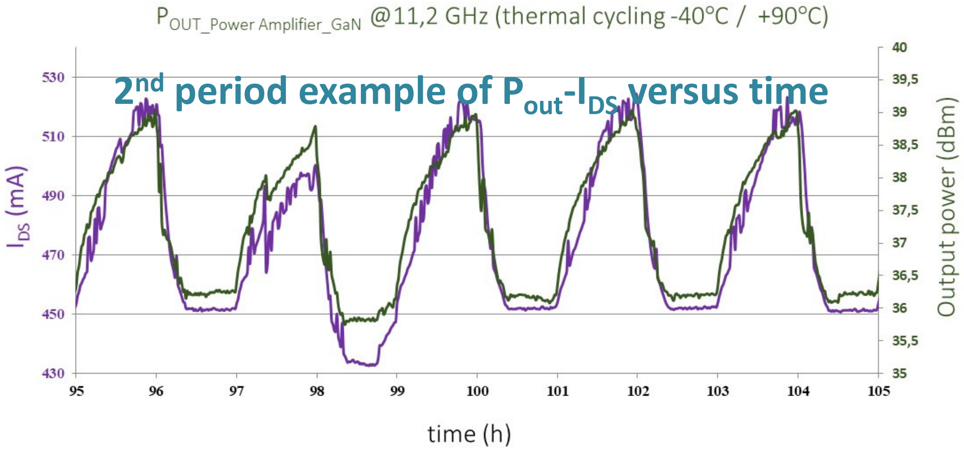
Reliability studies; example of an academic methodology and tools for non destructive defect analysis

▶ DC-RF-thermal stresses performed at LAAS (TRL 3-5)

Temperature profile: -40°C +90°C
Driver correction mode on the calibration path







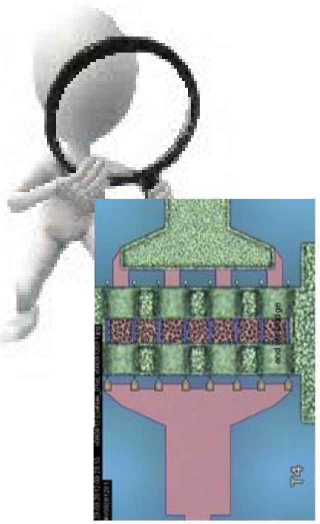
S-parameters measured without removing the device from its environment (X-parameters under development i.e. measurements under same RF stress condition)

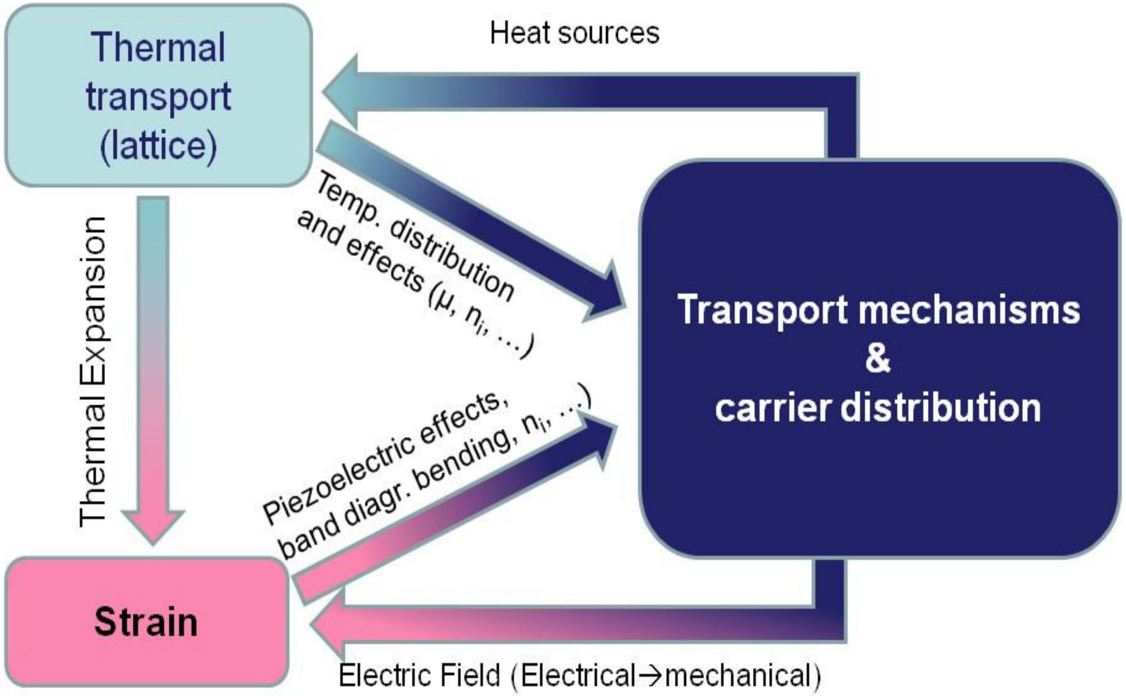
Reliability studies; example of an academic methodology and tools for non destructive defect analysis

▶ Device Level : strong interactions between electrical, thermal, mechanical effects

The know-how on perf/reliability of GaN technologies will be improved by T-CAD models maturity

based on





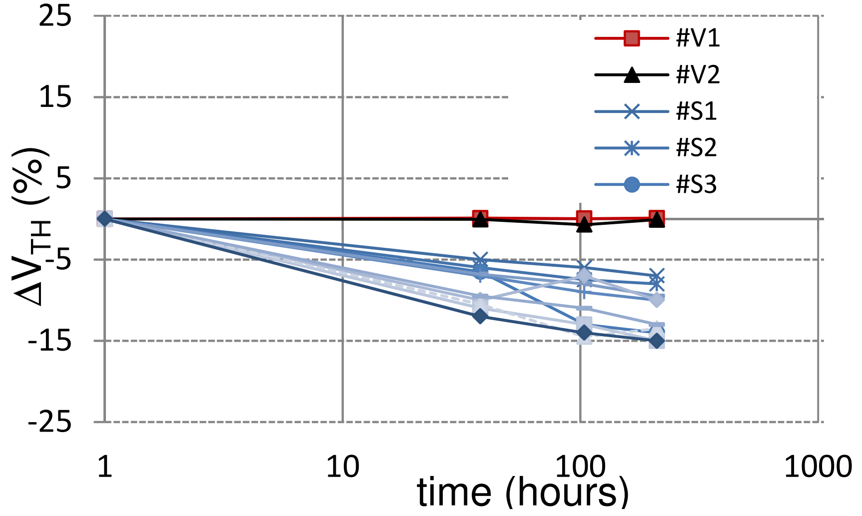
Cross experiments :

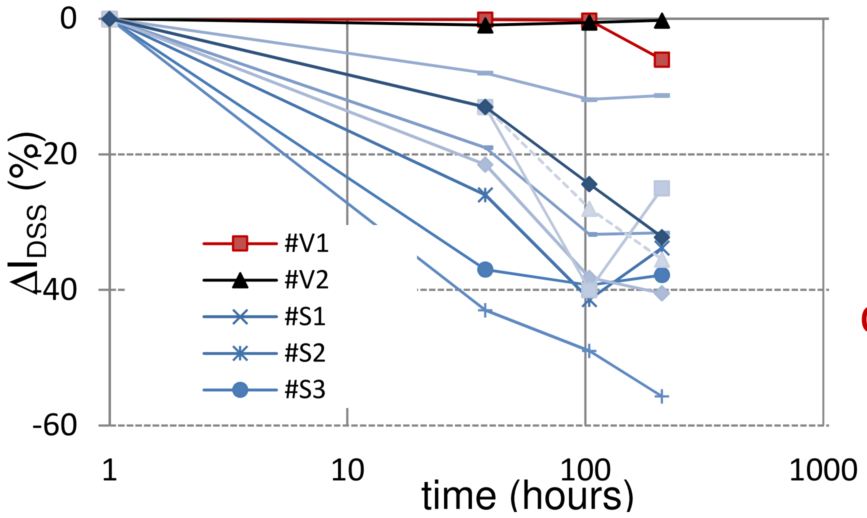
▶**non invasive techniques** (I-V-T static and pulsed, [S] CW / pulsed / large-signal, ?-DLTS, TLS & EL, Low Frequency Noise, nanostructural analysis by Raman spectr., OBIRCh …)

▶ destructive techniques (FIB-cut, TEM & EDX, …) *? (still uncertainty on the weight of the detected defects; DOES IT PLAY A ROLE IN THE FAILURE PROCESS ?)*

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

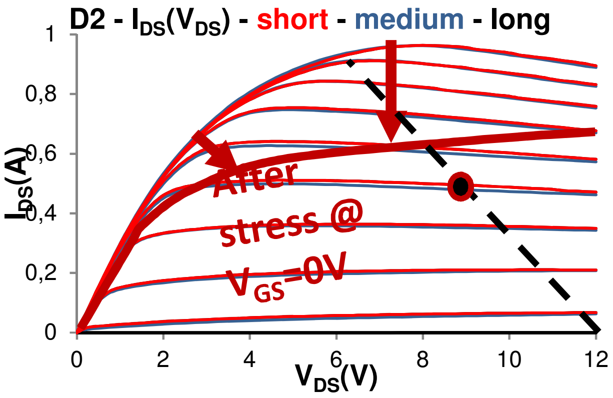
- ▶ HTOL and HTRB stresses, various batches, samples and techn. declinations



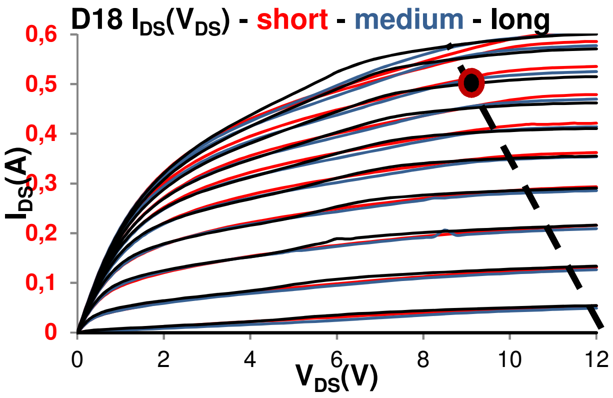


Possible alteration of the Load Line from DC quiescent point (class A)

Virgin



Stressed

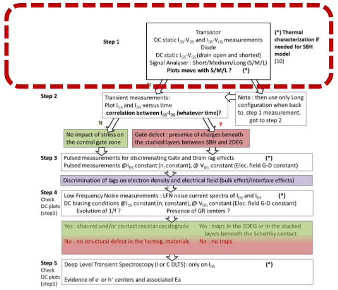


From pulsed measurements:
Virgin #TD6 lag<2%

Stressed (all devices)
-Gate lag : 7%-15%
(-Drain lag <5%)

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

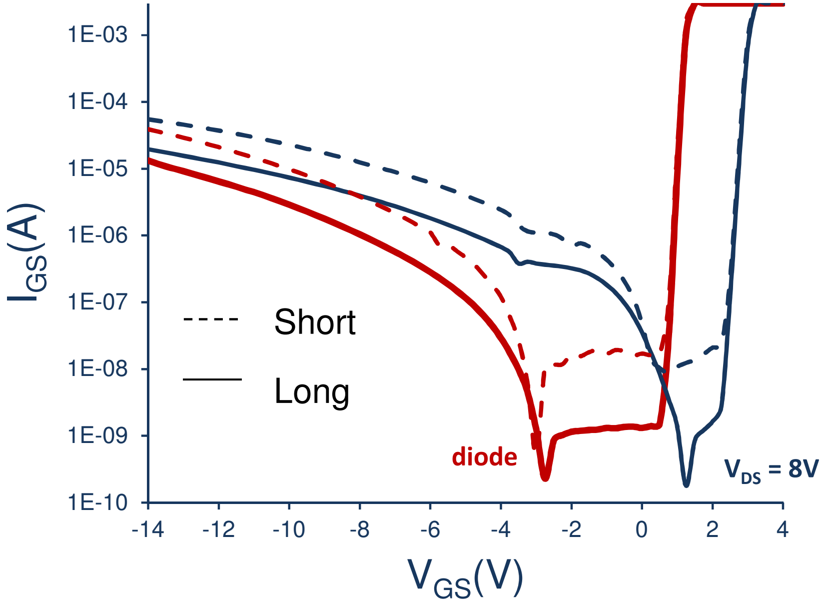
▶ CASE STUDY: AlGaN/GaN GH50 & GH25-10 (UMS)

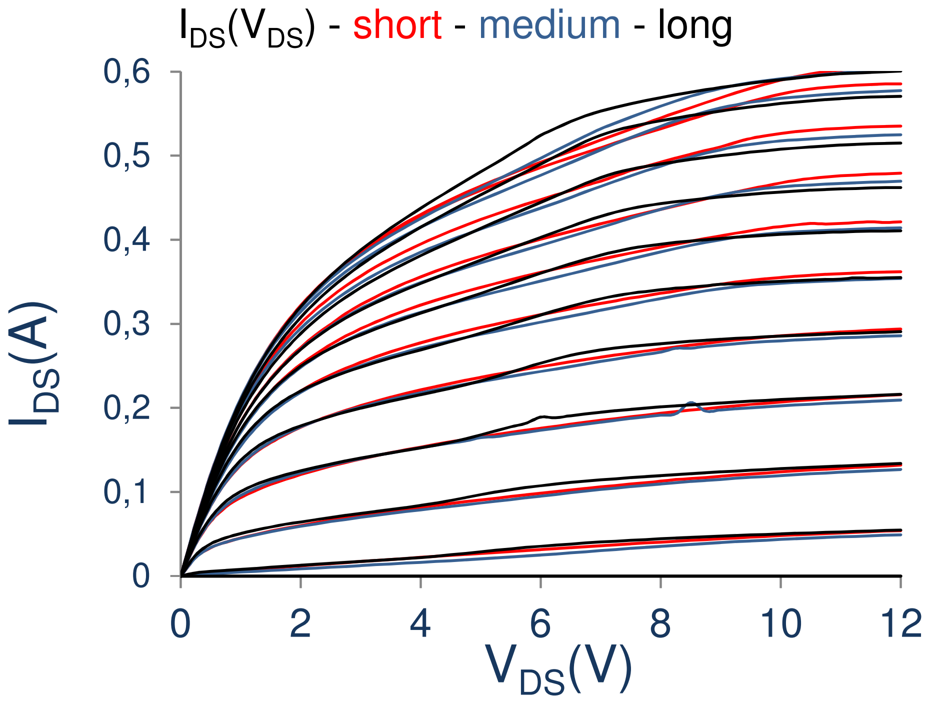


"DC" characterization

Integration Time
short: 640 µs
medium: 20 ms
long: 320 ms

I_{GS} (diode) and I_{GS} transistor

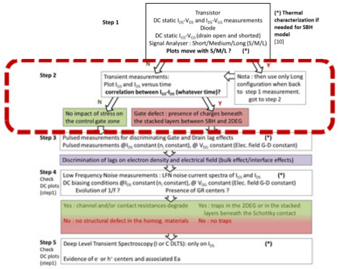




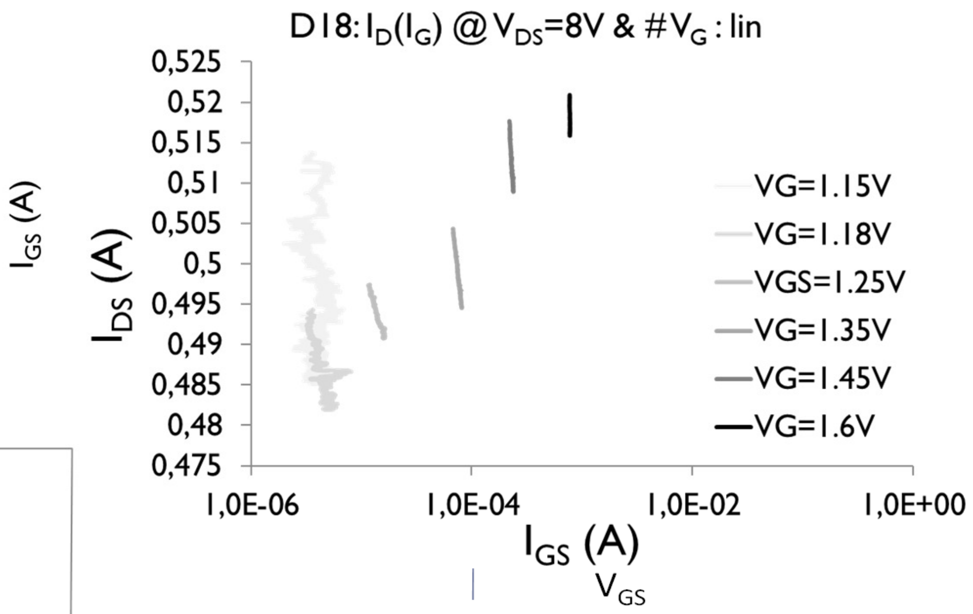
Interaction of charges with specific zones of the transistor !
→ Consequences on S.O.A for space or large volume markets

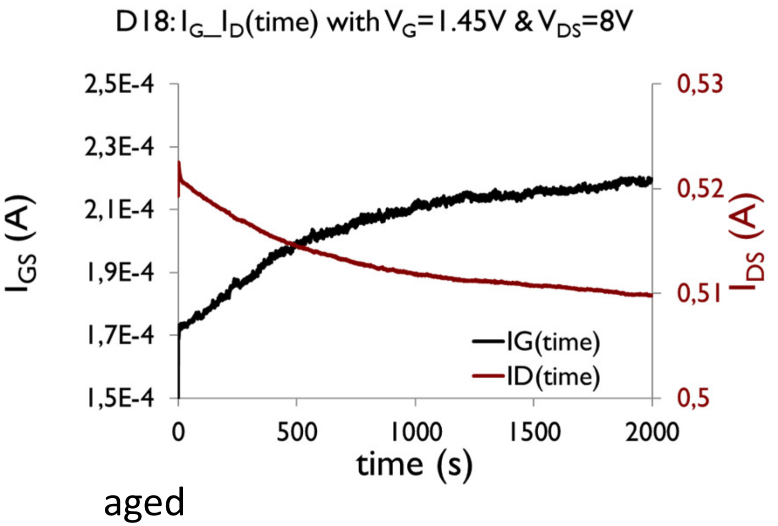
Reliability studies; example of an academic methodology and tools for non destructive defect analysis

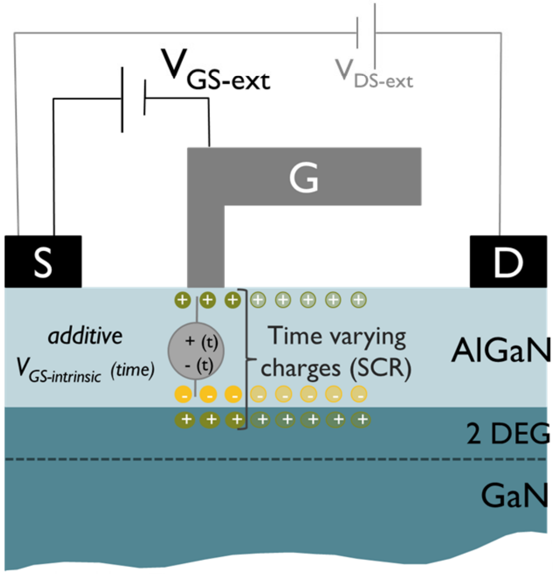
► CASE STUDY: AlGaN/GaN GH50 & GH25-10 (UMS)



Time domain characterization

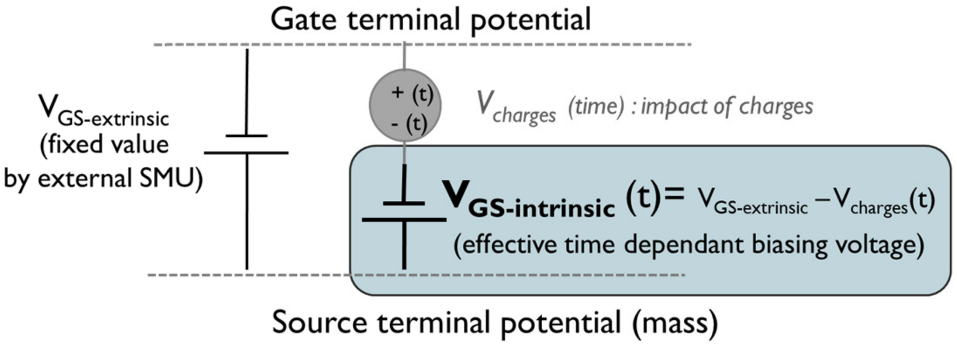






Correlation between I_{DS} and I_{GS} versus time (ONLY FOR STRESSED DEVICES)

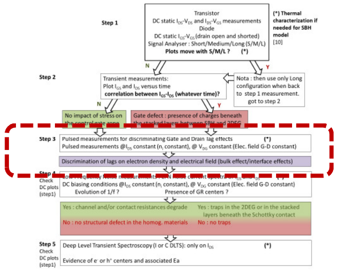
→ **same induced cause: real time variations of DC quiescent V_{GS}.**



Ref : Lazar et al. in Microelectronics Reliability Journal – Elsevier- 2015

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

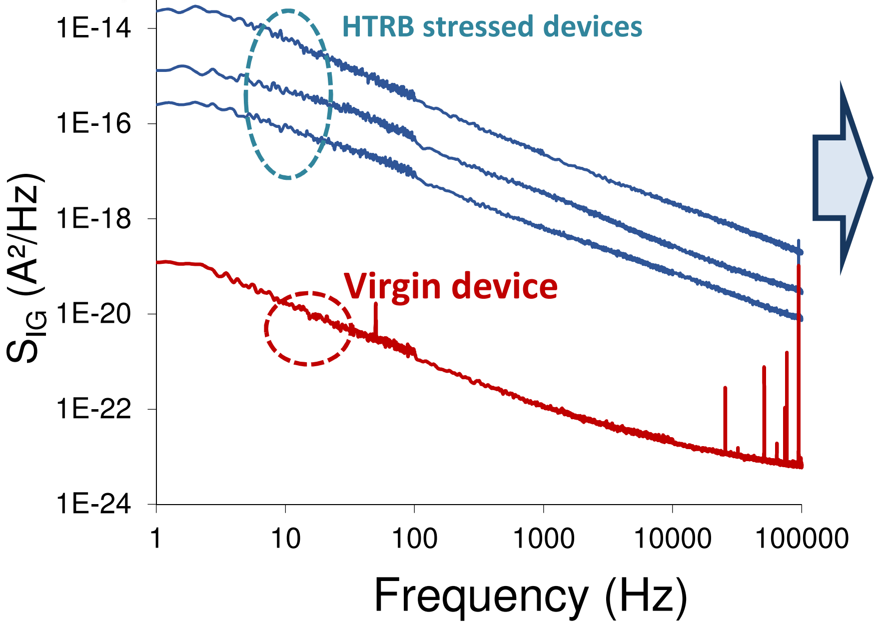
▶ CASE STUDY: AlGaN/GaN GH50 & GH25-10 (UMS)

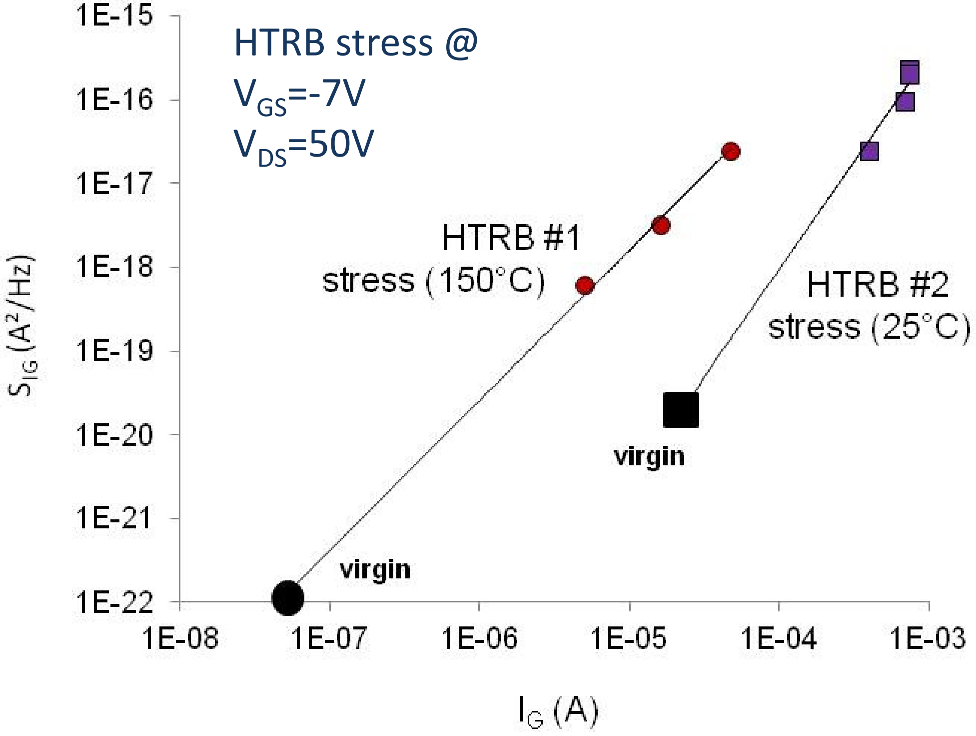


Noise spectroscopy

-diode alone
-transistor mode

Ref : Tartarin et al. IEEE ICNF 2017

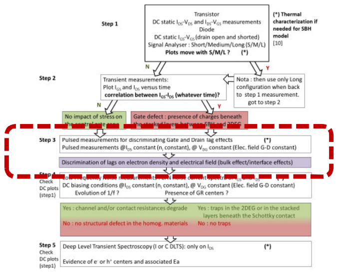




Leakage current as marker of failure events ! S_{ig} also gives a finest signature of carrier’s path/interactions in the control zone and lateral/vertical leakage zones

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

▶ CASE STUDY: AlGaN/GaN GH50 & GH25-10 (UMS)

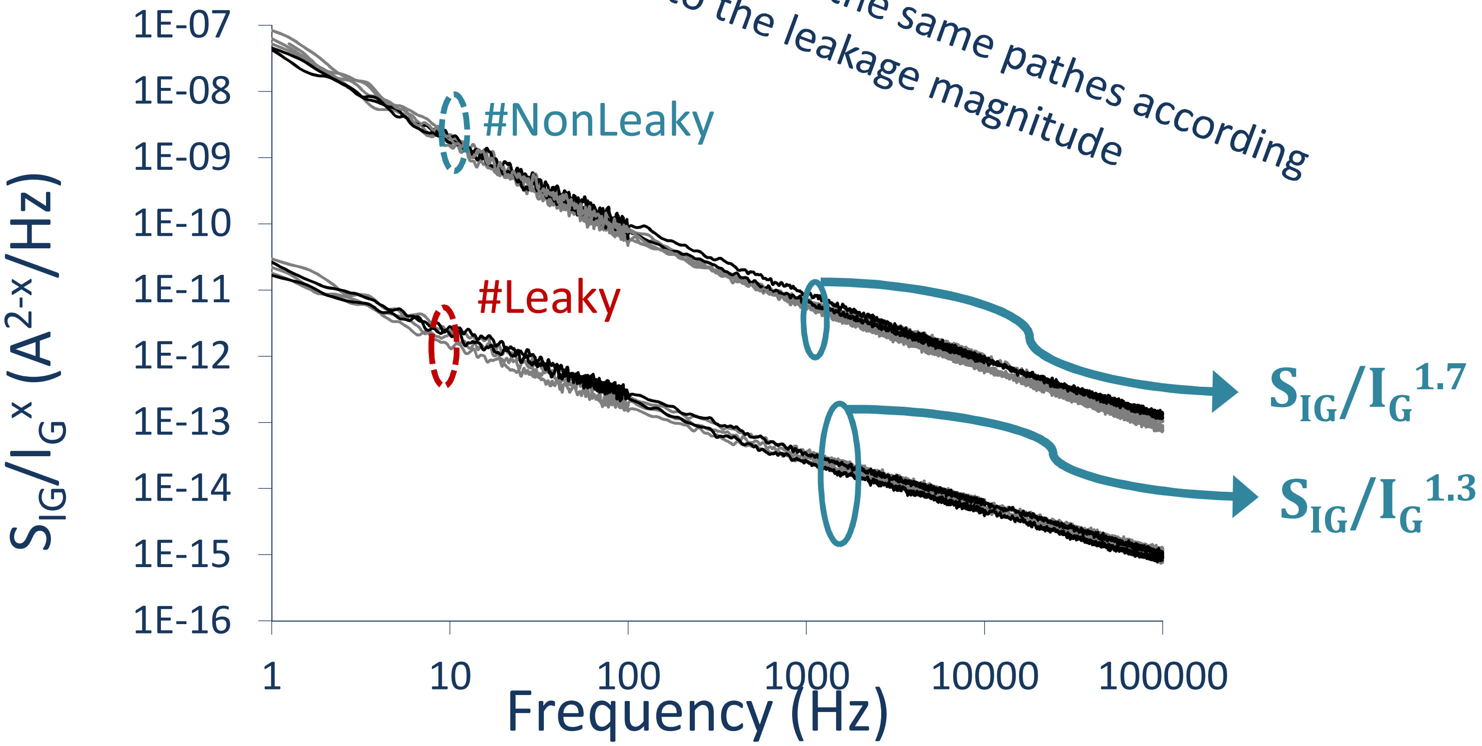


Noise spectroscopy

-diode alone

-transistor mode

But not the same pathes according to the leakage magnitude



▶ LFN

(#Leaky and #NonLeaky)

dim. 0,5x4x400µm²

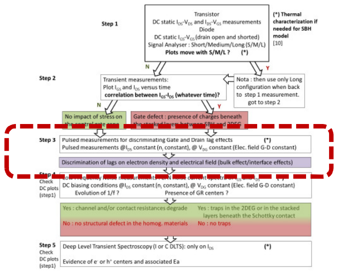
-diode alone

-transistor (saturated) mode

i.e. same leakage mechanisms, same defects in **Transistor** and **Diode** biasing mode

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

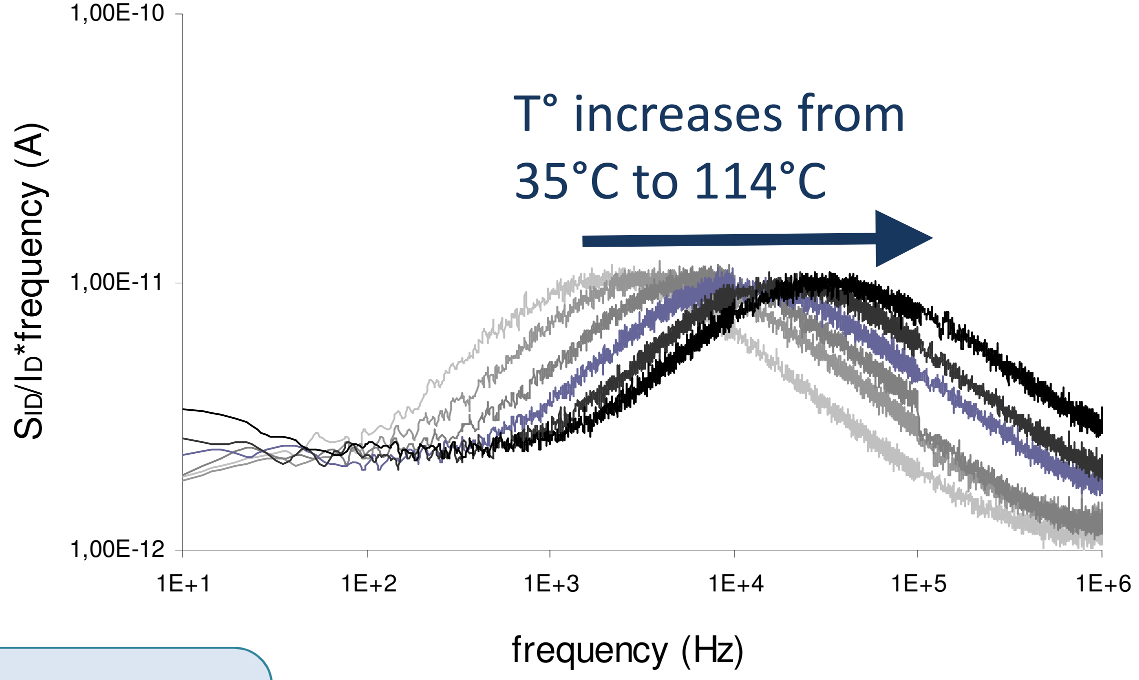
▶ CASE STUDY: AlGaN/GaN GH50 & GH25-10 (UMS)

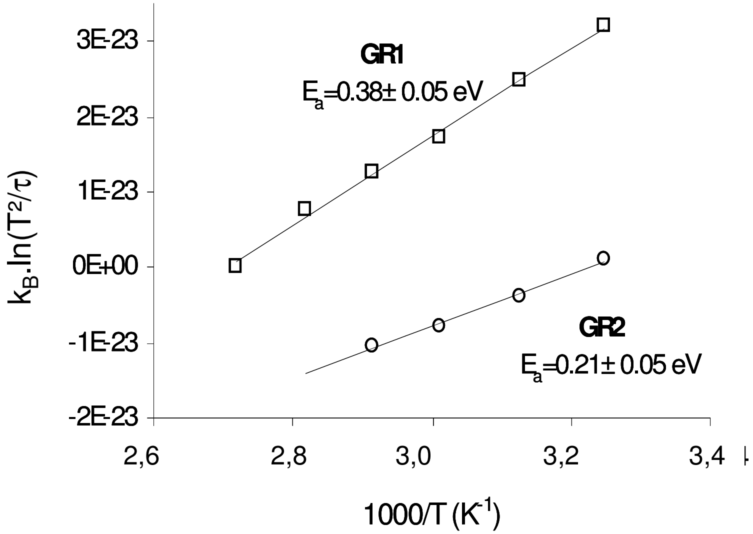


Noise spectroscopy

- ▶ The magnitude of S_{ID} x frequency is constant
- ▶ Extraction of GR_1 and GR_2 from each GR ‘bulge’ (T°)
- ▶ Extraction of E_A from Arrhenius plots

GR centers evolution vs temperature (saturated zone)





E_{A1}=0.38 ± 0.05 eV

E_{A2}=0.21 ± 0.05 eV

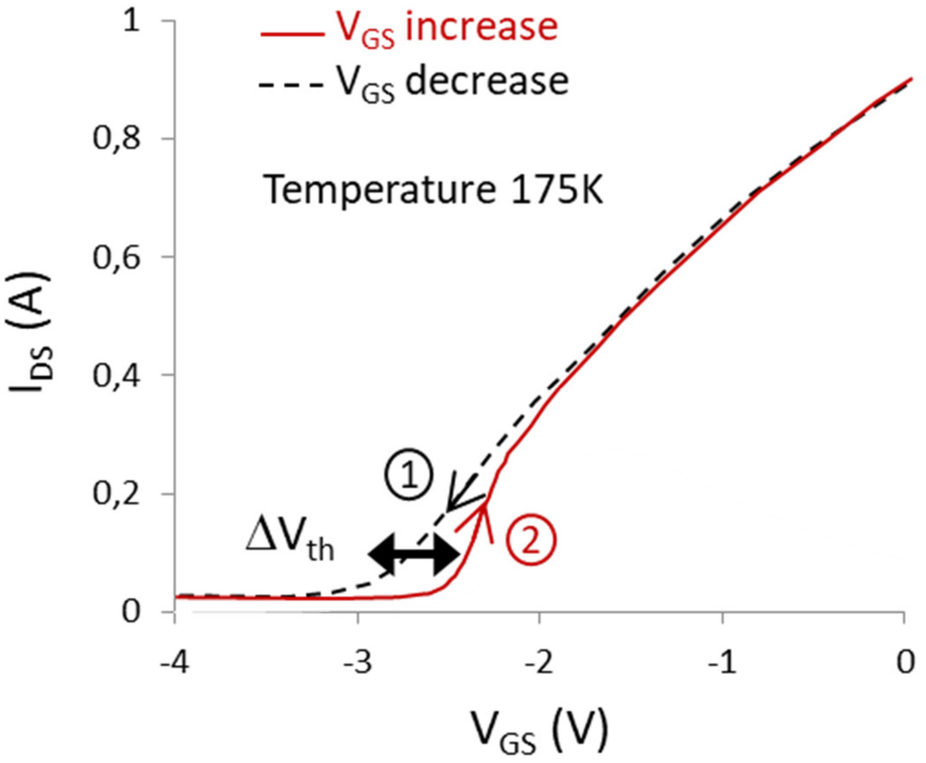
Ref : Soubercaze IEEE MTTS 2006

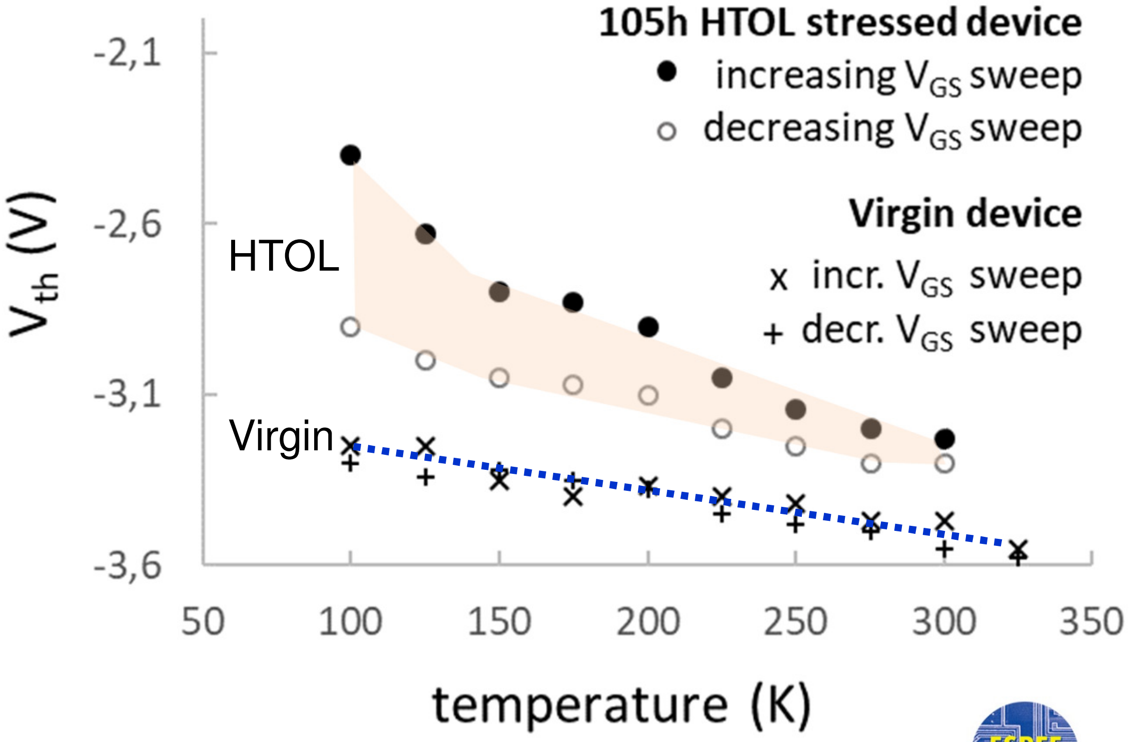
Thermal charac: V_{th} drift

(incr. decr. V_{GS} sweeps)

. V_{th} also depends on the sweeping conditions for V_{GS}

. Sweeping conditions (increasing/decreasing V_{GS})





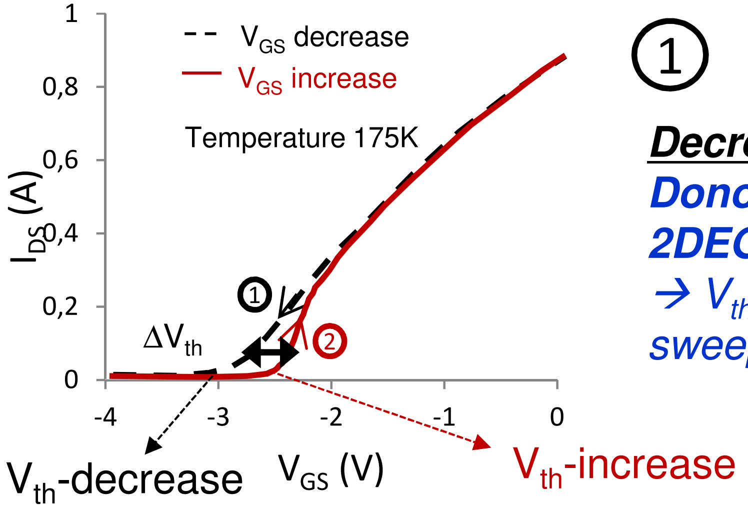
ESREF 2020

Thermal charac: V_{th} drift

(incr. decr. V_{GS} sweeps)

- V_{th} drift depends on V_{GS}↗ or ↘ sweeping condition

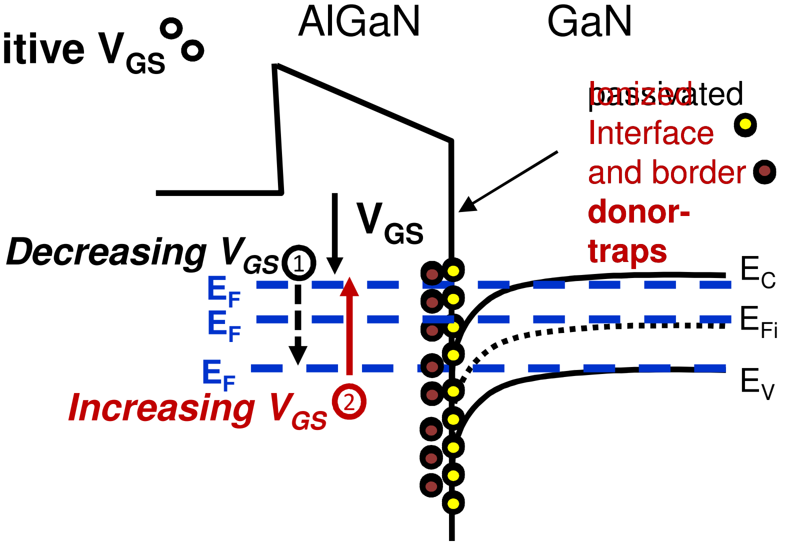
ΔV_{th}=0,1V @ 200 K
ΔV_{th}=0,5 @ 100 K



① **donor-traps are passivated at positive V_{GS}** ○ ○

<u>Decreasing V_{GS} from +3V to -6V:</u>
Donor remain passivated till the 2DEG is fully depleted
→ $V_{th\text{-}decr.}$ is not modified during V_{GS} sweep (so $n_{i\text{-}decr.}$ in the 2DEG)

<u>@ reversed V_{GS}, donors are ionized</u>

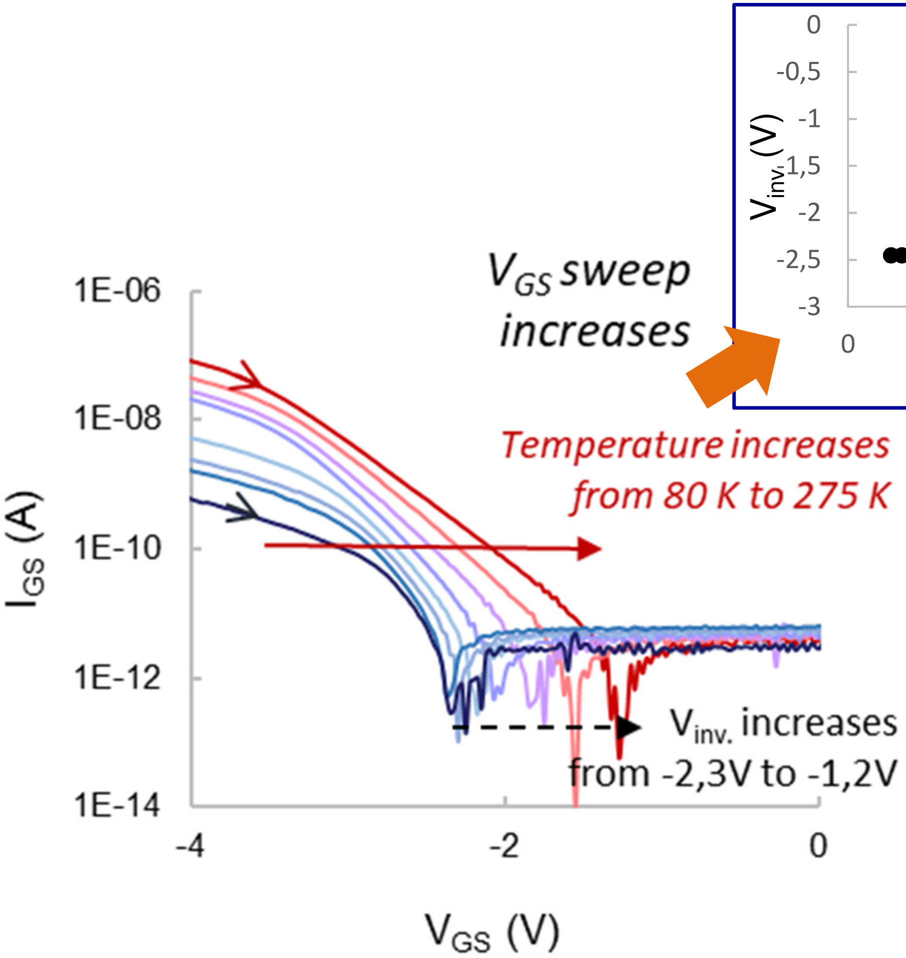


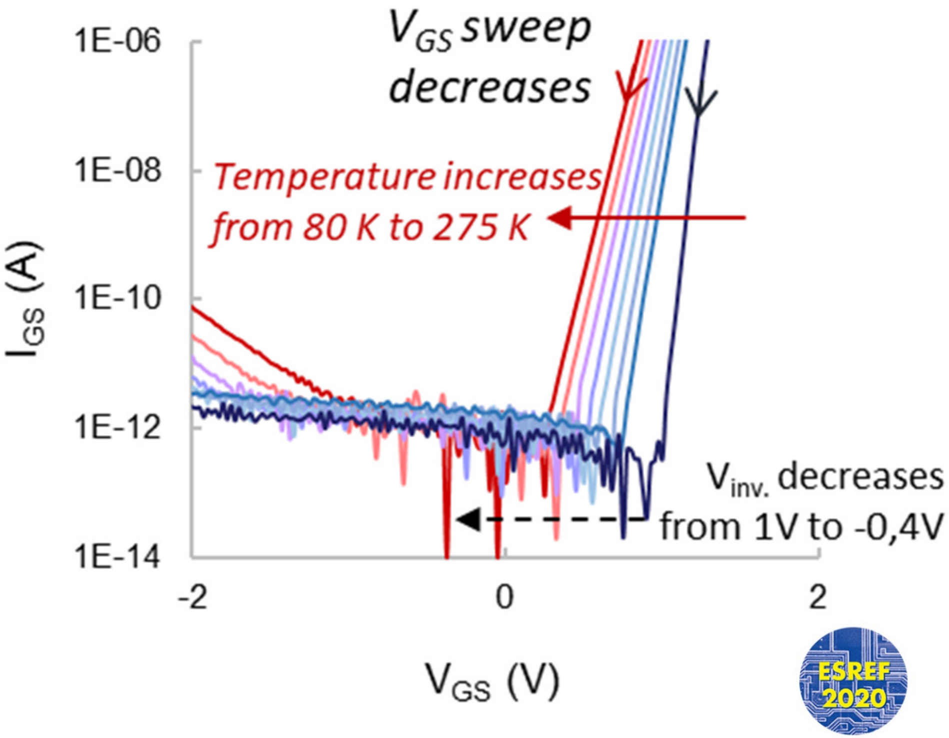
② **donor-traps are ionized at very negative V_{GS}** ● ●

<u>Increasing V_{GS} from -6V to +3V:</u>
***<u>Donor are ionized (N_D^+) at very low V_{GS}</u>**. These positive charges act as an **internal generator which field is opposite to the applied voltage V_{GS}**, and **$V_{th\text{-}incr.}$ > $V_{th\text{-}decr.}$** (thus $n_{i\text{-}incr.} < n_{i\text{-}decr.}$), till $V_{th\text{-}incr.}$. **When the 2DEG starts to conduct electrons, <u>ionized donor-traps</u> recombine with electrons from the 2DEG** (few electrons that do not change ni), **and <u>become passivated</u>**. The **internal generator disappears and V_{th} changes to a lower value as for the decreasing sweep**)*

Thermal charac: $V_{inv.}$ drift
(incr. decr. V_{GS} sweeps)

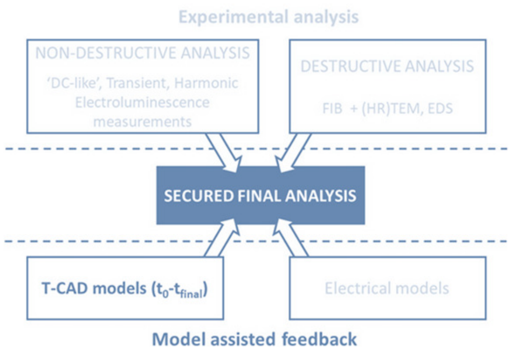
- Also noticed : $V_{inv.}$ drifts with temperature and depends on V_{GS} sweep direction





Reliability studies; example of an academic methodology and tools for non destructive defect analysis

► CASE STUDY: AlGaN/GaN GH50 & GH25-10 (UMS)


Experimental analysis

NON-DESTRUCTIVE ANALYSIS
'DC-like', Transient, Harmonic
Electroluminescence
measurements

DESTRUCTIVE ANALYSIS
FIB + (HR)TEM, EDS

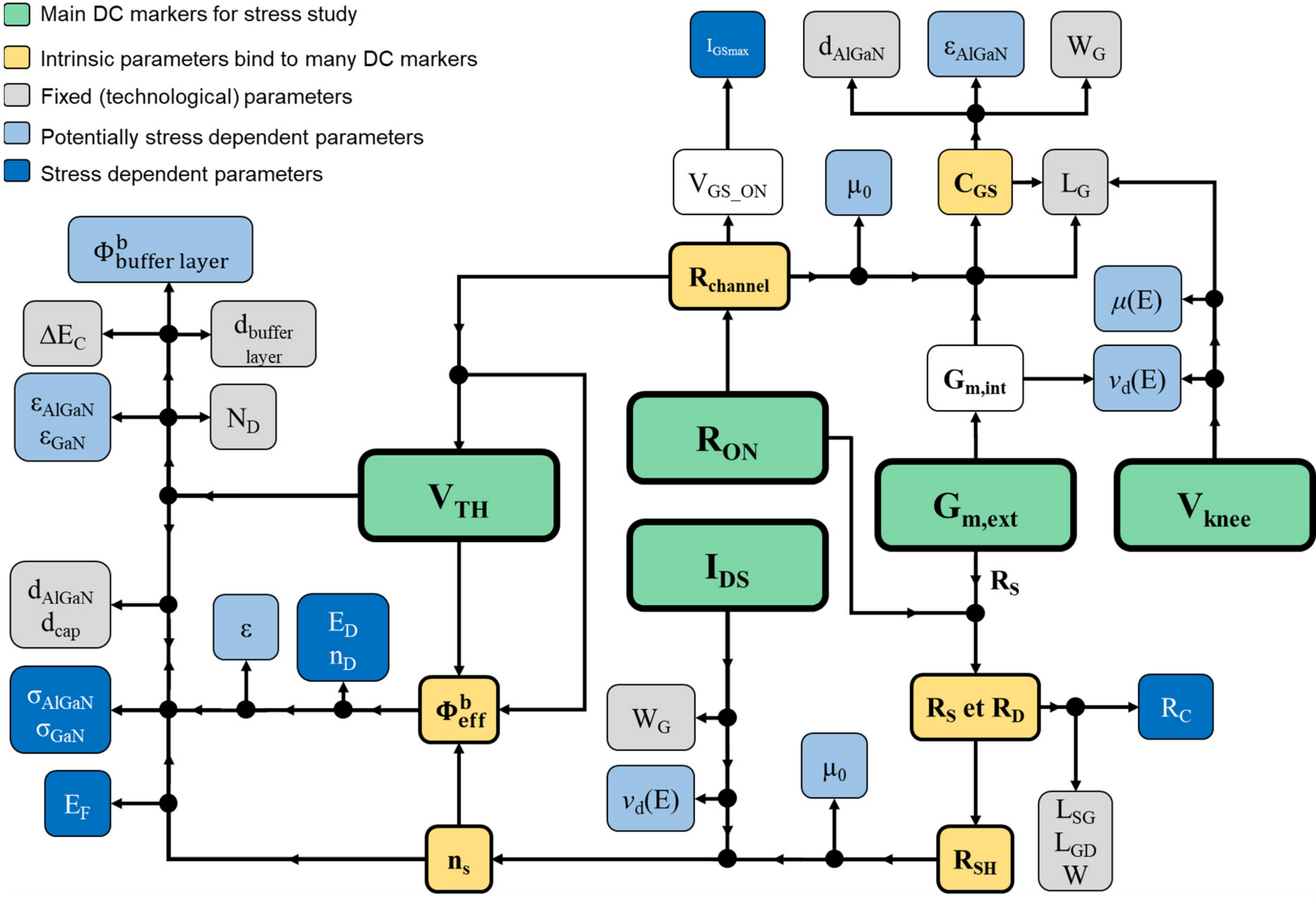
SECURED FINAL ANALYSIS

T-CAD models (t_0-t_{final})

Electrical models

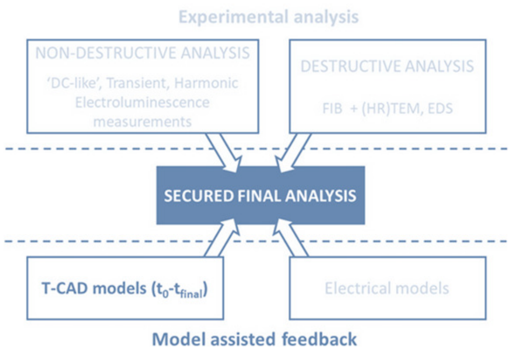
Model assisted feedback

► Considering an accurate procedure for T-CAD model instruction


- 🟩 Main DC markers for stress study
- 🟨 Intrinsic parameters bind to many DC markers
- ⬜ Fixed (technological) parameters
- 🟦 Potentially stress dependent parameters
- 🟦 Stress dependent parameters

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

▶ CASE STUDY: AlGaN/GaN GH50 & GH25-10 (UMS)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T-CAD models (t_0-t_{final})

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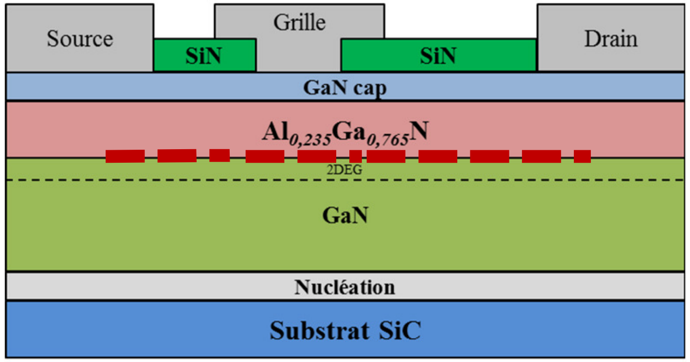
SENTAURUS Software

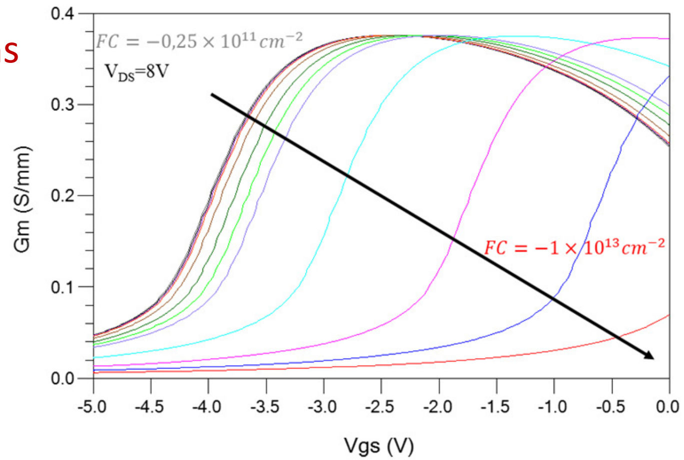
Fixed Charges variations @ interfaces (ΔFC)

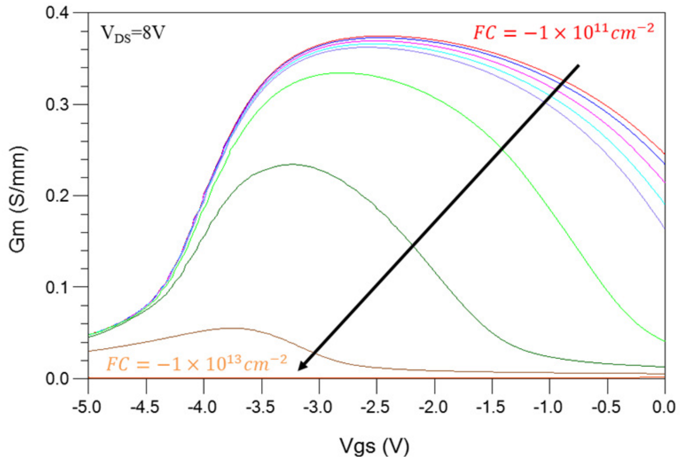


ΔFC at AlGaN/GaN/2DEG are the more sensitive *(vs AlGaN/GaN GaNcap or GaNcap SiN)*

$\Delta FC=3.10^{12}\ cm^{-2}$ explains both

- *1V V_{th} shift*
- *30% I_{DS} reduction*





Reliability studies; example of an academic methodology and tools for non destructive defect analysis

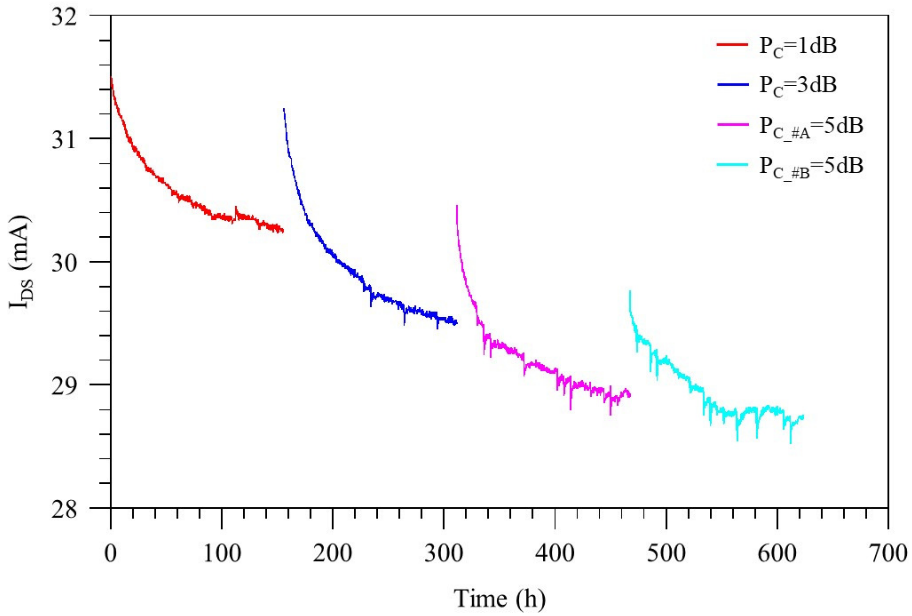
▶ RF-stresses of HEMT at x-dB compression (AlGaN/GaN 2x0,15x50µm²)

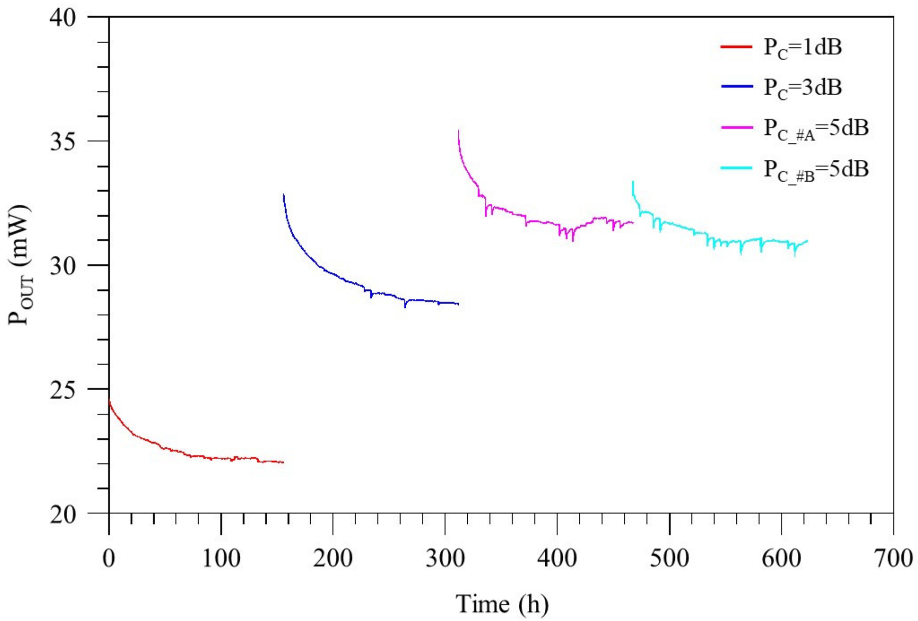
-Under 1dB, 3dB, 5dB output compression, also tracking [S] parameters

Static-Dynamic correlations: ORIGIN(S) of the defects (direct proof? Speculative assumptions?)

Static+RF+[S]-param → useful for technological development to remove speculative assumptions on degrad. Origin

- ▶ RF stresses @P_{xdB}, each for a 156h period (624h cumulated)
- ▶ 3 D.U.T.s biased under V_{DS}=15V & I_{DS}=0,33 A/mm, class A operation





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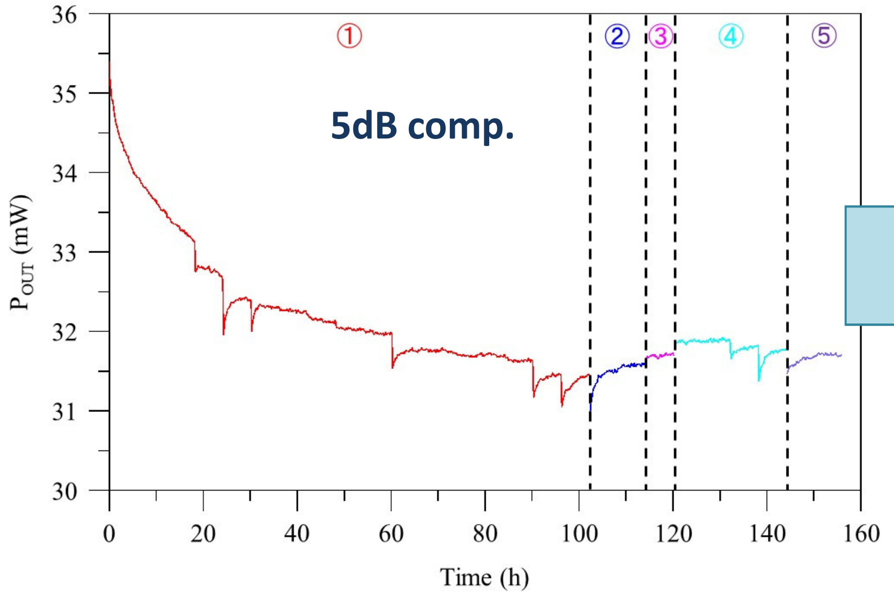

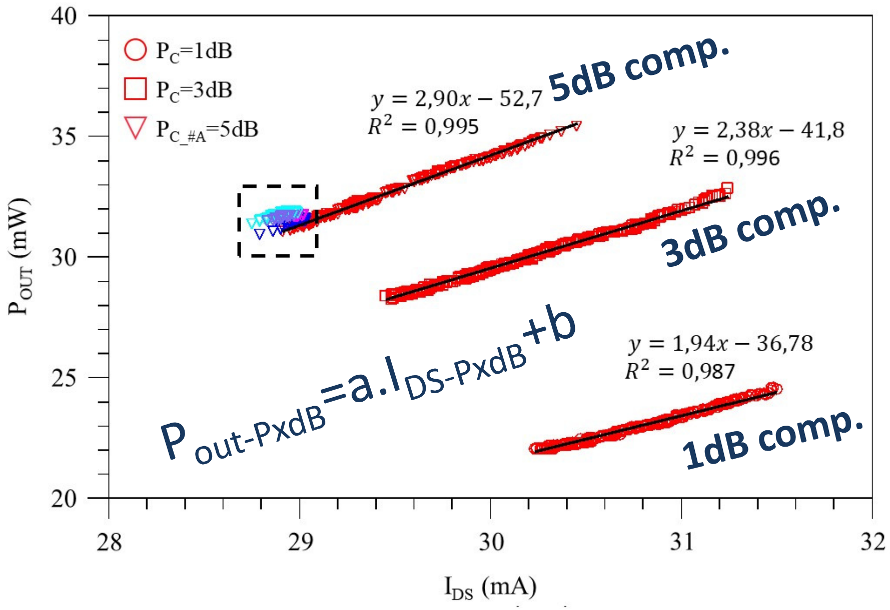

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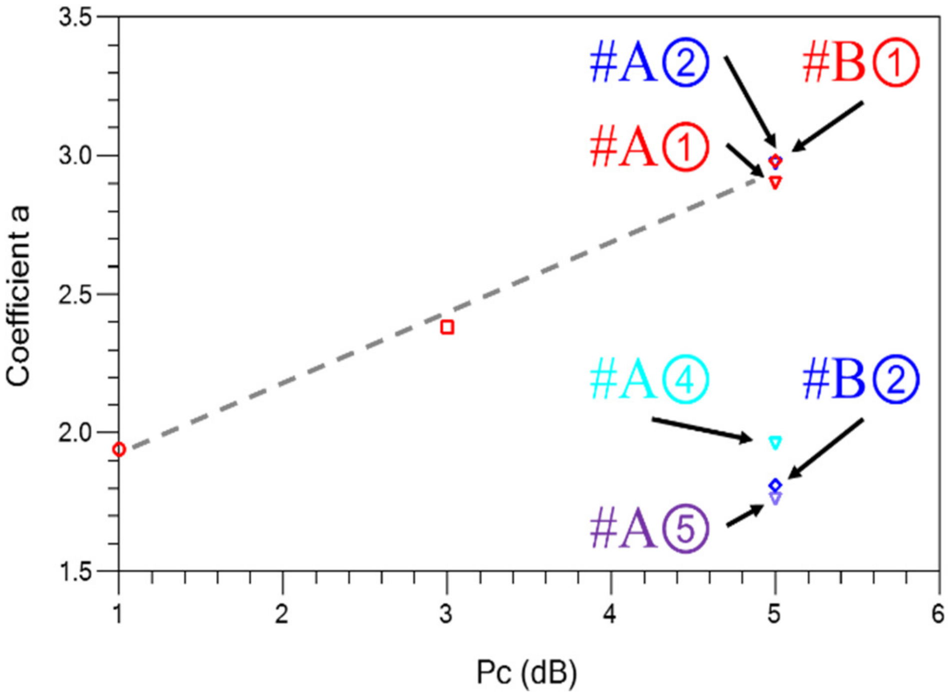
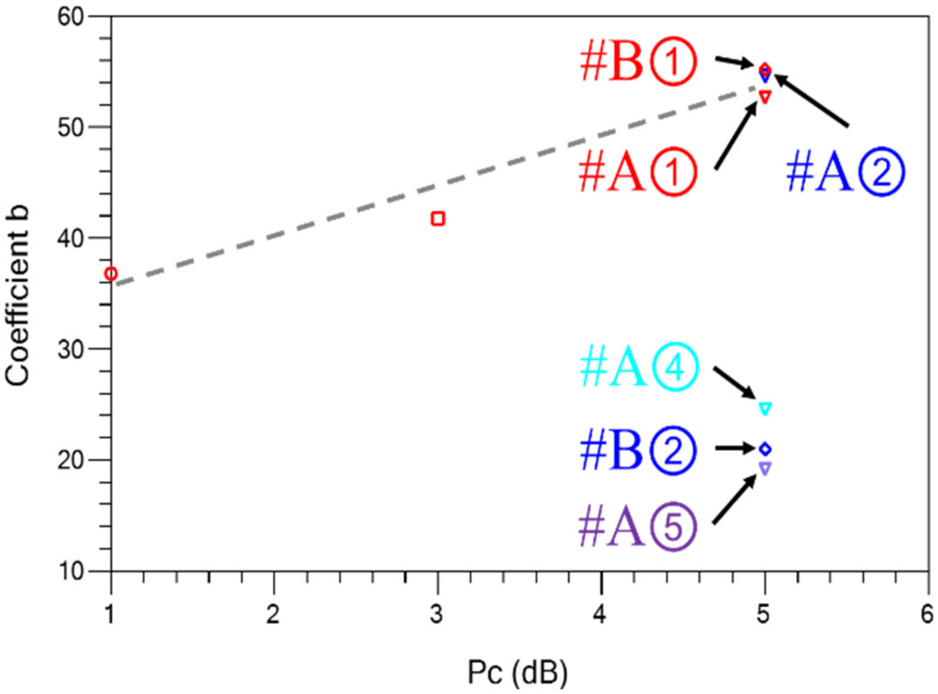
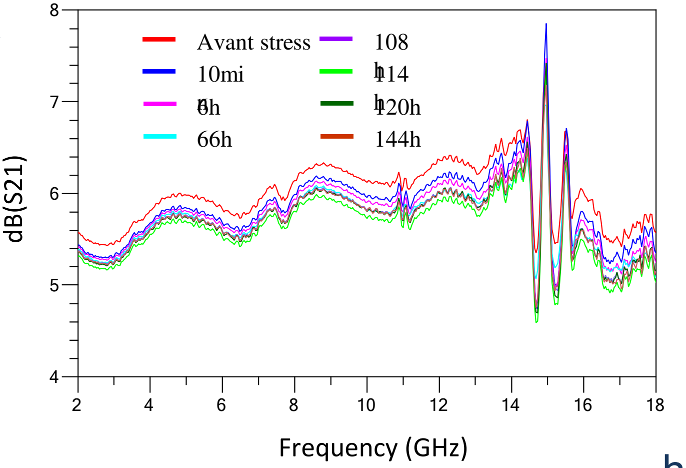


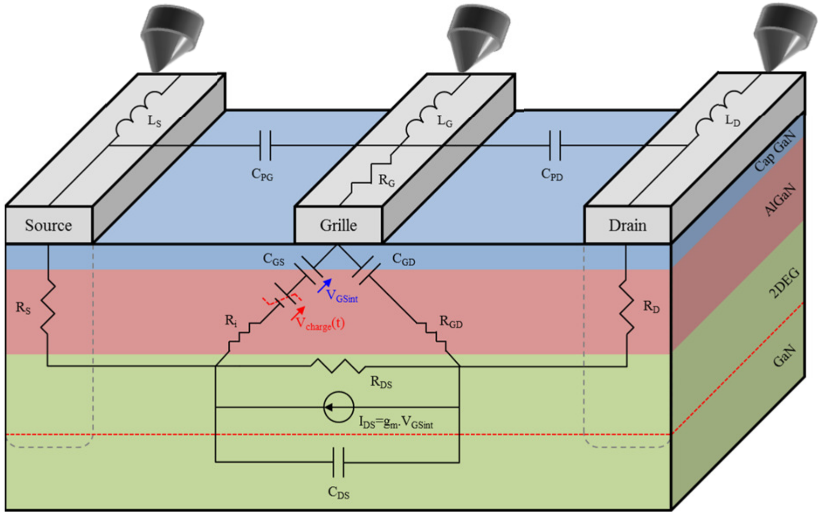


Reliability studies; example of an academic methodology and tools for non destructive defect analysis

- ▶ RF-stresses of HEMT at x-dB compression (AlGaN/GaN 2x0,15x50µm²)
- ▶ S21 variations correlated to P_{OUT} & I_{DS}

S_{11}, S_{12} & S_{22} parameters are stable
→ C_{GS}, C_{GD}, C_{DS}, R_{GD} & R_i
not modified by stress
(all dev. under test)





Where do variations on S_{21} come from ?

$S_{21} \rightarrow g_m.V_{GSint}$ ← $V_{int}(t) = V_{GSext} - V_{charge}(t)$

hyp. ①

Hyp. ②

Charge variations under the gate $V_{charge}(t)$

Change in biasing conditions
(cf. shift in V_{GSext} to get the same I_{DS} !)

S_{11} does not change versus time during 1dB, 3dB, 5dB#A, 5dB#B
S_{21} changes (beginning, then stable) → change in V_{GS} to keep I_{DS}

$\left.\begin{array}{l} C_{GS} \\ C_{GD} \\ R_i \end{array}\right\}$ unchanged

→ **Intrinsic charges under the gate modify the intrinsic $V_{GS\text{-}int}$ controlling the 2DEG**

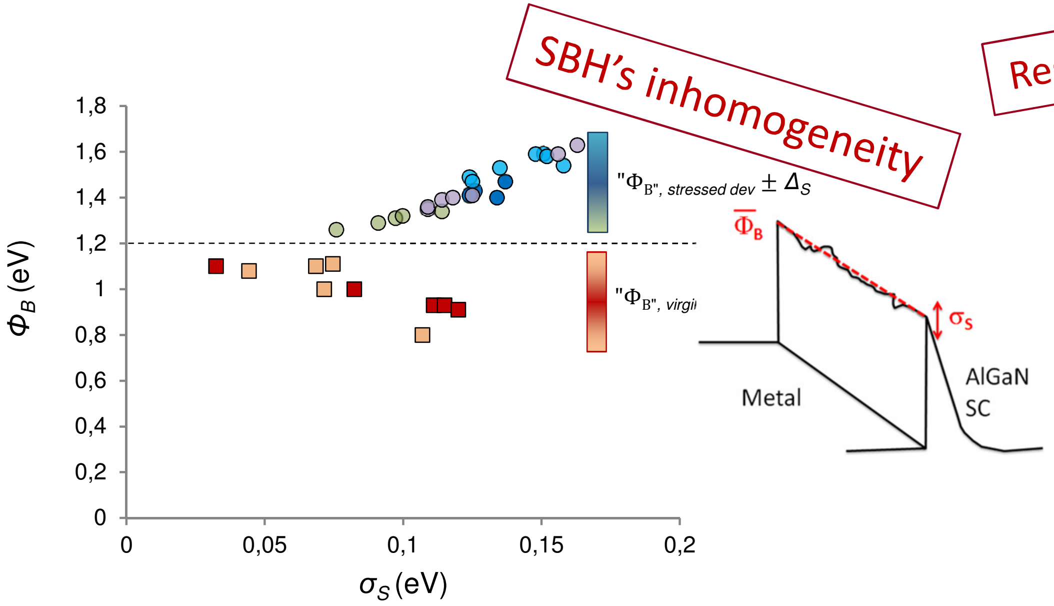
Reliability studies; example of an academic methodology and tools for non destructive defect analysis

- ► Assessment for location and nature of defects (but destruction of device)

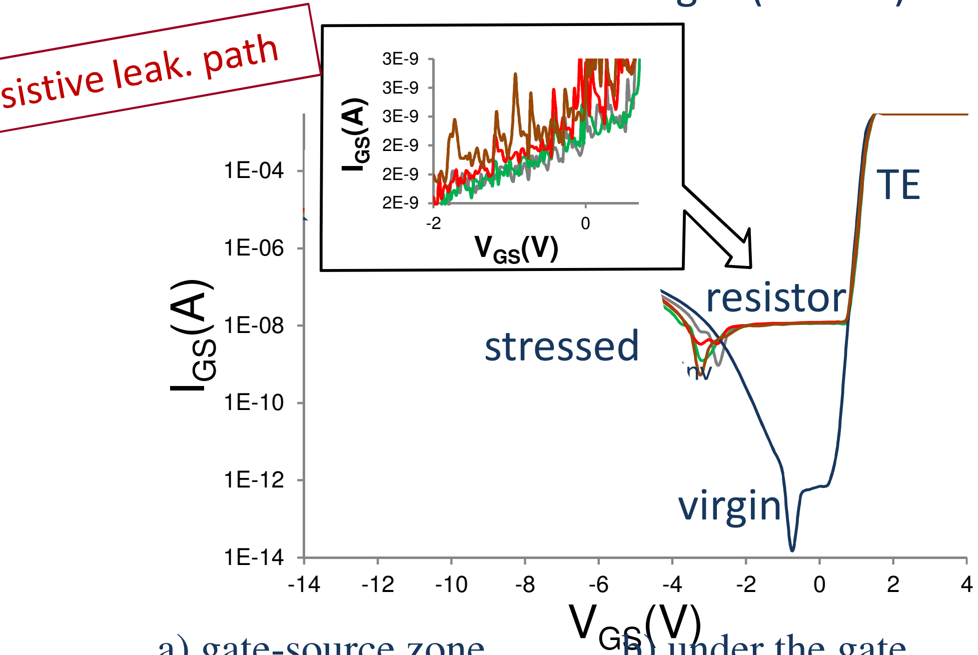
Destructive tests performed by DGA (French DoD) and SERMA

Top view of the gate finger

STEM-HAADF images (FIB cut)



TEM lamella (after removing the gate pad)



a) gate-source zone

b) under the gate zone

Ref : Lazar, IEEE IMS 2013

Ref : Tartarin, ESREF 2017

Reliability studies; example of an academic methodology and tools for non destructive defect analysis

- Assessment for location and nature of defects (but destruction of device)

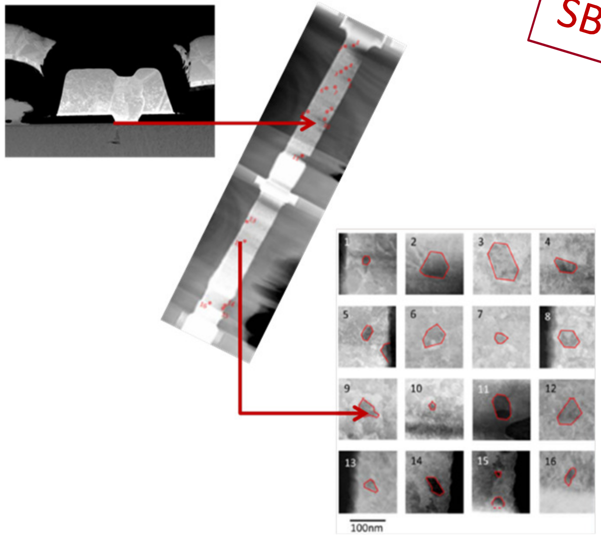
Destructive tests performed by DGA (French DoD) and SERMA

Top view of the gate finger

STEM-HAADF images (FIB cut)

SBH’s inhomogeneity

Resistive leak. path



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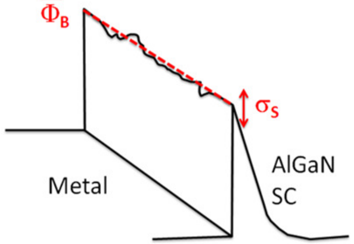
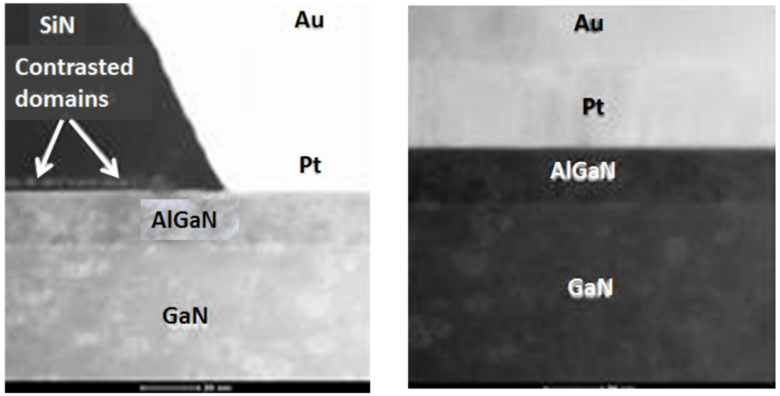




a) gate-source zone

b) under the gate zone

Ref : Lazar, IEEE IMS 2013

Ref : Tartarin, ESREF 2017

PLAN DE LA PRÉSENTATION

LES OUTILS DU LAAS, L'EXPERIENCE et LE POSITIONNEMENT NATIONAL/INTERNATIONAL

LES PROJETS DEPUIS 2002 + SUIVI DES ÉVOLUTIONS TECHNOLOGIQUES GaN
(substrats SiC, Si, GaN, Diamant)

QUELQUES CAS D'ÉTUDES

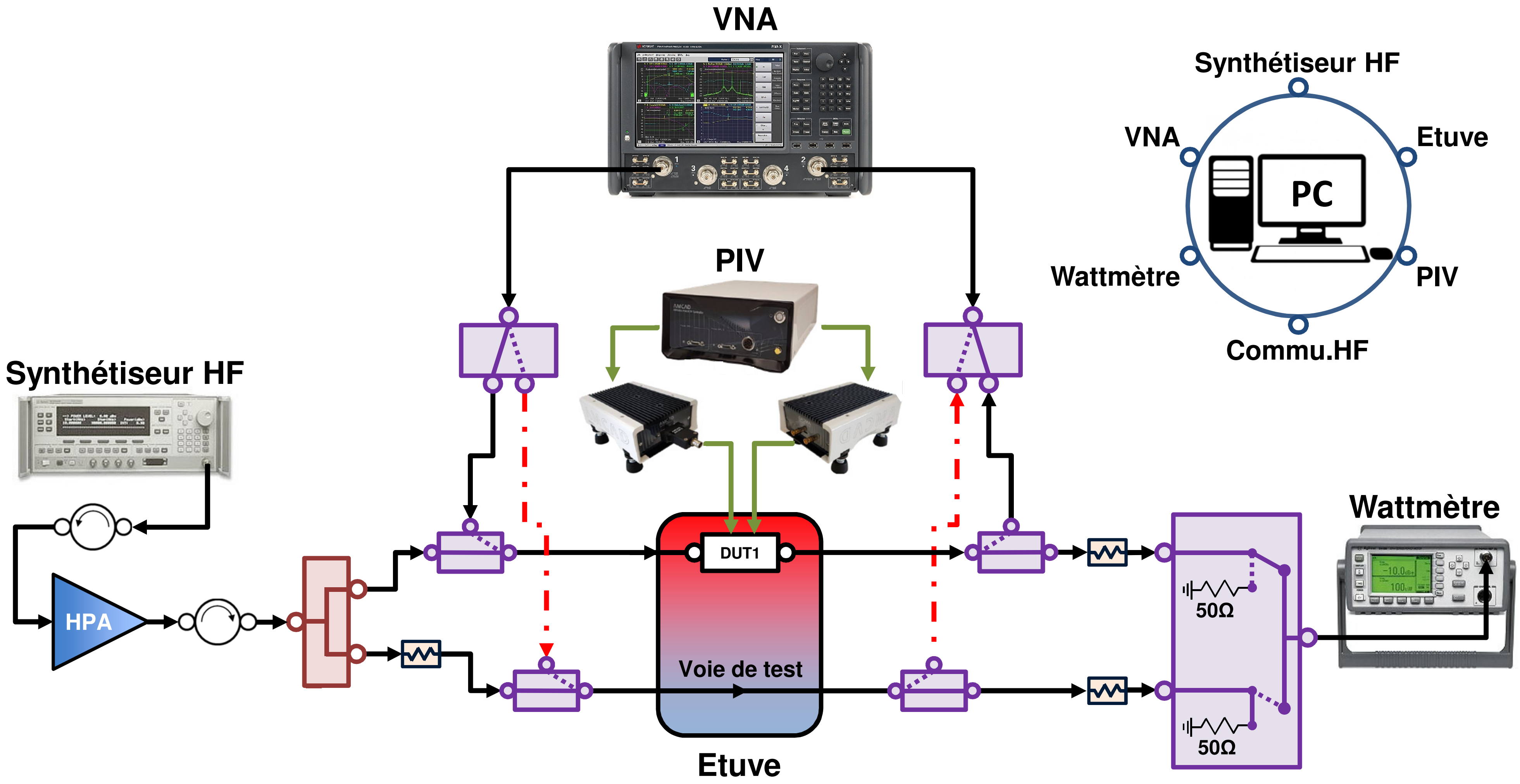
LES PROSPECTIVES ET LES OPPORTUNITÉS VIA PROOF

SYNTHÈSE et DISCUSSIONS

Evolution du banc de vieillissement

Synoptique général banc de vieillissement thermique à haute fréquence

Configuration stress circuit en mode pulsé

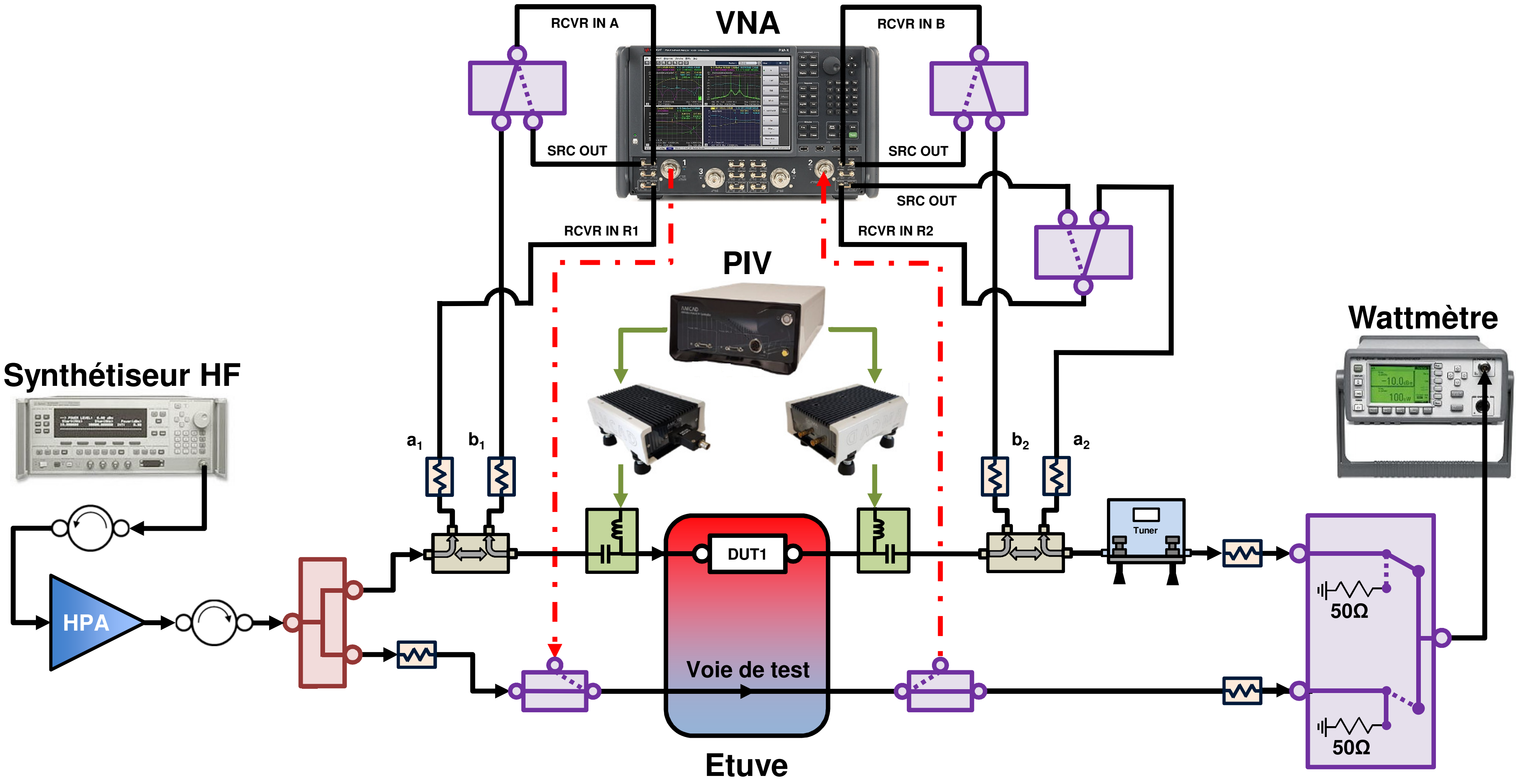


DUT : Device Under Test HF : Haute Fréquence VNA : Vector Network Analyzer PIV : Pulsed I(V)

Evolution du banc de vieillissement

Synoptique général banc de vieillissement thermique à haute fréquence

Configuration Load Pull stress transistor en mode pulsé



DUT : Device Under Test HF : Haute Fréquence VNA : Vector Network Analyzer

positionnement au niveau national et international (plat. PROOF)

Collaborations par projet possibles avec Labo. (inter)nationaux

-**BRUIT HF (IEMN – couverture très hautes fréquences jusqu'à 300 GHz):**
(LAAS 1-40 GHz, pas de spécificité LAAS sur les 4 param. de bruit)
PROOF → banc de stress avec NF50 intégré au VNA (LAAS)

-BRUIT BF (XLIM et IMS - aquitaine):
LAAS référencé centre Européen (4 bancs, LFN + RTN – S_{ID} & $\mathbf{S_{IG}}$).
LAAS : Nombreuses études de cas multi-physiques (DC, transitoire, pulsé, param. S, TCAD)
PROOF → analyses de reprises durant stress (analyse fine des évolutions des défauts)

-**Analyse pulsée P2P (IEMN et XLIM): bancs sous pointes solution AMCAD**
PROOF : PIV-param-S pulsés INTÉGRÉ au banc de stress RF – thermique (unique)
Ajout mesures émulation « multi-porteuses par bruit blanc » (court/moyen terme)
Selon besoins, analyses multi-signaux EVM-APCR-NPR (diag. Œil) –selon intérêt partenaires et financement – toujours en approche STRESS RF

-Analyse de fiabilité (IMS et LPN)
PROOF : STRESS RF +thermique avec mesures intégrées $S_{pulsées}$, NF50, PIV
mesures de reprises LFN et
PULSÉ : - sous pointe @ Temp.stress constante (1 voie)
- en boitier avec cyclage thermique (1 voie, sinon duplication des PIV pour chaque voie)
CW (déjà en place [S-CW]) : possibilité d'aménagement [S-pulsé] et NF50 en mesures intermédiaires (effets de charges en quasi isotherme) sur 4 voies.

PLAN DE LA PRÉSENTATION

SYNTHÈSE et DISCUSSIONS